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**Front Matter**

Title

* Marine heatwave formation in and around western boundary currents
* Marine heatwaves in western boundary currents

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**Abstract**

The abstract should be a single paragraph (**no more than 150 words**) written in plain language that a general reader can understand. It should include

* An opening sentence that states the question/problem addressed by the research AND
* Enough background content to give context to the study AND
* A brief statement of primary results AND
* A short concluding sentence.

Climate change is generally seen as a gradual warming in centennial global mean surface temperatures, but the associated increase in the frequency and severity of extreme events are increasingly recognized. Western boundary currents (WBCs) have the highest kinetic energy, carry the greatest amounts of heat, and express the fastest rates of warming in the world’s oceans. Past analyses have been too coarse-grained to reveal regional nuances and mechanistic underpinnings of warming trends. We apply a marine heatwave (MHW) analysis to daily Optimally Interpolated Sea Surface Temperature (dOISST) data, and provide an analysis of warming trends in the mean and extreme temperatures of WBC regions. Contextualised by the spatial patterns in mean and eddy kinetic energy (MKE and EKE) and the meandering properties of the WBCs, we show that the boundary current jets, eddy fields, and meanders are not equal in their potential to drive trends in heat transport. The jets and the eddy fields minimally influence warming trends in the mean SST and the extremes, but the lateral meandering of the currents into the cooler, poleward water masses cause MHW-like phenomena. <What about mean SST?> <So what?>

**MAIN TEXT**

**The manuscript should be a maximum of 15,000 words.**

**Introduction**

Climate change is generally understood to manifest as a gradual long-term warming in centennial global mean surface temperature (*1*), but it is also associated with an increase in frequency and severity of extreme events (*2*). Impacts of extreme events such as floods, wind storms, tropical cyclones, heatwaves and cold-spells occur suddenly, often with serious consequences (*3*). The increased focus on extreme events in addition to the background mean state has emerged as a critical direction in climate change research (*4*).

A common extreme event is a ‘heatwave.’ A heatwave has traditionally had vague definitions such as “a period of abnormally and uncomfortably hot […] weather” (*5*). In recent years, however, there has been a move towards more objective definitions of heatwaves based on statistical properties of the temperature record being used (*6*–*8*), and which relate to their potential impact. The heatwave concept has been extended to include extended warm events in the oceans, termed ‘Marine Heatwaves’ (MHWs) (*9*, *10*).

MHWs are becoming more frequent (*11*–*13*), and can have devastating ecosystem impacts. There have been well-known MHWs in the Mediterranean Sea in 2003 (*14*, *15*), off the coast of Western Australia in 2011 (*16*–*18*), in the north-west Atlantic Ocean in 2012 (*19*, *20*), and more recently the ‘Blob’ in the north-east Pacific Ocean (*21*). These can have devastating ecosystem consequences: the 2003 Mediterranean MHW affected up to 80% of the gorgonian fan colonies in some areas (*14*), and the 2011 event off the west coast of Australia caused substantial loss of temperate seaweeds and a corresponding tropicalisation of reef fishes (*18*). A recent global analysis highlighted that MHWs were more common in particular areas of the ocean, including Western Boundary Currents (WBCs) (*22*). This broad-scale analysis, however, precluded an analysis of whether MHWs were concentrated in particular regions within WBCs, lacked the ability to identify potential mechanisms for why WBCs might be sites of increasing marine heatwaves, and did not assess whether and did not assess whether MHWs were increasing in frequency, duration, or intensity. Such information will be invaluable for more effective ecosystem management and forecasting of extreme thermal phenomena, particularly for ecosystems that might be connected ‘downstream’ of WBCs.

Five WBCs dominate heat transport in the world’s oceans: the Agulhas, Brazil and East Australian Currents in the Southern Hemisphere (SH), and the Kuroshio Current and Gulf Stream in the Northern Hemisphere (NH). As a long-term mean, the seemingly stable WBC jets are defined by their fast geostrophic velocities and high mean kinetic energy (MKE)—much of the global ocean’s MKE is concentrated in the WBCs (refs.). These boundary currents exhibit strong synoptic variability: over shorter time scales of weeks to months, instabilities generate meanders and mesoscale eddies, the latter forming a ‘field’ of high eddy kinetic energy (EKE) around the jets (refs.). WBCs are prominent drivers of global climate systems and regional weather (23). Their meridional heat transport loads the atmosphere with moisture and drives rainfall over eastern portions of south-east Africa, Brazil, Australia, the coast of Japan, and the United States. The northern hemisphere WBCs also mark the beginning of the North Pacific and North Atlantic storm tracks where tropical cyclones are generated (24).

