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

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**Abstract**

**Introduction**

The ocean’s temperature is continuing to warm as a result of anthropogenic forcing of the climate system, and this change is generally understood to result in a centennial rise in global mean surface temperature (Pachauri et al., 2014). Associated with this centennial change is an increase in the frequency and severity of extreme events that affect humans and ecosystems in the short-term (Oliver et al. 2018). Extreme events such as floods, wind storms, tropical cyclones, heatwaves, and cold-spells may occur suddenly, often with catastrophic consequences (*e.g.* Shongwe et al., 2009). The recognition to focus more on the extremes and less on the background mean state has emerged as a critical direction of climate change research (Jentsch et al., 2007).

The term ‘heatwave’ has traditionally referred to atmospheric phenomena using subjective definitions such as “a period of abnormally and uncomfortably hot […] weather” (Glickman, 2000). Recently it was noticed that prolonged periods (≥5 days) of extreme temperatures (≥90th percentile) have become more frequent, last longer, and are more intense in some regions of the world’s oceans (DeCastro et al., 2014; Lima and Wethey, 2012; Sura, 2011; check refs.). These events have now become known as ‘marine heatwaves’ (MHWs, *sensu* Hobday et al., 2016) or ‘extreme thermal events.’ It is becoming common practice to quantify them using objective statistical metrics relate to their potential impact. By definition, such events are infrequent enough for them not to contribute much to the ocean’s climatological thermal regime. The episodic nature of their occurrence implies that organisms have not become physiologically adapted to tolerate their excessive heat impact, meaning that thermal pulses often exceed organismal thermal survival limits. It should therefore come as no surprise that MHWs have caused catastrophic, large-scale reconfigurations of marine benthic ecosystems. In the Mediterranean in 2003, extreme temperatures affected up to 80% of the gorgonian fan colonies in some areas (Garrabou et al., 2009; Olita et al., 2007), and off the coast of Western Australia in 2011 (Feng et al., 2013; Pearce and Feng, 2013; Wernberg et al., 2013) a thermal event caused substantial loss of temperate seaweeds and a tropicalisation of reef fishes. Other examples include extensive damage to multiple fisheries in the north west Atlantic Ocean in 2012 (Chen et al., 2014, 2015; Mills et al., 2012) and more recently ‘the Blob’ in the north east Pacific Ocean (Bond et al., 2015).

Assessing the mean and time-varying ocean surface thermal ocean state in a framework that incorporates MHW metrics—*e.g.* their frequency, duration, and intensity—will provide a deeper understanding of how climate change is unfolding, and add to a mechanistic understanding of the drivers of climate change. It has been known for some time, at least theoretically, that the frequency and intensity of extreme climatic events will increase (Alexander, 2016). This indeed seems to be the case for the global ocean for which a recent analysis has shown that more extreme thermal events accompany the increase in mean SST (Oliver et al., 2018). However, the local or regional drivers of such increases cannot be extracted from a global analyses, and a more detailed quantification of extreme events using the framework provided by Hobday et al. (2016) within specific regions will give us this information. Western boundary currents (WBCs) experience some of the fastest rates of centennial SST increases, up to three times faster than that of the global average (Wu et al., 2012; Yang et al., 2016). A recent global analysis of MHWs has also suggested that WBCs were key areas for MHWs, but there was little information on the mechanisms behind their formation (Oliver et al., 2018). Consequently, WBCs are ideal ocean regions within which an investigation of MHWs and their properties can be undertaken.

The east coasts of continents constrain the direction and path of fast geostrophic flows that result from easterly trade winds pushing water across the ocean basins and causing the sea surface height (SSH) to increase against the bounding land barriers. Further intensification of the boundary currents results from the Coriolis force coupled with Ekman transport (Hu et al., 2015; Seager and Simpson, 2016) and ensures the poleward return of their gyre’s wind-driven transport and heat that originates in the tropics (Palter, 2015). Seen as a long-term average, the seemingly stable WBC jets are defined by their fast geostrophic velocities and high mean kinetic energy (MKE); in fact, much of the global ocean’s MKE is concentrated in the WBCs (refs.). Over shorter time scales of weeks to months, however, instabilities generate meanders and mesoscale eddies to form a ‘field’ of high eddy kinetic energy (EKE) around the current trajectories (refs.). Due to the amount of heat they convey and their strong synoptic variability, WBCs are prominent drivers of the global climate and weather patterns over the eastern portions of continents (Cronin et al., 2010). Their meridional heat transport coupled with the sea-to-atmosphere flux of sensible and latent heat moderates the temperature at these latitudes (Cronin et al., 2010) and is responsible for the generally higher rainfall received over eastern portions of south-east Africa, Brazil, east Australia, the coast of Japan, and the eastern United States. The northern hemisphere WBCs also mark the beginning of the North Pacific and North Atlantic storm tracks where tropical cyclones are generated (Nakamura et al., 2008). The ability of WBCs to modulate climate and influence weather locally and remotely and across time scales of days to decades has therefore prompted numerous investigations of various properties of these currents under global change.

