Understanding the changing nature of marine cold spells

By

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Content

The style of thesis follows the guidelines for submitting a thesis as a scientific paper. Chapter One is a comprehensive introduction to the field of the study, giving the background to the project and outline the key focus and scope of the research. Chapter Two is a manuscript prepared for submission to *Climate Dynamics* scientific journal. As Chapter One and Chapter Two were drafted as independent documents, there is necessarily some duplication of information between these two chapters.

Declaration

I declare that all material in this thesis is my own work, and contains no material that has been accepted for the award of any other degree or diploma in any tertiary institution and that, to the best of my knowledge, contains no material previously published or written by another person, except where due reference is made in the text of this thesis.

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9 July 2020

Abstract

Prolonged oceanic temperature extremes – also known as marine cold-spells (MCSs) and marine heatwaves (MHWs) – can have severe and long-term impacts on ecosystems, with subsequent socioeconomic consequences. However, compared with increasing number of studies and published literature on MHWs, there are relatively few published studies on MCSs, and no comprehensive global assessment of MCSs has been undertaken. In this study, we have investigated four fundamentally important questions. These are: (1) How global spatial distribution of mean MCS metrics looks like? (2) How have MCSs changed across the globe over the past several decades? (3) Are changes in MCSs around the world mostly due to rising mean ocean temperatures, changes in ocean temperature variance, or a combination of the two? (4) What are the implications of our findings?

Specifically, we address these questions for surface MCSs based on analysis of satellite observations of sea surface temperature (SST), using the National Oceanic and Atmospheric Administration (NOAA) optimum interpolation SST (NOAA-OI SST) dataset from 1982–2016. We show that over this 35-year period, MCSs show a less frequent, weaker in intensity and shorter lasting trend over most of the global ocean. However, we identify a few significant regions, such as in the southwest Atlantic, where MCSs show a more frequent, stronger in intensity and longer-lasting trend. We applied a statistical climate model to test whether observed trends in MCS properties could be explained by trends in SST mean or variance. We find that neither trends in SST mean nor SST variance explained trends across all of the investigated MCS metrics, i.e. MCS duration, frequency and mean intensity, over most of the global ocean. Rather, we find that multi-decadal warming explained trends in MCS frequency in over one third of the ocean. MCSs can not only cause impacts on ecosystems. Considering the warmer water due to the continued global warming, marine species who prefer cold water (e.g. cold-water fish) can have survival crisis, MCSs can provide some cold refugia for them. This study fills the knowledge gap in MCS global analysis and can provide information to fisheries, ecosystem study and social sectors.

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First and foremost, I would like to give my sincere gratitude to my supervisors Professor Neil Holbrook, Professor Lisa Alexander, Dr Jules Kajtar and Dr Gabriela Semolini Pilo for their encouragement, patience and guidance during my honours year. Neil is like my dad; he is always patient and teaches me how to be a real scientist. Jules is like my elder brother; he is always attentive and patient to me. He always helped me out when I was stuck with problems in my research and encouraged me at every stage of my honours year. Lisa and Gabi are like my sisters and friends; they always encouraged me and gave me a hand when I need their help. They are not only my supervisors in research, but also my families in Australia.

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Chapter One: Introduction

1 Research background

1.1 What is a marine cold spell?

‘Cold spells’ usually refer to atmospheric phenomena. Qualitatively, cold spells are defined as prolonged periods when temperatures are lower than a particular frequency distribution (Ryti et al. 2016). Atmospheric cold spells over land can cause severe impacts on terrestrial ecosystems as well as on economic productivity and human health (Ryti et al. 2016; Scannell et al. 2016; Frolicher and Laufkotter 2018). However, with the recent realisation that the health and productivity of marine ecosystems can be affected as detrimentally as of terrestrial ecosystems, the definitions of cold spells have been expanded to also include the ocean.

The definition of a marine cold spell (MCS) is based on the definition of a marine heatwave (MHW) in Hobday et al (2016). A MHW is generally defined as a discrete prolonged anomalously warm water event in a particular location (Hobday et al. 2016). Therefore, a marine cold spell (MCS) has been defined in the same manner as a MHW, with the exception of ‘anomalously cold water event’ (i.e. a discrete prolonged anomalously cold water event in a particular location) in Schlegel et al. (2017). We also came up with a figure to show the definition of a MCS (Fig. 1).

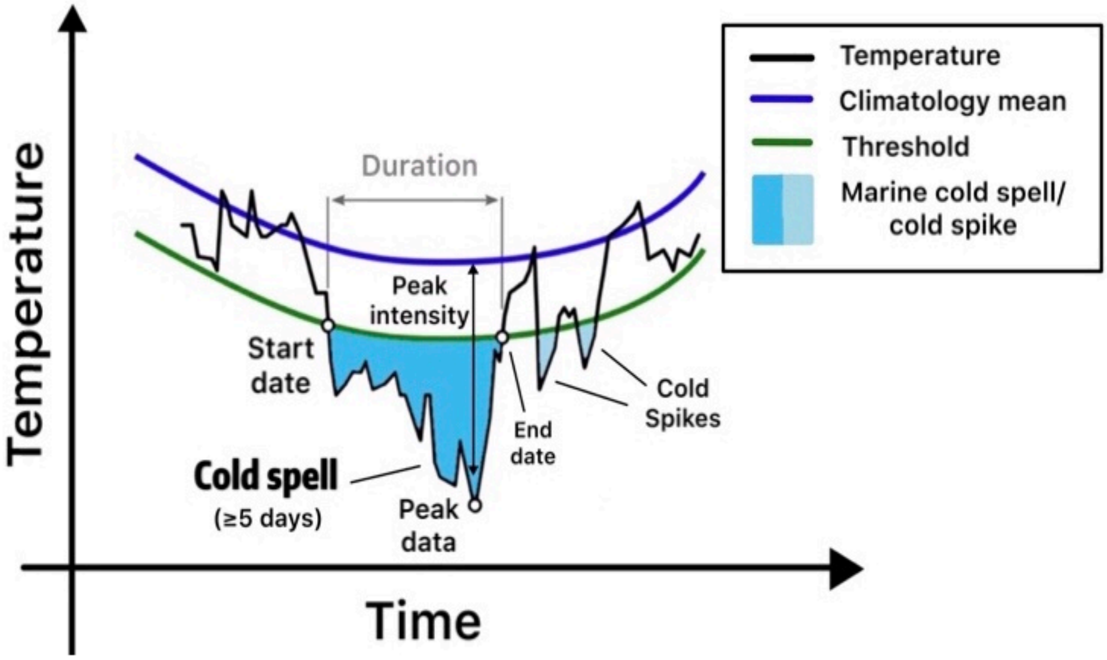

Fig. 1 Definition of a marine cold spell. A marine cold spell is defined when sea surface temperature is below a seasonally varying threshold (usually the 10th percentile) for at least 5 consecutive days. Successive cold spell with gaps of 2 days or less are considered part of the same event.
Adapted from Hobday et al. (2016), Fig. 1

Quantitatively, as shown in Fig. 1, 'discrete' describes an identifiable event with a definite start and end date, 'prolonged' implies the duration of a MCS event which should last for at least 5 days and 'anomalously cold' is defined on the basis of a seasonally varying threshold compared to a baseline reference climatology of ideally 30 years or more (Schlegel et al. 2017). For a MCS, 'anomalously cold' means that water during the event is colder than a low percentile threshold (usually the 10th percentile) based on the reference climatology (Schlegel et al. 2017). Some metrics of MCSs are quantitatively defined based on their properties. These include the duration (i.e. the number of days the MCS lasts), frequency (i.e. the number of MCS events during a specific time period), the rates of onset and decline of a MCS (°C/day), and the intensity (i.e. the amplitude of the difference between the measured temperature and the local seasonal threshold in °C). Intensity can be further described by three different metrics, namely mean and maximum intensity during the MCS as well as cumulative intensity (i.e. the integrated temperature throughout the period of the MCS). The quantitative definition for MCSs allows better identification and comparison of MCS events across different regions around that world (Schlegel et al. 2017).

1.2 Why studying marine cold spells?

Whereas extreme hot events (e.g. MHWs) have been shown that they can be demonstrably damaging to organisms and ecosystems, extreme cold events, such as MCSs, also have the potential to negatively impact marine creatures and marine ecosystems, leading to coral mortality (Lirman et al. 2011), reduction of fish species diversity (Gunter 1941; Gunter 1951; Holt and Holt 1983; Woodward 1987; Leriorato and Nakamura 2019) and changes in the structure of marine ecosystems (Donders et al. 2011). For example, in January 2010, the reefs of the Florida Reef Tract were impacted by an unusually low sea surface temperature (SST) event. This anomalously cold event not only caused widespread coral mortality but also reversed prior resistance and resilience patterns that will take decades to recover (Donders et al. 2011). In early 2018, the approximately two-month long extremely cold water event in Tosa Bay, southwestern Japan, caused about 80% of fish species richness and more than 80% of their abundance to decrease (Leriorato and Nakamura 2019).

Cold temperatures are very important for the timing of the onset of growing seasons (Jentsch et al. 2007) and for setting geographical limits to species' population distributions (e.g. the distribution of invasive mussel, Atlantic croaker and shrimp), particularly limiting their range north- or southwards towards higher latitudes (Hare et al. 2010; Firth et al. 2011; Morley et al. 2016). Changes in population distribution can drive many ecosystem responses (Kreyling et al. 2008, Rehage et al. 2016). In fact, the range contractions (i.e. retreat of a population's distribution at the edge of its geographic range) of ecosystem engineer species such as mussels have been shown to relate to MCSs (Firth et al. 2011; Firth et al. 2015).

Therefore, MCSs can have many significant impacts on marine creatures and marine ecosystems, however, they are less studied than other extreme events (e.g. MHWs), and hence, there are many knowledge gaps in MCS studies. This is the motivation for our MCS study.

1.3 What causes marine cold spells?

MCSs have been found to be generated by atmospheric cold spells (Gunter 1941; Firth et al. 2011). Schlegel et al. (2017) hypothesised that MCSs are manifestations of extreme atmospheric cold weather phenomena causing rapid heat loss from the mixed layer. On the other hand, large-scale teleconnections can also influence marine thermal properties (Schlegel et al. 2017). For example, large-scale atmospheric-oceanographic coupling is being affected by global warming and is expected to lead to the intensification of upwelling winds, which in turn will cause the intensification and increase the frequency of upwelling events (see García-Reyes et al. 2015 for a review of this and alternative hypotheses). It is therefore possible that the development of some MCSs may be attributed to an intensification of upwelling.

Surface MHWs are the direct result of local-scale processes acting within the mixed layer (e.g. horizontal advection, horizontal mixing and vertical mixing) or of remote processes that reach the region via teleconnections (Holbrook et al. 2019; Fig. 2a). In the majority of MHW studies and some MHW global analyses conducted to date, MHWs have been identified and characterized based on SST (Holbrook et al. 2019). Here, we generated a figure, based on MHW forcings, to show the possible causes of MCSs (Fig. 2b).

