Understanding the changing nature of marine cold spells

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Abstract

Marine heatwave (MHW) characteristics - such as frequency, intensity and duration - are increasing, largely due to global warming. However, while corresponding marine cold spell (MCS) characteristics have decreased over most regions, importantly, concomitant changes in MHW and MCS characteristics remain unclear. Here, we provide a comparative global assessment of these changes based on satellite sea surface temperature (SST) observations over 1982-2020. Across the planet, we find distinct differences in mean MHW and MCS metrics. Furthermore, decreasing trends in MCS characteristics are not necessarily aligned with increasing trends in MHW characteristics. While differences in intensity trends are mainly explained by SST variance trends, differences in exposure trends are less clear. Overall, decreasing MCS exposure and intensities are found to be largely driven by warming SST, rather than changes to SST variance, so it is expected that MCS will continue to diminish in their frequency, intensity and duration under global warming.

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Understanding the Changing Nature of Marine Cold Spells

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Key Points:

- Marine cold spells (MCSs) are decreasing in their intensity and occurrence in most regions of the global ocean.
- The differences between marine cold spell and heatwave intensity trends can be largely explained by sea surface temperature (SST) variance changes.
- The decreasing trends in MCS exposure and intensity can be largely explained by SST warming trends, in line with global warming.

Abstract

Marine heatwave (MHW) characteristics – such as frequency, intensity and duration – are increasing, largely due to global warming. However, while corresponding marine cold spell (MCS) characteristics have decreased over most regions, importantly, concomitant changes in MHW and MCS characteristics remain unclear. Here, we provide a comparative global assessment of these changes based on satellite sea surface temperature (SST) observations over 1982-2020. Across the planet, we find distinct differences in mean MHW and MCS metrics. Furthermore, decreasing trends in MCS characteristics are not necessarily aligned with increasing trends in MHW characteristics. While differences in intensity trends are mainly explained by SST variance trends, differences in exposure trends are less clear. Overall, decreasing MCS exposure and intensities are found to be largely driven by warming SST, rather than changes to SST variance, so it is expected that MCS will continue to diminish in their frequency, intensity and duration under global warming.

Plain Language Summary

Persistent oceanic temperature extremes – known as marine heatwaves (MHWs) and marine cold spells (MCSs) – can cause severe impacts on marine ecosystems and fisheries. MHWs have been shown to be increasing in frequency and intensity over the last decades, which is largely explained by the mean warming of

sea surface temperature (SST). Although MCSs have decreased in frequency and have weakened globally, we examine whether long-term SST warming can similarly explain the changes in MCSs. To address this, we characterise MCSs and MHWs using 39 years (1982-2020) of SST satellite observations. We find that the mean exposure and intensity changes of MHWs are not entirely commensurate with MCS mean exposure and intensity changes. Our findings imply that there is a non-uniform shift in temperature extremes, and therefore in SST variations. Statistical tests on the decrease in MCS exposure and intensity, however, suggest that these can be largely explained by mean warming.

1 Introduction

Numerous recent studies have focused on the devastating effects of discrete and prolonged extreme oceanic warm water events, also known as 'marine heatwaves' (MHWs; Pearce & Feng, 2013). Such events cause devastating impacts to marine biodiversity (e.g. Smale et al., 2019) and the economies of regional fisheries (e.g. Caputi et al., 2016; Holbrook et al., 2021; Smith et al., 2021). Conversely, marine cold spells (MCSs) – discrete and prolonged extreme oceanic cool water events – can also have crucial negative impacts, such as coral mortality (Lirman et al., 2011) and shifts in marine ecosystem structure (Donders et al., 2011). Conversely, MCSs may be beneficial to marine ecosystem recovery when damaged by MHWs (e.g., Caputi et al., 2016; Feng et al., 2021).

Studies have shown that MHWs have increased in frequency, duration and intensity over the past century (Oliver et al., 2018), while MCSs have decreased in these same characteristics across most of the global ocean (Schlegel et al., 2021). Hot spots for MHWs (Oliver et al., 2018) and cold spots for MCSs (Schlegel et al., 2021) have also been highlighted. These separate studies of MHW and MCS characteristics provide important estimates of global trends in these extremes. However, we are less aware of comparative differences in changes of these extremes' characteristics and background statistics. Oliver (2019) demonstrated that multi-decadal increases in MHW intensity and exposure are largely a result of mean sea surface temperature (SST) warming, rather than SST variability. Although MCS characteristics have decreased over most of the global ocean (Schlegel et al., 2021), how different climate change scenarios might alter MCS changes remain unclear. While we might reasonably expect decreasing trends in MCS characteristics to follow global ocean warming, regional differences in these trends compared with MHWs are also possible.

