Global marine heatwave events using the new CMIP6 multi-model ensemble: from shortcomings in present climate to future projections

Sandra M Plecha and Pedro M M Soares

Instituto Dom Luiz (IDL), Faculdade de Ciências da Universidade de Lisboa, Campo Grande, Lisbon, Portugal

E-mail: smplecha@fc.ul.pt

Keywords: sea surface temperature, extreme events, climate change, global climate models

Abstract

In recent years, research related to the occurrence of marine heatwave (MHW) events worldwide has been increasing, reporting severe impacts on marine ecosystems which led to losses of marine biodiversity or changes in world fisheries. Many of these studies, based on regional and global coupled models, show relevant biases in the MHW properties when compared with observations. In this study, the MHW frequency of occurrence, the duration and mean intensity over the global oceans are characterized, taking advantage of the new global climate model (GCM) dataset, from the Coupled Model Project Intercomparison Phase 6 (CMIP6). The MHWs result for the historical period are compared with observations, and the future projected changes are characterized under three socioeconomic pathways (SSPs) (SSP1, SSP2 and SSP5), for the middle and end of century (2041–2070 and 2071–2100). The results show a reasonable agreement between the modeled and observed MHW property trends, indicating increases in the frequency, duration and intensity of MHWs along the historical period. For the period 1982–2014, both the ∼2 mean observed events per year and the mean intensity of 0.35 °C above the threshold are underestimated by the multi-model ensemble (MME) mean by 21% and 31%, respectively, while the observed duration of ∼12 d are overestimated by 100%. The future MHWs are expected to increase in duration and intensity, where a near permanent MHW occurs with reference to the historical climate conditions, mainly by the end of the 21st century. The future MHWs intensity, projected by the MME mean, increases in the range of 0.2 °C to 1.5 °C, from the least to the most severe pathways. The GCMs biases obtained with CMIP6 revealed to be in line with the CMIP5 biases, reinforcing the need to use high spatial resolution models to characterize MHW.

1. Introduction

In recent years, several studies reported a worldwide occurrence of sea surface temperature (SST) extremes prolonged in time. These extremes called marine heatwaves (MHWs [1]), can have substantial impacts over extended areas persisting for several months [2]. Severe impacts on ecosystems and economy have been reported such as damages and losses of marine biodiversity [3–9] or changes in world fisheries and aquaculture industries [6, 10–13].

To better understand and characterize MHW events it is imperative to rely on SST long records, which allow to compute the local climatology and detect MHWs through the SST persistent exceedance of a certain local. Several authors [1, 14–17] based their global MHWs research on the National Oceanic and Atmospheric Administration Optimum Interpolation Sea Surface Temperature (NOAA OISSTV2) analysis, which is a composite of several observational platforms (satellites, ships, buoys and Argo floats) interpolated to a regular global grid [18]. This dataset is available since 1982 until the present and includes daily SSTs at 0.25° spatial resolution. All studies show global increases of the frequency, duration and intensity of MHW events over the recent past climate. Based on NOAA OISSTV2 data [17], showed that over the last century, the global MHW frequency
and duration increased on average 34% and 17%, respectively, pointing to 30 additional MHW days per year by the end of the 1982–2016 period. The authors observed that the highest increase in the number of the events occurred in the northern latitudes of the North Atlantic Ocean, while in the highest latitudes of the Southern Ocean the frequency decreased. During this period, the events intensity also increased over 65% of the global ocean, mainly in regions characterized by large SST variability. Based on the fifth phase of the Coupled Model Intercomparison Project (CMIP5) it is projected that the MHWs intensity and duration under the effects of global warming [2, 16] increase significantly.

The analysis of the future MHW properties under climate change is performed using SST projections based on regional [19] or global [2, 16] coupled models. These projections should be preceded by the evaluation of the MHW representation by the global climate models (GCMs) or Earth system models (ESMs), at the global and regional scales, in the present climate historical period. Based on the comparison of Coupled Model Project Intercomparison Phase 5—(CMIP5) multi-model dataset and observations [16], identified substantial biases in the duration, cumulative mean intensity and absolute spatial extent patterns, resulting in longer and more extensive events than those observed. Similarly [2], also based on CMIP5 GCMs obtained MHWs slightly longer and less intense than the observed. The associated future projections revealed considerable increases in MHW durations and intensities that could lead to a near-permanent MHW state by the end of 21st century [2, 16, 19].

In the current study, we analyze and characterize the global MHW projections taking advantage of the recent generated multi-model ensemble (MME) of GCMs, from the CMIP Phase 6—(CMIP6). This dataset has available 12 GCM results of daily SSTs that allow a critical view of the models performance when compared with observations, for the present historical climate. In this way, a comparison of the MHW properties between observations and simulations is performed, for the 1982–2014 (NOAA OISSTV2) and for 1971–2014 (CMIP6) periods. Subsequently, the analysis of the future MHW properties is conducted for the mid and end of the 21st century, composed by two 30 year periods between 2041 and 2100.