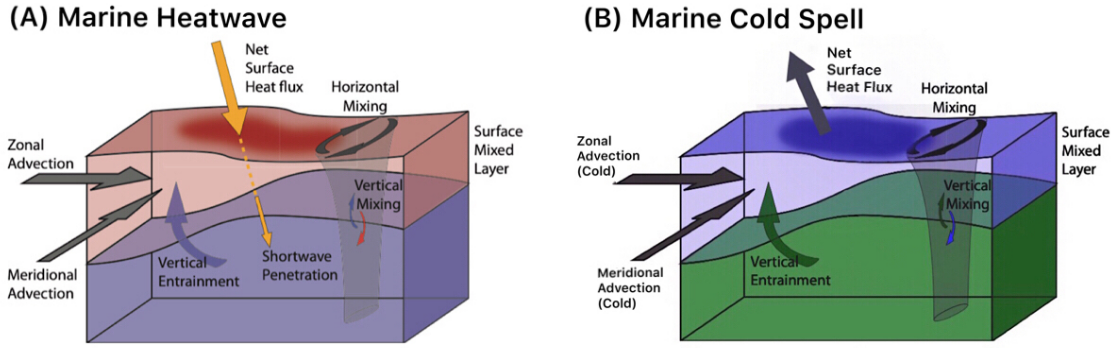

Fig. 2 Local factors that affect the evolution of ocean temperature within the surface mixed layer at a certain location, i.e. net surface heat flux (comprising of net shortwave radiation flux + longwave radiation flux + sensible heat flux + latent heat flux at the ocean surface), radiative heat flux at the base of the mixed layer, horizontal advection (from the mean circulation or high-frequency small-scale flow), vertical entrainment, and mixing. **(A)** When the net surface heat flux points out to the atmosphere, MHW can appear under some extreme situation. **(B)** When the net surface heat flux points out to the ocean, MCS can appear under some extreme situation.
Adapted from Holbrook et al. (2019), Supplementary Fig. 1

2 How can the changes in sea surface temperature mean and variance influence marine cold spells?

Studies have shown that MHWs have increased in exposure and intensity under global warming scenarios over the past several decades (Frölicher et al. 2018(1); Frölicher et al. 2018(2); Oliver et al. 2018; Darmaraki et al. 2019; Oliver 2019). Oliver (2019) illustrates this conceptually by showing how the increase of both mean SST and the variance of SST can drive increasing intensity and frequency of MHWs (Fig. 3).

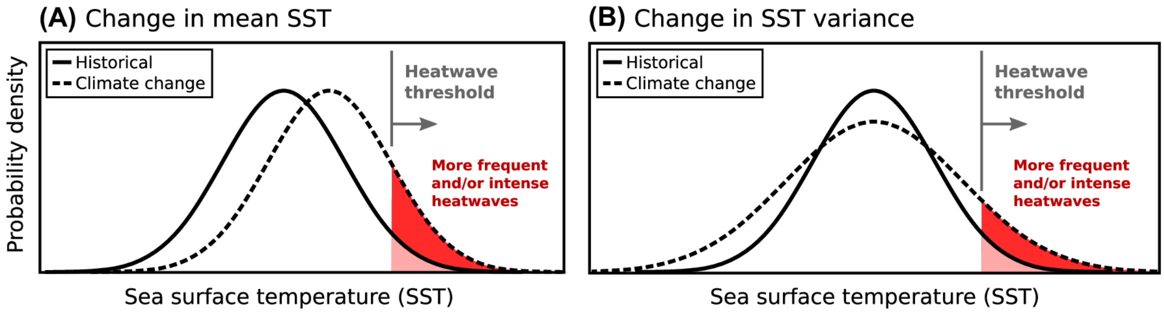

Fig. 3 The effect of changing (**A**) the mean SST and (**B**) the variance of SST on the likelihood of marine heatwaves.

Adapted from Oliver (2019), Fig. 1

In Fig. 3, the pink shading beneath the right tail of the probability density function curve represents the likelihood of an MHW occurring. With increases in SST mean, the probability density function can just shift to the right so that there are more frequent and/or more intense MHWs (the union of pink and red shading areas in Fig. 3a). Increases in SST variance can also widen the distribution, also leading to more frequent and/or more intense MHWs (the union of pink and red shading areas in Fig. 3b).

Oliver (2019) finds that the changes in mean SST play a dominant role in the changes in exposure to MHW days across most of the global ocean. While changes in mean SST can only lead to changes in MHW maximum intensity (max SST anomaly) across one-third of the global ocean (Oliver 2019). Besides this, it has been found that changes in mean SST can provide better explanations for changes in MHW days and intensity than changes in SST variance (Oliver 2019).

Whilst it might be expected that the occurrence of MCSs will diminish under global warming, this is not necessarily true. An increase in mean temperature does not necessarily equate to a uniform shift in temperature extremes, we also need to consider the changes in temperature variance. Hence, the regional change of MCS under temperature changes might be complex.

We generated a figure to show how the increase of SST mean and variance might influence the intensity and frequency of MCSs (Fig. 4). The light blue region under the left tail of the temperature distribution curve in Fig. 4 represents the likelihood of MCSs before SST changes. The dark region under the left tail of the temperature distribution curve in Fig. 4 represents the likelihood of MCSs after SST changes. Here, the light blue region decreased to the dark blue region by shifting the curve to the right (i.e., an increase of mean SST, Fig. 4a). The light blue region increased to the union of dark blue and light blue regions by widening this distribution (i.e., a rising in SST variability, Fig. 4b).

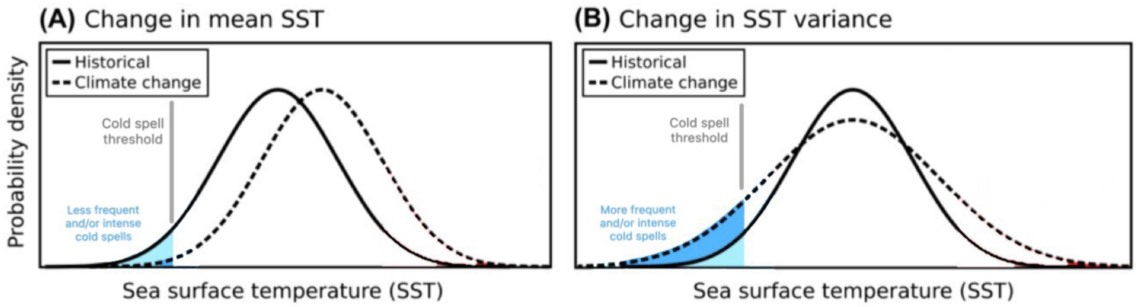

Fig. 4 The influence of increasing (**A**) SST mean and (**B**) increasing SST variance in the occurrences probability of marine cold spells.

Adapted from Oliver (2019), Fig. 1

As shown in Fig. 4, the changes in average SST and changes in SST variance have conceptually important effects on MCS trends. However, whether trends in SST mean and trends in SST variance can explain trends in MCS has not yet been investigated in the global real marine environment. Here, we investigate this question, on a global scale, using a simple statistical climate model. The observed ranges of mean warming and trends in variability from the satellite record are used to drive this statistical model, from which trends in MCS properties are derived.

3 Research aim and objectives

Sustained extreme marine thermal events, such as MCSs and MHWs, can have huge impacts on marine ecosystems and marine creatures. Though equally significant to marine ecosystems and marine creatures, MHWs have been well studied in recent years, while MCSs have received less attention. A comprehensive global assessment of MCSs is missing. The distribution of MCSs, the global trends in MCSs, as well as the relationship between SST and MCSs, are still unclear. Therefore, this study aims to understand the changing nature of marine cold spells globally to fill the knowledge gaps in MCS research. We set three objectives to help us achieve our aim:

The first objective is to characterise the global distribution of mean MCS metrics (frequency, duration and mean intensity) during 1982-2016 and assess regional differences in MCSs. A small number of studies has previously investigated mean MCS metrics at the local scale, but, to the best of the authors' knowledge, this current study will be the first to mean MCS metrics at the global scale. Based on this objective, we provide a global map of MCS distribution, giving a general understanding about MCS to the public.

The second objective is to assess trends in the frequency of MCSs over the period 1982-2016 (i.e. how often they occur), the duration of MCSs (i.e. how many days, weeks, or months they persist) and the mean intensity of MCSs (i.e. how many degrees Celsius below the long-term average temperature) in global scale. Trends in many extremes like MHWs have been examined globally, however, this is the first study to look at MCSs. To fulfil this objective, we examine whether MCSs simply show a decreasing trend overall due to the influence of global warming or whether there are regional differences.

The third and the final objective is to assess whether the trends in SST mean or the trends in SST variance can explain trends of MCS metrics. To accomplish this, we investigate whether trends in MCS can simply be explained by changes in SST. Do trends in MCS and trends in SST have a strong relationship, or do they lack correlation?

By pulling together the threads of the results in stages, the thesis finally synthesizes the results in a scientific discussion to contextualise the findings both here and in existing literature.

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Chapter Two: Manuscript

Understanding the changing nature of marine cold spells

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Abstract

Prolonged oceanic temperature extremes – also known as marine cold-spells (MCSs) and marine heatwaves (MHWs) – can have severe and long-term impacts on ecosystems, with subsequent socioeconomic consequences. However, compared with increasing number of studies and published literature on MHWs, there are relatively few published studies on MCSs, and no comprehensive global assessment of MCSs has been undertaken. In this study, we have investigated four fundamentally important questions. These are: (1) How global spatial distribution of mean MCS metrics looks like? (2) How have MCSs changed across the globe over the past several decades? (3) Are changes in MCSs around the world mostly due to rising mean ocean temperatures, changes in ocean temperature variance, or a combination of the two? (4) What are the implications of our findings?

Specifically, we address these questions for surface MCSs based on analysis of satellite observations of sea surface temperature (SST), using the National Oceanic and Atmospheric Administration (NOAA) optimum interpolation SST (NOAA-OI SST) dataset from 1982–2016. We show that over this 35-year period, MCSs show a less frequent, weaker in intensity and shorter lasting trend over most of the global ocean. However, we identify a few significant regions, such as in the southwest Atlantic, where MCSs show a more frequent, stronger in intensity and longer-lasting trend. We applied a statistical climate model to test whether observed trends in MCS properties could be explained by trends in SST mean or variance. We find that neither trends in SST mean nor SST variance explained trends across all of the investigated MCS metrics, i.e. MCS duration, frequency and mean intensity, over most of the global ocean. Rather, we find that multi-decadal warming explained trends in MCS frequency in over one third of the ocean. MCSs can not only cause impacts on ecosystems. Considering the warmer water due to the continued global warming, marine species who prefer cold water (e.g. cold water fish) can have survival crisis, MCSs can also provide some cold refugia for them. This study fills the knowledge gap in MCS global analysis and can provide information to fisheries, ecosystem study and social sectors.

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' (Pearce and Feng 2013). Such events can cause devastating impacts to marine biodiversity, ecosystems (e.g. Smale et al. 2019) and the economies of regional fisheries (e.g. Mills et al. 2013; Caputi et al. 2016). Marine heatwaves (MHWs) can persist from a few days to several months (Hobday et al. 2016) and even years (e.g. Di Lorenzo and Mantua 2016; Holbrook et al. 2019). Since they have caused many devastating effects, such as coral bleaching, wilt of seaweed and kelp, and changes in the structure of marine ecosystems (Jentsch et al. 2007; Smale and Wernberg 2013; Wernberg et al. 2013; Tuckett et al. 2017), they have been studied widely in recent years.

Conversely, marine cold spells (MCSs) are discrete and prolonged extreme oceanic cool water events, which can also have negatively impact on marine ecosystems. However, these extremes have been far less studied. MCSs have been shown to cause coral mortality (Lirman et al. 2011), reduce fish species diversity (Leriorato and Nakamura 2019) and result in shifts in marine ecosystem structure (Donders et al. 2011). For example, the Florida Reef Tract in the United States, the third largest coral barrier reef system in the world, experienced an anomalously low sea surface temperature (SST) in 2010 winter that resulted in extensive coral mortality. Furthermore, this cold event reversed established resistance and resilience patterns that is expected to take decades to recover (Donders et al. 2011). In early 2018, an extreme cold-water event in Tosa Bay, southwestern Japan, lasted for roughly two months and led to a reduction in fish diversity and abundance by up to 80% (Leriorato and Nakamura 2019). Although MCSs are known to significantly impact ecosystems, the global distribution of MCS and how different climate change scenarios might alter MCS' distribution patterns are still unclear. Thus, questions around how MCSs have changed in the past several decades due to climate change, and what this might mean for marine ecosystems and society, needs consideration.

While we might expect MCS occurrences to reduce overall as a global-average under climate change, this is not necessarily going to be the case everywhere around the world's oceans. Furthermore, an increase in mean temperature does not necessarily equate to a uniform shift in temperature extremes, which can also be influenced by changes in the temperature variance (e.g. Oliver 2019). Hence, regional changes in MCSs in a changing climate might be complex. Fig. 1 shows how increases in the SST mean and variance might influence the intensity and frequency of MCSs. Clearly, cold extremes can change by either increases in the mean SST or changes in the SST variance as shown in Fig. 1. Although the changes in mean SST and changes in SST variance have conceptually important effects on MCS trends, whether trends in SST mean and trends in SST variance can explain trends in MCS has not yet been investigated in the global real marine environment.

