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**Front Matter**

Title

* Marine heatwave formation in and around western boundary currents
* Marine heat waves 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.

**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 catastrophic 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, 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 also been extended to include those in the oceans, termed ‘Marine Heat Waves’ (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 may have 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 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 MHWs were increasing.

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). Compared to the surrounding oceans over the latitudes across which WBCs are active, they carry zzz% more heat {or exhibit a zzz% higher SST}.

Most WBCs are increasing in strength with climate change. All WBCs, except for the Kuroshio Current, are extending poleward due to shifts in the radiative forcing of 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 have increased over the four decades in the five major WBCs of the world (*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 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 MHWs in WBCs. Last, given that MHWs are 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.
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* 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***

The similarity in formation, maintenance, and dynamics of the world’s five WBCs is remarkable, and consequently, we represent figures only for the AC. In agreement with the classical pattern of the WBCs along the coasts of their bounding continents, the plot of long-term MKE clearly visualises 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 region 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 particularly around the extensions and retroflections (see Fig. 1b for the AC, and Fig. S1b, f, j, n, r for all WBCs). Again, a 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 areas where the AC retroflection form that the formation of eddies extracts 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 exactly the same 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 a polygon that captures the location where mean MHW intensity ≥ 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.*

**~~Figure x.~~** ~~MHW metrics duration and frequency of MHWs in~~

~~Fig. Sx. Full set of panels matching Fig. x.~~

Outlines tracing the fields of maximal MKE and EKE, and areas of intense MHW activity, aid in localising the regions where each of these phenomena are most dominant relative to each other (Fig. 2a-e). 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 association of MHW activity with respect to the EKE field is not perfect, as is especially evident for the AC, GS, and KC. In the AC, GS, and KC, 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 seem 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.

***Pixel-by-pixel correlations between time series***

Looking at MKE and mean MHW intensity, we see that there is a negative correlation between them in the areas that are dominated by the fastest current speeds. This is most visible in the AC and KC jets, but less clear in the GS, EAC, and BC. In other words, when the current flows fastest along its path, thermal events tend to be of lower intensity (note that thermal events localised to these jets are not intense at all, and so they are not visible or only faintly visible in the panels showing mean intensity). Additionally, in the AC, the region of the return current where mean kinetic energy is high also produces less intense thermal events; this response in the return current or extension portions of the WBCs is not visible in the other four regions.

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

***Trends in selected MHW metrics***

**Figure 4 |** Trends in the **(a, c, e, g, i)** mean HMW 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-d).*** *Full set of panels of SST mean trend.*
* ***Fig. S4.*** *Full set of panels matching Fig. S3, including also trend in 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.

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*). 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 colder regions opposite the thermal fronts poleward of the boundary current jets that cause MHWs to form there.

Heat transport in WBCs is associated with the current jets (represented here by MKE), the lateral field of high kinetic energy (as EKE) (*27*), and the meandering jet. This heat flux is a significant modulator of regional weather (*23*), and evidence suggests that WBCs—which are responding in centennial warming at rates up to three times that of the global average (*26*)—are also responsible for regional warming over land (refs.). Studies that have examined these warming trends generally 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 views of the WBC regions show that the jets, eddy fields, and meanders are not equal in their potential to drive centennial trends and MHWs. The WBC jets themselves 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 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 northwards flowing retroflection of the BC.

Our analysis <talk about MKE and centennial SST change; MHWs>

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.

This finding resulted from an analysis of the right-hand tail of the extreme temperature value distribution (*i.e.* ≥ 5 consecutive days of temperatures above the 90th percentile relative to the seasonally-varying long-term climatology) of WBC regions. The analysis sheds light on the evolution of the dynamics of heat transport that is associated with the variability or increased variability observed in WBCs. 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*). 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*).

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.

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]

[link with extreme thermal events here]

With WBCs warming at an increased rate to the global average, it may be asssumed 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 speies 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 specifically interested in the relationship between the development of the extreme thermal events and the synoptic variability of the boundary currents and their extensions or retroflection. To evaluate whether mesoscale eddies might contribute towards the development of thermal events in the regions surrounding the WBCs, we used gridded data on sea surface temperature (SST), the components of ocean surface geostrophic velocities, and data on 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, which give the WBC jet trajectories and the eddy ‘field’ around these jets. The last dataset, derived from the above altimeter product, is the 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, kinetic energy, and geostrophic velocities***

We wish to understand whether MHW formation that is associated with 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 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 was calculated as , where and , and because it is calculated as an anomaly with respect to the long-term mean, indicates the ‘field’ of eddy propagation around the mean trajectory. Kinetic energy (KE) on any individual day of the time series was taken as or as an anomaly relative to a 5-day running mean, and daily geostrophic velocity as .

For extreme thermal events we use the MHW definition of Hobday et al. (2016). The algorithm finds extreme thermal events 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 thermal extremes have changed globally or regionally within the observational SST record. Out calculation of extreme thermal events used the MHW 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.

***Associations between MKE, EKE, and thermal events***

‘Masks’ representing the fields of maximal influence of MKE, EKE (called ‘zones of influence’ henceforth), and mean intensity were made by selecting their respective values ≥ their 90th percentile over the extent of the time series. The MKE masks we interpret as representing the long-term averaged quasi-stationary WBC jets, the EKE masks define the field of maximal mesoscale eddy activity surrounding the jets, and the MHW mean intensity masks 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.

The question of whether periods of high MKE or EKE coincide with periods of high mean event intensity on a per pixel basis was addressed by subjecting MKE, EKE, and mean event intensity to a 30-day wide moving average smoother over the period 1993-01-01 to 2018-09-30, and correlating the time series for each latitude × longitude location within the focal areas as defined by the mask unions. The resultant correlation coefficients (r) were then represented geographically.

To assess whether large-scale WBC meanders and rings might transport warm water into the ocean regions flanking the field dominated by high EKE, we created animations of daily geostrophic velocities and the occurrence of MHWs. These MHWs (represented by their mean intensity metric) had been subjected to a 5-day moving average smoother post-detection to ensure that only events lasting five days or longer were flagged as heatwave events. These animations were manually examined for co-occurrences of meanders and thermal events.

To quantify the relationship between meanders and MHWs outside of WBCs we looked at the pixels surrounding the pre-determined 90th percentile MKE boundaries. When anomalously strong MKE values were detected in these pixels the occurrence of any MHWs were noted and the duration/intensity were used to calculate the strength of this potential relationship. [Or select a section of ocean in this region where the meanders are forming, of about the same size or smaller than a meander, and create a time series of the average of all of the pixels inside. Do for both MHW intensity and KE. Apply wavelet analysis on both and see if they match.]

***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 3.5.2 (R Core Team, 2018). 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.

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