2. Data and methods

In the current study, the MHW identification method proposed by [1] is followed. This consists in detecting in a location a daily SST above a threshold, for at least five consecutive days. Consecutive events with a maximum gap of 2 d between them are considered as the same event. The threshold is defined as the SST 90th percentile of a 30 year period record and is calculated at each grid cell for each calendar day within an 11 d window centered on the calendar day of interest across all years, and then smoothed using a 31 d moving average on each Julian day.

As present climate the National Oceanic and Atmospheric Administration Optimum Interpolation Sea Surface Temperature V2 data, hereafter NOAA OISSTV2 (used as the baseline observations) is considered. The future projections are based on the available GCM data collected from the CMIP6 multimodel database [20]. The SST data and MHW characteristics are analyzed over 37 year for observations (1982–2018) and over three periods for CMIP6 GCMs: a historical period of 1971–2014 and two periods of future climate 2041–2070 (mid century) and 2071–2100 (end century). Since there is a 33 year common period between observations and the CMIP6 historical run, the MHW properties are also inspected for the period between 1982 and 2014. The 30 year period used to compute the historical baseline climatology, and therefore, the threshold of daily SST records is 1983–2012. In order to identify and characterize future MHWs, the SST threshold obtained for the 30 year climatic period of 1971–2000 is used, in order to characterize the future changes with respect to a historical reference period.

The NOAA OISSTV2 dataset is derived from remotely sensed SST by the Advanced Very High Resolution Radiometer (AVHRR) and is available within a regular grid of 1/4° × 1/4° [18]. The SST global climate model data is collected from 16 ESMs (see tables 1 and S1 (is available online at https://stacks.iop.org/ERL/15/124058/mmedia), variable name tos) available for all periods studied. As described in table S1, the GCMs analyzed have spatial and ocean native nominal resolutions spanning from approximately 1° to 5° in the atmosphere to approximately 0.25° to 2.5° in the ocean (https://wcrp-cmip.github.io/CMIP6_CVs/docs/CMIP6_source_id.html). Also in table S1 are listed the equilibrium climate sensitivity (ECS, long term time scale) and the transient climate response (TCR, short term time scale) (when available [21, 22]), which are indicators of the temperature increase under an atmospheric carbon dioxide doubling. According to both indicators, the NESM3, CanESM5 and both EC-Earth3 models are expected to be more susceptible to temperature increases due to their high climate sensitivity.

Both NOAA OISSTV2 dataset and model’s SST daily data are interpolated to a common grid of 1° × 1° resolution using the nearest neighbor remapping, in order to allow direct comparisons between them. The MHWs properties were computed for both spatial resolution grids and as can be observed in the last two rows in table 1, the relative difference by interpolating the NOAA OISSTV2 data into a coarser grid is 0.05 events per year, 0.26 d and 0.01 °C, for the frequency, duration and intensity, respectively. Three future scenarios are considered following
| Model           | Frequency | Duration | Intensity |
|-----------------|-----------|----------|-----------|
| ACCESS-CM2      | Mean      | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 1.40      | −0.60    | 0.62      | 0.81        | 25.48     | 12.63    | 12.65     | 0.82        |
| ACCESS-ESM1-5  | Mean      | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 1.37      | −0.64    | 0.67      | 0.81        | 28.49     | 15.62    | 15.68     | 0.90        |
| AWI-CM-1-1-MR  | Mean      | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 1.71      | −0.33    | 0.45      | 0.72        | 20.74     | 7.94     | 8.19      | 0.69        |
| CanESM5         | Mean      | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 1.53      | −0.48    | 0.58      | 0.93        | 25.32     | 12.48    | 12.70     | 0.81        |
| CESM2-WACCM     | Mean      | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 1.40      | −0.61    | 0.62      | 0.75        | 26.34     | 13.51    | 13.53     | 0.82        |
| CMCC-CM2-SR5   | Mean      | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 1.52      | −0.49    | 0.53      | 0.86        | 21.30     | 8.63     | 8.81      | 0.75        |
| EC-Earth3       | Mean      | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 1.51      | −0.51    | 0.58      | 0.95        | 25.84     | 13.07    | 13.30     | 0.89        |
| EC-Earth3-Veg   | Mean      | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 1.52      | −0.49    | 0.54      | 0.83        | 23.05     | 10.31    | 10.50     | 0.81        |
| KIOST-ESM       | Mean      | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 1.43      | −0.58    | 0.63      | 0.89        | 26.68     | 13.96    | 13.99     | 0.59        |
| MIROC6          | Mean      | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 1.29      | −0.69    | 0.71      | 0.83        | 29.36     | 16.83    | 16.84     | 0.52        |
| MPI-ESM1-2-HR  | Mean      | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 1.60      | −0.41    | 0.49      | 0.85        | 22.51     | 9.82     | 9.96      | 0.68        |
| MPI-ESM1-2-LR  | Mean      | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 1.46      | −0.55    | 0.58      | 0.85        | 23.40     | 10.75    | 10.87     | 0.73        |
| MRI-ESM2-0      | Mean      | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 1.43      | −0.59    | 0.60      | 0.79        | 25.45     | 12.57    | 12.60     | 0.66        |
| NEM3            | Mean      | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 2.11      | 0.07     | 0.46      | 1.01        | 15.69     | 3.10     | 4.32      | 0.85        |
| NorESM2-LM      | Mean      | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 1.54      | −0.48    | 0.52      | 0.91        | 22.48     | 9.83     | 10.00     | 0.73        |
| NorESM2-MM      | Mean      | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 1.35      | −0.66    | 0.67      | 0.77        | 26.45     | 13.74    | 13.79     | 0.70        |
| MME mean        | Mean      | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 1.56      | −0.42    | 0.46      | 0.79        | 25.18     | 12.90    | 12.91     | 0.64        |
| NOAA OISSTV2 1° × 1° | Mean  | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 1.97      | 0.07     | 0.46      | 1.01        | 15.69     | 3.10     | 4.32      | 0.85        |
| NOAA OISSTV2 0.25° × 0.25° | Mean | Bias     | MAE       | Spatial corr | Mean      | Bias     | MAE       | Spatial corr |
|                 | 2.02      | 0.07     | 0.46      | 1.01        | 15.69     | 3.10     | 4.32      | 0.85        |

