Co-occurrence of marine heat waves and cold spells in nearshore and offshore regions along South Africa

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Abstract

The term marine heat wave (MHW) was first coined in 2013 with no central definition having been agreed upon before. This lack of a definition had led to an inability of different research groups to compare their findings on this phenomenon before 2013. In order to assuage this issue, a research team has recently created a definition for MHWs that will be valid anywhere in the world. We have taken this algorithm and applied it to the *in situ* time series available for the coast of South Africa that are longer than 10 years and with at least 90% complete daily records. It was also decided to apply the algorithm to cool temperatures and investigate the presence of marine cold spells (MCSs). We found that MHWs and MCSs can be found along the entire stretch of South Africa's coastline and with some temporal and spatial agreement between the largest events detected. MHWs occur more often, last longer than MCSs and have greater cumulative intensities. There was little variance in the cumulative intensity [°C × days] around the mean for MHWs and MCSs however, several were much larger and there tended to be specific time series that displayed more dramatic results than others. The coastline was further divided into three sections (west, south, and east) to investigate the effect of geography on MHWs and MCSs and it was found that the south coast experiences more, longer and more intense MHWs and MCSs than the other two coastlines. The mechanism driving the higher intensity of events on the south coast, which is much greater than the other coasts, requires further study. The largest three MHWs of most time series along the coast of South Africa have occurred in the second half of the time series whereas the largest three MCSs have occurred in the first half. These same calculations were conducted for offshore temperatures from NOAA optimally interpolated sea surface temperature (OISST) data, too. It was found that the proportion of co-occurrence between *in situ* and OISST data ranged from 0.5–0.0 for each coastline with co-occurrence rates being the largest on the south coast. Few time series showed co-occurrence amongst the 50% largest events.

Keywords: marine heat waves, marine cold spells, OISST, *in situ* data, co-occurrence, climate change, extreme events, South Africa, coastal

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1. Introduction

Over the past three decades, global-scale anthropogenically mediated warming has negatively affected marine and terrestrial realms with far reaching consequences for humanity and natural ecological functioning. Although climate change is generally understood as a gradual long-term rise in global mean surface temperature [1], which will continue for decades or centuries, it is generally the associated increase in frequency and severity of extreme events that affects humans and ecosystems alike in the short-term [2]. Impacts are often sudden with catastrophic consequences. Such extreme events include droughts, floods, wind storms, tropical cyclones, heat waves and cold spells. 'Pulse' events exceeding certain thresholds of frequency, intensity (extremeness), duration, timing and rate of onset (abruptness) can drive punctuated perturbations to species distributions, which eventually modify the structure and function of ecosystems [3, 4], and the recognition to focus more on events and less on trends has emerged as a recent direction of climate change research [5].

Is this the best way we want to start framing this work? Given that we can't really say much about the long-term trends given that most stations are in the 10-20 years range of data record length.

This is good and important, but extreme events happen regardless of climate change. This paper mostly focusses on the mean state not the changes. Is this not better suited to the discussion when you need to start talking about impacts/implications?

The focus of this paper is on periods of consecutive days when seawater temperature is statistically extreme with respect to normal, thereby including seasonally anomalous warm (or cold) events. The concept of heat waves is usually applied to atmospheric phenomena where vague definitions such as "a period of abnormally and uncomfortably hot and usually humid weather" are invoked [6], but there are also examples of more precise definitions that rely on statistical properties and other metrics of the temperature record that are relative to location and time of year (e.g. [7, 8, 9, 10]). Recent years have seen investigations of heat waves in the ocean due to them becoming more frequent over time (e.g. [11, 12, 13, 14, 15]). Well documented marine heat waves (MHW) have occurred in the Mediterranean in 2003 (e.g. [16, 17, 18]), off the coast of Western Australia in 2011 (e.g. [19, 20, 3]), in the north west Atlantic Ocean in 2012 (e.g. [21, 22, 23] and now the "Blob" from 2014 to 2016 in the north east Pacific Ocean [24]. The extreme temperatures from these events, and others like them, may have wide ranging negative impacts upon the local ecology for the regions in which they occur. For example, the 2003 Mediterranean heat wave may have affected up to 80% of the gorgonian fan colonies in certain areas of this sea [18], whereas the 2011 event off the west coast of Australia has been recognized as being a driving factor in the regime shift there from temperate kelp forests to the beginnings of a coral reef system [3]. Because the inquiry into MHWs is a relatively new endeavour none of these studies provided adequate definitions for what constitutes a MHW, and to that end Hobday et al. (2016) [25] have defined it as "a prolonged discrete anomalously warm water event that can be described by its duration, intensity, rate of evolution, and spatial extent". By applying the MHW definition to the aforementioned events, Hobday et al. (2016) [25] were able to derive statistical features of the MHWs, such as their frequency along a time series and maximum and cumulative intensity. Whereas extreme hot events may be demonstrably damaging to organisms and ecosystems, extreme cold events also have the potential to negatively impact organisms and ecosystems.

While MHWs are becoming reasonably well known by virtue of their increasing frequency and intensity, there is less information about the ecological effects of extreme cold events. Anomalous cold events are projected to become less frequent under future climatic scenarios, but there are also examples of them becoming more frequent in some small localities [26, 27]. Extreme cold events (here called 'marine cold spells', MCS) are frequently lethal [28] and are known to cause mass fish [29, 30, 31] and invertebrate [30, 32] kills, the death of juvenile and sub-adult manatees [33, 34] as well as affecting organismal physiological tolerances, life history strategies, and habitat requirements [35]. Cold temperatures are therefore very important in setting species distribution limits, particularly limiting their range north- or southwards towards high latitudes [36], and the timing of the onset of the growing season [5]. At an ecosystem level there is still a paucity of information on effects of MCSs, but it is easy to postulate how population-level consequences might aggregate to drive whole ecosystem responses (e.g. [37, 4]). Indeed, the range contractions of ecosystem engineer species such as mussels have been shown to relate to extreme cold events (e.g. [36, 38]). Many of the extreme cold events that have had recorded negative impacts on individuals and ecosystems have been caused by atmospheric cold events, not by oceanographic phenomena (e.g. [29, 36]). The question then is, in what way do MCSs, as defined here, affect ecosystems differently than routine upwelling? Is it the link to atmospheric forcing, or may a MCS capable of mass mortalities and ecosystem change be caused by the intensifications of coastal upwelling processes? Little research yet exists that investigates this question other than to link anoxia and other negative factors from problematic phytoplankton blooms caused by extreme upwelling events to create lethal conditions for species living within upwelling regions (e.g. [39]). Whereas anoxia is a problem attributable to phytoplankton blooms themselves [40] and not the extreme cold temperatures *per se*, if a relationship can be shown between MCSs and anoxia resulting from algal blooms it would provide extremely valuable insight into how coastal ecosystems respond to climatic change. To this end it serves as a constructive first step to define MCSs as the negative inverse of MHWs for the purposes of this investigation however.