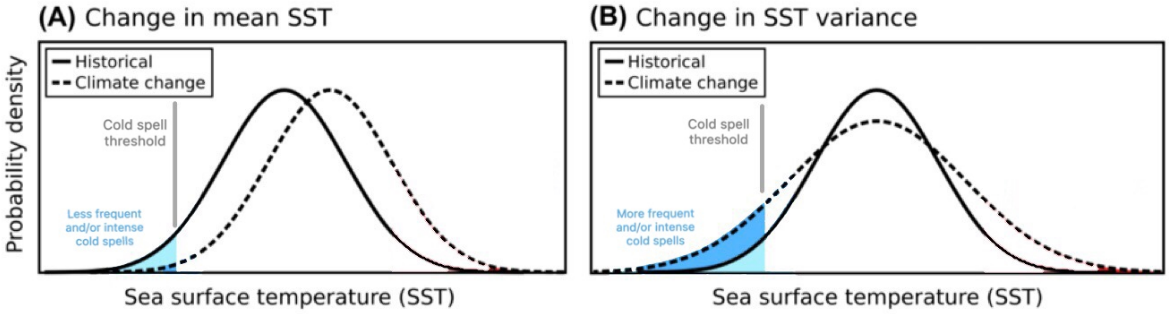

Fig. 1 The influence of increasing SST mean **(A)** and increasing SST variance **(B)** in the occurrences probability of marine cold spells. The light blue region under the left tail of the temperature distribution curve represents the likelihood of MCSs before SST changes. The dark region under the left tail of the temperature distribution curve represents the likelihood of MCSs after SST changes. **(A)** The light blue region decreased to the dark blue region by shifting the curve to the right (i.e., an increase of mean SST). **(B)** The light blue region increased to the union of dark blue and light blue region by widening this distribution (i.e., a rising in SST variability).
Adapted from Oliver (2019), Fig. 1

Using a quantitative MCS framework, which allows for comparisons across regions and events, this paper provides the first ever global-scale analysis of changes in MCS metrics from 1982-2016. Specifically, the paper endeavours to answer the following questions: (1) How global spatial distribution of mean MCS metrics looks like? (2) How have MCSs changed across the globe over the past several decades? (3) Are changes in MCSs around the world mostly due to rising mean ocean temperatures, changes in ocean temperature variance, or a combination of the two? (4) What are the implications of our findings? To address these questions, we used daily satellite SST data to investigate changes in MCS intensity, duration, and frequency over the 35-year period from 1982–2016. In addition, we applied a statistical climate model to investigate the question of whether changes in MCSs are likely due to increasing mean SST, changes in SST variance, or a combination of the two. A statistical climate model was used to analyse individual SST time series point-by-point across the globe, with respect to the relative contributions of SST mean and variance to MCS trends. Finally, we provide some thoughts on the implications of the findings from this study for marine fisheries and ecosystem management.

2 Data and Methods

2.1 High resolution, daily and global SSTs covering 1982–2016

In this study, we used the National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation (OI) SST data set (Reynolds et al. 2007; Banzon et al. 2016) to detect MCSs and calculate MCS properties globally. The NOAA-OI SST dataset consists of observed satellite SST data measured by the advanced very high-resolution radiometer (AVHRR). The data is interpolated daily onto a 0.25° latitude×0.25° longitude spatial grid with global coverage from 1982 to 2016, providing high-quality SST data for detecting MCS events and calculating detailed MCS properties. We calculated MCS properties and their annual mean time series from 1982 to 2016 by using the NOAA-OI daily SST time series at each grid cell across the global ocean. We defined the baseline climatology and seasonally varying threshold value for MCSs (10th percentile of the climatology) by using a 30-year subset (1983–2012). For each of the annual mean MCS property time series, we calculated (i) a 35-year (1982-2016) mean value at each grid point, (ii) a linear trend of those time series over 1982-2016 at each grid point and (iii) a globally averaged (area-weighted) property annual mean time series and linear trend. Any grid cells with recorded SST datapoints below -1°C in the time series were assumed to have ice cover and were subsequently excluded from the analysis.

2.2 Defining marine cold spells

Qualitatively, a MCS is defined as a discrete prolonged anomalously cold water event in specific places. Quantitatively, the definitions of these terms are as follow.

• ‘anomalously cold’: The definition of an MCS is relative to a baseline climatology (Hobday et al. 2016). Ocean drivers have long-term time series of variability. Therefore, if possible, it has been recommended that the baseline climatology should be at least 30 years which is nearly equal to the entire time length of the available satellite SST observations (Schlegel et al. 2017). Climatology is defined as a 30-year (from 1983 to 2012) baseline. Considering that the variability of SST during a period can vary in different regions, it is recommended to define a MCS with a percentile threshold, rather than an absolute value below the climatology (Schlegel et al. 2017). In order to detect anomalously cold events, here we regarded the climatological 10th percentile as the threshold of MCS events. Daily climatological MCS threshold time series (i.e. the 10th percentile) were calculated for each calendar day using daily SSTs within an 11-day window centred on the date across all years within the climatology period. The climatology and MCS thresholds were smoothed with a 31-day moving average. The choices of an 11-day window and a 31-day moving average are motivated by ensuring a sufficient sample size for percentile estimation and a smooth climatology. This seasonally varying threshold allows the identification of anomalously cold events at any time of the year, rather than events only during the coldest months.

• 'prolonged': Hobday et al. (2016) tested for different minimum durations for the definition of MHWs. The authors find that a minimum length of 5 days allowed for more uniform global results in event detection. Therefore, the 5-day minimum duration was chosen for MHWs, and we just kept it for MCSs. However, Hobday et al. (2016) mention that, in the marine environment, the definition of marine extremes (e.g. MCSs) should be relevant to ecological processes and thresholds (based on evidence of impact). Hence, more information on sensitivity of marine life to the duration of a MCSs is required, and further studies might determine a different minimum duration threshold.

• 'discrete': An MCS event is discrete which means it has a distinct start and end date (Schlegel et al. 2017). If two successive MCS events occur with a gap of two days or less, they can be regarded as a single continuous MCS event (Schlegel et al. 2017). For example, five anomalously cold SST days followed by two warm SST days and then six anomalously SST cold days would be defined as a single MCS event with a 13-day duration [5cold, 2warm, 6cold]. Conversely, five anomalously cold SST days, followed by one warm SST day, and then four more anomalously cold SST days would be defined as a 5-day MCS event [5cold, 1warm, 4cold = 5 MCS days]; as would the converse [4cold, 1warm, 5cold]. A sequence of five anomalously cold days followed by three warm days and then six anomalously cold days [5cold, 3warm, 6cold] would be defined as two MCS events, one of five days duration, and one of six days duration.

2.3 Defining and calculating marine cold spell metrics

MCS events can be identified in each grid cell. MCS frequency is defined as the total number of MCS events in a certain time period. MCS duration is defined as the length of period over which the temperature is lower than the seasonally varying threshold value (10th percentile of a 30-year climatology, between 1983 and 2012). MCS mean intensity is defined as the mean SST anomaly during the MCS event. Note that MCS mean intensities are calculated as negative values (i.e. SST negative anomalies). Therefore, regions with less negative mean intensity of MCS have weaker MCSs (i.e. warmer) and a positive linear trend in MCS mean intensity over time represents a drop in MCS intensities.

To calculate the linear trends of MCS metrics at each point and linear trend of the global averaged MCS metrics, we first calculated annual statistics for each location, including the MCS frequency (i.e., total MCS events in each year), annual mean intensity (i.e. average MCS mean intensity in each year) and annual duration (i.e. average MCS duration in each year). We then used Theil–Sen estimates (Sen 1968) rather than ordinary least squares estimates to calculate the linear trends because the linear trends calculated by ordinary least squares estimates can be biased due to non-normally distributed data and the existence of outliers (Oliver et al. 2018). A Theil-Sen estimate of the linear trend is more robust for time series data that are heteroskedastic or have a skewed distribution (Oliver et al. 2018).

2.4 Investigating whether trends in marine cold spell metrics can be explained by trends in SST mean and trends in SST variance

For this analysis, we adopted the method outlined in Oliver (2019) for investigating the relationship between trends in MHW metrics and trends in SST mean and variance. We also suggest some improvements to this method, explain it in more detail, and provide detailed justification for each step in our methodology. We develop a statistical climate model to simulate the characteristics of MCS metric trends due solely to the trends in SST mean or SST variance. First, we used a first-order autoregressive (AR1) model to statistically simulate a daily SST time series with stationary statistical properties, in which both the SST mean and SST variance are constant over time. The AR1 model can be written as:

$$T(t+\Delta t) = aT(t)+\epsilon(t) \qquad (1)$$

where T(t) represents SST at time (day) t, Δt is the time between successive measurements of the response T (it will be taken to be one day in this study), a is the AR1 parameter, $\epsilon(t)$ is a white noise process, which is normally distributed with its mean equal to zero and variance equal to $\sigma_\epsilon{}^2$ at time t (Di Lorenzo and Ohman 2013).

An AR1 model is used to simulate stationary SST time series because this model is based on the concept that the dynamic ocean (slow system) can be expressed by a red noise signal (T), which is the integration of the weather noise [$\epsilon(t)$] (Di Lorenzo and Ohman 2013). In this MCS study, the AR1 model (Equation 1) represents the temperature of a motionless mixed layer forced by noisy surface heat fluxes (Frankignoul and Hasselmann 1997), which exactly satisfies the concept and requirements of our study. The temperature time series (red noise) has an intrinsic memory time scale τ (in days) which can be derived from the autoregressive parameter a as:

$$\tau = -1/\ln(a) \qquad (2)$$

Given an observed SST time series (T_o), the AR1 model parameters can be fitted by the following steps. The first step is called "detrending", which means eliminating the seasonally varying climatology as well as linear trends, and yields a new "detrended" time series $T_{0\_detrend}$. We removed the seasonal climatology and linear trends because removing seasonal climatology can be more consistent with the definition of MCS, while removing linear trend is done so that we can add prescribed trends later. Next, we used an ordinary least squares regression of $T_{0\_detrend}$ lagging itself by one day to get the value of a. Then we calculated the standard deviation of $T_{0\_detrend}$ ($\sigma_{0\_detrend}$) to derive the standard deviation of white noise (σ_ϵ) by:

$$\sigma_\epsilon = \sqrt{\sigma^2_{0\_detrend} * \left(1 - a^2\right)} \qquad (3)$$

The steps described above for calculating the autoregressive time scale (τ) and the standard deviation (σ_ϵ) of white noise were repeated for each grid point of the global ocean within the NOAA OI SST dataset for the time period 1982-2016. Then we plotted the global distribution of the autoregressive time scale (τ) (Fig. 2a) and the standard deviation of white noise (σ_ϵ) (Fig. 2b). Besides, we display the two-dimensional probability distribution of (τ, σ_ϵ) across all ocean grid-points (Fig. 2c), peaking at τ=12 days and σ_ϵ = 0.27°C and with most values (99%) in the range of τ=[5.4,45] days and σ_ϵ=[0.16,0.46] °C (Fig. 2c).