Using a quantitative MHW and MCS framework, this paper provides a global-scale comparative analysis of the differences between MHW and MCS mean characteristics and their multi-decadal trends, and how they are influenced by SST statistics over the 39-year period from 1982-2020. Specifically, the paper endeavours to answer the following questions: (1) Do global spatial patterns of mean MHW and MCS metrics differ? (2) Apart from the signs of the trends, how do changes in MCS characteristics differ from those of MHWs? (3) Given that increases in MHW characteristics are mainly due to long-term SST warming, can the same be said for changes in MCS characteristics? To address these questions, we analyse daily satellite SST data to investigate the means and trends in MHW and MCS exposure (i.e., counts of MHW/MCS days) and maximum intensity, and apply a statistical model to test the relative contributions of long-term SST warming and/or SST variance trends on the trends in MCS characteristics. Finally, we discuss the implications of our findings for marine fisheries and ecosystem management.

2 Data and Methods

2.1 Sea surface temperature data

The National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation (OI) SST dataset, version 2.1 (Reynolds et al., 2007; Banzon et al., 2016; Huang et al., 2021) was used to detect MHWs and MCSs, and to calculate their properties globally. Daily data are available on a 0.25° spatial grid with global coverage, and were analysed over the period 1982 to 2020. Any grid cells with recorded SST values <-1°C in the time series and with ice concentration >0 for 6 days or longer, were assumed to have sea ice cover and were subsequently excluded from the analysis.

2.2 Defining marine cold spells and marine heatwaves

MHWs and MCSs are discrete and prolonged extreme warm and cool water events respectively. MHWs are defined by temperature exceedances of the 90th percentile threshold, for at least 5 days, following the definition of Hobday et al. (2016). MCSs are similarly defined, but instead for temperatures below the 10th percentile threshold (Schlegel et al., 2021). If two successive MHW events (or two successive MCS events) occur with a gap of two days or less, they are regarded as a single continuous MHW event (or MCS event) (Hobday et al., 2016; Schlegel et al., 2017). Schematically, the MHW definition is shown in Figure 1 of Hobday et al. (2016), while we provide a schematic of the MCS definition (Figure S1). The percentile exceedance threshold is quantified relative to the seasonally varying baseline climatology of ideally 30 years or more (Hobday et al., 2016; Schlegel et al., 2021). Here, the baseline climatology and seasonally varying thresholds for MHWs and MCSs are computed over the full study period (1982–2020).

We here investigated two metrics of MHWs and MCSs: 'exposure', and 'maximum intensity'. MHW (or MCS) exposure is defined as the total number of MHW (or MCS) days in each year. The maximum intensity is defined as the largest magnitude SST anomaly occurring within all MHWs or MCSs in each year, rather than the peak SST anomaly over each single event duration (i.e., our maximum intensity is not the same metric shown by Schlegel et al. (2021)). Note that maximum MCS intensities are by definition negative values (i.e. negative SST anomalies). Therefore, a positive linear trend in maximum MCS intensity over time represents weakening MCSs. The non-parametric Theil–Sen estimator was used to compute linear trends since it is more robust for time-series that are heteroskedastic or have skewed distributions (Oliver et al., 2018). Due to long-term warming, it is possible that no MHWs are detected near the start of the study period and close to saturation at the end, or conversely a saturation of MCSs early and few or none later. Such periods of no MHWs/MCSs may cause biases when fitting trends to MHW/MCS characteristics. However, we find that MHWs occur early in the record in most regions, and MCS events continue to occur late in most regions (Figure S2).