Hobday et al. (2016) [25] applied their MHW framework to ¼° NOAA optimally interpolated sea surface temperature (hereafter referred to as OISST; [41]) data, but warned users to be cognisant that different data sets would provide different kinds of information pertaining to the heat waves. Our aims here were two-fold. Firstly, we applied the MHW (MCS) definition to datasets of *in situ* and gridded SST temperature time series collected at different scales along the South African coast for the three different coastal sections, each variously forced by the Agulhas and Benguela Currents and regional aspects of the coastal bathymetry and geomorphology. These regional drivers of the thermal regime (east, south and west coast) coupled with local modifications (coastal vs. offshore) can be expected to impart different thermal signatures on the temperature data sets and manifest in differences in the metrics of MHWs (MCSs). Secondly, we aim to discuss the significance of MHWs (MCSs) within the context of the data sets' inherent differences and the various dynamical properties that then emerge because of the regional oceanographic context, so as to provide a mechanistic understanding of the nature and origin of MHWs (MCSs) in three oceanographically distinct ocean/coastal regions.

To add a mechanistic understanding of the drivers of MHWs (MCSs) manifesting in the coastal environment, we hypothesised that coastal MHW (MCS) events could either be coupled with synoptic scale processes perturbing the offshore region at scales of 100s of kms, or originate solely at a local

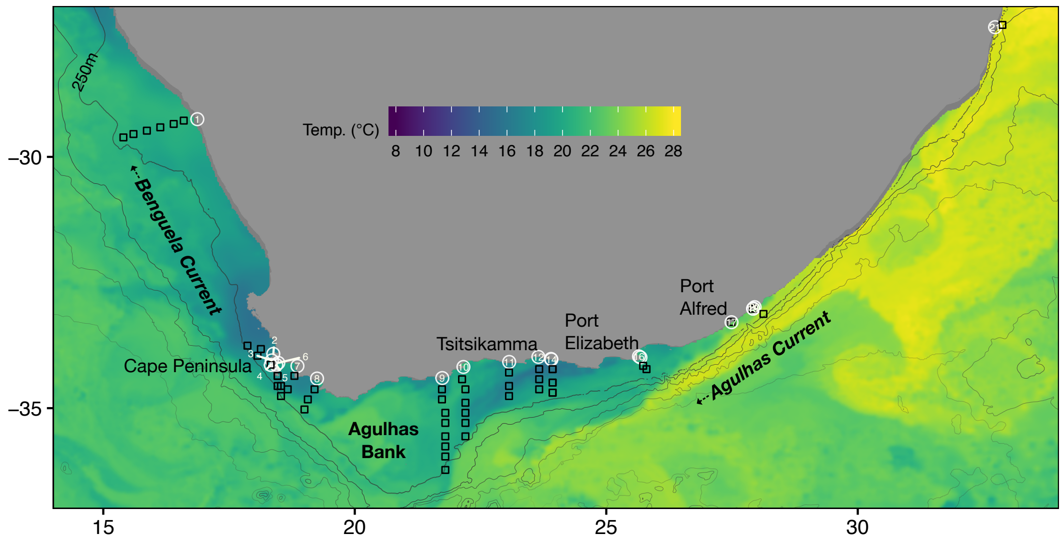

Figure 1: Map of South Africa showing the bathymetry (only the 250 m isobath is indicated), the location of the *in situ* thermal time series shown with circles and approximations of the pixels used along the shore-normal transects from the daily ¼° NOAA OISST [41] shown with black boxes. The SST field was derived from the JPL G1SST 1 km blended SST product and shows the state of the ocean on 2016-02-14. Sites 5, 6 and 7 are to the east of the Cape Peninsula and are situated along the shores of False Bay. The Agulhas Current along the east coast of the country is visualized here in a yellowish colour as a jet of relatively warmer water projecting in a south-westerly direction, and hugging the continental shelf. The blueish patches north of the Cape Peninsula represent upwelled water. Some upwelled water may also be present around Sites 14 (Tsitsikamma) and 15–16 (Port Elizabeth).

scale as isolated incidents. Investigating the former possibility required the assessment of concurrent gridded SSTs derived from daily OISST data product, extracted for the bounding boxes in Figure 1, averaged spatially, and lagged or led by a number of days relative to the onset of the events at the coast. This analysis centres around the top three MHWs (MCSs) ranked with respect to cumulative intensity for each of 21 coastal sites. The rates of co-occurrence of coastal with mesoscale MHWs (MCSs) are used in part to understand how many of the extreme events detected in all three coastal sections originate at the coast or are artefacts of warming (cooling) in the respective currents. We think that this approach will yield considerable insight into the nature and variability of the thermal regime of nearshore seawater.

2. Methods

2.1. Study region

The variety of oceanographic features around South Africa provide a natural testing bed for the potential effects of geographic forcing of oceanographic phenomena on the occurrence and frequency of MHWs and MCSs. The west coast of South Africa is dominated by the temperate Benguela Current, which is one of the four Eastern Boundary Upwelling System (EBUS) of the world [42]. This area may

I think this must be shortened significantly. It reads like a biologist wrote it — and it was!

experience large annual ranges in temperature and the many strong localised upwelling cells retard the more regular seasonal signal one would expect from ocean temperature. The Benguela Current does not regularly flow farther west than Cape Point before it meets the warmer Agulhas Current. The Agulhas Current flows in a south-westerly direction along the eastern shores of South Africa, which then retroflects back into the southern Indian Ocean [42]. The south coast is dominated by a wide slab of continental shelf, the Agulhas Bank, jutting out south of South Africa, which plays host to the Agulhas Current as it widens out thus causing the Agulhas Current to slow down and cool off [43]. This process is notoriously volatile and the south coast experiences the largest ranges in annual temperatures and variability of the three coasts. It has also been theorised that an upwelling cell exists along this coastline [43]. There are many embayments on the south coast and it is thought that the thermal heating that occurs therein lends to the range and variability in temperatures seen on this coastal section. As varied as the south coast is, the east coast is stable. The continental shelf along the east coast is very narrow and the Agulhas current flows evenly southward toward the south coast. There are some small upwelling cells along this stretch of coastline caused by sheer forcing from the speed of the Agulhas current [44].

