**Introduction** [some early text I wrote that might be useful]

Rather read the text under the yellow highlighted heading on the next page; I’ll keep some of the text immediately below, but it is too verbose right now. Please feel free to help me pull this text into shape!

Five Western Boundary Currents (WBC) 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). Their location along 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 current—the western intensification (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 that originates in the tropics (Palter, 2015).

WBCs are prominent drivers of global climate systems and weather patterns over the eastern portions of continents (Cronin et al., 2010). The ability of WBCs to modulate climate systems stems from their well-constrained paths and the transport large amounts of heat. The resultant redistribution of heat from the tropics to lower latitudes coupled with the sea-to-atmosphere flux of sensible and latent heat moderates the temperature at these latitudes (Cronin et al., 2010). This heat transfer loads the atmosphere with moisture and is responsible for the generally higher rainfall received 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 (Nakamura et al., 2008). The weakest and strongest WBCs are the XXX and YYY, respectively, with surface current velocities between xxx and yyy m/s (refs.). Their heat content ranges from xxx {units} in the XXX Current to yyy {units} in the YYY Current (refs.). Compared to the surrounding oceans over the latitudes across which WBCs are active, they carry zzz% more heat {or exhibit a zzz% higher SST}. They exhibit a strong synoptic variability as seen in the presence of mesoscale eddies and meandering. The key role of WBCs in modulating climate and weather locally and remotely and across time scales of days to decades has prompted numerous investigations of various properties of these currents under global change. 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]

‘Heatwaves’ usually refer to atmospheric phenomena where vague definitions such as “a period of abnormally and uncomfortably hot […] weather” are used (Glickman, 2000). More recently, more objective definitions have been proposed; these are based on statistical properties and other metrics of the temperature record that are relative to location and time of year (Fischer et al., 2011; Fischer and Schär, 2010; Perkins and Alexander, 2013). Recent years have seen investigations of ‘heatwaves’ in the ocean due to them becoming more frequent (DeCastro et al., 2014; Lima and Wethey, 2012; Sura, 2011). Well-known ‘marine heat waves’ (MHWs) have occurred in the Mediterranean in 2003 (Garrabou et al., 2009; Olita et al., 2007), off the coast of Western Australia in 2011 (Feng et al., 2013; Pearce and Feng, 2013; Wernberg et al., 2013), 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). The extreme temperatures from these events have had negative impacts on the local ecology for the regions in which they occur. For example, the 2003 Mediterranean MHW may have affected up to 80% of the gorgonian fan colonies in some areas (Garrabou et al., 2009), and the 2011 event off the west coast of Australia is now known to have caused substantial loss of temperate seaweeds and a tropicalisation of reef fishes (Wernberg et al., 2013).

~~The marine heat wave definition of (Hobday et al., 2016) 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 in the probability distribution of the data (~~*~~i.e.~~* ~~relative to the 10th or 90th percentiles) calculated based on an 11-day wide moving mean smoother centered on each day-of-the-year at each site (or pixel in the case of gridded data). 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 (below) the threshold (Hobday et al., 2016). Since there are surprisingly 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.~~ Combined with measurements of decadal 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 perhaps add to a mechanistic understanding of the drivers of climate change. It is well established that, on average, Earth’s surface temperature is increasing. The theoretical understanding is that the frequency and intensity of extreme climatic events will increase (*i.e.* pulses of unusually high temperatures) is also accepted (Alexander, 2016), but it remains poorly supported by empirical evidence. A quantification of extreme events using the framework provided by (Hobday et al., 2016) will give us this information.

Although climate change is generally understood to result in a gradual long-term rise in global mean surface temperature (Pachauri et al., 2014), it is generally the associated increase in frequency and severity of extreme events that affects humans and ecosystems in the short-term (Easterling et al., 2000). Impacts of 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). In this light, 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), and we hypothesise that this variability is associated with the development of extreme weather events.

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 the AC. Future conditions should be increasingly characterised by SSTs situated in the top-10% of hottest temperatures, 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).

**Background** [the more important text that gives the background to this study]

The ocean’s mean temperature is continuing to warm as a result of anthropogenic forcing of the climate system. This warming is also resulting in prolonged periods (≥5 days) of extreme temperatures (≥90th percentile)—called ‘marine heat waves’ (MHWs, *sensu* Hobday et al., 2016) or ‘extreme thermal events’—that have become more frequent, last longer, and are more intense that could lead to greater potential impacts. 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 the thermal survival limits of species. This has resulted in several well-documented catastrophic, large-scale reconfigurations of marine benthic ecosystems. 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.

