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

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**Keywords:** marine heatwaves, western boundary currents, extreme events, climate change

**Abstract**

**Introduction**

Although climate change is generally understood to manifest as a gradual long-term warming in centennial global mean surface temperature (Pachauri et al., 2014), it is also associated with an increase in frequency and severity of extreme events (Easterling et al., 2000). Impacts of extreme events such as floods, wind storms, tropical cyclones, heatwaves and cold-spells occur suddenly, often with catastrophic consequences (*e.g.* Shongwe et al., 2009). The increased focus on extreme events relative in addition to the background mean state has emerged as a critical direction in climate change research (Jentsch et al., 2007).

A common extreme event is a ‘heatwave.’ A heatwave has traditionally had vague definitions such as “a period of abnormally and uncomfortably hot […] weather” (Glickman, 2000), but this is changing. In recent years, there are an increasing number of studies applying more objective definitions based on statistical properties of the temperature record being used (Fischer et al., 2011; Fischer and Schär, 2010; Perkins and Alexander, 2013), and which relate to their potential impact. Further, the concept of heatwaves has been extended to include those in the oceans, termed ‘Marine Heat Waves’ (MHWs).

MHWs are becoming more frequent (DeCastro et al., 2014; Lima and Wethey, 2012; Sura, 2011), and can have devastating ecosystem impacts. There have been well-known MHWs in the Mediterranean Sea 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). These can have devastating ecosystem consequences: 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 caused substantial loss of temperate seaweeds and a tropicalisation of reef fishes (Wernberg et al., 2013). A recent global analysis by Oliver et al. (2018) highlighted that MHWs were more common in particular areas of the ocean, including Western Boundary Currents (WBCs). 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 in the future.

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). These boundary currents exhibit strong synoptic variability that manifests as mesoscale eddies and meanders. As a long-term average, 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.). Over shorter time scales of weeks to months, instabilities generate meanders and mesoscale eddies, forming a ‘field’ of high eddy kinetic energy (EKE) around the current trajectories (refs.). WBCs are prominent drivers of global climate systems and weather patterns over the eastern portions of continents (Cronin et al., 2010). 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 (Nakamura et al., 2008). 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 (Beal and Elipot, 2016), and they display the highest rates of decadal increases in sea surface temperatures in the world’s oceans (refs.). Collectively, these lines of evidence suggests that MHWs in WBCs could continue increase in the future.

Here we delve in more detail into the hypothesis of Oliver et al. (2018) that MHWs have increased over the past century in the five major WBCs of the world. 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 over the past century, 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.

**Methods**

***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.

**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.

**References**

Alexander, L.V., 2016. Global observed long-term changes in temperature and precipitation extremes: A review of progress and limitations in IPCC assessments and beyond. Weather and Climate Extremes 11, 4–16.

Backeberg, B. C., Penven, P., Rouault, M. (2012). Impact of intensified Indian Ocean winds on mesoscale variability in the Agulhas system. *Nature Climate Change*, *2*, 608–612. http://doi.org/10.1038/nclimate1587

Banzon, V., Smith, T. M., Chin, T. M., Liu, C., and Hankins, W., 2016. A long-term record of blended satellite and in situ sea-surface temperature for climate monitoring, modeling and environmental studies. Earth Syst. Sci. Data, 8, 165–176.

Beal, L.M., Elipot, S., 2016. Broadening not strengthening of the Agulhas Current since the early 1990s. Nature 1–8.

Bond, N.A., Cronin, M.F., Freeland, H., Mantua, N., 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. Geophysical Research Letters 42, 3414–3420.

Chen, K., Gawarkiewicz, G.G., Lentz, S.J., Bane, J.M., 2014. Diagnosing the warming of the Northeastern U.S. Coastal Ocean in 2012: A linkage between the atmospheric jet stream variability and ocean response. Journal of Geophysical Research: Oceans 119, 218–227.

Chen, K., Gawarkiewicz, G., Kwon, Y.-O., Zhang, W.G., 2015. The role of atmospheric forcing versus ocean advection during the extreme warming of the Northeast U.S. continental shelf in 2012. Journal of Geophysical Research: Oceans 120, 1–16.

Cronin, M.F., 2010. Monitoring Ocean - Atmosphere Interactions in Western Boundary Current Extensions, in: Proceedings of Oceanobs’09: Sustained Ocean Observations and Information for Society. European Space Agency, pp. 199–209.