Table 1. Evaluation of MHW events properties: frequency (events/year), duration (days) and intensity (°C), over the NOAA OISSTV2 and CMIP6 common period of 1982–2014, for 16 GCMs from CMIP6, MME mean and NOAA OISSTV2 (grid 1° × 1° and native grid 0.25° × 0.25°). The GCMs and MME mean bias, mean absolute error (MAE) and spatial correlation (spatial corr) are relative to the MHW properties observed.
the socioeconomic pathways (SSPs) SSP1, SSP2 and SSP5, which correspond to the Representative Concentration Pathways (RCP) 2.6, 4.5 and 8.5, respectively. All GCM data are from Run 1 (r1i1p1f1).

Once the MHW events are identified, its characterization is performed in terms of duration and mean intensity. The duration is defined as the period over which the SST is greater than the daily varying threshold value, representing the start and end dates. The mean intensity is the mean temperature anomaly relative to the threshold value during the MHW event. Additionally, globally averaged annual statistics are computed, taking into account the area-weighted method, including the number of MHW discrete events occurring in each year (frequency) and mean annual duration [17]. Furthermore, an MME mean is computed by simple averaging the CMIP6 model results.

The globally averaged time series trends were not computed by using standard trend-fitting in order to avoid biases in the slope values induced by bounded values. Thus, to estimate the magnitude of the monotonic trend the Theil–Sen’s Slope Estimator proposed by [23, 24] was used, using a confidence interval of 95%. The p-value of the significance test was determined by using the Mann–Kendall test [25].

3. Results

The globally averaged NOAA OISSTV2 data reveals positive trends for all the MHWs analyzed properties (figure 1) over 1982–2018. For the period 1982–2014, the frequency of occurrence increases at a rate of 0.52 annual events per decade; the mean duration grows 1.8 d per decade; and the mean intensity displays a positive trend of 0.03 °C per decade, resulting in an increase of 0.1 °C for the 33 year record.

As illustrated in figure 1, the MHW trend values obtained from the MME mean are similar to those with NOAA OISSTV2, particularly for the frequency and intensity. The frequency increases at a rate of 0.61 annual events per decade over 1982–2014, which is equivalent to an average increase of 2.0 annual events over the 33 year period. The trend value of the events duration is three times over the observed, corresponding to an increase of 5.62 d per decade. The MHWs intensity has approximately the same positive trend value of the observed: 0.04 °C per decade.

The CMIP6 values of the frequency of occurrence are consistent with those observed along the common period of 1982–2014, ranging from 0.5 to 4.0 annual events. However, an important spread amongst models is visible. Both observed and simulated MHW mean durations overlap during the first 15 years, diverging after that period with larger durations obtained with the CMIP6 data. Concerning the events intensity, most of the models underestimate the global average intensity when compared with the one observed, with the exception of the NESM3 model, which overestimates the NOAA OISSTV2 MHW intensities. Along with the overestimation of the MHWs intensity value, the NESM3 model also is characterized by simulating higher slopes in the intensity (0.036 °C per decade). However, the largest slopes are obtained with EC-Earth3 and CanESM5, respectively, 0.054 °C and 0.039 °C per decade. For all characteristics the model’s spread increases throughout the time period revealing a larger model dispersion in the recent years. Additionally, for the events intensity it is visible that the spread of the MME is highly dominated by NESM3 model. The behavior simulated by these three models is in agreement with their high climate sensitivities presented in table S1.