The sites selected for this study (see the section on *Temperature data* below) represent the full thermal range and variability along the coast. Annual mean (SD) coastal seawater temperatures range from 12.3 (1.2)°C at the north western limit near the Namibian border (Site 1) to 24.4 (2.0)°C on the east coast near the Mozambican border (Site 21). The Agulhas and Benguela Currents modulate temperatures along this *ca.* 2,700 km stretch of coastline. The southward flowing Agulhas Current has an overriding effect on the east coast of South Africa, and extends as far west as False Bay (Sites 5–21; Figure 1). This warm temperate region (Lüning 1990) occupies a continental shelf ranging in width from *ca.* 4–200 km (Figure 1). Within this region, particularly around the towns of Port Alfred and Port Elizabeth (Sites 15–17), topographically driven upwelling is sometimes present. The northward flowing Benguela Current is an Eastern Boundary Upwelling System (EBUS) maintained by prevailing south-easterly trade winds, which particularly influences the western side of the Cape Peninsula (Sites 2–4) northwards to about 16°S. The influence of the Benguela Current here defines a cool temperate regime, with the range of monthly mean temperatures at most sections intermediate between cold temperate and warm temperate [45].

The global latitudinal gradient of diminishing temperature with increasing latitude is only seen along the east coast (Figure 1), where the annual mean temperature decreases from 24.4°C (Site 21) to 17.9°C (Site 18). The alongshore thermal gradient for this 950 km stretch of coastline is *ca.* 0.7°C per 100 km, with steeper gradients near Sodwana. The latitudinal gradient largely reverses in direction along the west coast (Sites 1–4), i.e. temperatures become slightly cooler further north. On average, these data indicate an increase in inshore annual mean temperatures from west to east (Sites 1–21) of 12.3–24.4°C. In February the thermal range is 13.7°C, while in August it is 10.5°C. In August the west–east temperature transition is smooth whereas in February substantial warm fluctuations in the mean monthly temperature are observed in embayments such as Site 3, False Bay (Sites 5–7) and many sites along the south coast (Sites 8–17).

2.2. Temperature data

We use two sources of seawater temperature data. The first dataset is comprised of 127 records of *in situ* temperature records of daily measurements for up to 40 years in duration with a mean duration of *ca.* 19 years. Whereas these *in situ* time series are generally shorter than the recommended 30 year minimum [25] and have some small amounts of missing data, it is our opinion that the benefit of using *in situ* data over satellite data is that they give a better representation of the thermal characteristics near the coastline, a region where satellite SST measurements have been shown to perform poorly (e.g. [46, 47]). In a South African context, Smit et al. (2013) [48] have shown that satellite SST data display a warm bias as large as 6°C over *in situ* temperatures in the nearshore environment. In an attempt to compromise between the proscribed requirements in Hobday et al. (2016) [25] of a 30 year minimum and no missing data, all time series under 10 years in length were eliminated. Next, our 127 time series were screened and those missing more than 10% of their daily values were removed, leaving a total of 21 time series. Care was taken to select continuous series with as few as possible consecutive missing values, since having regions in the data with more than two consecutive missing data points interferes with the identification of the anomalous events (see below). These stations were classified into three coastal sections defined by properties of their oceanography and biogeography [48]. The meta data for these time series and the coastal sections they were aggregated into may be found in Table S1 and the site localities are displayed spatially in Figure 1.

The Supplementary material must still be put together.

The second set of temperature data used in this study are the daily ¼° NOAA optimally interpolated sea surface temperature (OISST; [41]) derived from the Advanced Very High Resolution Radiometer (AVHRR). To compare the OISST and *in situ* time series, shore-normal transects were drawn from each of the 21 sites extending to the 200 m isobath. The OISST data were then extracted at each of the roughly 25 × 25 km pixels along these transects, shown as black boxes in Figure 1. Where the shelf was less than 25 km wide (Sites 17–21) the nearest 'ocean pixel' to the *in situ* time series coordinate was used. The individual time series within each pixel were then averaged along each transect corresponding to the 21 *in situ* sites. This produced 21 OISST time series that could then be analysed for MHWs (MCSs) in the same way as the *in situ* data. Note that the OISST time series had valid data covering 1982–2014 which did not match exactly the coverage by individual *in situ* sites.

2.3. Defining and calculating MHWs and MCSs

MHWs are "discrete prolonged anomalously warm water events in a particular location." Here we introduce the opposite but analogous concept of a Marine Cold Spell (MCS), which is calculated in the same manner as a MHW, except that events are detected as deviations below a seasonally varying anomalously low threshold relative to the site's climatology. Although MCS intensities are calculated as negative values (i.e. anomalies) they are reported here as absolute values.

A Python script (https://github.com/ecjoliver/marineHeatWaves; see Hobday et al. (2016) [25]) was used to calculate the MHWs and MCSs for both the *in situ* and OISST time series, producing

Table 1: Metrics of MHWs and their descriptions as used by Hobday et al. (2016) [25]. In the case of MCSs, values are calculated with respect to the 10th percentile and absolute intensity values are reported.

Name [unit]	Definition
Count [no. events per year]	n: number of heatwaves per year
Duration [days]	D: Consecutive period of time that temperature exceeds the threshold
Maximum intensity [°C]	i_{max}: highest temperature anomaly value during the MHW
Mean intensity [°C]	i_{mean}: mean temperature anomaly during the MHW
Cumulative intensity [°C x days]	i_{cum}: sum of daily intensity anomalies

the metrics in Table 1. The individual events detected and their attendant statistics were meaned into a series of annual values. These annual values were then meaned for each coastal section for later comparison.