Since the increased internal synoptic variability of the WBCs has been conjectured to lead to changes in the amount of heat transported (*i.e.* heating or cooling; Beal and Elipot, 2016), this study undertakes an assessment of the dynamical properties of MHWs associated with the world’s five WBCs, namely the Agulhas (AC), Brazil (BC) and East Australian Currents (EAC) in the Southern Hemisphere, and the Gulf Stream (GS) and Kuroshio Current (KC) in the Northern Hemisphere. 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. We therefore undertake an analysis of daily sea surface temperature records (Reynolds et al., 2007) and altimetry data (Pujol et al., 2016) to determine the drivers and/or mechanisms of MHWs that occur alongside the world’s five WBCs. Specifically, 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.

**Methods**

***Data***

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***

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.

**Results**

***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 Figure 1a; retroflections and extensions of other WBCs in Suppl. Fig. 1a, 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 Figure 1b for the AC, and Suppl. Fig. 1b, 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. Figure 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 (Suppl. Fig. 1c, g, k, o, s). Also shown in Figure 1 is the areas where MHW intensity is greatest, and again this region is enclosed by a polygon that captures the location where mean MHW intensity ≥ their 90th percentile (Figure 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 (and Suppl. Fig. 1d, 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 Appendix A (Supplementary Materials, Figure 1).

* ***Suppl. Fig. 1 (a-t).*** *Full set of panels corresponding to Fig. 1.*

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

~~Suppl. Fig. x. 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 (Figure 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 Figure 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 intensity first, 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 Agulhas Current and Kuroshio Current ‘jets,’ but increasingly less clear in the Gulf Stream, East Australian Current, and Brazil Current. 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 Agulhas Current, 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 Figure 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 Figure 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 Figure 2 for details). These panels are repeated in Appendix A (Supplementary Materials, Figure 3), where the decadal trend in MHW duration is also shown.

* ***Suppl. Fig. 2 (a-d).*** *Full set of panels of SST mean trend.*
* ***Suppl. Fig. 4.*** *Full set of panels matching Fig. 3, including also trend in duration.*

***Eddy trajectories***

The plots of ‘dispersal’ of eddy trajectories away from the long-term mean current path defined by regions of high MKE show that these eddies occupy exactly the field of greatest EKE… so, eddies cause the regions of high EKE. The red-coloured trajectories highlight the individual eddies that were present during the top three MHWs that developed in the region, and these do not venture into the regions where the highest event intensities develop on average.

So where do the heatwaves come from? I now think that they come from the meanders. This notion is supported by the side-by-side animations of daily kinetic energy and daily event intensity. The meanders are very frequently located in time and space where the highest thermal exceedances are (*i.e.* SST above the climatological 90th percentile threshold). Meanders are large structures and can have far larger perturbations on the thermal regime of the region outside of the area dominated by high EKE when they bring large masses of water into those colder ocean regions.

**Discussion**

A recent analysis by Oliver et al. (2018) found that the greatest “hotspots of high intensity occurred in regions of large SST variability including the five [WBC] extension regions (+2–5 °C)…”. Our analysis shows that it is not the WBCs that manifest the extreme thermal events, *but rather that climatologically colder regions that flank the mean current trajectory (as per Aviso+ ocean surface velocities) experience the thermal pulses when they receive meanders and rings that deviate from the ‘mean current’ path*.

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 (Oliver et al., 2018). An increasing variability has been demonstrated for the AC (Beal et al.,

2016), and in particular enhanced eddy propagation and in the Agulhas leakage (Backeberg et al., 2012). 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 (Pohl et al., 2017).

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.

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