Also in figure 1 the interannual variability of an MME mean obtained from a set of 21 models from CMIP5 is illustrated for the period 1982–2005, considering a baseline of 1971–2000. It is visible that the slope of both CMIPs are similar, suggesting that the two generation GCMs analyzed share comparable shortcomings in reproducing MHWs.

The spatial distribution of the MHWs given by the NOAA OISSTV2 and the CMIP6 models, for the common period of 1982–2014, are illustrated in figure 2. The observational MHW frequency ranges from about 1 to more than 3 annual events (figure 2(a); table 1), and its global mean value is ~1.97 events. However, several regions are prone to the occurrence of more than two annual events, such as the Gulf Stream region, the North Hemisphere and almost all Southern subtropics, including e.g. the Agulhas and Benguela currents and the Brazil and Peru currents. A reduced number of events occur in the eastern tropical Pacific with ~1 event per year on average. The MME mean points to smaller MHW frequencies, and the yearly global average value is 1.56 events. In fact, the individual CMIP6 models underestimate the MHW frequencies in vast regions of the globe, with exception to the NESM3 model. This model shows larger MHW frequencies in widespread ocean regions, and a yearly global mean frequency ~2.1 events, which corresponds to a frequency bias of +0.07 events per year relative to the observations (table 1). On the other hand, models with lower mean global frequencies of occurrence are ACCESS-ESM1-5, MIROC6 and NorESM2-MM, displaying less than 1.4 annual events (i.e. bias over 0.64). The standard deviation of the MME (figure 2(a), last panel) shows that the equatorial region has maximum values (over 0.5 events in average per year) indicating a larger spread of the simulated frequency values. The MME mean presents for the MHWs frequency, a spatial correlation of 0.79 with the observation, and the AWICM-1-1-MR, CESM2-WACCM and NorESM2-MM models showed the lowest correlation values (0.72, 0.75 and 0.77, respectively).

The observed global mean duration (figure 2(b); table 1) of the MHWs based on NOAA OISSTV2 is ~12 d, ranging from more than 5 to almost 35 d.
Although, it is visible that longer lasting events are located in the eastern tropical Pacific, also characterized by low occurrence of MHWs. Imperative to this pattern is the El Niño-Southern Oscillation (ENSO) variability which, in its positive phase promotes strong positive SST anomalies, emerging as long and low frequent MHWs. The remaining regions are characterized by events with smaller durations, ranging from 10 d to 20 d. The CMIP6 models simulate much longer events, resulting in a MME mean duration of ~25 d, doubling the observed value. As with MHW frequency, the NESM3 model shows mean values closer to NOAA OISSTV2, and consequently the lowest bias, with durations of nearly 16 d and bias of 3.1 d. Longer MHWs are obtained with MIROC6 and ACCESS-ESM1-5 models, with mean biases and MAE of more than 15 d. As expected, the duration standard deviation of the MME is larger in regions where longer MHWs are obtained and approaches 20 d, mainly in the high latitudes.
Figure 2. (Continued).
Figure 2. (Continued).
Figure 2. Global maps of MHW properties averaged over the NOAA OISSTv2 and CMIP6 common period of 1982–2014. (a) Frequency, (b) duration and (c) intensity for each CMIP6 model, for NOAA OISSTv2 (last row), for the multi-model ensemble mean (last row, MME mean) and spread (last row, MME stdev.). The 30 year climatology was computed based on the common period of 1983–2012. In supplementary material the CMIP6 MHW characteristics for the climatology period 1971–2000 are shown. Sea ice regions are shaded in white.

of the north Atlantic and eastern tropical Pacific. Low spatial correlations below 0.6 are obtained with MIROC6 and KIOST-ESM models, contributing to a small MME mean spatial correlation of 0.64 for the events duration.

The global intensity based on NOAA OISSTv2 is up to 1.3 °C, with a mean value of 0.35 °C (figure 2(c); table 1). Spatially, larger intensity MHWs occur in highly dynamic regions where large SST variability occurs, such as the eastern and western boundary currents and the central and eastern equatorial Pacific Ocean. In these regions, MHW intensities reach values over 0.5 °C and are also emphasized in the MME mean, although with smaller intensities, of around 0.24 °C. The NESM3 model reveals the larger intensity values, even surpassing the observed mean value by 0.09 °C. The models with lowest mean MHW intensity are the ACCESS-ESM1-5, CESM2-WACCM
Figure 3. Global mean time series of the MHW properties under SSP1-RCP2.6 (green), SSP2-RCP4.5 (yellow) and SSP5-RCP8.5 (red) pathways: frequency (top panel), duration (middle panel) and intensity (bottom panel) for all CMIP6 models studied (thin color lines) and for the MME mean (solid thick lines). Dashed lines represent the 10th and 90th percentile. The baseline period considered corresponds to the historical period of 1971–2000.