To detect the individual events, a climatological mean and 90th and 10th percentiles were calculated for each day of the year by pooling all data within an 11-day window across all years. MHWs (MCSs) were detected as periods of time when temperatures exceeded the 90th (10th) percentile for at least five days. The implication is therefore that MHWs (MCSs) could develop in winter (summer) months. Since our *in situ* time series are of differing lengths we calculated the climatology over all available years; in the case of the OISST data, climatologies were calculated over a 30-year base period from 1982–2012. Furthermore, the algorithm found discrete events with well-defined start and end dates, but 'breaks' between events lasting $\leq$2 days followed by subsequent $\geq$5 day events were considered as continuous events. Once events were defined, a set of metrics were calculated including maximum and mean intensity (measured as anomalies relative to the climatological mean), duration (time between start and end dates), and cumulative intensity (the integrated intensity over the duration of the event, analogous to degree-heating-days).

Because MHWs (MCSs) are thus calculated by percentiles rather than maximum values centered around a window of time with respect to the Julian day, any time of year could be shown to be experiencing a MHW (MCS). This is an important consideration as unusually warm waters occurring during the winter months of a year, the time when many species need cold water for effective spawning spore release, can have a negative effect on the recruitment success of that population for the year [49].

It is important to understand that MHWs can result from a combination of atmospheric forcing and oceanic processes, but that the approach here aims only to shed light on the oceanic drivers by virtue of the inclusion of mesoscale OISST data linked with the coastal *in situ* data sets.

In order to better understand the potential impact mesoscale phenomena have on coastal events, the rates of co-occurrence between the MHWs (MCSs) found within each time series between the two datasets were compared. This was initially done by taking each event (warm and cold) within an *in situ* time series and looking for an event occurring within the OISST time series at the same site within a certain period of time before the *in situ* date. These co-occurrence proportions were then used to describe how often the mesoscale oceanography off the coast pre-empted the extreme events occurring along the coastline. All events occurring on dates not found in the matching time series were removed from this calculation. The sum of events found to occur within similar times was then divided by the total number of *in situ* events checked against the OISST data to produce a co-occurrence proportion.

The proportions of co-occurrence were then recalculated controlling for the amount of lag used when comparing the two different datasets for concurrent events, as well as the directionality used for this comparison. In other words, a range of lag from 2–14 was used for each site to see how far apart events generally occurred and the lag period used was also applied only after the *in situ* date, as well as both before and after the date, effectively doubling the range of the lag. This allowed us to see how often the *in situ* event pre-empted the mesoscale event as well as seeing broadly the amounts of co-occurrence occurring between the two data sets.

Besides controlling for the length and direction of lag, the size of the events themselves (ranked by cumulative intensity) were compared. This was accomplished by controlling the pool of events with which to compare the datasets per site in steps of 10th percentiles. This progressively removed smaller events until only the larger events were being compared. This allowed us to track the co-occurrence of only the largest events, reducing the overall proportion of co-occurrence found within each site as caused by the large amount of smaller events occurring at similar times as other larger events.

The top three MHWs (MCSs) for each *in situ* and OISST time series as defined by cumulative intensity were also noted in order to visually compare the co-occurrence of events in detail, both within and between the different datasets. Using the OISST data, images of the South African ocean temperature on the dates for the largest MHWs and MCSs (cumulative intensity) for the south and west coasts from the *in situ* datasets were extracted and displayed on a map to show the spatial extent of any potentially co-occurring event in regions offshore from the coastline of South Africa.

This last sentence here must probably be removed.

Given that the anthropogenic forcing of climate change is predicted to increase the temperature of most of the ocean over time, it stands to reason that, as a function of the 90th and 10th percentiles, one would expect to see the larger MHWs near the end of the time series, and the larger MCSs near the beginning. This can be tracked visually by looking at the top three warm and cold events for each time series.

Was this in fact done? I have started writing the code to quantify this, but need to finish it off.

3. Results

3.1. Events

One can see in Table 2 that the *in situ* time series show that the typically cooler west coast experiences the most MHWs per year, and that these are longer and more intense on average than those along the other two coastal sections. Whereas the east coast experiences slightly more MCSs per year than the other two coastal sections, it is the volatile south coast that experiences the longest and most intense MCSs, on average.

Need to insert the results of the ANOVA/ Tukey HSD tests in the following two paragraphs.

Results from the analysis of the OISST data (Table 3) are significantly different than that of the *in situ* data for most metrics. The mean annual frequency and duration of MHWs and MCSs are greater for all coastal sections whereas the intensity of both events type on all coastal sections are less than the results of the *in situ* data. With this in mind we still see that the pattern of MHW and MCS event sizes along the coastline differs from the *in situ* data, too. The largest annual number of MHWs is here occurring on the warmer east coast whereas the longest MHWs are occurring on the volatile south

Table 2: The mean (sd) annual values for event frequency, duration and intensity for MHWs and MCSs for each coastal section as calculated from the *in situ* time series. All individual events were first aggregated into annual means before being averaged into overall mean values for each coastal section.

coast	MHW [count]	duration [days]	intensity [°C]	MCS [count]	duration [days]	intensity [°C]
all	1.6	9.3	2.65	1.5	9.0	2.79
west	1.8	9.1	2.86	1.5	8.5	2.32
south	1.5	9.1	2.50	1.5	9.7	3.08
east	1.5	7.7	2.85	1.6	7.1	2.37

Table 3: The mean (sd) annual values for event frequency, duration and intensity for MHWs and MCSs for each coastal section as calculated from the OISST time series. All individual events were first aggregated into annual means before being averaged into overall mean values for each coastal section.

coast	MHW [count]	duration [days]	intensity [°C]	MCS [count]	duration [days]	intensity [°C]
all	2.2	10.2	1.72	2.2	10.2	1.83
west	2.1	10.9	1.75	2.3	9.8	1.87
south	2.2	10.6	1.74	2.1	10.7	1.79
east	2.5	8.3	1.64	2.2	9.4	1.93

coast with the most intense events nearly split between the west and south coasts respectively. The cooler west coast sees the most frequent occurrence of MCSs with the OISST data. The longest MCSs are occurring on the south coast, same as the *in situ* data; however the most intense MCSs are seen off the east coast.