WCBs are vulnerable to changing climate. All WBCs, except for the Kuroshio Current, are extending poleward due to shifts in the predominant zonal wind systems (refs.). The current strength of WBCs is also intensifying under climate change for most WBCs, excluding the Gulf Stream (refs.). WBCs are responding by increasing mesoscale activity (*25*), and they display the highest rates of centennial increases in sea surface temperatures in the world’s oceans (*26*). Collectively, these lines of evidence suggest that MHWs in WBCs could continue to increase in the future.

Here we delve in more detail into the hypothesis that MHWs in the five major WBCs of the world have increased in frequency, duration, and intensity over the four decades (*22*). We have three primary aims. The first is to assess what aspects of MHWs in WBCs are increasing—is it their frequency or intensity or both—as these could have different ecosystem impacts. The second is to identify where MHWs are primarily found in WBCs—do they occur throughout the region or are they concentrated in specific places; for example, are MHWs concentrated in the main region of intense boundary current flow or in adjacent areas where instabilities including the formation of mesoscale eddies and meanders are greatest? This should inform our understanding of the primary mechanism underlying the increase in prevalence in MHWs in WBCs. Last, given that the severity of MHWs is increasing in WBCs, we test the hypothesis that MHWs are going to increase further in the future, and analyse whether it is primarily their frequency, intensity, or both.

**Results**

The results should describe the experiments performed and the findings observed. The results section should be divided into subsections to delineate different experimental themes. Subheadings should either be all phrases or all complete sentences. All data must be shown either in the main text or in the Supplementary Materials.

* All data should be presented in the Results. No data should be presented for the first time in the Discussion. Data (such as from Western blots) should be appropriately quantified.
* Subheadings must be either all complete sentences or all phrases. They should be brief, ideally less than 10 words. Subheadings should not end in a period. Your paper may have as many subheadings as are necessary.
* Figures and tables must be called out in numerical order. For example, the first mention of any panel of Fig. 3 cannot precede the first mention of all panels of Fig. 2. The supplementary figures (for example, fig. S1) and tables (table S1) must also be called out in numerical order.
* Display equations (set on their own line) can be included. Do not use the native Word 2007, 2008, 2010, or 2011 equation editor. This can in produce inaccurate MathML, the online markup language we use, which may result in display errors. Instead, use the legacy equation editor in Word (Insert menu; select insert object; select word equation) or use MathType (recommended). If you enter equations in simple LaTeX, check that they will convert accurately (Word 2007 and higher can convert simple LaTeX equations). Display equations should be numbered at the right—(1), (2), etc.
* The same guidelines apply to mathematical expressions within a sentence of text; however, MathType (or the equivalent) should be used within text only when the desired result cannot be achieved using ordinary Word characters. Reserve MathType for when its use is unavoidable—for example, characters with overbars or carets, with stacked superscripts and subscripts, or within square root symbols.

***Spatial patterns of MKE, EKE, and MHW metrics***

In agreement with the classical pattern of the WBCs along the coasts of their bounding continents, the plot of long-term MKE clearly shows the quasi-stable current jet and its retroflection (AC in Fig. 1A; retroflections and extensions of other WBCs in fig. S1A, E, I, M, Q). This zone of influence is clearly represented by MKE values ≥ their 90th percentile. Being extremely energetic, WBCs are hydrodynamically unstable, and fields of high EKE form around the jets, and in particular around the extensions and retroflections (see Fig. 1B for the AC, and fig. S1B, F, J, N, R for all WBCs). Again, the zone of influence of the field of maximal eddy energetics can be traced by ocean regions where EKE are ≥ their 90th percentile. Fig. 1C indicates traces of the mesoscale eddies populating the AC zone of influence of the EKE field around 13 to 40°E, and 36.5 to 41°S. In this case it is particularly the area where the AC retroflection form that the formation of eddies extract energy from the mean AC path; some of these eddies eventually dissipate back into the retroflection, and are therefore also responsible for maintaining this retroflection as it extends eastwards into the ﻿south Indian Ocean between 37° and 41°S, as far as 40°E. The formation of eddies that contribute towards the EKE field is visually indistinguishable in the other WBCs (fig. S1C, G, K, O, S). The area where MHW intensity is greatest is indicated, and again this region is enclosed by as zones of influence that captures the location where mean MHW intensities ≥ their 90th percentile (Fig. 1D). For the AC this region is just south of 40°S, from 10°E to 27°E, near the field of high EKE. The situation is the same for the BC, EAC, GS, and KC (fig. S1D, H, L, P, T).