DeCastro, M., Gõmez-Gesteira, M., Costoya, X., Santos, F., 2014. Upwelling influence on the number of extreme hot SST days along the Canary upwelling ecosystem. Journal of Geophysical Research: Oceans 119, 3029–3040.

Dudley B., Chelton, Schlax, M.G., Samelson, R.M., 2011. Global observations of nonlinear mesoscale eddies, Progress in Oceanography, 91, 167–216.

Easterling, D.R., Meehl, G.A., Parmesan, C., Changnon, S.A., Karl, T.R., Mearns, L.O., 2000. Climate extremes: observations, modeling, and impacts. Science 289, 2068–2074.

Feng, M., McPhaden, M.J., Xie, S.-P., Hafner, J., 2013. La Niña forces unprecedented Leeuwin Current warming in 2011. Scientific Reports 3, 1277.

Fischer, E.M., Lawrence, D.M., Sanderson, B.M., 2011. Quantifying uncertainties in projections of extremes - a perturbed land surface parameter experiment. Climate Dynamics 37, 1381–1398.

Fischer, E.M., Schär, C., 2010. Consistent geographical patterns of changes in high-impact European heatwaves. Nature Geoscience 3, 398–403.

Garrabou, J., Coma, R., Bensoussan, N., Bally, M., Chevaldonné, P., Cigliano, M., Diaz, D., Harmelin, J.G., Gambi, M.C., Kersting, D.K., Ledoux, J.B., Lejeusne, C., Linares, C., Marschal, C., Pérez, T., Ribes, M., Romano, J.C., Serrano, E., Teixido, N., Torrents, O., Zabala, M., Zuberer, F., Cerrano, C., 2009. Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave. Global Change Biology 15, 1090–1103.

Glickman, T.S., 2000. Glossary of Meteorology. American Meteorological Society, Boston, USA.

Hobday, A.J., Alexander, L.V., Perkins, S.E., Smale, D.A., Straub, S.C., Oliver, E.C.J., Benthuysen, J.A., Burrows, M.T., Donat, M.G., Feng, M., Holbrook, N.J., Moore, P.J., Scannell, H.A., Sen Gupta, A., Wernberg, T., 2016. A hierarchical approach to defining marine heatwaves. Progress in Oceanography 141, 227–238.

Hobday, A. J., Oliver, E. C. J., Sen Gupta, A., Benthuysen, J. A., Burrows, M. T., Donat, M. G., … Smale, D. A. (2018). Categorizing and naming marine heatwaves. *Oceanography*, *31*. Retrieved from https://doi.org/ 10.5670/oceanog.2018.205.

Hu, D., Wu, L., Cai, W., Gupta, A.S., Ganachaud, A., Qiu, B., Gordon, A.L., Lin, X., Chen, Z., Hu, S., Wang, G., Wang, Q., Sprintall, J., Qu, T., Kashino, Y., Wang, F., Kessler, W.S., 2015. Pacific western boundary currents and their roles in climate. Nature 522, 299–308.

Jentsch, A., Kreyling, J., Beierkuhnlein, C., 2007. A new generation of climate-change experiments: events, not trends. Frontiers in Ecology and the Environment 5, 315–324.

Lima, F.P., Wethey, D.S., 2012. Three decades of high-resolution coastal sea surface temperatures reveal more than warming. Nature Communications 3, 704.

Mearns, L.O., Katz, R.W., Schneider, S.H., 1984. Extreme high-temperature events: Changes in their probabilities with changes in mean temperature. Journal of Climate and Applied Meteorology 23, 1601–1613.

Mills, K.E., Pershing, A.J., Brown, C.J., Chen, Y., Chiang, F.-S., Holland, D.S., Lehuta, S., Nye, J., Sun, J.C., Thomas, A.C., Wahle, R., 2012. Lessons from the 2012 ocean heat wave in the Northwest Atlantic. Oceanography 26, 60–64.

Nakamura, H., Sampe, T., Goto, A., Ohfuchi, W., Xie, S.-P., 2008. On the importance of midlatitude oceanic frontal zones for the mean state and dominant variability in the tropospheric circulation. Geophysical Research Letters 35.

Olita, A., Sorgente, R., Natale, S., Gaberšek, S., Ribotti, A., Bonanno, A., Patti, B., 2007. Effects of the 2003 European heatwave on the Central Mediterranean Sea: surface fluxes and the dynamical response. Ocean Science 3, 273–289.