2.3 Testing the influences of SST changes on MCS trends

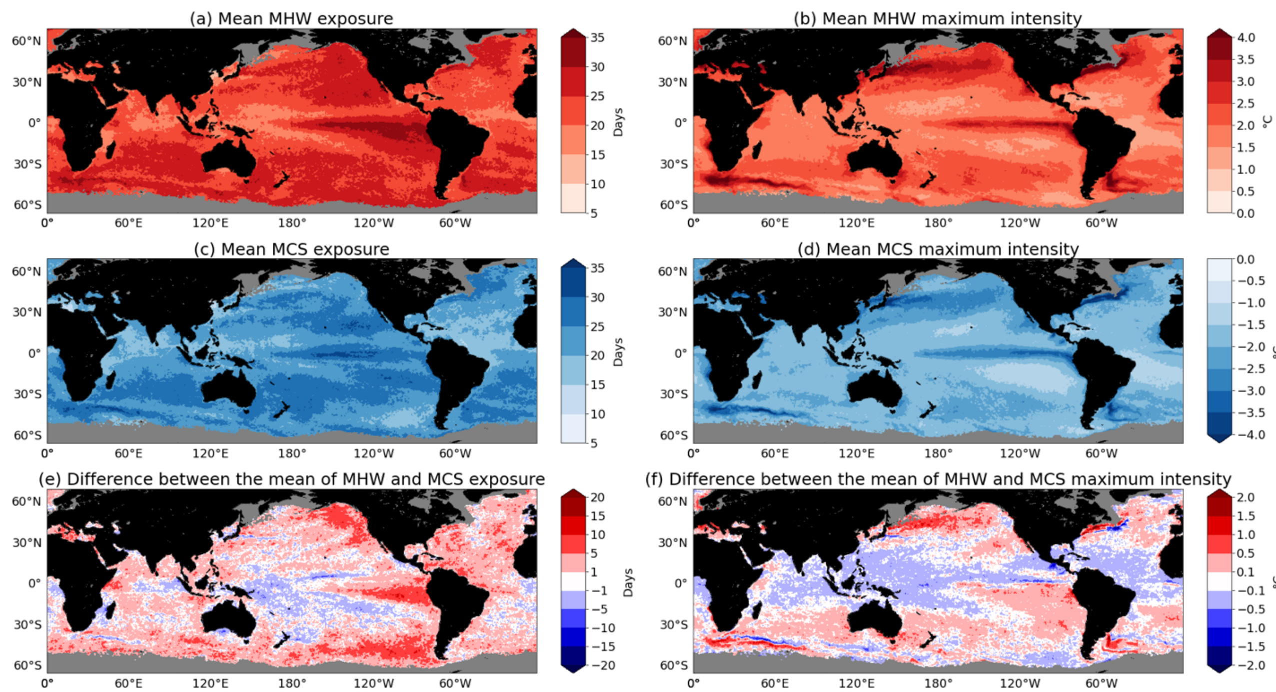
To test whether trends in MCS metrics are due to long-term SST warming, changes in SST variability, or both, we follow the approach of Oliver (2019). A brief description of this method is provided here, with further details given in the Supporting Information (Text S1).

For each OISST grid point, 500 synthetic SST time series were generated using a first order autoregressive (AR1) model, based on the observed local autoregressive time scale and stochastic variance (Equation S1). To each of the 500 realisations, the observed local linear SST trend was added, and then the MCS metrics (i.e. exposure and maximum intensity) and their trends were computed. If the central range of 95% of linear trends in MCS exposure, for example, did not span zero, then it was assumed that the local trend in MCS exposure could be explained by mean warming. Separately, the original 500 synthetic timeseries were modified to give the same linear trend in SST variance as in the observed local timeseries. Again, if the central range of 95% of linear trends in MCS metrics did not span zero, then it was assumed that the trend in that metric could be explained by the SST variance trend. The trend in a given MCS metric may be explained by both the linear SST trend and the SST variance trend.

Despite the timespan and version of the OISST dataset, there are some other minor differences with Oliver (2019) in the methodology, which are outlined in Text S1.

3 Results

3.1 Global patterns of mean MHW and MCS metrics



a comparative analysis, we first calculated the mean of the MHW and MCS metrics – exposure and maximum intensity – and then calculated the spatial pattern difference between these metrics (Figure 1). Large spatial variations exist in the mean of MHW and MCS exposure (Figure 1a, c), but they are not symmetric (Figure 1e). Both regions with large maximum MHW and MCS intensity (Figure 1b, d) are apparent in regions of large SST variability. The spatial pattern difference between the means of MHW and MCS maximum intensity (Figure 1f) is aligned with the pattern of SST skewness (Figure S6). This is similar to the result shown by Schlegel et al. (2021), but note there are differences in the baseline period and calculation of maximum intensity.