3.2. Top three events

The mean annual statistics shown in Table 2 and Table 3 represent the events occurring along the coastline; however, examining the largest MHWs and MCSs aid in our understanding of which coastlines may have the most extreme events. The ranking of these events is based on the cumulative intensity statistic as explained in Table 2. The three largest MHWs that occurred within the *in situ* dataset were all on the south coast at 310.30°C, 171.30°C and 156.4°C in the years 1999, 1993 and 1999 respectively (Figure 2), showing that 1999 was a particularly hot year. The size of the south coast events are larger than those occurring along the west coast (123.20°C in 1996, 99.66°C in 2005 and 99.41°C in 1975), with the largest three MHWs on the east coast being much smaller than those occurring on the south coast (93.31°C in 1995, 63.18°C in 1985 and 45.59°C in 1990). The cumulative intensity of the entire coastline and each section individually may be calculated for both datasets from Table 2 and Table 3 by multiplying the mean event length by the mean intensity. Here we see from the *in situ* data the cumulative intensity of MHWs for the entire coast is 42.13°C, meaning that the largest MHWs seen on the south and west coasts are massively larger than the coastal average.

I am going to include a table for the top three events rather than list them.

As with the MHWs, the largest three MCSs from the *in situ* data were also found on the south coast at -183.70°C in 1984, -155.61°C in 1992 and -150.10°C in 2000. Maintaining the pattern seen with the MHWs, the largest heat waves on the west coast were the next largest three events for the entire coastline (-126.60°C in 1990, -110.90°C in 1983 and -85.04°C in 2000) with the three largest events from the east coast being smaller than the other two coastal sections (-55.20°C in 2004, -48.44°C in 1984 and -45.13°C in 1995). The mean cumulative intensity for MCSs was -39.62°C over the entire

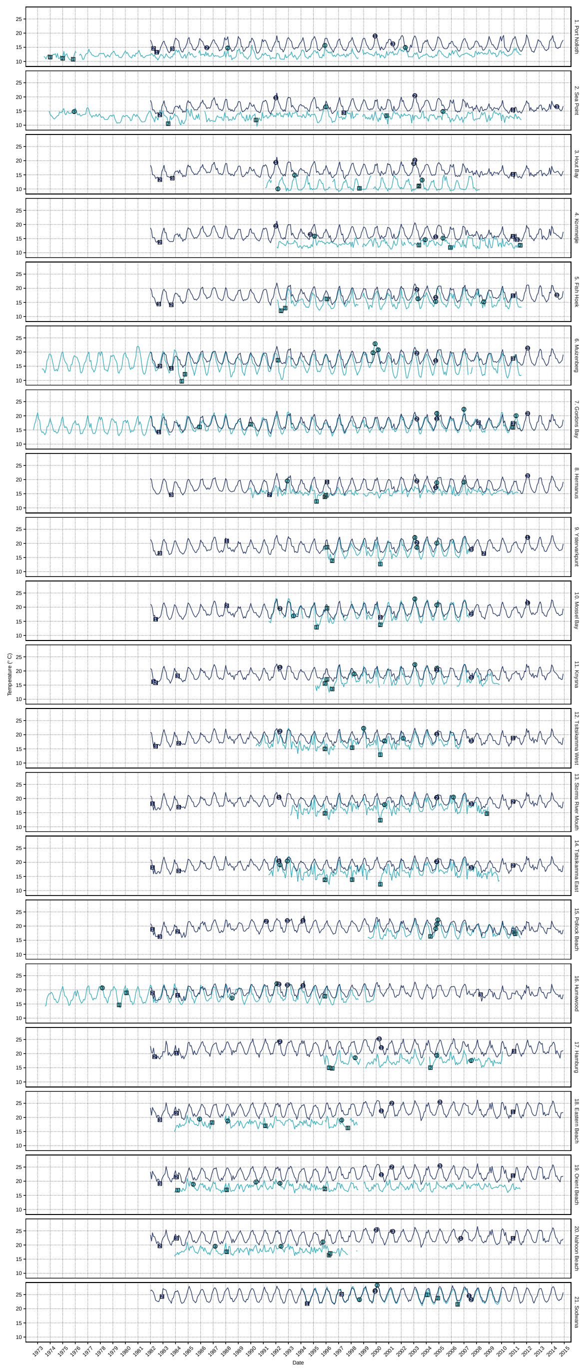

Figure 2: The daily temperature values for each *in situ* time series (grey) used in this study and the corresponding OISST time series (black) extracted for comparison as seen in Figure 1. The left column shows the top three MHWs (indicated by circles with the rank inside) for each site as judged by greatest cumulative intensity. The left column shows the top three MCSs for each site and dataset. The coastal sections to which each site belong may be seen in Table 1 and are delimited here by...

coastline.

As can be seen in Figure 2, the three largest events occurring for each time series within the OISST dataset are largely different from the *in situ* dataset and show a greater amount of co-occurrence for neighbouring coastal stations than the corresponding *in situ* time series. The pattern seen in the *in situ* data of the largest MHWs and MCSs occurring on the south, west and east coasts respectively is also not repeated with the OISST dataset. The cumulative intensity of the largest MHW in this dataset is 120.40°C and occurred on the south coast in 1992. The three largest MHWs from the west coast (115.60°C in 1992, 113.50°C in 1992 and 107.40°C in 2004) were larger than the second and third largest events from the south coast (101.60°C in 2004, 99.05°C in 1994) and the three largest MHWs from the east coast again came in below the other coasts at 45.34°C in 2006 and the next two heat waves tying at 41.12°C both in 2000. The coastal average was 40.59°C.

The largest cold wave from the OISST dataset occurred on the south coast in 1984 and reached a cumulative intensity °C of -254.2°C. The largest MCS occurring on the west coast came in second at -211.90°C in 2010. The second and third largest MCSs on the south coast (both -167.30°C in 1982) were larger than the second and third largest MCSs on the west coast (-166.30°C and -154.90°C both in 2010). The three largest MCSs on the east coast, like with both datasets and both types of events, were smaller than the other two coasts. The first and second largest east coast events both occurred in 2010 and reached a cumulative intensity of -92.85°C with the third largest event occurring in 1984 at -87.26°C. The coastal average was -45.75°C.

OISST temperature values of the ocean along the South African coastline during the time periods of the largest MHW and MCS for the west and south coasts from the *in situ* dataset may be seen in Figure 2. The range of dates across which these MHWs and MCSs occurred in the *in situ* data may be seen concurrently with the temperature values from the same OISST time series in Figure 4. One may see that when the largest events were occurring in the *in situ* data, nothing of note was occurring within the OISST data.