**Figure 1 |** (**A**) The location of the Agulhas Current along the east coast of South Africa is indicated by the long-term (1993-01-01 to 2012-12-31) MKE, with the jet clearly visible along the 1500 m isobath, and the eastward-flowing Agulhas Retroflection forming around 17°E, 40°S. The red polygon traces the region of the ocean where MKE ≥ 90th percentile. (**B**) The field of mesoscale eddies forming around the Agulhas Current, and in particular the retroflection, can be seen by the EKE; here the blue polygon marks the area of EKE ≥ 90th percentile. (**C**) Traces of individual eddies dissipating from the Agulhas Current jet (*i.e.* from within the red polygon) roughly match the area of high EKE. On this plot, MHWs that originated at the times of the three most intense heatwaves are coloured green. (**D**) The area of the most intense MHWs as per their mean intensity metric averaged over the data period 1981-09-01 to 2018-09-30 is located slightly south of the area of maximal MKE and EKE at a latitude of approximately -42°S. Isobaths are indicated for 500, 1000, and 2000 m. Similar figures for the Brazil Current, East Australian Current, Gulf Stream, and Kuroshio Current may be seen in fig. S1.

* **Fig. S1.** (**A-T**) Full set of panels corresponding to Fig. 1.

Outlines tracing the fields of maximal MKE and EKE (polygons in Fig. 2A-E), and areas of intense MHW activity, help to show the relationships between these phenomena. In all instances, MHW activity, as shown here by the mean MHW intensity, is associated more with high EKE regions, and less so with the boundary current jets. However, the location of peak MHW intensity is slightly displaced with respect to the position of the EKE field, as is evident for the AC, GS, and KC. For these boundary currents, the retroflections and extensions extend eastward into the south Indian Ocean, North Atlantic, and North Pacific Ocean, respectively. MHW activity is shifted to the north of the associated eddy fields of the GS and KC, and to the south thereof in the AC region. The separation between regions dominated by high EKE and MHW activity is less clear in the BC and EAC, but nevertheless seems to be most closely associated with the region of high EKE where the boundary currents retroflect north-eastwards into the western south Atlantic and southern west Pacific.

**Figure 2 |** The figures represent the (**A**) Agulhas Current, (**B**) Brazil Current, (**C**) East Australian Current, (**D**) Gulf Stream, and (**E**) Kuroshio Current. Three polygons are indicated on each panel—the red and blue outlined regions mark the location of the areas dominated by MKE and EKE ≥ 90th percentile as per Fig. 1A-B (*i.e.* zones of influence). The purple-filled regions are where the mean thermal event intensity taken over the duration of the data set averages to values ≥ 90th percentile.

***~~Maximum covariance analysis~~***

~~MCA takes into account coupled modes of covariance between KE and SST exceedance, and incorporates amplitude and frequency of the component signals. Modes 1 and 2, which account for 61% and 6% of the total covariance, respectively, do not show a well-defined coherent pattern within the mean event intensity zones of influence, but rather seem to be related to more dominant modes of variation such EKE. Mode 3 explains 5% of the covariance, and the covariance maps indicate (Fig. 4A-B) a greater coherence of the component signals within the mean intensity zone of influence. Time series of the expansion coefficients of Mode 3 are highly correlated, with~~ *~~r~~* ~~= 0.89 (Fig. 4C).~~

>> “The KE system exhibits large decadal fluctuations between relatively stable and unstable states”—in Revelard et al (2016).pdf… could explain the weak relationship between meandering and MHWs seen in the MCA.

When correlating the mean MHW intensity and EKE for all five WBCs (seen as deep purple in each panel of Fig. XXX), we tend to see a dipole-like structure. This structure shows positive correlations in EKE and mean intensity occurring within the poleward side of the high EKE regions, and negative correlations on the equatorward side.