Figure 1. Mean of MHW and MCS exposure and maximum intensity, and the spatial pattern difference between these metrics globally. Shown are global pattern of **a** mean MHW exposure, **b** mean MHW maximum intensity, **c** mean MCS exposure, **d** mean MCS maximum intensity, **e** the difference between mean MHW exposure and mean MCS exposure (i.e., **a** mean MHW exposure minus **c** mean MCS exposure), and **f** the difference between the mean maximum intensity MHW and mean MCS maximum intensity (i.e., **b** mean MHW maximum intensity plus **c** mean MCS maximum intensity). For the difference subplots (i.e., **e**, **f**), positive values (red regions) represent the MHW exposure as being greater than MCS exposure, MHW maximum intensities are more intense than MCS maximum intensities. Conversely, negative values (blue regions) represent the MCS exposure as being larger than MHW exposure, MCS maximum intensities are more intense than MHW maximum intensities. All subplots are

derived from NOAA OI SST data during period 1982–2020.

We note again that the baseline climatology here is from the full study period (1982-2020). To test the sensitivity to the baseline choice, the analysis was repeated for two other 30-year baselines (1983-2012 and 1990-2019; Figure S7, S8). Regardless of the baseline, the spatial difference patterns between maximum MHW and MCS intensity (Figure S7f, S8f) match the SST skewness spatial pattern (Figure S6). However, the difference between means of MHW and MCS exposure is sensitive to the baseline choice. Means of MHW exposure are mostly larger than MCS exposure over the global ocean using the 1983-2012 baseline (Figure S7e), but lower when using the 1990-2019 baseline (Figure S8e). The sensitivity is due to the long-term warming trend.

3.2 Globally averaged trends in MHW and MCS metrics

Clear trends are observed in the globally averaged annual means of MHW and MCS exposure and annual maxima of intensities (Figure 2a,b). The global mean linear trend in MHW exposure was an increase by 11.7 days per decade over 1982-2020 ($p < 0.01$), while the trend in MCS exposure was similar in magnitude, but a decrease of 11.9 days per decade ($p < 0.01$; Figure 2a). The linear trend in global mean MHW intensity was 0.145°C per decade ($p < 0.01$), and larger than the trend in MCS intensity of 0.086°C per decade ($p < 0.01$; Figure 2b). In the global mean sense, MHWs have intensified faster than MCSs have weakened.