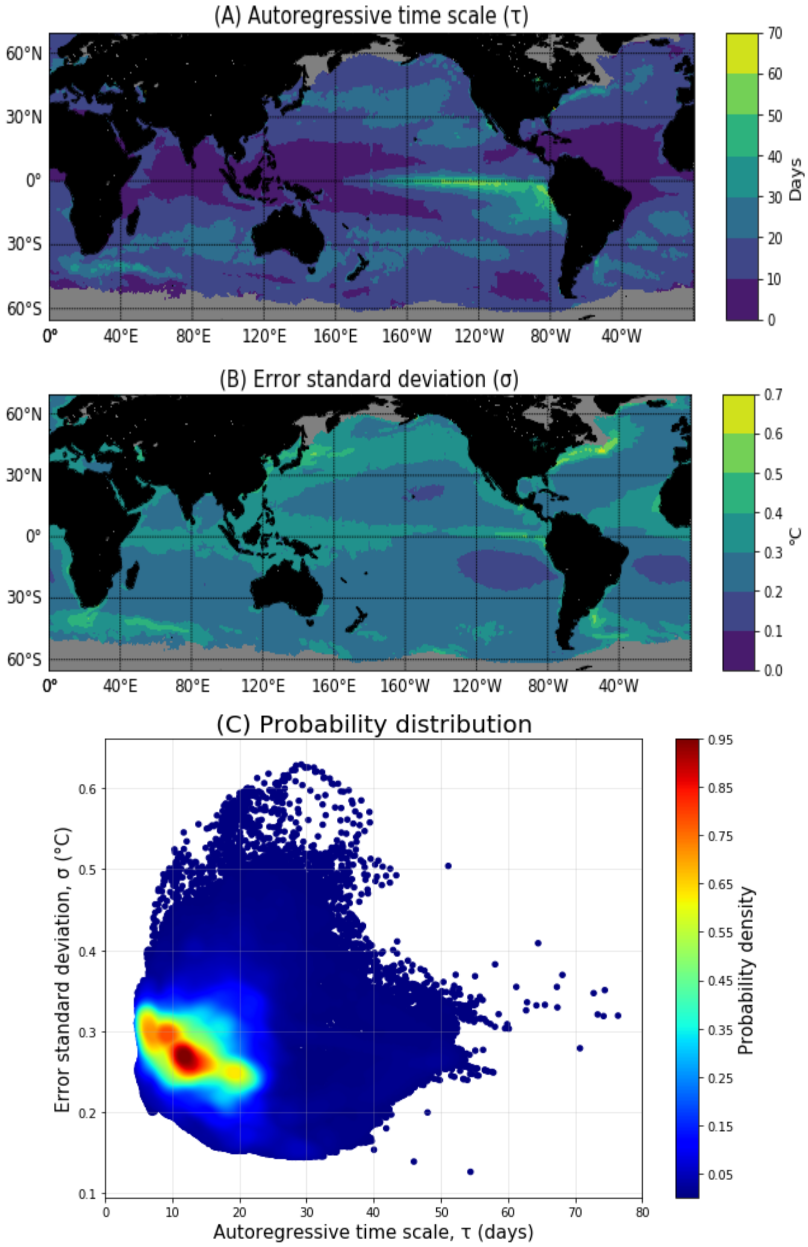

Fig. 2 Parameters for the AR1 stochastic climate model fit to NOAA OI SST over 1982–2016, for each pixel globally. Shown are **(A)** the autoregressive time scale τ and **(B)** the standard deviation $\sigma\epsilon$ of the white noise error forcing **(C)** the probability density function of all (τ, σ_ϵ) values.

To explore the effects of varying mean SST or SST variance on MCS, we generated a simulated 35-year (i.e. 1982-2016) stationary daily SST time series (using Equation. 1) at each grid-point by using spatially varying sets of parameters (τ, σ_ϵ), and random white noise data $\epsilon(t)$. Because there is no long-term trend of mean SST or SST variance in these stationary time series, we then modified these time series by specifying a constant linear trend in (i) SST mean or (ii) SST variance (see Appendix). We then applied the MCS definition we mentioned previously to the simulated SST time series and calculated the trends in annual MCS metrics. We repeated this process for N_ϵ=500 independent realizations of $\epsilon(t)$ for each (τ, σ_ϵ) to derive a set of MCS metric trends, each representing a different realization of SST variability. From this set we can derive a 95% confidence interval for the trends in MCS properties. The trend can be regarded as significant (p<0.05) when this confidence interval does not include 0. Note that when adding constant SST variance trends to stationary SST time series, Oliver (2019) simplified the process by neglecting non-linearities. However, the results produced by this simplified methodology significantly differ from those of a methodology that includes said non-linearities, which is why we found the simplification unreasonable. Therefore, we provided detailed calculation processes of adding constant SST variance trends to stationary SST time series with non-linearities (see Appendix for more detail).

Under a prescribed trend in mean SST, we only allowed the mean SST to vary and keep SST variance constant. Hence, the confidence interval provides the range of MCS trends solely from a change in the SST mean. Under a prescribed trend in SST variance, we only allowed the SST variance to vary and keep SST mean constant. Therefore, the confidence intervals provide the range of MCS trends solely due to a change in the SST variance. Then we can define four possible situations for MCS metrics (Fig. 3):

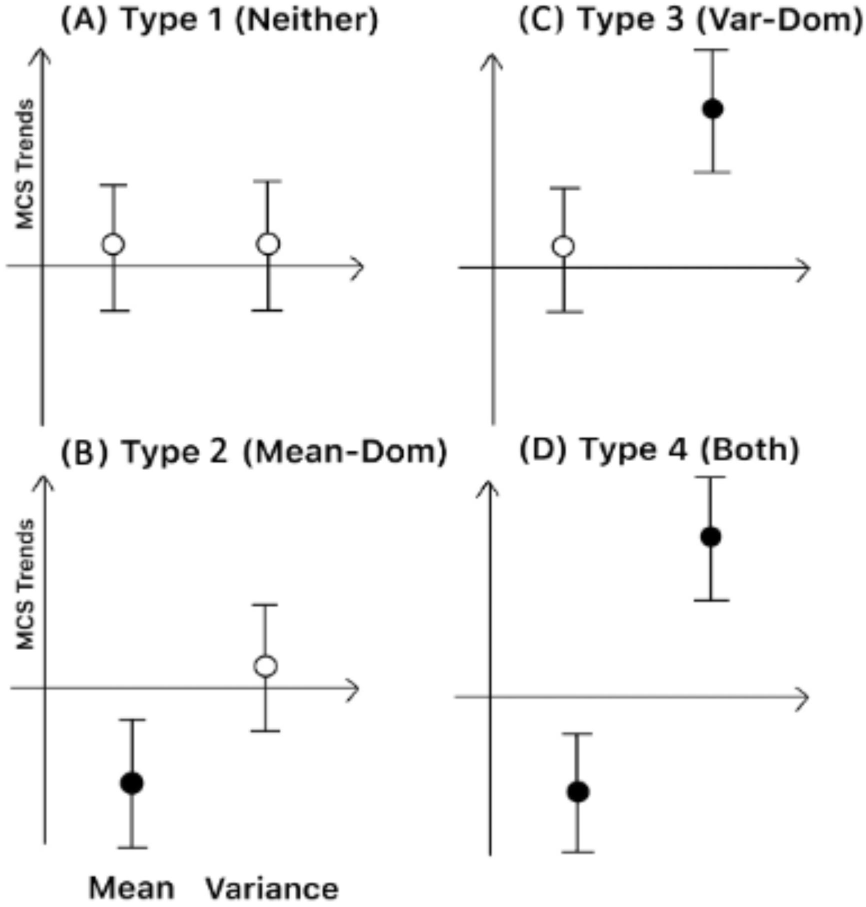

Fig. 3 Visualization of the four trend types. Each subplot describes a situation type. Each of them has two circles which represent the trend of MCS due to the trends of SST mean (left) and SST variance (right). There are also two error bars in each subplot indicating confidence interval of these trends. Filled black circles indicate the trends are statistically significantly different from zero while open circles represent trends that are not significantly different to zero.

Type 1: Trends in the MCS metric are not attributed to trends in SST mean nor trends in SST variance (Fig. 3a).

Type 2: Trends in the MCS metric due to SST variance trend not being significantly different from zero, but trend due to SST mean trend being significant (Fig. 3b).

Type 3: Trends in the MCS metric due to SST mean trend not being significantly different from zero, but trend due to SST variance trend being significant (Fig. 3c).

Type 4: Trends in the MCS metric due to both SST mean and variance trends being significantly different from zero (Fig. 3d).

We can give more examples for these types as follows. Type 1 implies that neither trends in SST mean nor trends in SST variance can explain trends in the MCS metric (Neither). Type 2 indicates that trends in the MCS metric can solely be explained by trends in SST mean (Mean-Dom). Type 3 represents trends in the MCS metric that can be solely explained by trends in SST variance (Var-Dom). Type 4 represents the case when both trends in SST mean and trends in SST variance can explain trends in MCS metric (both).

We aim to test the global distribution of the four types in the real ocean, given the observed trends in SST mean and variance and a fit of the AR1 model to the observed SST time series. This could be accomplished by looping over all pixels, globally, and running the Monte Carlo simulation N_ϵ times as described above at each grid-point across the global ocean. However, this would require > 10^5 (the number of grid cells multiply 500 times) independent simulations and would be prohibitively time consuming. Instead, we first pre-calculated the Monte Carlo simulation results for a specified set of (τ, σ_ϵ) values, chosen to uniformly sample the area enclosing 99% of the probability distribution shown in Fig. 2c. Values are chosen on a regular grid with step of $\Delta\tau$=2 days and $\Delta\sigma_\epsilon$=0.02 °C. The Monte Carlo trend simulation is then performed for each of these subsampled AR1 parameter values, leading to the requirement of less than 500 independent sets of simulations. In addition, for each pair of τ and σ_ϵ values, the simulations are run for a preselected set of mean SST and SST variance trends. The range of SST mean trends and SST variance trends are determined based on the observed linear trends fitted to the NOAA OI SST data (Fig. 4a, b). Ordinary least squares estimates of linear trends may be biased due to the presence of outliers or non-normally distributed data. Therefore, we calculated linear trends of SST mean and SST variance at each grid-point and linear trend time series of the globally averaged using Theil–Sen estimates. A

Theil–Sen estimate of the linear trend is more robust for time series data that are heteroskedastic or have a skewed distribution.

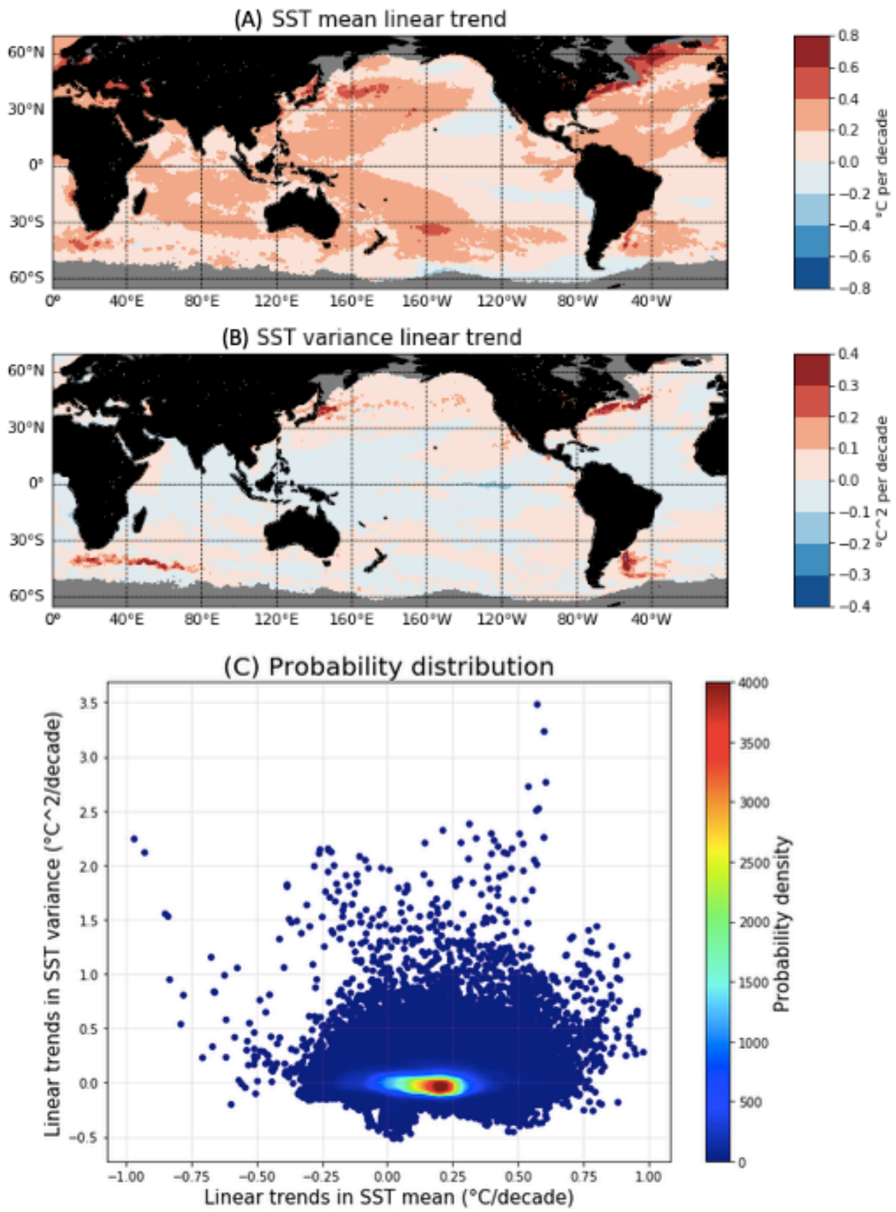

Fig. 4 Shown are linear trends in **(A)** annual mean SST and **(B)** annual SST variance from NOAA OI SST over 1982–2016 and **(C)** Probability distribution of all mean and variance trend values shown in **(A), (B)**.