3.3. Co-occurrence rates

The proportion of co-occurrence for events between the datasets for each coastal section may be seen in Figure 4. We see that as the length of lag is increased the proportion of co-occurrence increases linearly for both MHWs and MCSs with the largest increase in co-occurrence on the south coast and the least on the west. The directionality of the lag also affects the co-occurrence of events. A lag window before the *in situ* event gave higher rates of co-occurrence for all three coastal sections for both MHWs and MCSs when all events were compared. This pattern changed when the smaller events were screened from comparison. When only the largest half of the events were checked for co-occurrence a lag window after the *in situ* event gave larger rates of co-occurrence. The overall proportion of co-occurrence for MHWs is greater than that of MCSs. There is no co-occurrence for the largest MCSs between the datasets, whereas several of the time series on the south coast show co-occurrence for their most extreme MHWs. Interestingly the rates of co-occurrence for these largest MHWs was greater when the *in situ* event preceded the OISST event.

I feel like I need to describe more of these results here. I also need to calculate statistical significance between the different coast-lines/lags/directions/

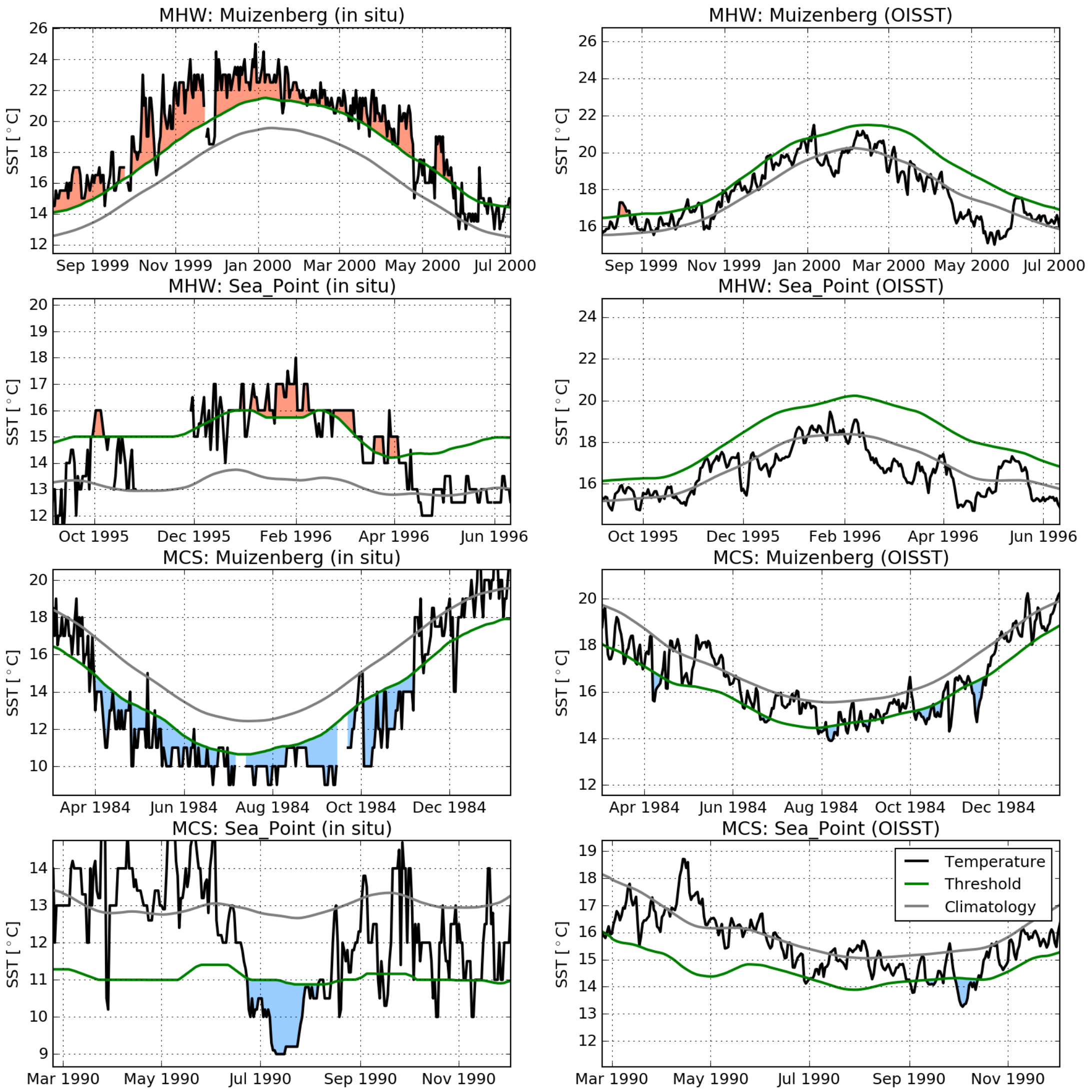

Figure 3: These eight panels show the profiles for the four events depicted in Figure YXZ. The left column shows the *in situ* event while the right column shows the OISST temperature occurring on the same dates. The top row shows the largest MHW that occurred on the south coast while the second row shows the largest MHW that occurred on the west coast. The bottom two rows show the largest MCS that occurred on the south and west coasts respectively.