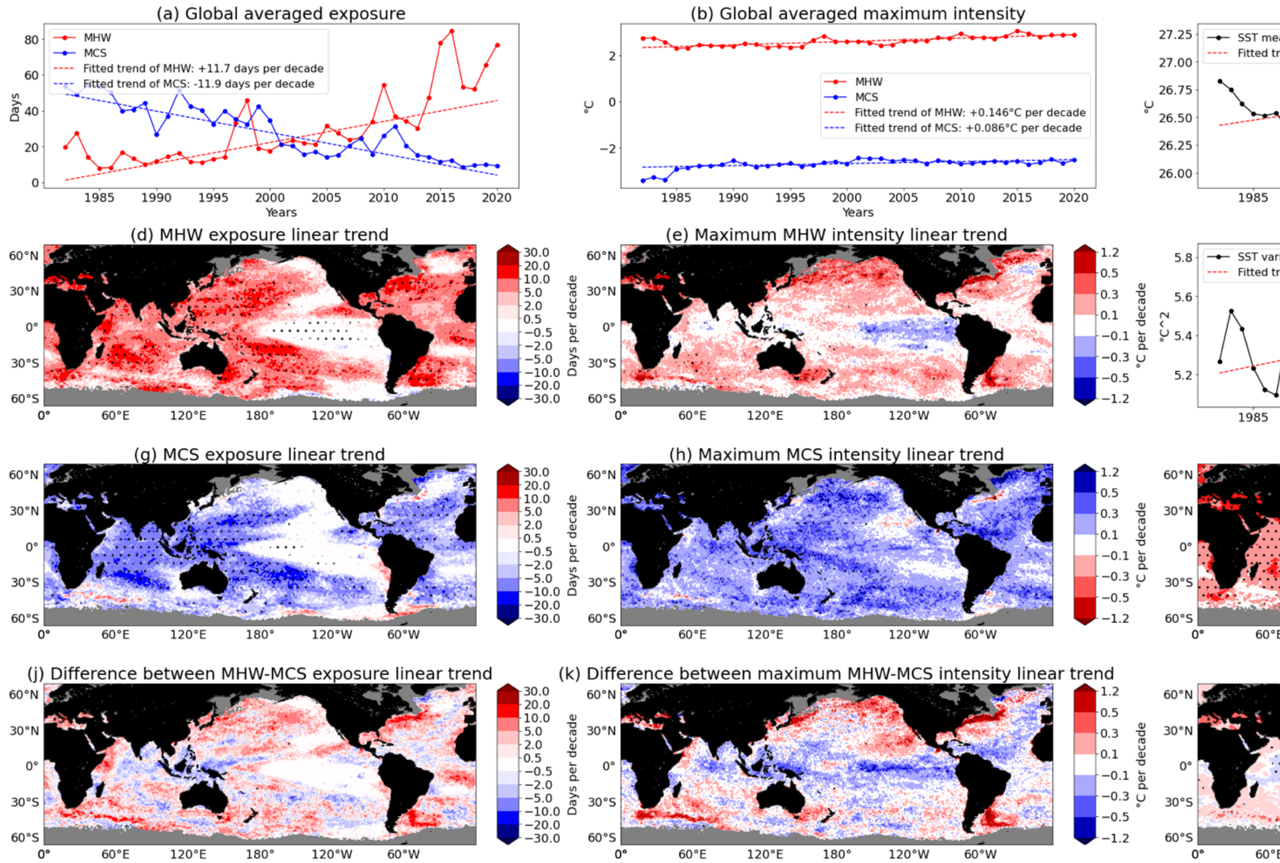


Figure 2. Trends in MHW and MCS metrics as well as SST properties in NOAA OISST over 1982–2020. **a, d, g, j** trends in MHW/MCS exposure, **b, e, h, k** trends in maximum MHW/MCS intensity, and **c, f, i, l** trends in SST properties. Shown are globally averaged annual mean time series of **a** MHW and MCS exposure, **b** maximum MHW and MCS intensity, **c** mean SST and **f** SST variance, as well as the spatial pattern of linear trends in **d** MHW exposure, **e** maximum MHW intensity, **g** MCS exposure, **h** maximum MCS intensity, **i** SST mean linear trend and **l** SST variance linear trend. **j** The spatial pattern of difference between MHW and MCS exposure linear trend (i.e., linear trend in **d** MHW exposure minus **g** MCS exposure). **k** The spatial pattern of difference between maximum MHW and MCS intensity linear trend (i.e., linear trend in **e** maximum MHW intensity plus **h** maximum MCS intensity). In **d**, **e**, **g**, **h**, all dot hatching areas are where trends are statistically significant at the 95% level. For the difference subplots (i.e., **j, k**), positive values (red regions) represent MHW exposure increasing faster than MCS exposure decrease, and maximum MHW intensities strengthening faster than maximum MCS intensities weakening. Negative values (blue regions) represent those locations

where MCS exposure decreases faster than MHW exposure increases, and MCS maximum intensities weaken faster than MHW maximum intensities have been strengthening.

The baseline robustness test was also done for this analysis (Figure S9a,b, S10a,b). The results for maximum intensity are again not too sensitive to the baseline choice. However, the results for exposure entirely depends upon the baseline, with global mean MHW exposure increasing faster than MCS exposure decreasing using the 1983-2012 baseline, but slower when using the 1990-2019 baseline.

The linear trend in global mean annual SST is 0.154°C per decade (Figure 2c), similar to the trend in maximum MHW intensity, but almost double the trend in MCS intensity. The global mean in raw SST variance is also increasing, at a linear rate of 0.119°C^2 per decade (Figure 2f). In the following section, the relationships between SST changes and MHW/MCS metric trends will be explored on a regional basis.

3.3 Spatially varying trends in MHWs, MCSs and SST

Linear trends in MHW and MCS exposure and maximum intensity considerably vary spatially across the globe (Figure 2d,e,g,h). MHW exposure has increased across most of the global ocean over 1982-2020 (Figure 2d), with some regions experiencing trends greater than 20 days per decade. Conversely, MCS exposure has decreased over a large proportion of the global ocean (Figure 2g), following a similar spatial pattern to the trends in MHW exposure (cf. Figure 2d). However, in contrast to MHW exposure trends, which are almost exclusively positive, there are some regions where MCS exposure has increased, such as the west coast of South America and in the Southern Ocean poleward of 50°S.