The majority of SST mean (variance) trends are between − 0.4 and 1°C per decade (− 0.2 and 1.5 °C^2 per decade; Fig. 4c); the pre-selected set of trends we used are [− 0.4, − 0.2, − 0.1, 0, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0] °C per decade for mean SST and [− 0.2, − 0.1, 0, 0.1, 0.2, 0.35, 0.5, 0.75, 1.0, 1.5] °C^2 per decade for SST variance. Then, for each gird-point the nearest value of subsampled AR1 parameters (τ, σ_ϵ) and trends to the true values (the true values shown in Figs. 2a, b and 2.4a, b) was chosen and the pre-calculated Monte Carlo simulation results were used to determine which of the four types was present at the gird-point.

While using the statistical climate model to investigate whether trends in MCS/MHW metrics can be explained by SST trends, we discover a methodological limitation. This limitation is: when adding an SST trend to a time-series artificially, it is not clear what should be used as the climatology (against which to compute MCSs and MHWs). For example, consider a raw SST time-series with no trend. MCSs and MHWs will be detected throughout the timeseries. Now add a positive linear SST trend to that timeseries. If the climatology of the raw timeseries is taken as the baseline, MCS may no longer occur at the end of the timeseries if a strong linear trend is added. Conversely, a permanent MHW state may be entered. In this case, computing the trend of MCS/MHW metrics in timeseries is a tough problem. What we did to try to solve this problem was to use the climatology of the new timeseries (i.e. the time series with trend added). However, it still does not solve the problem very well, there nevertheless can be an absence of MHWs at the start of the time series, and an absence of MCSs near the end (again biasing the calculation of trends in MCS metrics). However, even with this limitation, this method is still deemed a reasonable approach because it fits the concepts and requirements of our MCS study well and it has already been used to carry out a similar analysis for MHWs (i.e. relationship between SST trends and MHW trends) by Oliver (2019). Therefore, it is fair to use the approach for this MCS study as well.

3 Results

3.1 Marine cold spells over 1982-2016

We first investigate spatial distribution of mean MCS metrics over 1982-2016 (Fig. 5).

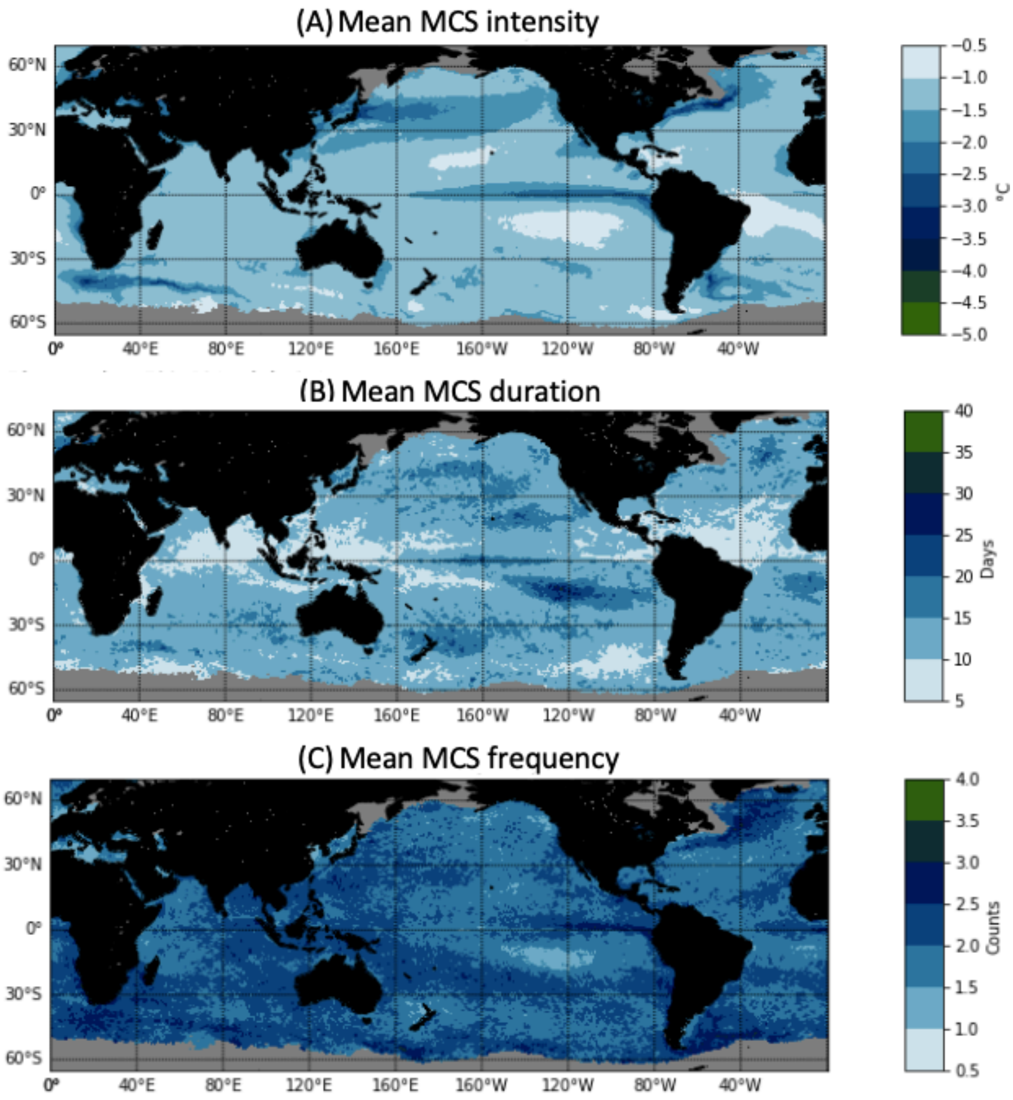

Fig. 5 Identification of marine cold spell properties globally. Shown are mean in **(A)** marine cold spell intensity, **(B)** marine cold spell duration, **(C)** marine cold spell frequency (i.e., mean number of events per year) from NOAA OI SST over 1982–2016.

The MCS mean intensity showed large spatial variation across the global ocean (Fig. 5a). Cold spots of strong mean intensity (dark blue regions in Fig. 5a) existed in places with large SST variability, such as the western boundary currents and their extension regions (where the

MCS mean intensity ranged from -5°C to -2°C) as well as the central and eastern equatorial Pacific Ocean (where the MCS mean intensity ranged from -1°C to -3.5°C).

The typical duration of MCSs varied substantially, depending on location (Fig. 5b). We found that the eastern tropical Pacific (0°-30°S) was characterised by an average MCS duration of up to 40 days, while some regions, such as the northern Indian Ocean, tropical portions of the Atlantic (a region between 0°-30°N), western tropical portion of the Pacific (a region between 0°-30°N) and eastern parts of the South Pacific poleward of 50° S had average MCS durations of less than 10 days.

Mean MCS frequency varied considerably across the global ocean, ranging from 1 to 2.5 annual events (Fig. 5c). However, the tropical part of the South Pacific showed a low mean MCS frequency (fewer than 1 event per year). Conversely, there are some notable locations that recorded up to three annual MCS events. One of the notable locations is the Southwest Atlantic Ocean (about 50°S) where a northward flow of the Antarctic Circumpolar Current, known as the Malvinas Current (cold water current), flows past. The Malvinas Current transports cold sub-Antarctic water and can cause frequent MCSs there. Another notable location is the region of the North Atlantic Gyre, between 40°S - 60°S. The frequent MCSs can be caused by the cold water brought by the Labrador Current and the East Greenland Current. Both currents are cold water currents transporting cold water masses from the Arctic Ocean. Another region which is also worth mentioning is the eastern tropical Pacific, where La Niña events occur. La Niña events can result in more MCS events by cooling of the ocean surface in the eastern tropical Pacific Ocean region.

Mean MCS duration and frequency should be negatively correlated, which means that regions with long MSC durations usually have low MSC frequency, and vice versa. Therefore, we expect the global map of MCS frequency and MCS duration to be somewhat mirror images. However, according to our results (Fig. 5b and Fig. 5c), our expectation was not always true. This can be the result of the following. According to the definition of MCSs, we use the 10th percentile of the climatology as MCS event threshold, indicating that 10% of SST days in each time series can be MCS days in theory. However, fewer than 10% of SST days in most time series are characterized as MCS days, since a MCS event needs to last at least 5 consecutive days. In some cases, there are many cold days on which SSTs are lower than the MCS threshold, but they cannot be regarded as MCS days. This will result in fewer MCS days in those cases, and thus alter the relationship between mean MCS duration and frequency.

3.2 Globally averaged time series of annual mean MCS metrics

We calculated globally averaged MCS annual mean frequency, annul mean duration and mean annual mean intensity from 1982 to 2016, and compared these results to the same calculations for MHWs (Fig. 6).

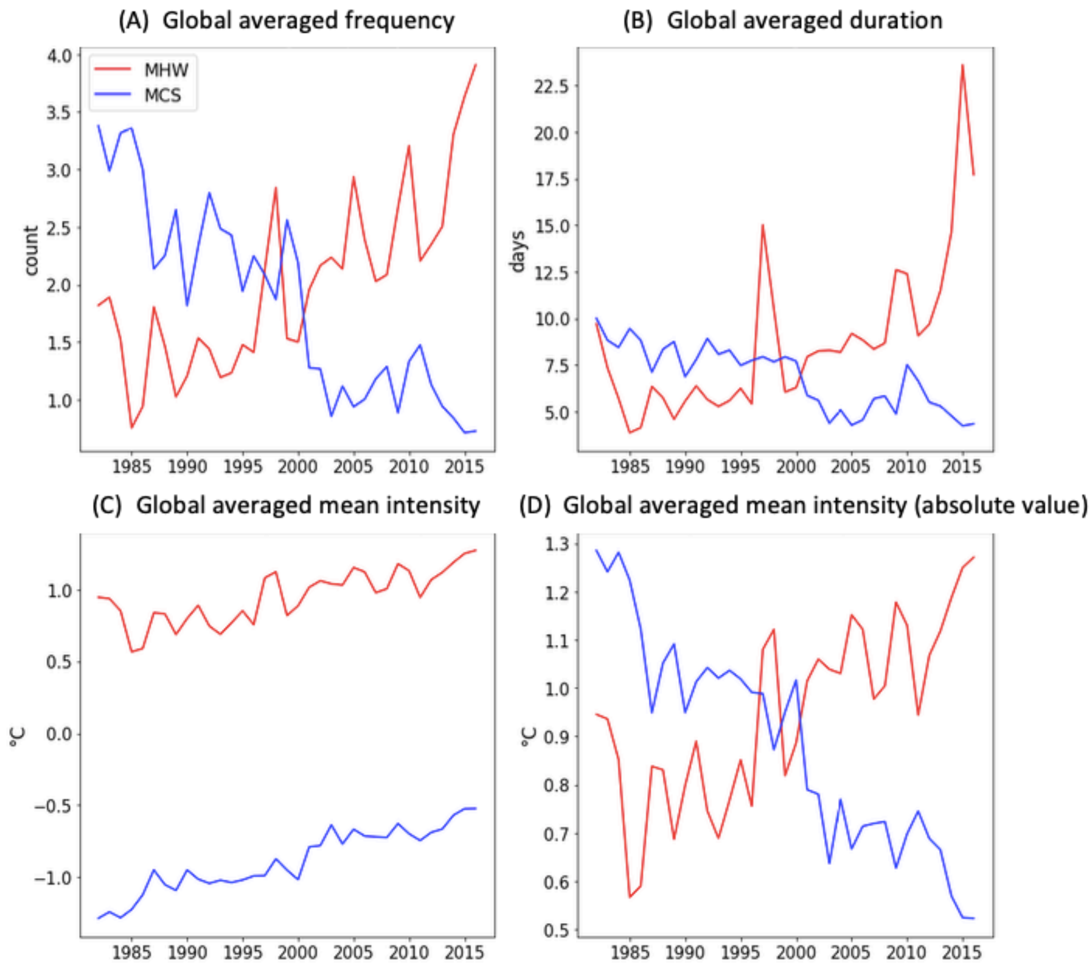

Fig. 6 Globally averaged marine heatwave and marine cold spell time series of annual mean. The red lines show the globally averaged marine heatwave time series and the blue lines show the globally averaged marine cold spell time series.