and MRI-ESM2-0 models, with mean intensity events below 0.2 °C. The spatial correlation regarding the MHWs intensity is smaller than 0.5 for 56% of the models, resulting in a MME mean spatial correlation of 0.34. The standard deviation of the MME intensity shows large values, over 0.16 °C, in regions coincident with high intensity events, such as the eastern tropical Pacific and the western boundary currents of the Gulf Stream (North America eastern coast), the Brazil Current (South America eastern coast), the Kuroshio Current (coast of Japan) and the Agulhas Current (South Africa).

Among all models it is observed that the NESM3 depicts MHW events very differently from the remaining CMIP6 models analyzed. Despite presenting smaller bias w.r.t. to observations, the simulated frequency and intensity of the events are in fact larger than those observed. This overestimation could be linked to a persistent positive models downward energy flux into the ocean identified by the model developers [26], which results in ocean surface warming. This process may be related to a shortcoming of the cloud and convection parameterization. The ACCESS-ESM1-5 strong negative bias in frequency and intensity of the events might be related to the cold SST bias over much of the world, which is associated with known errors in the atmospheric model used of the UK MetOffice Unified Model [27, 28]. Additionally, and as described in table S1, these models also have high climate sensitivities.

The CMIP6 model simulations for the future climate are used to study the signal of climate change on global MHW events, applying a similar analysis to the one described for the historical period. At first, we examine the trends of the MHW properties for the period between 2040 and 2100, for the three SSPs...
considered, and then the spatial anomalies of the properties are analyzed.

All pathways project negative trends for the MHWs frequency (figure 3, top panel), decreasing in a rate of 0.03, 0.2 and 0.3 annual events per decade, which indicates a decrease of 0.2, 1.2 and 2 annual MHWs over the 60 year period, for SSP1, SSP2 and SSP5 respectively. This decrease occurs since the SST warming promotes multiple year events and consequently a decrease in the mean annual counting. Also common to the three pathways are the slightly larger negative trends obtained for the first 30 year period, corresponding to the mid-century period of 2041–2070. The models spread illustrated by the 10th and 90th percentile remain almost constant for SSP1 and SSP2 along the period (≈0.8 events per year), while for SSP5 the models strongly converge to the MME mean values at the end century. Considering all pathways, the CMIP6 model’s minimum frequency is very close to the 10th percentile, while the difference between the upper shaded line and the 90th percentile shows that the models spread is amplified by one GCM only (NESM3).

The MHWs duration (figure 3, middle panel) of all projections indicate positive trends in the average number of days under MHW conditions of 5.3 d, 43.1 d and 140.2 d per year for the 60 year period, for each SSP, respectively. All SSPs present higher positive trends during the 2041–2070 period, with an amplification of the GCM’s spread right from the start of the time series. The MME duration range increases with the severity of the SSPs, with 1, 6 and 19 additional years under MHW conditions along the analyzed period.

The projected MHWs intensity considering all scenarios are similar during the mid-century period, indicating an increase of 0.01 °C/0.1 °C/0.3 °C per decade for SSP1/SSP2/SSP5, for the 30 year period. During the end-century period, the intensity trends remain positive but decrease in value approximately 95%, 44% and 37%, respectively. For the end of the century and under SSP5 strong MHWs events are projected to occur, with intensities 1.5 °C higher than those in the mid century. Similarly, to the previous behavior for the MHWs frequency and duration, the GCMs spread shows a clear asymmetry to larger values.

For all MHW properties the climate sensitivity of NESM3, CanESM5 and EC-Earth3 models is evidenced by their slopes along the 60 year period and slope range among the three SSPs. For the frequency and duration, NESM3 model has the largest slopes, with a maximum decrease of 0.7 events per decade and an increase in the duration of 44.9 d per decade, under SSP5. Concerning the events intensity, the highest range is obtained by EC-Earth3. It is also observed that higher slopes under SSP4 than SSP5 are obtained with CanESM5 model (for frequency and duration), and with EC-Earth3-Veg and NESM3 models (for intensity).

The future relative anomalies of the MHW properties for 2071–2100 are illustrated in figure 4 (in percentage w.r.t. the period 1971–2000 (1971–2000 illustrated in figure S1); for 2041–2070 in
supplementary material, figure S2). In these figures, the white color represents regions where models agreement is below 80% (80% of the models agree in the signal change) and the anomalies are not statistically significant at a confidence level of 95% (t-test applied to the historical and scenario MME means). For the MHW frequency the future anomalies are below the criteria defined in a substantial part of the global domain, mainly due to the similar statistics of both periods.