Maximum MHW intensity has increased over most of the global ocean (Figure 2e), but there are some regions where it has decreased. The largest increases occurred in mid-to-high northern latitudes, and the western boundary currents and their extension regions (by up to 1.2°C per decade). In contrast, maximum MHW intensities in the tropical central-eastern Pacific in particular, have been decreasing. Conversely, maximum MCS intensities have weakened over most regions (Figure 2h). Note that negative (blue) trend values in maximum MCS intensity indicate locations where MCS maxima are becoming less intense (i.e., weakening) over time. The largest MCS intensity weakening (>1.2°C per decade), occurred in the high-latitude North Atlantic Ocean (north of 50°N).

An Interdecadal Pacific Oscillation (IPO)-like pattern is evident in the patterns of MHW and MCS trends, as well as in SST trends (Figure 2i). This reflects a largely negative IPO trend over the period (1982–2020), switching from its positive to negative phase. The global pattern of SST trends, whilst increasing overall, exhibits the negative IPO pattern, with negligible change in SST in a broad chevron extending from the equator at 180°E diagonally poleward into the midlatitude eastern Pacific, in contrast to clear increases in the northwest and southwest Pacific Ocean (Figure 2i).

The differences between the trends of MHW and MCS exposure and maximum intensity are also shown (Figure 2j,k). It is evident that the spatial difference patterns of MHW and MCS exposure trends is regionally varying (Figure 2j). The pattern of differences between MHW and MCS maximum intensity trends (Figure 2k) is more regionally dependent. Trend magnitudes of maximum MHW intensity are greater than maximum MCS intensity in some regions, such as the North Pacific, northwest Atlantic, and southwest Atlantic. However, the opposite is true in the equatorial Pacific region and eastern Atlantic.

By applying the baseline robustness test to this analysis (Figure S9, S10), we find that the baseline choice has little impact on spatial patterns of trends in maximum MHW and MCS intensity as well as their differences. However, the results for exposure differ with baselines, as the trends of MHW exposure are larger than trends of MCS exposure mostly across the globe when using 1983-2012 baseline, but lower when using 1990-2019 baseline.

Linear trends in SST variance (Figure 2l) are also shown alongside trends in SST (Figure 2i). While clear SST variance increases are evident in western boundary current regions, and in the North Pacific and central and eastern equatorial Pacific Ocean, decreasing trends are seen in a broad region extending through the western Pacific and Indian Ocean. In some regions, most notably around the Maritime Continent, the North Pacific, the Southern Indian Ocean, and the North and South Atlantic, there is a strong correspondence between the SST variance trend (Figure 2l) and the difference pattern between maximum MHW and MCS intensity trends (Figure 2k). This suggests that changes to SST variance can largely explain the changes in differences between MHW and MCS intensities. Where the SST variance decreases, the probability density function (PDF) narrows, and hence cool tail shifts towards the warm tail. Conversely where the SST variance increases, the PDF broadens, and the warm tail trends away from the cool tail (Figure S11).

The broad alignment in the spatial pattern of SST trends (Figure 2i) with those of MHW and MCS exposure days and intensities (Figures 2d,e,g,h), reinforces that mean temperature trends due to global warming are largely responsible for the changes in not just MHWs (Oliver, 2019), but also MCSs, though trends in SST variance may also play some role. In the following section, tests are conducted to determine whether trends in SST, trends in SST variance, or both, are responsible for the trends in MCS exposure and intensities.

3.4 SST drivers of MCS trends

Each grid point was tested to establish whether the local linear SST trend or SST variance trend, or both, were statistically significant drivers of the local MCS exposure or maximum intensity trend (Figure 3). For MCS exposure, 78.87% of the ocean surface is categorised as 'Mean Dominant' (trends can be explained by trends in SST only; Figure 3a), with most of the remainder of the ocean surface characterised by 'Neither' (21.05%; where neither trends in SST or SST variance explain the trends in MCS exposure). In only very small regions is the MCS exposure trend characterised as 'Variance Dominant' (0.05%; the trend can be explained by the SST variance trend), or 'Both' (0.03%; the trend can be explained by both trends in SST and SST variance).