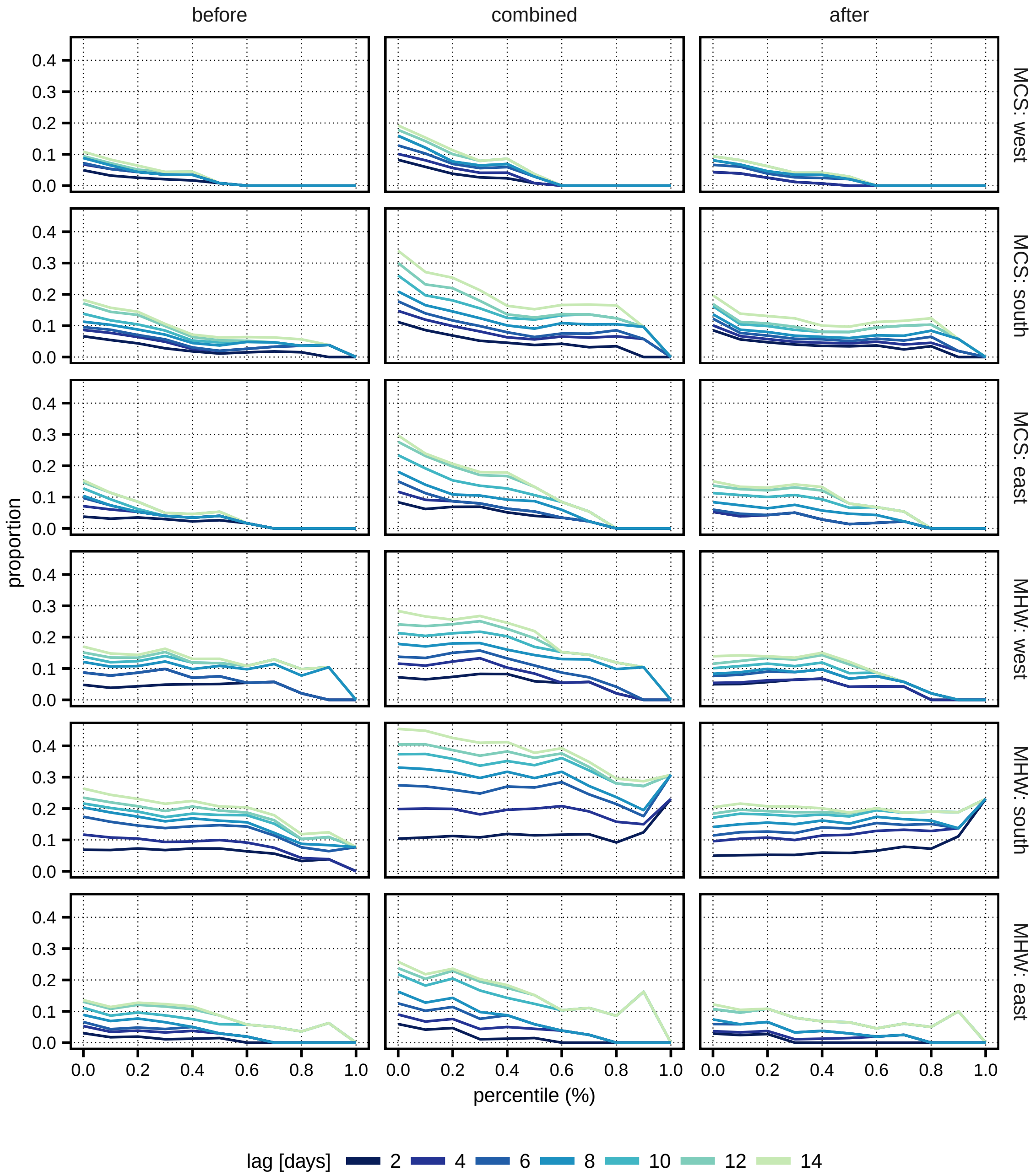

Figure 4: Proportion of MHW and MCS co-occurrence between *in situ* and OISST datasets for each coastal section. The left column denotes the proportion of co-occurrence when only events in the OISST data occurring on dates preceding the *in situ* event are used. The left column shows the proportion of co-occurrence when only OISST events occurring after the *in situ* date are compared. The central column shows the overall proportion of co-occurrence when the lag window is extended in both directions. The x-axis indicates the size of the events, based on percentiles, used for calculating the co-occurrence proportions. As the smaller events are removed from the pool of comparison, the proportion of co-occurrence diminishes.

4. Discussion

4.1. Events

Having never been calculated before, it was not yet known that every time series from each coastal section of South Africa experiences on average more than one MHW and one MCS per year. It was surprising to find that the mean intensity of MCSs on the south coast was significantly larger ($p =$ XX) than the west coast, which is in an EBUS. Even though the south coast is known to be the most volatile of the three coasts, it was not expected that the duration (days) of both the MHWs and MCSs occurring there would be significantly longer ($p =$ XX) than the other two coasts. From these results we may now hypothesise that there is an additional driver on the south coast affecting the extreme events there that is not present on the other two coastal sections. It was assumed that the east coast would experience the fewest and least intense events. Whereas the duration of its events were significantly smaller than the other two coasts ($p =$ XX), the frequency and mean intensity of its MHWs and MCSs was not the smallest found. This means that every portion of the coastline has the potential to experience an event strong enough to affect its species assemblage and/or local ecology.

The difference between the *in situ* and OISST datasets was also striking. One may see in Table 2 and Table 3 that the patterns presented by the data are intrinsically different, it is not simply a matter of the statistical significance between the statistics. The OISST data show many weak events occurring often whereas the *in situ* dataset shows fewer, stronger events. This implies that events occurring in the different datasets are unrelated, and any co-occurrence is simply by chance. Besides this difference, both datasets tend to show that the south coast has the longer and more intense results than the other two coastal sections, but this too is not a consistent result. Before calculating the proportions of co-occurrence, it was already clear from these results that the events occurring within the OISST data would differ from the *in situ* data.

Another important difference found between the datasets was that MHWs are shown to be longer and more intense in the *in situ* dataset, whereas the OISST dataset shows MCSs being longer and more intense. This also supports the argument that the events detected by these two datasets are not the same, even when they are found to occur within similar time frames. It is also counter-intuitive to what we expected to find. One would assume that as the *in situ* data are measured at *ca.* 5 m deep on average, which is below the bulk surface layer (*ca.* 0.5 m) that the OISST data measure [50], they would be predisposed to picking up cold upwelling events and less exposed to thermal heating, which would appear as larger MCSs and smaller MHWs compared to the OISST data. The cause of this discrepancy warrants further research.

This apparent discrepancy also places doubt on the use of MCSs as a proxy for upwelling. If the *in situ* data had recorded longer and/or more intense MCSs than the OISST data it would have shown that the MCS algorithm was detecting more extreme cold events near the coastline, where upwelling is known to occur [42, 51]. Instead the results show that offshore MCS are, on average, longer and more intense. It is the suggestion of the authors that using the MCS algorithm to detect upwelling be done with extreme caution. The MCS algorithm detects cold events based on their intensity outside of a locally produced climatology, and because most upwelling occurs at seasonally predictable times, the cold events detected here are likely due to other factors.

4.2. Top three events

It was hypothesised that the south coast would experience the most extreme events as measured by cumulative intensity, but it was unanticipated that these events would be so much larger than the other two coastal sections. On the opposite side of the coin, it was hypothesised that the east coast would experience the least extreme events however, besides the largest two MHWs recorded, very few of the events are greater than the coastal average.