Outside of the these regions of maximal intensity there are also spatial patterns in the *r*-values, but they are more complex and quite difficult to describe.

**Figure 3 |** Pixel-by-pixel time series correlations between (**A**, **C**, **E**, **G**, **I**) MKE *vs.* mean MHW intensity, and (**B**, **D**, **F**, **H**, **J**) EKE *vs.* mean MHW intensity. Time series cover the period 1993-01-01 to 2018-09-30. Polygons representing the zones of influence of EKE and MKE are indicated on the left and right sets of panels, respectively (refer to Fig. 2 for details).

**Figure 4 |** Covariance maps for KE (left) and SST exceedance (right), and the time series of the expansion coefficients (bottom) for mode 3 of the MCA. The time series plot indicates the SFC, which indicates the amount of the total co-variance explained by mode 3, and the Pearson’s correlation coefficient indicates the strength of association between the two time series.

***Trends in selected MHW metrics***

**Figure 5 |** Trends in the (**A**, **C**, **E**, **G**, **I**) mean MHW intensity (°C per decade), and the (**B**, **D**, **F**, **H**, **J**) number of MHW (MHW days per decade). Polygons representing the zones of influence of EKE and MKE are indicated on the left and right sets of panels, respectively (refer to Fig. 2 for details). These panels are repeated in fig. S3, where the decadal trend in MHW duration is also shown.

* **Fig. S2.** (**A**-**T**) Full set of panels of SST mean trend, and trends in MHW mean intensity, count, and duration.

**Discussion**

Include a Discussion that summarizes (but does not merely repeat) your conclusions and elaborates on their implications. There should be a paragraph outlining the limitations of your results and interpretation, as well as a discussion of the steps that need to be taken for the findings to be applied. Please avoid claims of priority.

Look also at this paper: O'Reilly, C. H., & Czaja, A. (2015). The response of the Pacific storm track and atmospheric circulation to Kuroshio Extension variability. Quarterly Journal of the Royal Meteorological Society, 141(686), 52-66.

Our analysis shows that it is not the WBCs themselves that manifest MHWs, but rather that cross-frontal exchange due to the jets’ meandering into the climatologically cooler regions adjacent to the thermal fronts poleward of the boundary current jets that cause MHWs to form there.

<…the number of MHWs is increasing in all western boundary currents, predominantly in the area of strongest flow. The intensity of MHWs is increasing in most western boundary currents, mainly in the area of maximum eddy kinetic energy…>

A recent analysis found that the greatest “hotspots of high intensity occurred in regions of large SST variability including the five [WBC] extension regions (+2–5 °C)…” (*22*).

Heat transport in WBCs is associated with the current jets, the lateral field of high kinetic energy (*27*), and the meandering jet. This heat flux is a significant modulator of regional weather (*23*), and are responsible for regional warming over land (refs.). WBCs are responding with centennial warming at rates up to three times that of the global average (*26*), but studies that have examined these warming trends have done so with insufficient spatial resolution to allow the localisation of areas experiencing high warming rates with adequate spatial fidelity (*22*, *26*).

Our more detailed analysis of the WBC regions shows that the jets, eddy fields, and meanders are not equal in their potential to drive centennial trends in heat transport. WBC jets are minimally important in influencing warming trends in both the mean SST or the extremes. Regions of high rates of increase in centennial mean SST trends are generally localised *ca*. 5° south-west of the point of inception of the AC, and *ca*. 5° and 10° poleward of the GS and KC and their extensions, respectively. In the EAC, the highest rate in mean SST increase is to the east of the Bass Strait, and at the point of inception of the northward-flowing retroflection of the BC.