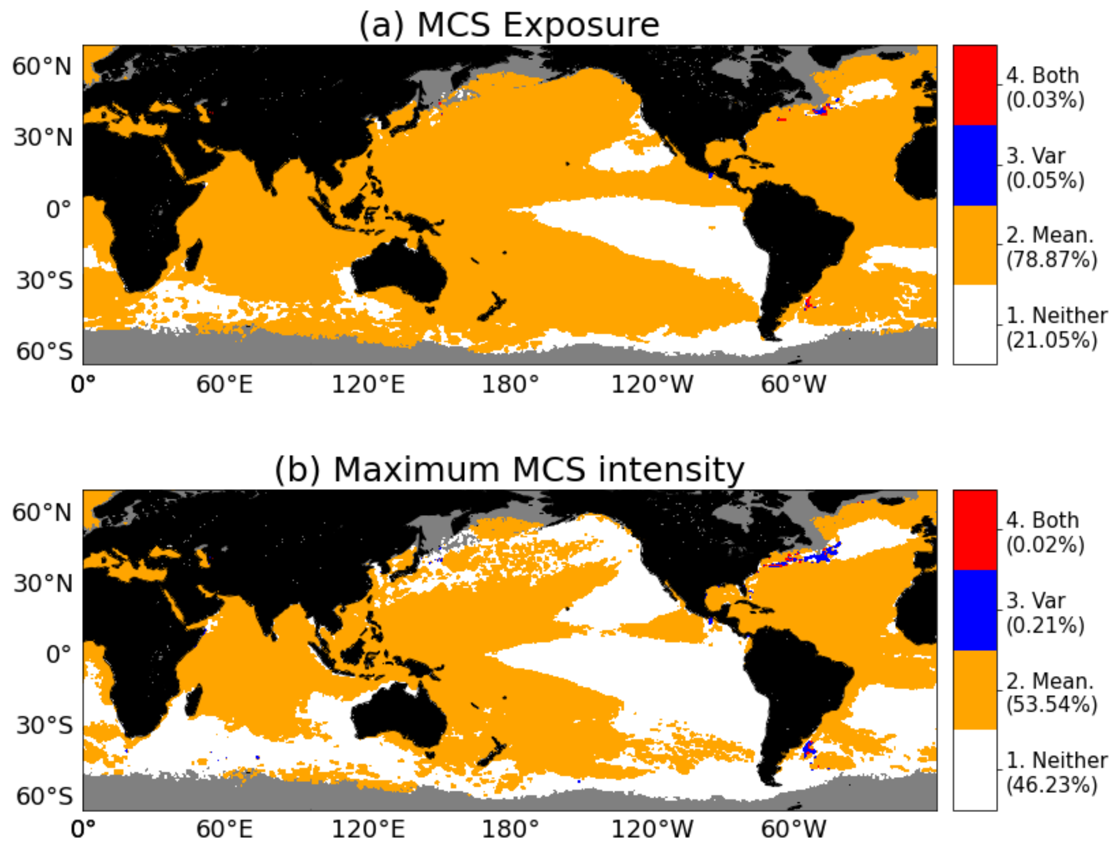


Figure 3 Relative importance of changes in SST mean and variance in driving changes in MCS exposure and maximum intensity. Colours indicate whether trends in MCS a exposure and b maximum intensity are dominated by trends in SST variance and/or trends in mean SST. Four situation types are shown: 'neither' (white), 'mean-dominant' (orange), 'variance-dominant' (blue), and 'both' (red). The proportion of the globe covered by each type is indicated in the colour bar. Both subplots are derived from NOAA OISST over 1982–2020.

With regard to maximum MCS intensity, the 'Mean Dominant' type and 'Neither' type explain the trends in close to 50% of the global ocean each (53.54% and 46.23% respectively; Figure 3b). In only 0.23% of the global ocean can maximum MCS intensity trends be explained by trends in SST variance (0.21% for 'Variance Dominant' and 0.02% for 'Both'). Hence, SST variance trends explain a marginally greater proportion of the trends in maximum MCS intensity compared to MCS exposure trends.

The relative importance of trends in SST and trends in SST variance in driving changes in MHW exposure and maximum MHW intensity based on SST data over the period 1982-2017 has been discussed previously (Oliver, 2019; see their Fig 6). We applied a similar statistical approach here but using SST data over period 1982-2020 (see Figure S12) and a slightly modified approach to testing SST variance trends (see Section 2.3 and Supporting Information Text S1). Comparing our Figure S12 to Figure 6 in Oliver (2019), we find two key differences: (i) 'Mean' type regions extend over a larger area here than in Oliver (2019), possibly due to the use of a longer period here, during which the effects of decadal variability on long-term trends are slightly diminished; and (ii) variance trends explain fewer changes here than in Oliver (2019), likely due to the slightly different methodologies (figure not shown).