The disagreement between the *in situ* and OISST datasets continued into the detection of the top three events along the coastline. The pattern of event sizes within the *in situ* data are very clear in that the south coast is much more volatile than the west and east coasts in that order. The OISST data are less conclusive on whether the south or west coast experiences the most extreme events, but it is apparent from all of the analyses from both datasets that the east coast experiences very few extreme MHWs or MCSs. Indeed, these findings support the hypothesis that the east coast is the most stable of the three coasts in that in both datasets the most extreme events occurring here barely exceed the coastal mean for cumulative intensity.

The sites along the south coast could be further divided into those within False Bay (Sites 5–7) and those on the Agulhas Bank (Sites 8–17). False Bay, which is 50 km across, is situated within the transition zone between the Benguela and Agulhas Currents [48]. Many satellite temperatures products therefore inadequately resolve the SST within this body of water (cite.). This is problematic as it is important to precisely monitor the large ranges in temperature this area experiences (cite.) as it is important both ecologically (cite.) and to the many stakeholders that use this embayment. Two of the three largest MHWs and MCSs from the *in situ* dataset were recorded within False Bay, whereas only one large MHW and no MCSs were detected with the OISST dataset. This illustrates the problem of using satellite temperature data for coastal ecology.

The example of the discrepancies for the size of the events recorded in False Bay also serves to illustrate the usefulness of satellite SST data to detect events near the coastline. For example, Roberts (2004) [43] argues for a wind forced coastal upwelling cell near Tsitsikamma (Sites 12—14). That these three sites show greater cumulative intensities for MCSs than all but one time series for the OISST dataset supports the hypothesis of such a coastal upwelling cell. This is an intriguing use of the MCS algorithm to validate multiple competing hypotheses that as of yet may not have been able to be tested in any other way.

Need to relate MCSs not showing upwelling though...

4.3. Co-occurrence rates

As one may see in Figure 4, when looking at the the lag window before the *in situ* events occurred, the rates of co-occurrence for MCSs are much lower than for the MHWs. This shows that more MHWs are likely being caused by meso-scale activity than MCSs, as was expected. This finding is supported further by comparing the rates of co-occurrence for MCS lagged before and after the *in situ* event occurred. More MCS from the OISST data are shown to occur after the *in situ* events for all coastal sections. The co-occurrence rates of MHWs before and after the *in situ* events are similar.

One may also infer from the result that the proportions of co-occurrence for time series on the south coast being much larger than the other two coasts is caused by the much higher level of influence from meso-scale phenomena occurring on the Agulhas Bank. We also see that there is a higher proportion of co-occurrence for the larger MHWs and MCSs on the south coast when a lag window after the *in situ* event is used (Figure 4). This supports the argument that events originating in the nearshore are then propagating out onto the Agulhas Bank and affecting the oceanography there more often than meso-scale events originating on the Agulhas Bank are affecting the nearshore environment. The overall low rates of co-occurrence for all three coastal sections reinforces the argument that it is not the meso-scale phenomena of the open ocean around the coastline that is causing extreme events in the nearshore.

The very low proportion of co-occurrence between the datasets, and the decline in the proportion as the smaller events are screened out is strong evidence against the hypothesis that meso-scale activity, both warm and cold, is causing nearshore extreme thermal events. The small increases in co-occurrence as outlined above do imply that there is some relationship between the inshore and offshore, but that some other variable(s) is having a greater effect on the inshore. This is likely atmospheric forcing (cite.).

4.4. Climate change

As MHWs and MCSs are temperature related phenomena we would be remiss not to discuss the potential of our findings in relation to climate change. The count of the MHWs and MCSs occurring throughout the coastline is less telling in this regard than the trend in these events themselves. Although the *in situ* time series used in this investigation are too short to draw adequate conclusions on the trends seen in MHWs and MCSs, one can see in Figure 2 that most sites have their top three MCSs in the first half of the time series whereas the top three MHWs occur in the second half of the time series. As the algorithm used to calculate these events is based on percentiles, it stands to reason that as the mean temperature of South Africa's coastal waters increases by 0.1°C per decade on average (Schlegel and Smit, in press), that there will be an increase in MHWs and a decrease in MCSs. The gradual mean increase in temperature will cause the algorithm used here to be biased in its detection of MHWs as time progresses simply because temperatures are generally warmer in the later half of the time series therefor, the chances of the algorithm detecting a MHW increases because the base temperature from which the MHW will be fluctuating from will be greater than the beginning of the time series. Ultimately, for the species and ecosystems experiencing this increase in duress, the semantic argument of the viability of percentiles provides little solace.

But we can do this using the OISST data — and we should!

Not sure how to reference this...

Nice concluding statement here!

4.5. Conclusion

Given that the MHW algorithm is based on the percentiles found within each time series and not on arbitrarily decided minimum or maximum thresholds, one will always find a certain number of

MHWs and MCSs. This is evident in the results of our analysis (Table 2 and Table 3) in that every time series used from both datasets experiences on average at least one MHW and MCS per year. Within each dataset, but not between, the lengths of these events are similar throughout the coastline, regardless of the local oceanographic and geographic properties. It is the cumulative intensity of the events occurring on the different coastal sections that most clearly defines them. We expected to see the most intense MCSs on the west coast as this is part of an EBUS however, the south coast, a region dominated by the warmer Agulhas Current, but with some influence from the colder Benguela, had both the most intense and longest MHWs and MCS in the *in situ* data. Even though it had been hypothesized that the south coast would have intense events, the magnitude of intensity of the events that occurred here over the other coastlines is surprising.

This statement needs to be supported by the statistical results of an ANOVA.

Also perform ANOVA on the cumulative events to support this statement statistically.

We have also shown that MCSs are not a good indicator for upwelling. As upwelling tends to occur at seasonally predictable times, the MCS algorithm does not consider these events as anomalous. Therefore the MCSs measured here are indicators of non-seasonal or atypical forcing, which is assumed to be largely atmospheric.

As the rates of co-occurrence between *in situ* and OISST data are generally low, this implies that some other force is contributing to extreme inshore events. This is likely due to atmospheric forcing and warrants further research to better understand what is driving the occurrence and intensity of these events.

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