The SSP1 scenario w.r.t. the historical period reveals that there is a general increase between 50% to 150% of events per year. On the opposite, the SSP5 scenario projects decreases in the frequency of MHW events for most of the globe. For the mid-century period (supplementary material, figure S2) the areas of statistically significant anomalies decrease globally from SSP1 to SSP5, while for the end century the statistically significant anomalies are mostly located in the southern ocean for SSP1 and in the northern hemisphere oceans for SSP5.

Global positive and statistically significant anomalies are obtained for the MHWs duration and intensity, with increasing relative anomaly values from mid century to end century. The events duration strongly increases in the northwestern Atlantic low latitudes for all pathways, reaching a permanent MHW state for the most severe scenario SSP5 by the end of century. Smaller duration increases are obtained in the eastern tropical Pacific and in the high latitudes of the southern Ocean, where events up to 100 d long for mid century and up to 1000 d long for end century occur. The strongest increases in the intensity are obtained for the northern high latitudes where the mean intensities of ~0.1 °C are projected to increase to 1 °C and 2 °C for mid century and end century. In the central region of the Atlantic Ocean all pathways project minimum relative anomalies of 200%, corresponding to increases ranging from 0.8 °C to more than 2 °C.

4. Discussion and conclusions

In the current study, the global MHW events are analyzed based on observations and on an ensemble of 16 GCMs available from the CMIP6, both for a historical period of 1971–2014 and for the 21st mid- and end-century model projections, under the socioeconomic pathways SSP1, SSP2 and SSP5.

Similarly to other global ocean studies based on observations and on CMIP5 GCMs [14–17, 29], in this study global positive trends for the MHWs properties are obtained for the recent past climate, as well as globally heterogeneous spatial distribution of those characteristics. For the future periods the MHWs duration and intensity trend remains positive, while for the frequency the trend is negative.

For the historical period, the comparison of the MHW properties observed and simulated by CMIP5 (presented in figure 1 and table 1 and in [16, 17, 29] and by CMIP6 (in this study) ensembles, suggests that the two generation GCMs share comparable shortcomings in reproducing MHWs.

As in previous studies, it should be acknowledged that the coarse resolution of the GCMs leads to longer MHWs due to the underestimation of the SST anomalies produced by small-scale features, simulating SSTs that are spatially and temporally too smooth [2, 16]. In spite of the new generation CMIP6 models, this study points out to the persistence of this limitation. In fact, in figure 1 the observed variability is larger than the one simulated by the models, and consequently the lack of inter-annual variability consistent to all GCMs results in a MME mean with less intense or even the absence of peaks. Additionally, the MHWs patterns simulated are too smooth as can be seen in figure 2 by comparing the MHWs features obtained by NOAA OISSTV2 and by GCMs.

All MHWs properties based on NOAA OISSTV2 have positive trends showing that along the time frames analyzed the events became more frequent, longer and intense. The observed frequency trend of +0.52 annual events per decade over 1982–2018 is slightly larger than the +0.45 value over 1982–2016 from [17], with 0.04 annual events per decade of this difference due to the increasing number of events observed in recent years. In fact, the trend is closer to the +0.57 events per decade over 1982–2015 obtained by [16] that considered the 99th percentile as threshold to detect MHW events. The global mean rate of the observed events duration is approximately 1.76 d per decade, which is slightly higher than the 1.3 d per decade achieved by [17] that examined the MHWs in NOAA OISSTV2 original grid resolution. A positive rate is also obtained for the MHW mean intensity of 0.03 °C per decade, which is approximately half of the computed by [17] of 0.085 °C per decade. This rate difference might be mainly related to the distinct intensity analyzed since herein we analyzed the mean intensity above the 99th percentile and [17] analyzed the maximum intensity above the climatology. Therefore, the maximum intensity has a higher positive rate than the mean intensity of the events.

Spatially, and in agreement with other authors [14, 17], regions where MHWs are more (less) frequent are also characterized by short (long) living events, indicating a negative correlation between the events frequency and duration. The maximum duration occurs in the eastern equatorial Pacific region where ENSO events emerge as long duration events with less than one MHW per year on average. Spots of high MHWs intensities occur in regions of large SST variability including the eastern and western boundary current regions and the central and eastern equatorial Pacific Ocean. In fact [17], obtained a correlation of 0.77 between the standard deviation of annual mean SST and mean MHW intensity.
The simulated frequency trend based on CMIP6 GCMs is +0.61 annual events per decade for the 1982–2014 period, resulting in an increase of ~2 events for the complete period. The models also simulate a rate of +5.62 d per decade and an intensity rate of +0.04 °C.