Since the tests for SST drivers of MCS and MHW trends are based on the same SST data and approaches, here we only compare Figure 3 with Figure S12, rather than with Figure 6 of Oliver (2019). The spatial patterns for MHWs and MCSs are in fact largely the same. For both MHW and MCS exposure and maximum intensity, trends in SST dominate over the role of SST variance trends across a significantly larger proportion of the world's oceans. This is most apparent in the influence on MHW and MCS exposure. However, SST variance trends play a slightly more significant role in regional changes in MCS and MHW maximum intensity.

4 Discussion and conclusions

Our study has investigated the differences in mean values and trends between marine heatwaves (MHWs) and marine cold spells (MCSs), and how these characteristics are likely to have been influenced by SST change statistics globally over the 39-year period from 1982-2020. First, we have shown that the global mean spatial patterns of MHW and MCS exposure or maximum intensity are not identical, with the spatial pattern of differences between the mean MHW and MCS maximum intensities is similar to the spatial pattern of SST skewness. However, the differences between mean MHW and MCS exposure depends on baseline choice. Second, we have shown that the globally averaged annual MHW exposure days and maximum intensity have increased over time, while the MCS exposure days and maximum intensity have decreased. However, these rates of change are different. While the spatial trend patterns in MHW and MCS metrics are broadly similar, some regional differences are evident. We found differences in maximum intensity trends to be a result of rates of changes in SST variability, but differences in exposure trends were sensitive to the baseline choice.

Given that the differences in the rates of change of MHW and MCS intensities have varied in different regions around the global ocean, and these differences are related to rates of change in SST variance, it is essential to understand whether the changes are robust, and whether they might be expected to continue into the future. Firstly, it is important to note that trends in SST variance can be calculated in many ways, e.g., in moving time windows, as differences over two time windows (Prigent et al., 2020a, 2020b), or as linear trends with or without the seasonal cycle subtracted (Oliver et al., 2018; Oliver, 2019). Each method may result in different estimates of the variance trends. Some studies have shown that SST warming trends due to greenhouse gas heating are stronger in summer than in winter in the midlatitudes (Dwyer et al., 2012; Chen & Wang, 2015; Alexander et al., 2018; Liu et al., 2020), in agreement with the SST variance trends shown here for the North Pacific, North Atlantic, and a large part of the Southern Hemisphere. Conversely, we found weak or no variability trends in the tropical Atlantic, counter to some studies (Prigent et al. 2020a, 2020b). Hence, a robust method for computing SST variance trends is essential for drawing conclusions about long-term changes.

Finally, following the approach outlined by Oliver (2019), we have shown the relative importance of changes in mean and variance of SST in driving changes to MCS and MHW exposure and maximum intensity using SST data over the 39-year period from 1982-2020. With continued increases in greenhouse gas emissions into the future, we expect continued increases in mean SST. This will be expected to influence the continued increase in MHW exposure and intensity and continued decrease in MCS exposure and intensity with even the disappearance of MCSs relative to present-day baselines.

To our knowledge, this is the first global study to identify the differences between MHW and MCS in trends, and how they are driven by SST changes. Our findings may provide some grounding to researchers in ecosystems science. One of the potential benefits is to help explain ecological phenomena by considering the presence or absence of both warm water and cold water. For example, many studies have investigated how warm water influences the distributions of marine species, but these could also be regulated by how cold it does not get (Hare et al., 2010; Freitas et al., 2016; Morley et al., 2016; Fredston-Hermann et al., 2020). Further study is needed to determine the ecological impact of the changing nature of marine cold spells.

In summary, we have found that linear trends in SST, rather than trends in SST variability, are the dominant cause of changes in exposure and maximum intensities of MHWs and MCSs. But furthermore, trends in SST variance can largely explain the differences in the trends of MHW and MCS intensities. However, our fitted linear trends reflect a statistical modelling representation that does not specifically remove the influences of multi-decadal modes. Hence, our study highlights the need to further explore changes in MHWs/MCSs by considering such features as multi-decadal variability.

Acknowledgments

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Data Availability Statement

The NOAA OISST version 2.1 data sets are publicly available at: https://www.ncei.noaa.gov/data/sea-surface-temperature-optimum-interpolation/v2.1/access/avhrr/.

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