**Marine heat wave 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. 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).

‘Heatwaves’ traditionally referred to atmospheric phenomena where subjective definitions such as “a period of abnormally and uncomfortably hot […] weather” were used (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.). They have become known as ‘marine heat waves’ (MHWs, *sensu* Hobday et al., 2016) or ‘extreme thermal events’ and it is becoming common practice to quantify them using several objective statistical metrics that may relate to their potential impact. By definition, such events are infrequent enough for them not to contribute to the ocean’s mean thermal regime (the long-term climatology localised to a particular point on Earth). The episodic nature of their occurrence implies that organisms have not become physiologically adapted to tolerate the excessive heat impact of extreme thermal events, meaning that thermal pulses often exceed organismal thermal survival limits. MHWs have caused catastrophic, large-scale reconfigurations of marine benthic ecosystems. In the Mediterranean in 2003, extreme temperatures have 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 has caused substantial loss of temperate seaweeds and a tropicalisation of reef fishes. Other examples include 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).

The utility of characterising MHWs objectively is that, combined with measurements of centennial trends in the mean SST, additional trend estimates involving the frequency, duration, and intensity of extreme events 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 ocean (Wu et al., 2012; Yang et al., 2016). A recent global analysis of MHWs has also suggested that western boundary currents were key areas for MHWs, but there was little information on their potential mechanisms (Oliver et al., 2018). Consequently, WBCs are ideal ocean regions within which an investigation of MHW generation and the properties of these events can be undertaken.

The east coasts of continents constrains 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 (Hu et al., 2015; Seager and Simpson, 2016) results from the Coriolis force coupled with Ekman transport 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 enhanced 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), we hypothesise that this variability is associated with the development of extreme weather events. In this light, this study undertakes an assessment of the dynamical properties of MHWs associated with the world’s five WBCs, namely the Agulhas, Brazil and East Australian Currents in the Southern Hemisphere, and the Gulf Stream and Kuroshio Current 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 retroflections. 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.* high laminar/bulk current transport as seen in 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 meanders from the WBCs.

**Methods**

***Data***

Three sources of data were used for this analysis. The first 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 were calculated. The second data set 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 MKE and EKE. The last data set, derived from the above altimeter product, is the Aviso+ Mesoscale Eddy Trajectory Atlas version 2.0 Experimental (Dudley et al., 2011) to obtain 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, kinectic 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 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 . To evaluate whether areas of high MKE or EKE might contribute towards the development of thermal events in the regions surrounding the long-term WBC trajectories, we defined such regions as the spatial domain occupied by values ≥90th percentile MKE and EKE, and selected only those pixels using a ‘mask’. These masked pixels were used in the analysis of association between measures of the long-term mean current path and the eddy field, and selected MHW metrics (see *Associations between MKE, EKE, eddy trajectories, and thermal events*, below).

For extreme thermal events we use the ‘marine heat wave’ (MHW) definition of Hobday et al. (2016). The algorithm finds extreme thermal events within a long-term (typically >30 years) daily time series of sea surface temperatures (SSTs). 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, including, but not limited to, the number of events per year, their duration, and the mean, maximum and cumulative intensity above the threshold. 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. Using the masks defined above, we selected pixels spatially to coincide with regions dominated by high MKE and EKE. Our 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.

***Linear decadal trends***

Linear decadal trends in mean SST and selected thermal event metric were calculated using a Generalized Least Squares (GLS) fitted with restricted maximum likelihood (REML; Pinheiro and Bates 2006) and an error structure that accommodates serially-correlated residuals (ARMA). dOISST time series that had been converted to monthly means were used. For the thermal event metrics, *viz*. mean intensity, maximum intensity, cumulative intensity, and event duration, we first calculated annual averages over the time series duration and then fitted a simple linear model. In the case of event count per annum, we used the linear model with a Poisson (*log*-link) error distribution.

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

To address the question about the extent to which the spatial pattern of the long-term mean event intensity matches that of the long-term mean MKE and EKE, we undertook a ‘pattern correlation.’ This was done by converting the 2D (latitude × longitude) matrices of the spatial patterns in MKE, EKE, and mean event intensity into into matching 1D vectors, and performing Pearson’s Product Moment correlations of MKE and EKE with respect to mean event intensity. Whereas the pattern correlation shows the association between kinetic energy and mean event intensity in space, the question of whether times of high MKE or EKE coincide with times of high mean event intensity on a per pixel basis also needed to be addressed. This was accomplished 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. The resultant correlation coefficients (*r*) were then represented geographically.

To evaluate whether eddy trajectories might contribute towards the development of thermal events in the regions surrounding the long-term WBC jets, we used the MKE mask and selected only those eddy trajectories that originated from within these regions. All such eddies over the temporal extent of the eddy database (1993-01-01 to 2018-01-18) were plotted together to visualise how far they ‘disperse’ from the boundary current cores; additionally, eddies that occurred during periods of the top three most intense thermal events were tagged.

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 exceedances of daily SST above the 90th percentile climatological SST threshold. These data had previously been subjected to a five-day moving average smoother to ensure that only events with lasting five days or longer were flagged as heat wave events. These animations were manually examined for co-occurrences of meanders and thermal events.

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**

***Correlations of spatial patterns***

**Table 1.** ‘Pattern correlation’ (Pearson’s *r*) of extreme thermal event mean intensity, total count of events, and decadal trend in mean SST *vs*. long-term mean kinetic energy and eddy kinetic energy.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Mean kinetic energy | | | Eddy kinetic energy | | |
|  | Decadal SST trend | Mean intensity | Event count | Decadal SST trend | Mean intensity | Event count |
| Agulhas Current | 0.023 | -0.458 | 0.286 | -0.207 | -0.343 | 0.640 |
| Brazil Current | -0.057 | 0.035 | -0.286 | 0.214 | 0.295 | 0.191 |
| East Australian Current | -0.328 | -0.465 | 0.109 | -0.431 | -0.211 | -0.078 |
| Gulf Stream | -0.068 | -0.443 | 0.334 | -0.221 | -0.579 | 0.724 |
| Kuroshio Current | 0.065 | -0.459 | 0.386 | -0.329 | -0.573 | 0.248 |

The results in Table 1 support the attached figure ‘Combo\_figs3.png’. The *location* of thermal events averaged over the data period matches the *location* of areas with high long-term eddy kinetic energy, but less so with mean kinetic energy.

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

The problem with the above analysis is that, because it looks at averages across the *entire* portion of time where the OISST and Aviso data sets overlap, we have no insight into the temporal connection between extreme thermal events and kinetic energy. In other words, on a per pixel basis, are time series of thermal events in phase or out of phase with time series of kinetic energy? My prediction is that times with the highest eddy kinetic energy will coincide with times when thermal events tend to take place—*i.e.* the development of extreme events is in phase with times of higher EKE. The outcome is in ‘Combo\_figs3.png’ in the two columns of panels on the right.

Looking at long-term mean kinetic energy 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 visible in the Agulhas Current, East Australian Current, Gulf Stream, and Kuroshio Current ‘jets,’ but not so clearly in the 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.

There is a greater tendency for thermal event intensity to be positively correlated with eddy kinetic energy (*i.e.* I am referring to the mean intensity maps where intensity is highest), and this pattern that holds true for all five WBCs. Outside if 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.

***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*.

An analysis of the right-hand tail of the extreme temperature value distribution (*i.e.* temperature values above the 90th percentile relative to the seasonally-varying long-term climatology) of ocean regions could shed light on the evolution of the dynamics of heat transport that may be associated with the increased variability observed in WBCs. 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.

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]

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