A recent analysis by Oliver et al. (2018) highlighted that the greatest “hotspots of high intensity occurred in regions of large SST variability including the five [WBC] extension regions (+2–5 °C)…”. Here we assess this hypothesis, by focusing in on these regions.

However, the analysis outlined below 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 inquiry therefore undertakes an analysis of OISST and Aviso+ data to determine the drivers and/or mechanisms of MHWs that occur alongside the world’s five WBCs.

***Aims***

1. Understand the role of MHW formation that is associated with
2. the large-scale circulation (*i.e.* high laminar/bulk current transport) *vs*.
3. areas where instabilities result in the formation of mesoscale eddies (*i.e.* areas where EKE increases) *vs.*
4. areas that receive meanders from the WBCs.
5. To quantitatively show that there is a link between the number of meanders/rings produced by the WBCs and the MHW occurrences; specifically,
6. quantify and frequency of MHWs, and the frequency of the meanders/rings;
7. relate some property of the meanders/rings to the metrics (duration, intensity, *etc.*) of the MHWs;
8. to show that the trends in MHW dynamics (they are becoming more intense, last longer, happen more frequently) relate to some coupled dynamic of WBCs;
9. to show that the same pattern/mechanism generalises to all five WBCs;
10. to find corresponding effects (at the same frequency of the MHWs) at ecosystem level—this might be most visible in chl-*a* data;
11. to relate some metrics of MHWs to the Coefficient of Variability (specifically, 1/CV) of chl-*a* in regions that experience increased exposure to HMWs *vs*. areas that are exposed to such pulses less often, and to explore ideas around the concept of ecosystem stability;
12. to explore ideas around whether or not MHWs are actually meaningful phenomena in the context of pelagic ecosystems (we do know that benthic ecosystems are severely impacted).

***Notes***

EKE in the northern Agulhas Current is less pronounced than the southern regions near the retroflection, which is expected (Ducet et al., 2000), since the southward-flowing Agulhas Current proper maintains a stable current trajectory while it is topographically constrained east of South Africa offshore of the 2000 m isobath.

**Methods**

***Data***

Three sources of data were used for this analysis. The first is the global 1/4° National Oceanic and Atmospheric Administration (NOAA) daily Optimally-Interpolated Sea Surface Temperature (dOISST, v.2) (Reynolds et al., 2007; Banzon et al., 2016). The second data set is the Ssalto/Duacs global ocean gridded multi-mission (‘allsat’) altimeter product from the Copernicus Marine Environment Monitoring Service (CMEMS) (refs.), which was regridded to the 1/4° dOISST grid. 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). All data were subsetted to regions encompassing the WBCs and their meanders, retroflections, and extensions.

***Calculation of thermal events, kinectic energy, and geostrophic velocities***

﻿Mean kinetic energy (MKE) and eddy kinetic energy (EKE) were calculated from altimeter-derived zonal (*u*) and meridional (*v*) components of geostrophic velocities. MKE is defined as , with and being the overall mean of each component for the full period (hence-forth ‘long-term’; 1981-09-01 to 2018-09-30); used here, it defines the mean boundary current trajectory over the long term. 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 , and daily geostrophic velocity as .

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 surprisingly 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.

***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, 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 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 first averaging the daily MKE, EKE, and mean event intensity data into monthly means over the 1993-01-01 to 2018-09-31 period, and correlating the time series for each latitude × longitude location. The resultant correlation coefficients (*r*) were then represented geographically.

To evaluate whether mesoscale eddies might contribute towards the development of thermal event in the regions surrounding the long-term WBC trajectories, we defined the WBC paths as the ocean regions dominated by ≥90th percentile MKE 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. (previously subjected to a five-day moving average smoother to ensure that only events with lasting five days or longer were flagged) above the 90th percentile climatological SST threshold. 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 | 0.185 | 0.079 | 0.291 | 0.250 | 0.374 | 0.576 |
| Brazil Current | 0.151 | 0.386 | 0.128 | 0.394 | 0.688 | 0.543 |
| East Australian Current | -0.027 | 0.070 | 0.270 | 0.027 | 0.502 | 0.346 |
| Gulf Stream | 0.061 | 0.081 | 0.268 | 0.048 | 0.241 | 0.566 |
| Kuroshio Current | 0.077 | -0.017 | 0.176 | -0.126 | 0.004 | 0.070 |

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 ‘space’ 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.

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