In addition to examining changes in mean SST, our analysis also includes the right-hand tail of the extreme temperature value distribution (*i.e.* with ‘extreme’ here defined as ≥ 5 consecutive days of temperatures above the 90th percentile relative to the seasonally-varying long-term climatology) of WBC regions. <‘Normal’ extreme value theory talks about the occurrences of data points in the extreme tails of the PDF; here, however, it is the occurrences of days about the 90th percentile × duration.> <Talk about the generalised extreme value distribution (GEV); extreme value theory.> This empirical analysis sheds light on the physical evolution of the dynamics of heat transport that is associated with the variability or increased variability observed in WBCs. <What insights useful to understanding the climate system come from looking at the extremes as compared to the mean?> <Implications for GCMs? Will they benefit from including the kinds of outputs that MHW metrics might provide?> <Basically, what I am trying to understand is, aside from the ecosystem implications that everyone talks about, is there some deeper understanding of climate change/the climate system (or the statistical nature of extreme values given that here they are defined as exceedance × duration) to be found if one looks at the extremes?> Turbulent flows are an important part of the ocean’s physical dynamics. Since meanders are here implicated for their role in conveying heat at the upper extremes of what is considered normal for ocean regions at the periphery of WBCs, this insight could lead to an improved parameterization of turbulence and heat flux in Global Climate Models (GCMs). <What remains unknown?>

Interannual variability attributed to the EAC has been demonstrated to be responsible for explaining approximately 50% of the interannual variability in the number of MHW days off eastern Tasmania (*28*). An increasing variability has been demonstrated for the AC (*25*), and in particular enhanced eddy propagation and in the Agulhas leakage (*29*). <More about BC, KC, GS> Future conditions should be increasingly characterised by SSTs situated in the top-10% of hottest temperatures of those represented in a climatological record, in a manner similar to that found for extreme rainfall, which is also expected to occur in less frequently but more intense events (*30*).

<What other mechanisms have been attributed to MHW formation? Integrate below.> Marine heatwaves are generally caused by one of two processes, *i.e.* heat transfer from the atmosphere to the ocean surface layers, or the horizontal bulk flux of warm water into adjacent colder water mases. The marine heatwave in the shelf waters of the northeast USA (﻿Gulf of Maine and the Middle Atlantic Bight) in 2012 was caused by atmosphere-ocean heat flux (*19*, *28*); similarly, the 2003 marine heatwave in the Mediterranean was also caused by heat transfer from the atmosphere to the ocean surface layers (*14*). The 2011 ‘Ningaloo Niño’ was caused by an anomalous intensification of the Leeuwin Current, which brought warm water to the shore of Western Australia (*16*). Often these processes involve teleconnections with large-scale climate modes… *e.g.* the ‘blob’ (North Pacific Gyre Oscillation (NPGO) and the Pacific Decadal Oscillation (PDO); Di Lorenzo and Mantua 2016), the Ningaloo Niño (La Niña; Feng et al. 2013).

<Eddy heat flux is generally not important in much of the world’s oceans, but it is an important with boundary currents is an important component of global heat flux, unlike in most other ocean regions.>

All WBCs are responding in similar key ways… Except for the Kuroshio Current, WBCs are extending poleward due to shifts in the radiative forcing of the predominant zonal wind systems (refs.). Reports of intensification of the currents exist for all WBCs, excluding the Gulf Stream (refs.). They are responding by increasing mesoscale activities (refs.), and they display the highest rates of decadal trends in increasing sea surface temperatures in the world’s oceans (refs.). <expand here>

As yet no permanent impact on pelagic ecosystems have been reported, raising questions around whether MHWs should be considered a threat to the world’s oceanic ecosystems. MHWs have, however, been extensively documented to cause damage to coastal ecosystems and so any increase in shoreward meanders of WBCs would be of concern. With WBCs warming at an increased rate to the global average, it may be assumed that duration and intensity of MHWs in these regions will also increase at a rate greater than the global average. Due to the high internal variability (*i.e.* high EKE) normally found within WBCs, it is likely that any species adapted to live within this oceanographic feature is not adversely affected by MHWs. The concern is rather for areas with the ‘meander zone’ of WBCs and whether or not these regions reach into shallower waters where they can adversely affect benthic ecosystems found along the coastline.

**Materials and Methods**

The materials and methods section should provide sufficient information to allow replication of the results. Begin with a section titled Experimental Design describing the objectives and design of the study as well as prespecified components.

In addition, include a section titled Statistical Analysis at the end that fully describes the statistical methods with enough detail to enable a knowledgeable reader with access to the original data to verify the results. The values for N, P, and the specific statistical test performed for each experiment should be included in the appropriate figure legend or main text.

Also see Experimental Design and Statistics Guidelines below for details.

All descriptions of materials and methods should be included after the Discussion. This section should be broken up by short subheadings. Under exceptional circumstances, when a particularly lengthy description is required, a portion of the materials and methods can be included in the Supplementary Materials.