The simulated MHWs show a mean frequency of occurrence of ~1.6 events per year, last in average for ~25 d and display a mean intensity of 0.24 °C. In general, the models simulate a slightly lower annual frequency (MME mean bias of −0.42 events per year), slightly higher durations (MME mean bias of +12.9 d) and also underestimate the mean intensity (MME mean bias of −0.1 °C) of the events that occur globally. A similar behavior was also observed by [19] that analyzed the MHWs in the Mediterranean Sea, using a local climatological 99th percentile threshold based on observations from the AVHRR Pathfinder Version and Regional Climate System Models from Med-Cordex initiative. Computing the global MHW based on CMIP5, [2, supplementary figure 1] also obtained a bias between the global average intensity by NOAA OISSTV2 and CMIP5 that was nearly constant between the period analyzed from 1982 to 2005 (+0.6 °C bias). Furthermore, the CMIP5 models examined by these authors showed a clear increase in the bias of the total annual MHW days after the end of the 20th century, with CMIP5 models simulating more days under MHWs conditions.

The CMIP6 model bias (not shown) for the MHW frequency is ±0.3 events per year over the majority of the ocean. Exceptions are seen in equatorial (±0.6) and high latitudes (−0.6) regions. The duration bias is positive for almost the entire domain and up to 20 d. Higher biases are revealed for high-mid latitudes and tropical parts of the Pacific and Atlantic Oceans. The MME mean bias for the intensity is ±0.1 °C over most of the ocean, with exception of the southern high latitudes with positive bias between 0.1 °C and 0.2 °C, and regions with negative bias below −0.1 °C in the western and eastern boundary current regions. Most of those regions with stronger biases were also stressed by [2, supplementary figure 1] based on CMIP5 GCMs.

The projections for the future MHW properties show that the SST increase over the 21st century result in longer and more intense events especially towards the end of the century, in agreement with previous global and regional ocean projections [2, 16, 19]. Also, the spatial variability of the future anomalies displays a pattern close to those obtained with CMIP5 [2, 16].

The MHW duration increases consistently and globally for both periods and for all pathways, reaching a permanent MHW state of 365 d per year by the end century, similarly to [2] and [16]. For the end century, high relative intensity anomalies are projected to the tropics, which amount more than 100% under SSP5 (>200% for SSP1, >600% for SSP2). In fact, the projected MHWs intensity increases in the range of 2 °C–4 °C (<1 °C for SSP1, 1 °C–2 °C for SSP2). More moderate anomalies are identified for the high latitudes of the north Atlantic Ocean and the southern Ocean that are below +600% (increases <2 °C) [2] and [16] also pointed out that the small increases in these regions are consistent with the SST anomalies between the historical and mid-century periods and with the historical rates of low warming and cooling in the north Atlantic subpolar gyre and in parts of the Antarctic Circumpolar Current [30, 31].

In summary, this study reinforces the need of improving the models ability to simulate MHWs, which as shown did not improve considerably when the two CMIP ensembles (CMIP5 and CMIP6) are analyzed. Thus, it is recommended to develop further regional coupled models and/or global high spatial resolution coupled models to improve the representation of MHWs. At higher resolution it is expected that models will be able to simulate better the meso-scale processes in the atmosphere and ocean that drive MHWs.

**Data availability statement**

The NOAA High Resolution SST data is available in NOAA/OAR/ESRL PSD website at https://www.esrl.noaa.gov/psd/. The CMIP6 GCMs data are available to download in the CMIP6 website https://pcmdi.llnl.gov/CMIP6/.

The data that support the findings of this study are available upon reasonable request from the authors.

**Acknowledgments**

The authors would like to acknowledge the financial support FCT through project UIDB/50019/2020—IDL, funded by FCT. Pedro MM Soares is grateful to the FCT funded LEADING (PTDC/CTA-MET/28914/2017). The authors would like to acknowledge to NOAA High Resolution SST data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at https://www.esrl.noaa.gov/psd/

**ORCID iDs**

Sandra M Plecha https://orcid.org/0000-0002-9364-2090
Pedro M M Soares https://orcid.org/0000-0002-9155-5874

**References**

[1] Hobday A J et al 2016 A hierarchical approach to defining marine heatwaves Prog. Oceanogr. 141 227–38
[2] Oliver E C J et al 2019 Projected marine heatwaves in the 21st century and the potential for ecological impact Front. Mar. Sci. 6 734
[3] Straub S C, Wernberg T, Thomsen M S, Moore P J, Burrows M T, Harvey B P and Smale D A 2019 Resistance, extinction, and everything in between—the diverse responses of seaweeds to marine heatwaves Front. Mar. Sci. 6 763

[4] Thomsen M S, Mondardini L, Alestra T, Gerrity S, Tait L, South P, Lilley S A and Schiel D R 2019 Local extinction of bull kelp (Durvillaea spp.) due to a marine heatwave Front. Mar. Sci. 6 84