Global average MCS frequency decreased considerably, with a trend of 0.75 fewer annual events per decade in the period of 1982 to 2016 ($p<0.05$; Fig. 6a, blue line). This is equivalent to an average decrease of 2.6 annual events by the end of the 35-year record. For comparison, MHW frequency increased significantly with a trend of +0.58 annual events per decade from 1982 to 2016 ($p<0.05$; Fig. 6a, red line). This is equivalent to an average increase of 2.03 annual MHW events by the end of the 35-year record.

Averaged across the global ocean, mean MCS duration has become significantly shorter by 1.4 days per decade ($p<0.05$; Fig. 6b, blue line) while MHW duration has become significantly longer by 2.3 days per decade ($p<0.05$; Fig. 6b, red line) since 1982.

The linear trend in global average MCS intensity was 0.20°C weakening per decade ($p<0.05$; Fig. 6c, blue line), punctuated by large interannual variability. Interestingly, this trend is weaker than the global SST warming trend (+0.16°C per decade). The linear trend in global average MCS intensity is +0.15°C per decade ($p<0.05$; Fig. 6c, red line). To compare the amplitude of global average MCS duration trend and MHW duration trend between 1982 and 2016, we change MCS intensity to its absolute value (Fig. 6d).

In conclusion, the global average of annual mean MCS metrics show a less frequent, weaker, and shorter lasting trend in the period of 1982 to 2016. However, this can differ regionally.

3.3 Marine cold spells metrics trends in 1982-2016

To be more specific, we calculated the linear trends of MCS annual frequency, annual mean duration, and annual mean intensity at each location over 1982–2016 (Fig. 7).

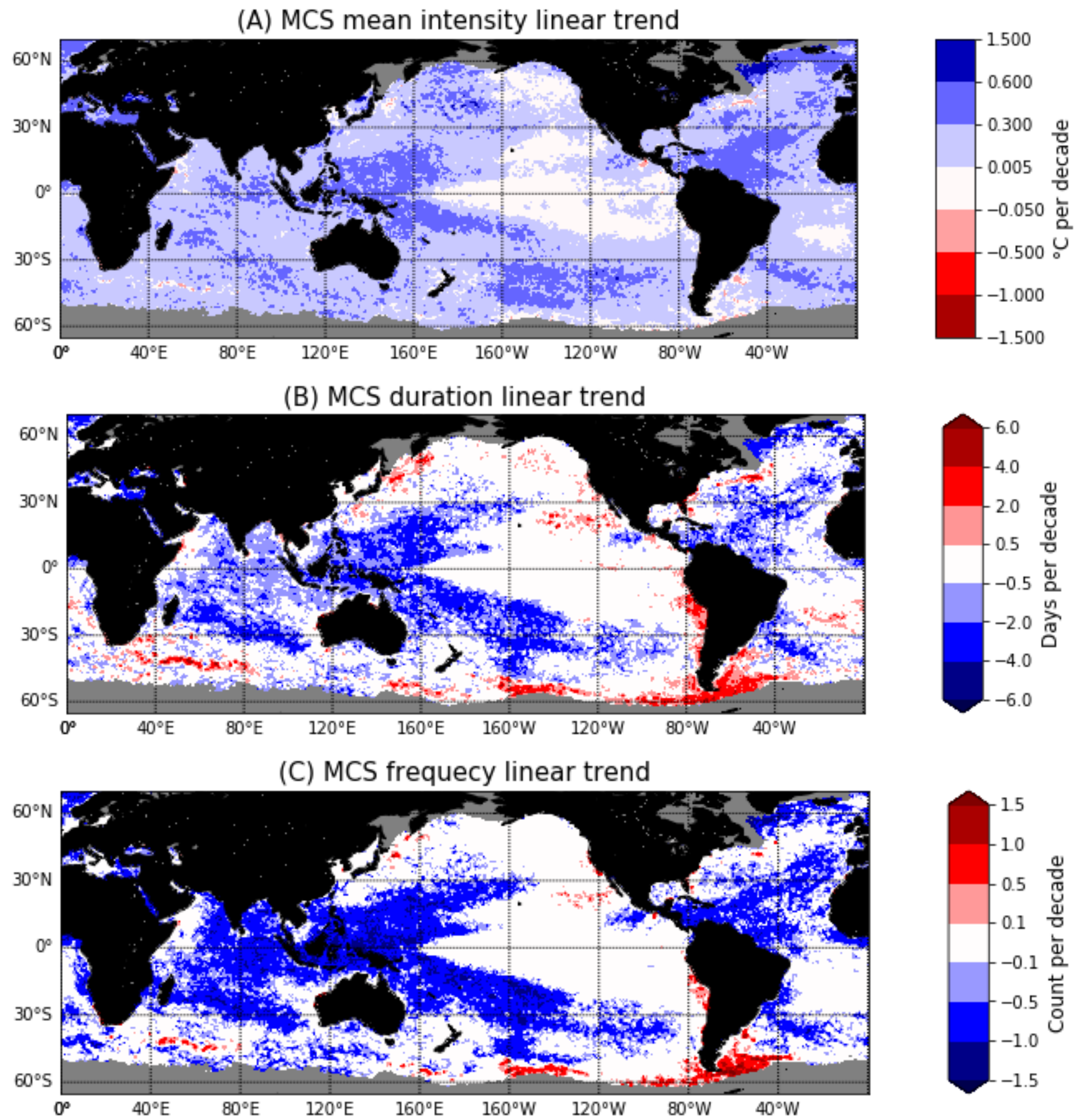

Fig. 7 Trends in marine cold spell properties globally. Shown are linear trends in **(A)** marine cold spell frequency, **(B)** marine cold spell intensity, **(C)** marine cold spell duration from NOAA OI SST over 1982–2016.

MCS mean intensity increased in over most of the regions in the ocean across the globe during the period 1982–2016 (Fig. 7a). Note that intensities of MCS are negative values, therefore, positive trends in MCS mean intensity mean that the MCS events became less cold (weaker) over time. The largest MCS weakening region is the high-latitude North Atlantic Ocean (north of 50° N, dark blue area in Fig. 7a, a weakening of 0.3 °C – 1.5°C per decade from 1982 to 2016). Less pronounced weakening (lighter blue regions in Fig. 7a) occurred in the southern portion of the South Pacific Ocean (south of 30°S – 50°S), as well as the tropical and subtropical portions of the North Atlantic Ocean (north of 0° - 30° N), tropical and subtropical portions of the western portions of the North and South Pacific Ocean, and parts of the Indian Ocean, with a weakening trend in MCS mean intensity of 0.05 °C – 0.6 °C per decade between 1982 and 2016.

MCS duration decreased over a large proportion of the global ocean between 1982 and 2016 (Fig. 7b). The largest decreases occurred in the central and western portions of the North and South Pacific Ocean, and the sub-tropical Southern Indian Ocean (a decrease of 2 – 6 days per decade between 1982 and 2016). We also found more moderate decreases in MCS duration to occur in the tropical and subtropical parts of Atlantic Ocean (north of 0° - 30° N) and the tropical part of the Indian Ocean (a decrease of 0.5 – 4.0 days per decade over 1982–2016). Conversely, MCS duration increased in parts of the Eastern Pacific and Southern Ocean poleward of 50° S, especially the South Pacific section and Atlantic section, where MCS duration increased up to 6 days per decade over 1982–2016.

The spatial pattern of MCS frequency linear trends (Fig. 7c) was quite similar to MCS duration linear trends (Fig. 7b). The largest decreases in MCS frequency occurred in the tropical Indian Ocean as well as central and western parts of the North Pacific Ocean and South Pacific Ocean (a decrease of 0.5–1.5 annual events per decade over 1982–2016). More moderate decreases appeared in the tropical and subtropical parts of the North Atlantic (a decrease of 0.1–1.0 annual events per decade over 1982–2016). Conversely, MCS frequency increased in the Eastern Pacific and in parts of the Southern Ocean poleward of 50° S, especially the South Pacific section and South Atlantic section, where MCS frequency increased to up to 2 annual events per decade from 1982 to 2016.

Comparing the results shown in Fig. 7 to the SST mean linear trend shown in Fig. 4a, regions where MCSs showed a less frequent, weaker and shorter lasting trend align with regions where the SST mean warming has been considerably faster than the global average. While those locations where MCSs showed a more frequent, stronger, and longer-lasting trend are the locations where the SST mean show a decreasing linear trend. Solely from the spatial patterns, it seems that mean SST warming can influence MCS metrics to some extent.

However, to draw the final conclusion of whether trends in SST mean can explain MCS metrics, statistical significance testing would be needed. We will do this statistical significance testing in the follow-up section (Section 3.5).

3.4 SST trends drive marine cold spell changes

We show the relationship between MCS metrics and trends in SST mean and SST variance were demonstrated for a representative SST time series (Fig. 8), generated using the most probable model parameter values (the peak in Fig. 2c: τ = 12 days and σ_ϵ = 0.27°C). This result can help us to understand the statistical significance testing we did later. Note that the detailed analysis in this section only applicable to the grid cell with τ = 12 days and σ_ϵ = 0.27°C. The regions with this pair of τ and σ_ϵ values is the most common across the global ocean, they are most representative. Therefore, we only used them as an example here, but actually we did the same analysis for every pair of τ and σ_ϵ values.