***Data***

We are interested in the relationship between the development of the NHWs and the synoptic variability of the boundary currents and their extensions or retroflections. To evaluate whether mesoscale eddies might contribute towards the development of MHWs in the regions surrounding the WBCs, we used gridded data on sea surface temperature (SST), sea surface altimetry, and eddy trajectories for this analysis. The first dataset is the global 0.25° National Oceanic and Atmospheric Administration (NOAA) daily Optimally-Interpolated Sea Surface Temperature (dOISST, v.2) (Reynolds et al., 2007; Banzon et al., 2016) from which MHW metrics and their rate of change were calculated. The second dataset is the Ssalto/Duacs global ocean gridded multi-mission (‘allsat’) altimeter product from the Copernicus Marine Environment Monitoring Service (CMEMS) (Pujol et al., 2016), which was regridded to the 0.25° dOISST grid. This dataset was used to compute aspects of kinetic energy (KE), which give the WBC jet trajectories and the eddy ‘field’ around these jets. The last dataset, derived from the above altimeter product, is the Archiving Validation and Interpretation of Satellite Data in Oceanography (Aviso) Mesoscale Eddy Trajectory Atlas version 2.0 Experimental (Dudley et al., 2011) for information about the eddy fields around WBCs. All data were subsetted to regions encompassing the WBCs and their meanders, retroflections, and extensions.

***Calculation of thermal events and kinetic energy***

We wish to understand whether MHW formation is associated with two components of KE, *viz*. i) the large-scale circulation (*i.e.* the quasi-stationary jet represented by the long-term mean MKE); ii) areas where instabilities result in the formation of mesoscale eddies (*i.e.* areas where EKE increases); and iii) areas influenced by meanders from the WBCs. MKE and EKE were calculated from the altimeter-derived zonal (*u*) and meridional (*v*) components of geostrophic velocities. MKE is defined as , with and being the per-pixel climatological mean of each component over the first two decades of the satellite altimeter period (hence-forth ‘long-term’; 1993-01-01 to 2012-12-31); used here, it defines the mean, quasi-stationary boundary current jet trajectory. EKE is calculated as the mean over the climatological period, where and ; in this instance, and are the running means with a window width of 30-days applied over the time series on a per-pixel basis. Because EKE is calculated as an anomaly with respect to the running mean, it indicates the field of eddy propagation around the mean trajectory.

We use the MHW definition of Hobday et al. (2016) to calculate the metrics of the extreme thermal events. The algorithm finds MHWs within a long-term (recommended >30 years) daily time series of SST. It does so by finding the occasions that SST exceeds a threshold (the 90th percentile) in the probability distribution of the data based on an 11-day wide moving mean smoother centred on each day-of-the-year at each pixel. These events are atypical relative to the normal climatology by definition, and various metrics that define their properties may be calculated. We include here the count of event days per year (MHW days per year), their duration (days), and mean intensity (°C). Since there are many such extreme events within long time series, and due to them showing a great deal of spatial cohesion in gridded daily data sets, they are statistically robust; as such, we can use them to study how MHWs have changed globally or regionally within the observational SST record. Our calculation of MHW uses the algorithm as implemented by the ‘heatwaveR’ package (Schlegel and Smit, 2018), with a 30-year climatological baseline from 1982-01-01 to 2011-12-31.

***Zones of influence of KE and MHWs***

Polygons representing the fields of maximal influence of MKE and EKE, and that of the mean MHW intensity (called ‘zones of influence’ henceforth), were made by selecting their respective values ≥ their 90th percentile over the extent of the time series. The MKE zones of influence we interpret as representing the long-term averaged quasi-stationary WBC jets, the EKE zones of influence define the field of maximal mesoscale eddy activity surrounding the jets, and the MHW mean intensity zones of influence represent the ocean regions experiencing the most intense thermal events. To reinforce our understanding of how far away from the boundary current jets mesoscale eddies exert their influence, we selected only eddy trajectories that originated from within the ocean regions within the MKE masks. All such eddies over the temporal extent of the eddy database (1993-01-01 to 2018-01-18) were plotted together to visualise their ‘dispersal’ away from the boundary current jets; additionally, eddies that occurred during periods of the top three most intense thermal events were tagged.