[5] Hughes T P, Kerry J T, Álvarez-Noriega M, Álvarez-Romero J G, Anderson K D, Baird A H and Bridge T C 2017 Global warming and recurrent mass bleaching of corals Nature 543 373–7

[6] Oliver E C J, Benthuysen J A, Bindoff N L, Hobday A J, Holbrook N J, Munday C N and Perkins-Kirkpatrick S E 2017 The unprecedented 2015/16 Tasman Sea marine heatwave Nat. Commun. 8 16101

[7] Wernberg T et al 2016 Climate-change-driven regime shift of a temperate marine ecosystem Science 353 169–72

[8] Bond N A, Cronin M F, Freeland H and Mantua N 2015 Heatwaves under global warming Nat. Clim. Change 6 223–8

[9] Garraudeau J et al 2009 Mass mortality in northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave Glob. Change Biol. 15 1090–103

[10] Caputi N, Kangas M, Denham A, Feng M, Pearce A, Hetzel Y and Chandrapavan A 2016 Management adaptation of invertebrate fisheries to an extreme marine heat wave event at a global warming hot spot Ecol. Evol. 6 3583–93

[11] Chandrapavan A, Caputi N and Kangas M I 2019 The decline and recovery of a crab population from an extreme marine heatwave and a changing climate Front. Mar. Sci. 6 510

[12] Cavole L M et al 2016 Biological impacts of the 2013–2015 warm-water anomaly in the northeast Pacific: winners, losers, and the future Oceanography 29 273–85

[13] Mills K E et al 2013 Fisheries management in a changing climate: lessons from the 2012 ocean heat wave in the northwest Atlantic Oceanography 26 191–5

[14] Holbrook N J et al 2019 A global assessment of marine heatwaves and their drivers Nat. Commun. 10 2624

[15] Smale D A, Wernberg T, Oliver E C, Thomsen M, Harvey B P, Straub S C and Feng M 2019 Marine heatwaves threaten global biodiversity and the provision of ecosystem services Nat. Clim. Change 9 306–12

[16] Frölicher T L, Fischer E M and Gruber N 2018 Marine heatwaves under global warming Nature 560 360–4

[17] Oliver E C J et al 2018 Longer and more frequent marine heatwaves over the past century Nat. Commun. 9 1324

[18] Reynolds R W, Smith T M, Liu C, Chelton D B, Casey K S and Schlax M G 2007 Daily high-resolution-blended analyses for sea surface temperature J. Clim. 20 5473–96

[19] Darma raki S, Somot S, Sevaault F, Nabat P, Narvaez W D C, Cavicchia I and Sein D V 2019 Future evolution of marine heatwaves in the Mediterranean Sea Clim. Dyn. 53 1371–92

[20] Eyring V, Bony S, Meehl G A, Stevens B, Stouffer R J and Taylor K E 2016 Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization Geosci. Model. Dev. 9 1937–58

[21] Meehl G A, Senior C A, Eyring V, Flato G, Lamarque J F, Taylor K E and Schlund M 2020 Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models Sci. Adv. 6 eaba1981

[22] Zelinka M D et al 2020 Causes of higher climate sensitivity in CMIP6 models Geophys. Res. Lett. 47 e2019GL085782

[23] Theil H 1950 A rank-invariant method of linear and polynomial regression analysis (parts 1–3) Ned. Akad. Wet. Proc. Ser. A 53 1397–412

[24] Sen P K 1968 Estimates of the regression coefficient based on Kendall’s tau J. Am. Stat. Assoc. 63 1379–89

[25] Hussain M et al 2019 pyMannKendall: a python package for non parametric Mann Kendall family of trend tests J. Open Sour. Softw. 4 1556

[26] Cao J, Wang B, Yang Y-M, Ma L, Li J, Sun B, Bao Y, He J, Zhou X and Wu L 2018 The NUIST Earth system model (NEMS) version3: description and preliminary evaluation Geosci. Model. Dev. 11 2975–2993

[27] Williams K D, Harris C M, Bodas-Salcedo A, Camp J, Corner R E, Copsey D, Fereday D and Xavier P K 2015 The MetOffice Global Coupled model 2.0 (GC2) configuration Geosci. Model. Dev. 8 1309–24

[28] Ziehn T, Katteg J, Knorr W and Scholze M 2011 Improving the predictability of global CO2 assimilation rates under climate change Geophys. Res. Lett. 38 L10404

[29] Plecha S M, Soares P M M, Silva-Fernandes S M and Cabos W 2020 On the uncertainty of future projections of marine heatwave events in the North Atlantic Ocean Clim. Dyn. (https://doi.org/10.1007/s00382-020-05529-3)

[30] Menary M B and Wood R A 2018 An anatomy of the projected North Atlantic warming hole in CMIP5 models Clim. Dyn. 50 3063–80

[31] Salée J-B 2018 Southern ocean warming Oceanography 31 52–62