Oliver, E. C. J. J., Donat, M. G., Burrows, M. T., Moore, P. J., Smale, D. A., Alexander, L. V., … Wernberg, T. (2018). Longer and more frequent marine heatwaves over the past century. *Nature Communications*, *9*, 1324.

Oliver, E. C. J., Lago, V., Hobday, A. J., Holbrook, N. J., Ling, S. D., & Mundy, C. N. (2018). Marine heatwaves off eastern Tasmania: Trends, interannual variability, and predictability. *Progress in Oceanography*, *161*, 116–130. <http://doi.org/10.1016/j.pocean.2018.02.007>

﻿Pujol, M., Faugère, Y., Taburet, G., Dupuy, S., Pelloquin, C., Ablain, M., Picot, N., 2016. DUACS DT2014: the new multi-mission altimeter data set reprocessed over 20 years. Ocean Science, 1067–1090. http://doi.org/10.5194/os-12-1067-2016

Pachauri, R.K., Meyer, L., Van Ypersele, J.-P., Brinkman, S., Van Kesteren, L., Leprince-Ringuet, N., Van Boxmeer, F., 2014. Climate Change 2014 Synthesis Report.

Palter, J.B., 2015. The Role of the Gulf Stream in European Climate. Annual Review of Marine Science 7, 113–137.

Pearce, A.F., Feng, M., 2013. The rise and fall of the marine heat wave off Western Australia during the summer of 2010/2011. Journal of Marine Systems 111-112, 139–156.

Perkins, S.E., Alexander, L.V., 2013. On the measurement of heat waves. Journal of Climate 26, 4500–4517.

Pohl, B., Macron, C., Monerie, P.-A., 2017. Fewer rainy days and more extreme rainfall by the end of the century in Southern Africa. Scientific Reports 7, 1–7.

Pujol, M., Faugère, Y., Taburet, G., Dupuy, S., Pelloquin, C., Ablain, M., Picot, N., 2016. DUACS DT2014: the new multi-mission altimeter data set reprocessed over 20 years. *Ocean Science*, 1067–1090. http://doi.org/10.5194/os-12-1067-2016

R Core Team, 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Reynolds, R. W., T. M. Smith, C. Liu, D. B. Chelton, K. S. Casey, and M. G. Schlax, 2007. Daily high-resolution-blended analyses for sea surface temperature. Journal of Climate, 20, 5473–5496.

Schlegel, R.W., Oliver, E., Wernberg, T., Smit, A., 2017. Nearshore and offshore co-occurrence of marine heatwaves and cold-spells. Progress in Oceanography 151, 189–205.

Schlegel, R.W., Smit, A.J., 2018. heatwaveR: A central algorithm for the detection of heatwaves and cold-spells. Journal of Open Source Software, 3(27), 821, https://doi.org/10.21105/joss.00821

Seager, R., Simpson, I.R., 2016. Western boundary currents and climate change. Journal of Geophysical Research: Oceans 121, 7212–7214.

Shongwe, M.E., Oldenborgh, G.J. van, Hurk, B.J.J.M. van den, Boer, B. de, Coelho, C.A.S., Aalst, M.K. van, 2009. Projected Changes in Mean and Extreme Precipitation in Africa under Global Warming. Part I: Southern Africa. Journal of Climate 22, 3819–3837.

Sura, P., 2011. A general perspective of extreme events in weather and climate. Atmospheric Research 101, 1–21.

Wernberg, T., Thomsen, M.S., Connell, S.D., Russell, B.D., Waters, J.M., Zuccarello, G.C., Kraft, G.T., Sanderson, C., West, J.A., Gurgel, C.F.D., 2013. The footprint of continental-scale ocean currents on the biogeography of seaweeds. PLOS ONE 8, e80168.

﻿Wu, L., Cai, W., Zhang, L., Nakamura, H., Timmermann, A., Joyce, T., … Giese, B., 2012. Enhanced warming over the global subtropical western boundary currents. Nature Climate Change, 2(3), 161–166.

Yang, H., Liu, J., Lohmann, G., Shi, X., Hu, Y., Chen, X., 2016. Ocean-atmosphere dynamics changes associated with prominent ocean surface turbulent heat fluxes trends during 1958–2013. Ocean Dynamics 66, 353–365.