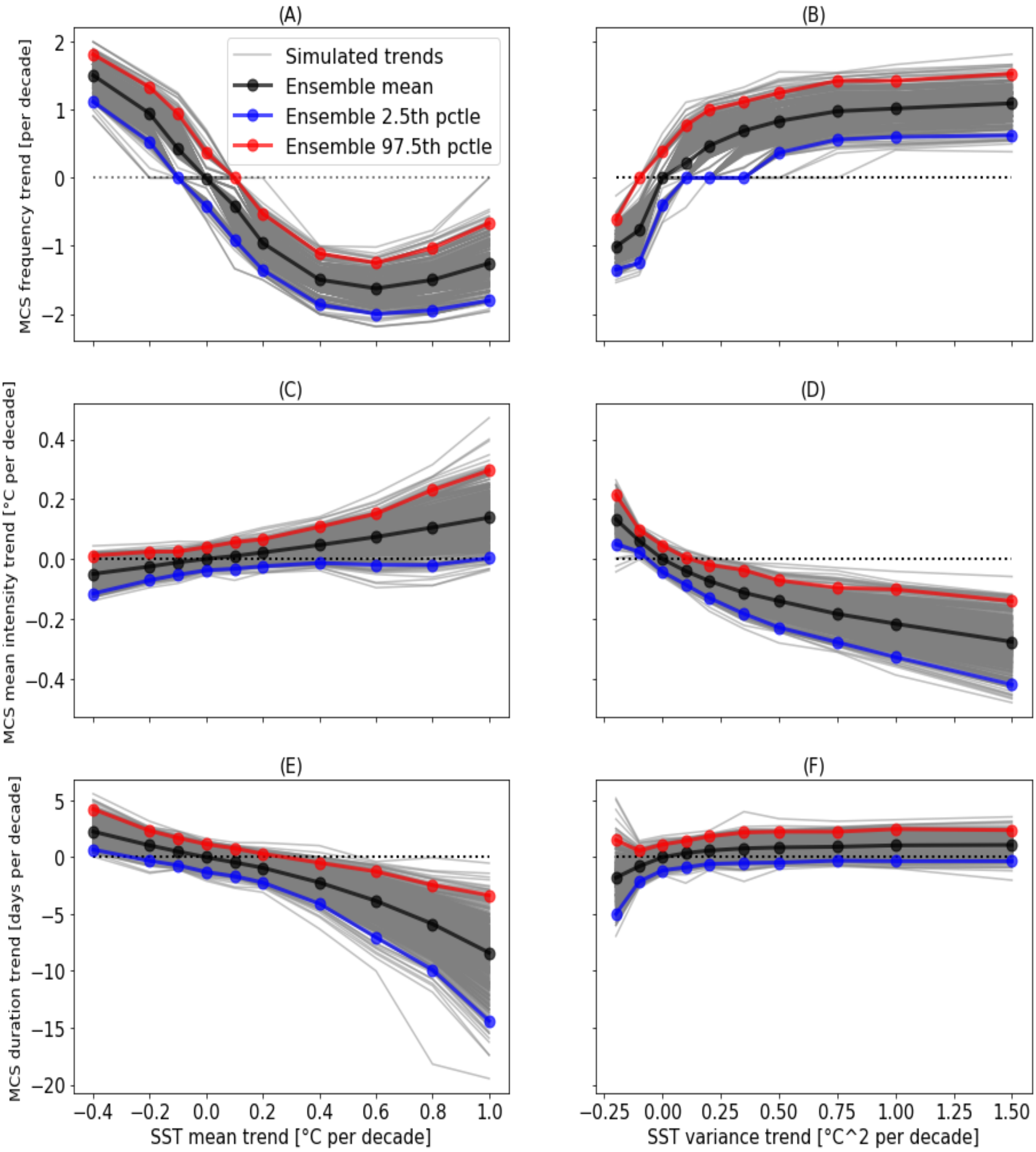

Fig. 8 Simulated MCS trends as a function of trends in mean and variance of SST. Trends in **(A), (B)** MCS frequency and **(C), (D)** MCS mean intensity and **(E), (F)** MCS duration are shown over a range of trends in **(A), (C), (E)** mean SST and **(B), (D), (F)** SST variance. The grey lines indicate the N=500 ensemble of individual simulations, with model parameters tau=12 and sigma=0.27, while the black, blue and red lines indicate the ensemble mean, 2.5th percentile, and 97.5th percentile, respectively. The interval between the blue and red lines indicates the 95% confidence interval.

MCS frequency trends decreased for SST mean trends lower than 0.6°C per decade, dropping to a minimum of about -1.5 annual events per decade when SST mean trends reached 0.6°C per decade and then slightly increased for SST mean trends larger than 0.6°C per decade (Fig. 8a). We also noticed that trends in MCS frequency are significantly different from zero (i.e. confidence intervals don't include 0) when adding a prescribed SST mean trend. This implies that we may expect that, in regions where have significant SST mean trends, trends in MCS frequency can be explained by trends in SST mean. MCS frequency increased non-linearly with increasing SST variance, peaking at about 1.5 annual events per decade for variance trends larger than 0.75°C per decade (Fig. 8b). However, we noticed that trends in MCS frequency are significantly different from zero only when adding a relatively large prescribed SST variance trend (e.g. SST variance trend = 0.50, 0.75, 1.0, 1.5 °C^2/decade). This implies that we may expect that trends in MCS frequency can be explained by trends in SST variance only in regions where have relatively large SST variance trends.

MCS mean intensity increased almost linearly with increasing mean SST (Fig. 8c) and decreased non-linearly with increasing SST variance (Fig. 8d). Interestingly, though MCS mean intensity increased with increasing mean SST, trends in MCS mean intensity are not significantly different from zero (i.e. confidence intervals include 0) with prescribed SST mean trend. This implies that it is hard to explain trends in MCS mean intensity solely by trends in SST mean. We also noticed that trends in MCS mean intensity are significantly different from zero only when adding a relatively large prescribed SST variance trend (e.g. SST variance trend = 0.50, 0.75, 1.0, 1.5°C^2/decade). This implies that we may expect that trends in MCS mean intensity can be explained by trends in SST variance only in regions where have relatively large SST variance trends.

MCS duration decreased nearly linearly with increasing mean SST (Fig. 8e) and increased non-linearly with increasing SST variance (Fig. 8f). MCS duration trends peak at about 1 days per decade for variance trends larger than 0.35°C per decade (Fig. 8f) while they continued to decrease by up to 15 days per decade with increasing mean SST trends (Fig. 8e). The amplitude of MCS duration trends were much larger for trends in mean SST (down to about -15 days per decade) than for trends in SST variance (up to 3 days per decade). However, we noticed that trends in MCS duration are significantly different from zero only when adding a relatively large prescribed SST mean trend (e.g. SST mean trend = 0.6, 0.8, 1.0 °C/decade). This implies that we may expect that trends in MCS mean intensity can be explained by trends in SST variance only in regions where have relatively large SST mean trends. Interestingly, we also found that trends in MCS duration are not significantly different from zero (i.e. confidence intervals include 0) with prescribed SST variance trend. This implies that it is hard to explain trends in MCS duration solely by trends in SST variance.

3.5 Relative roles of SST mean and variance on MCS in real ocean

Given the observed trend in SST mean and variance, we can then determine from plots like Fig. 8 if trends in MCS properties are significantly different from zero. This is performed for the global ocean in this section, as described in the Methods.

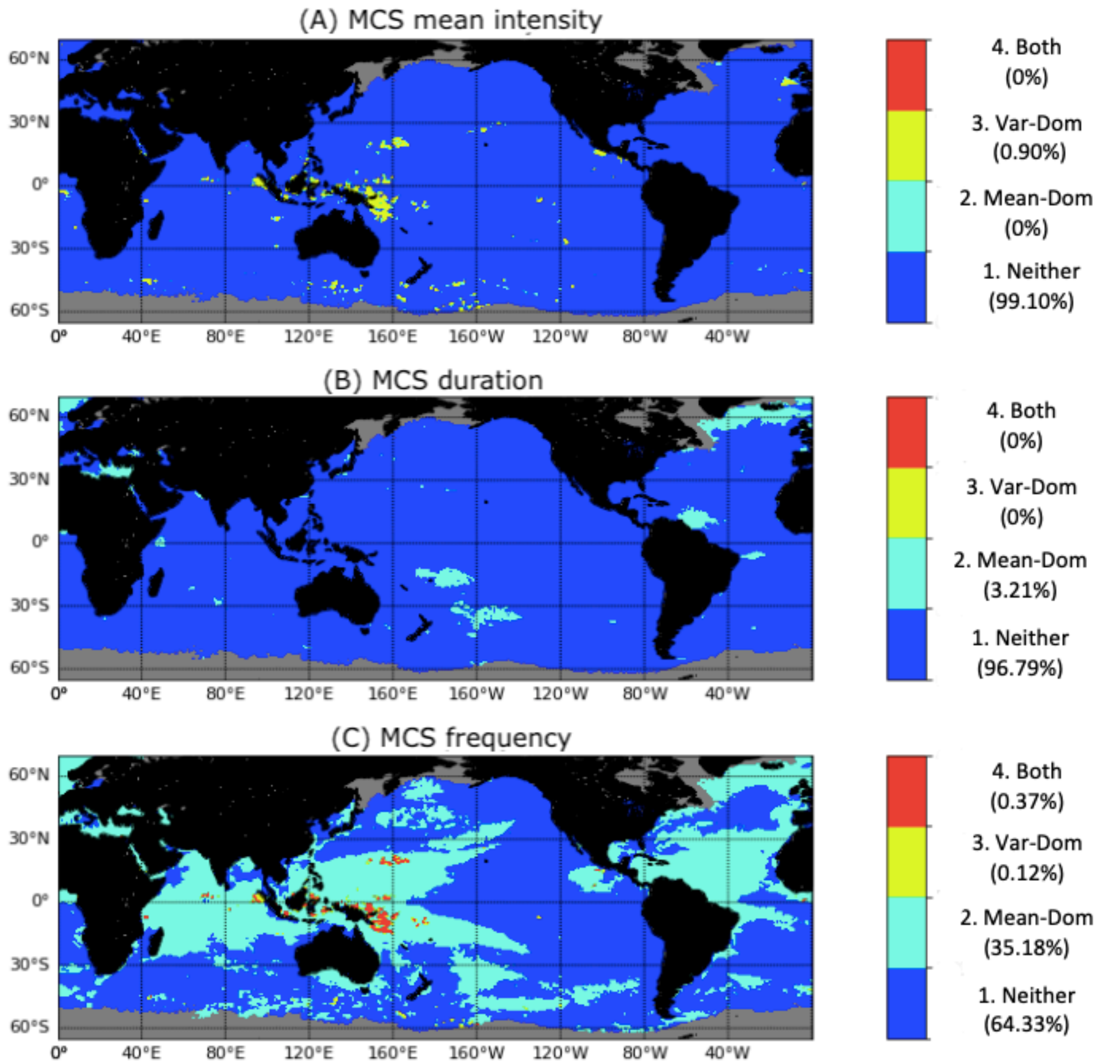

Fig. 9 Relative importance of changes in mean and variance of SST in driving changes to MCS duration, frequency and mean intensity. The colours indicate whether trends in **(A)** MCS mean intensity and **(B)** MCS duration and **(C)** MCS frequency are dominated by trends in SST variance and/or trends in mean SST. The four situation types are shown as neither in dark blue, mean-dominated in light blue, variance-dominated in yellow and both in red. The proportion of the globe covered by each type is indicated in the colour bar.

For MCS mean intensity, we saw an absolute dominance of Type 1 (99.05%, neither trends in SST mean nor trends in SST variance can explain trends in MCS mean intensity; Fig. 9a, dark blue). Only for a very small proportion of ocean surface, the analysis indicated that solely SST variance trends can explain trends in MCS mean intensity (Type 3, 0.95%, Fig. 9a, yellow).

According to our statistical significance test, no region presented Type 2 or Type 4 trends, implying that trends in SST mean could not explain the trends in MCS duration in the global ocean.

With regard to MCS duration, up to 96.48% of the global ocean surface exhibited Type 1 (Neither) situation (Fig. 9b, dark blue), implying that based on our statistical significance testing, MCS duration trends could not be explained by either SST mean trends or SST variance trends. Only a very small proportion of the ocean surface exhibited Type 2 trends (Mean-Dom) (3.51%; Fig. 9b, light blue), indicating that trends in MCS duration could be explained solely by trends in SST mean based on the testing we applied. No region exhibited Type 3 (Var-Dom) and Type 4 (Both) (0%) trends. This indicated that trends in SST variance could not explain the trends in MCS duration in the global ocean by our statistical significance testing.

Regarding MCS frequency, up to two-thirds of the ocean surface (63.44%) exhibited Type 1 (neither trends in SST mean nor trends in SST variance can explain trends in MCS frequency; Fig. 9c, dark blue) with most of the remainder exhibiting Type 2 (36.05%, only trends in SST mean can explain trends in MCS frequency; Fig. 9c, light blue). We found that Type2 regions were the regions where mean warming has been considerably faster than the global average (Fig. 4a), such as the North Atlantic Ocean, central and western portions of the North and South Pacific Ocean and parts of the Indian Ocean. Very little of the ocean surface exhibited Type 3 (0.13%; Fig. 9c, yellow) or Type 4 (0.38%; Fig. 9c, red) conditions, indicating that trends in SST variance could explain the trends in MCS frequency for only 0.51% (Types 3 and 4) of the global ocean surface.

In conclusion, globally, the Type 1 (Neither) situation was most common for MCS duration, frequency and mean intensity. This indicates that based on our statistical significance testing, neither SST mean trend nor SST variance trend could explain trends in MCS metric across most of the global ocean. Trends in mean SST could explain trends in MCS frequency for nearly one third of the ocean across the globe but could only explain trends in MCS duration for a very small proportion of the ocean. Interestingly, we did not find any regions where trends in SST mean could explain trends in MCS mean intensity. Therefore, trends in mean

SST could better explain trends in MCS frequency than trends in MCS duration and mean intensity. However, trends in SST variance explained trends in all MCS metrics we investigated (MCS duration, frequency and mean intensity) but only for a very small proportion of the global ocean. We also found that trends in SST mean explained trends in both MCS duration and frequency over a significantly larger proportion of the world's ocean than trends in SST variance.