***Association between KE and MHWs***

The question of whether MKE or EKE co-vary with mean MHW intensity was addressed by subjecting MKE, EKE, and SST exceedance (*i.e.*, SST exceeding the 90th percentile) to a 30-day wide moving average smoother over the period 1993-01-01 to 2018-06-10. This was done for smaller sections encapsulating the various zones of influence. For the BC and EAC the mean MKE, EKE, and mean MHW intensity across latitude were calculated to obtain the meridional gradient; similarly, the zonal gradient in these variables were calculated for the AC, GS, and KC. For each latitude or longitude, Pearson correlations along the time dimension were calculated between MKE and mean MHW intensity, and between EKE and mean MHW intensity.

***Calculation of linear decadal trends***

Linear decadal trends in mean monthly SST (°C per decade), MHW days (MHW days per year per decade), their duration (MHW duration, in days per event per decade), and mean intensity (°C per event per decade) were calculated using a Generalized Least Squares (GLS) fitted with restricted maximum likelihood (REML; Pinheiro and Bates 2006), and in the case of trend in mean SST, an error structure that accommodates serially-correlated residuals (ARMA).

All analyses in this paper were done with R version 3.6.2 (R Core Team, 2019). Scripts used for the analyses are available at https://github.com/ajsmit/Western\_Boundary\_Current\_MHWs.

**H2: Supplementary Materials**

You may include up to a total of ten figures and/or tables (combined) throughout the supplemental text. Include supporting text (including supplementary materials and methods, tables, and figures) at the end of the main manuscript file, in a separate section titled Supplementary Materials, if this can be easily done and if the total file size does not exceed 6 MB. Alternatively, Supplementary Materials can be included as a separate file that can be uploaded as the final figure file within the 6 MB upload limit. In that case, use one of the file types specified above (.doc or .docx preferred).

If you have any Supplemental Materials please list them by sections in the following order: supplementary materials and methods (if any), supplementary figures, supplementary tables, and other supplementary files (such as movies, data, interactive images, or database files). Be sure to submit all Supplementary Materials with the manuscript. Example:

Materials and Methods

Fig. S1. Title of the first supplementary figure.

Fig. S2. Title of the second supplementary figure.

Table S1. Title of the first supplementary table.

Data file S1. Title of the first supplementary data file.

Movie S1. Title of the first supplementary movie.

References and Notes

There is only one reference list for all sources cited in the main text, figure and table legends, and Supplementary Materials, and this main list **should not exceed 40 citations**. Do not include a second reference list in the Supplementary Materials section. References cited only in the Supplementary Materials section are not counted toward length guidelines.

Each reference should have a separate number and should be on a separate line ending in a period.

See the Author Instructions for details of correct reference style, with examples.

You can use a numbered list in MS Word.

Please do not include any extraneous language such as explanatory notes as part of a reference to a given source. *Science Advances* prefers that manuscripts do not include end notes; if information is important enough to include, please put into main text. If you need to include notes, please explain why they are needed in your cover letter to the editor.

1. R. K. Pachauri, *Climate Change 2014 Synthesis Report* (2014).

2. D. R. Easterling, Climate Extremes: Observations, Modeling, and Impacts. *Science (80-. ).* **289**, 2068–2074 (2000).

3. M. E. Shongwe *et al.*, Projected Changes in Mean and Extreme Precipitation in Africa under Global Warming. Part I: Southern Africa. *J. Clim.* **22**, 3819–3837 (2009).

4. A. Jentsch, J. Kreyling, C. Beierkuhnlein, A new generation of climate-change experiments: events, not trends. *Front. Ecol. Environ.* **5**, 365–374 (2007).

5. T. S. Glickman, W. Zenk, *Glossary of meteorology* (American Meteorological Society, 2000).

6. E. M. Fischer, C. Schär, Consistent geographical patterns of changes in high-impact European heatwaves. *Nat. Geosci.* **3**, 398–403 (2010).

7. E. M. Fischer, D. M. Lawrence, B. M. Sanderson, Quantifying uncertainties in projections of extremes-a perturbed land surface parameter experiment. *Clim. Dyn.* **37**, 1381–1398 (2011).

8. L. V. Alexander, Global observed long-term changes in temperature and precipitation extremes: A review of progress and limitations in IPCC assessments and beyond. *Weather Clim. Extrem.* **11**, 4–16 (2016).