4 Discussion and Conclusions

This study investigated the changing nature of marine cold spells from 1982 to 2016. Marine cold spells have been shown to have many impacts on marine ecosystems, marine life, aquaculture and many other society sectors, because they induce coral bleaching, are lethal to marine organisms, and influence species population distribution (Donders et al. 2011; Lirman et al. 2011; Leriorato & Nakamura 2019). Marine cold spells have been studied to a much lesser extent than other marine temperature extremes, such as marine heat waves, though marine cold spells are equally significant for ecosystems, marine life and society. This study represents the first comprehensive global assessment of marine cold spells. Our findings not only contribute to a general understanding of marine cold spells, but could also be of benefit to many fields, such as fishery and ecosystem science.

In this study, we first investigated the spatial distribution of mean marine cold spell metrics from 1982 to 2016. We found that marine cold spells of strong mean intensity occurred in the western boundary currents and their extension regions as well as the central and eastern equatorial Pacific Ocean. Oliver et al. (2018) found that marine heatwave with strong mean intensity also occur in those regions. These places all have one thing in common, that is, the sea surface temperature variability there are large. The upwelling area and trade winds are important factors to affect the sea surface temperature variance in the central and eastern equatorial Pacific Ocean. In the central and eastern equatorial Pacific Ocean, there is a distinct upwelling area governed by the interaction between atmospheric and oceanic processes (Deser et al. 2009). This can explain the strong intensity marine cold spells there. Moreover, the easterly weak Pacific trade winds in tropical regions enhance the warming of the surface ocean under global warming (Jiang et al. 2016). This can explain the strong intensity marine heatwave in the central and eastern equatorial Pacific Ocean. While western boundary currents (e.g. Gulf Stream in North Atlantic, Kuroshio current in Northwest Pacific, Brazil-Falklands Confluence in Southwest Atlantic and Agulhas current in Southwest Indian Ocean) are turbulent areas with strong ocean-atmosphere interaction, poleward heat transport and ocean-atmosphere heat exchange (Lea et al. 2000; Kwon et al. 2010). Therefore, western boundary currents can also lead to strong intensity temperature extremes (i.e. marine cold spells and marine heatwaves).

We also investigated the linear trends of marine cold spell metrics globally from 1982 to 2016. Firstly, we investigated trends in globally averaged marine cold spell metrics. We found that during the period from 1982 to 2016, not surprisingly, globally averaged marine cold spells have become less frequent, weaker and shorter-lasting. Globally averaged MCS frequency and duration decreased by 78% and 57%, respectively, resulting in a 90% decrease in annual MCS days globally during these 35 years. But this result is within our expectations, as the global warming scenario, both historic and modelled research shows that climate change is leading to a decreasing trend in extreme cold events in the atmosphere (Meehl and Tebaldi 2004). However, changes in marine cold spells can be different from region to region. Thus, to look into the regional changes in marine cold spells, we then used Theil-Sen estimates to investigate trends in marine cold spell metric at each grid cell globally from 1982 to 2016. We found that marine cold spells typically occurred less frequently, and were weaker as well as shorter in most of the global ocean, especially in the tropical section of Indian Ocean, the North Atlantic, the tropical East Pacific and the central subtropical South Pacific. However, we surprisingly identified some regions where marine cold spells showed more frequent, stronger and longer-lasting trends, such as the Southern Ocean poleward of 50° S, especially the south-eastern Pacific section and southwestern Atlantic section. These regions with more marine cold spells are also the regions where marine heatwaves were typically becoming less frequent, weaker and shorter lasting as reported by Oliver et al. (2018). Kostov et al. (2017) find an increasing northward transport of cold glacial melt waters from Antarctica caused by the strengthening westerly winds. The rise in frequency of marine cold spells and drop in frequency of marine heatwaves in the Southern Ocean poleward of 50° S, especially the south-eastern Pacific section and southwestern Atlantic section, might relate to changes in the transport of glacial waters. We found evidence of decadal and multi-decadal variability in the patterns of linear trends in marine cold spell metrics (Fig. 7). The short data record (1982–2016) is constrained by the satellite sea surface temperature data, which cannot distinguish multi-decadal climate variability from long-term trends. Within this period, in the early 2000s, there was a strong negative interdecadal Pacific oscillation (IPO) phase and a positive phase of the Atlantic Multidecadal Oscillation (AMO). Thus, the IPO and AMO patterns are evident in the map showing trends in sea surface temperature mean over this period. Trends in marine cold spell metrics also clearly indicated signatures of a negative IPO pattern (sea surface temperature decreased in the central and eastern tropical Pacific and in the eastern extra tropical Pacific Ocean) and of a positive AMO pattern (sea surface temperature increased in the North Atlantic particularly away from the mid-latitudes). The spatial patterns of trends in marine cold spell frequency, mean intensity, and duration were consistent with observed patterns of sea surface temperature warming and cooling over the same period. Solely from the spatial patterns, it seemed that mean sea surface temperature trends could explain trends in marine cold spell metrics to some extent.

We then explored whether trends in marine cold spell metrics we examined previously could be explained by trends in sea surface temperature mean and sea surface temperature variance. We assessed this question by using a dataset of global satellite observations of sea surface temperature (1982–2016) and a statistical climate model which provided simulated sea surface temperature time series, with prescribed trends in sea surface temperature mean and sea surface temperature variance. We found that, based on our statistical significance testing, for all marine cold spell metrics we investigated (marine cold spell duration, frequency and mean intensity), trends in sea surface temperature mean could not explain those trends in marine cold spell metrics across most of the global ocean. However, there was still one-third of the global ocean where marine cold spell frequency decrease could be explained by global warming (i.e. positive trends in mean sea surface temperature), especially in the tropical section of the Indian Ocean, the North Atlantic, the tropical West Pacific and the central subtropical South Pacific. With continuing greenhouse gas emissions, we expect continued rising mean ocean temperatures. This could significantly influence the continued reduction in MCS frequency or even lead to a disappearance of MCSs in this one-third of the global ocean. Oliver et al. (2018), who used the same method but for analysing marine heatwaves, showed that trends in mean sea surface temperature could explain trends in marine heatwave frequency, intensity and duration across most of the global ocean, particularly for frequency. Based on the same statistical significance testing, trends in sea surface temperature mean explained trends in marine heatwave metrics better than trends in marine cold spell metrics. However, for both marine cold spells and marine heatwaves, trends in sea surface temperature mean explained trends in their frequency better than trends in their duration and intensity. Trends in sea surface temperature variance only explained trends in marine cold spell metrics for a very small proportion of the global ocean (i.e., the Solomon Sea).

Our findings not only contribute to the general understanding of MCSs but also provide some benefits to many fields, such as fisheries and ecosystems science. One of the potential benefits is that our marine cold spell study provides information on species refugia to fisheries managers. There are many cold-water species which are likely to decline in numbers within this century due to global warming. Considering the continuing global warming, marine cold spell regions could provide important refugia for species that prefer cold waters. For example, Antarctic krill, a target species in the high latitudes of the Southwestern Atlantic, have low tolerance to warming waters (Mintenbeck 2017; Veytia et al. 2020). Mintenbeck (2017) mentioned that future global warming might reduce the population of Antarctic krill. In this case, our study showed the high latitude region of the Southwestern Atlantic is a region with more frequent and longer-lasting marine cold spells, which can provide the reference for fisheries managers about potential cold refugia for Antarctica krill. The other potential benefit is that our study can help explain ecological phenomena by considering the presence or absence of cold water. For example, many studies have investigated how warm water influences the distribution of marine species, however, marine species distributions can not only be regulated by how hot it gets, but also by how cold it does not get (Hare et al. 2010; Freitas et al. 2016; Morley et al. 2016; Fredston-Hermann et al. 2020). Therefore, our marine cold spell study can provide information about the absence of cold water to explain such ecological phenomena over those regions with less frequent, weaker and shorter lasting marine cold spells, such as the tropical section of the Indian Ocean, the North Atlantic, the tropical East Pacific and the central subtropical South Pacific.

While this study provides new knowledge around changes in marine cold spells, there are also some limitations. As an observational study of marine cold spells from a sea surface temperature perspective, we can only infer the dynamics underpinning the observed patterns. For convenience, we also regarded the grid cells that include any SST in the time series below -1°C as ice-covered grid cells in this study. While it would be more accurate to use the real ice cover data, the results and findings from this study are unlikely to change significantly.

The results of this study show that trends in sea surface temperature cannot explain trends in marine cold spell metrics significantly across most of the global ocean. Therefore, we highlight that future research should focus on other aspects, such as physical and dynamical oceanography, for further interpretation of trends in marine cold spell metrics, rather than focusing only on the statistical aspect (i.e. trends in sea surface temperature). Besides, it would be worthwhile to examine marine cold spell trends at the regional scale more closely, especially in those ecologically important regions. For example, the regions that presented more frequent, stronger and longer-lasting marine cold spells (i.e. the high latitude South pacific and the Southwest Atlantic) would be a good region to go further marine cold spell study. As mentioned before, there can be an increased flow of glacial melt water from Antarctica due to global warming, and the strengthening westerly winds can help to transport that cold melting water to the high latitude South pacific and Southwest Atlantic. They can cause more marine cold spells there, bringing refugia for cold water coral and cold water species there under global warming.

Data availability

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/. This work was supported by the National Computational Infrastructure.

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Appendix

Start with a stationary time series T(t), where t is time, with mean μ=0 and variance σ^2 and neither change over time. We wish to generate two new time series: $T_m(t)$ which has a linearly increasing mean value (but constant variance σ^2) and $T_v(t)$ which has linearly increasing variance (but constant mean μ).

Increasing mean

Let us define $T_m = T+mt$, where m is a constant. This time series has a mean and variance given by

$\mu_m = E[T_m] = E[T+mt] = E[T]+mt = \mu+mt = mt$,

(4)

$\sigma_m^2 = E[(T_m-\mu_m)^2)] = E[(T+mt-\mu-mt)^2] = E[T^2] = \sigma^2$,

(5)

where $E(\cdot)$ is the expectation operator and noting that $E(T) = \mu = 0$. Therefore, T_m has a linearly increasing mean and the same (constant) variance as T, σ^2.

Increasing variance

Let us define $T_v = T(1+vt)$, where v is a constant. This time series has a mean and variance given by

$\mu_v = E[T_v] = E[T(1+vt)] = E[T+vtT] = E[T]+vtE[T]$,

(6)

$= \mu+vt\mu = 0$,

(7)

$\sigma_v^2 = E[(T_v-\mu_v)^2] = E[(T+vtT)^2] = E[T^2+2vtT^2+(vtT)^2]$,

(8)

$=E[T^2]+2vtE[T^2]+(vt)^2E[T^2] = \sigma^2+2vt\sigma^2+(vt)2\sigma^2$,

(9)

$=\sigma^2(1+2vt+(vt)^2)$

(10)

and noting that $E(T^2) = \sigma^2$. Oliver (2019) neglect nonlinearities, they simplify this to a linear dependence on time

$\sigma_v^2 \simeq \sigma^2+ v^*t$,

(11)

where v^* is the SST variance trend we prescribe, $v^*=2v\sigma^2$.

We do not simplify like him; we just keep calculating:

Back to Equation (10), we can get

$\sigma_v^2 = \sigma^2 + (2\sigma^2 v)t + (\sigma^2 v^2)t^2$,

(12)

because $\sigma_v^2 - \sigma^2 = v^* t$,

(13)

Then we can get

$v^* t = (2\sigma^2 t)v + (\sigma^2 t^2)\, v^2$,

(14)

Solve the quadratic equation of one variable with v as independent variable, then we can get

$$v = \frac{-\sigma \pm \sqrt{\sigma^2 + v * t}}{\sigma t}$$

(15)

Substitute Equation (15) into $T_v = T(1+vt)$,

$$T_v = T * \sqrt{1 + \frac{v^* t}{\sigma^2}}$$

(16)