9. A. J. Hobday *et al.*, A hierarchical approach to defining marine heatwaves. *Prog. Oceanogr.* **141**, 227–238 (2016).

10. A. J. Hobday *et al.*, Categorizing and naming marine heatwaves. *Oceanography*. **31** (2018) (available at https://doi.org/ 10.5670/oceanog.2018.205.).

11. M. DeCastro, M. Gómez-Gesteira, X. Costoya, F. Santos, Upwelling influence on the number of extreme hot SST days along the Canary upwelling ecosystem. *J. Geophys. Res. Ocean.* **119**, 2439–2461 (2014).

12. F. P. Lima, D. S. Wethey, Three decades of high-resolution coastal sea surface temperatures reveal more than warming. *Nat. Commun.* **3**, 1–13 (2012).

13. P. Sura, A general perspective of extreme events in weather and climate. *Atmos. Res.* **101**, 1–21 (2011).

14. J. Garrabou *et al.*, Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave. *Glob. Chang. Biol.* **15**, 1090–1103 (2008).

15. A. Olita *et al.*, Effects of the 2003 European heatwave on the Central Mediterranean Sea: surface fluxes and the dynamical response. *Ocean Sci.* **3**, 273–289 (2010).

16. M. Feng, M. J. McPhaden, S. P. Xie, J. Hafner, La Niña forces unprecedented Leeuwin Current warming in 2011. *Sci. Rep.* **3**, 1–9 (2013).

17. A. F. Pearce, M. Feng, The rise and fall of the “marine heat wave” off Western Australia during the summer of 2010/2011. *J. Mar. Syst.* **111**–**112**, 139–156 (2013).

18. T. Wernberg *et al.*, An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. *Nat. Clim. Chang.* **3**, 78–82 (2012).

19. K. Chen, G. G. Gawarkiewicz, S. J. Lentz, J. M. Bane, Diagnosing the warming of the Northeastern U.S. Coastal Ocean in 2012: A linkage between the atmospheric jet stream variability and ocean response. *J. Geophys. Res. Ocean.* **119**, 218–227 (2014).

20. K. E. Mills *et al.*, Lessons from the 2012 Ocean Heat Wave in the NorthwestAtlantic. *Oceanography*. **26**, 60–64 (2012).

21. N. A. Bond, M. F. Cronin, H. Freeland, N. Mantua, Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophys. Res. Lett.* **42**, 3414–3420 (2015).

22. E. C. J. J. Oliver *et al.*, Longer and more frequent marine heatwaves over the past century. *Nat. Commun.* **9**, 1324 (2018).

23. M. F. Cronin *et al.*, Monitoring ocean-atmosphere interactions in western boundary current extensions. *Proc. the" Ocean. 09 Sustain. Ocean Obs. Inf. Soc. Conf.* **2** (2010), (available at http://faculty.washington.edu/luanne/mypapers/CWP\_WBCE\_Cronin.pdf).

24. H. Nakamura, T. Sampe, A. Goto, W. Ohfuchi, S. P. Xie, On the importance of midlatitude oceanic frontal zones for the mean state and dominant variability in the tropospheric circulation. *Geophys. Res. Lett.* **35**, 1–5 (2008).

25. L. M. Beal, S. Elipot, Broadening not strengthening of the Agulhas Current since the early 1990s. *Nature*. **540**, 570–573 (2016).

26. L. Wu *et al.*, Enhanced warming over the global subtropical western boundary currents. *Nat. Clim. Chang.* **2**, 161–166 (2012).

27. S. R. Jayne, J. Marotzke, The Oceanic Eddy Heat Transport\*. *J. Phys. Oceanogr.* **32**, 3328–3345 (2002).

28. E. C. J. Oliver *et al.*, Marine heatwaves off eastern Tasmania: Trends, interannual variability, and predictability. *Prog. Oceanogr.* **161**, 116–130 (2018).

29. B. C. Backeberg, P. Penven, M. Rouault, Impact of intensified Indian Ocean winds on mesoscale variability in the Agulhas system. *Nat. Clim. Chang.* **2**, 608–612 (2012).

30. B. Pohl, B. Dieppois, J. Crétat, D. Lawler, M. Rouault, From synoptic to interdecadal variability in southern African rainfall: Toward a unified view across time scales. *J. Clim.* **31**, 5845–5872 (2018).

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