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The response of the Benguela Upwelling System to marine heatwaves off South Africa and Namibia

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ABSTRACT

Understanding the Benguela Upwelling System (BUS) response to marine heatwaves is important for managing fisheries and ecosystems along the coastline of Namibia and South Africa's western coastline. It is also important for predicting and mitigating the effects of future warming events. The National Oceanic and Atmospheric Administration (NOAA) gridded data was applied in this study to show varied occurrences of marine heatwave events in the Benguela. Upwelling and non-upwelling regions along Namibia's coastline and off the western coastline of South Africa were compared to properly understand the response of the Benguela Upwelling System on marine heatwaves. It was found that marine heatwave events off the southwest coast of Africa have increased in duration and severity over time. Furthermore, regions with upwelling experience fewer marine heatwave events than non-upwelling regions. The findings of this study suggest that marine heatwave events are becoming more common along Africa's southwest coast, particularly in the Benguela. Not only are they growing more common, but they are also lasting considerably longer and with greater intensity than in the past.

Keywords: Upwelling, climate change, Benguela, non-upwelling, El Niño, La Niña.

INTRODUCTION

The eastern boundary upwelling systems (EBUS) are extremely productive areas on the planet (Wang et al., 2023). The Benguela current system (BCS), Canary (CanCS), California (CalCS), and the Humboldt (HCS) are the four different EBUSs (Wang et al., 2023). The Benguela Upwelling System (BUS) is an upwelling system that is driven by wind in the ocean (Fennel, 1999). This is caused by the inshore of the Benguela current causing upwelling along the coastline due to southeasterly winds (Fennel, 1999). It runs along Africa's southwest coast (Fennel, 1999). The BUS brings cold water that is nutrient-rich to the surface (Fennel, 1999). Cross-shore geostrophic currents can either boost or diminish upwelling (Lamont et al., 2018). Because onshore spatial flow obstructs upwelling, the northern region of the BUS displayed concurrence of cold water being welled up to the surface (Lamont et al., 2018). However, geostrophic divergence causes a rise in upwelling in the southern region of the BUS (Lamont et al., 2018). The Lüderitz-Orange River is located off the shores of Namibia. It is known to be the strongest upwelling cell, separating the Benguela's northern and southern regions (Hutchings et al., 2009). In this region (26°C) there are strong winds, excessive offshore advection, and powerful turbulent mixing (Hutchings et al., 2009).

Marine heatwaves (MHWs) are events that occur over a period of time where the sea surface temperature becomes extremely and unusually warm by transcending a seasonally changing threshold (90th percentile) and persist for at least five days in a row (Hobday et al., 2016). Recently, there has been progress in the studies of MHW events (Varela et al., 2021). Varela et al. (2018) performed an analysis of temperature trends between coastal areas and their oceanic counterparts around the world. From that study, the authors observed significant differences between regions that experience upwelling and regions that don't experience upwelling (Varela et al., 2021). However, there are still some uncertainties such as the impact of upwelling systems on the events of marine heatwaves (Varela et al., 2021).

One of the first detected marine heatwave events in the world took place in the Mediterranean Sea in 2003 (Darmaraki et al., 2019a). During this event, the sea surface temperature exceeded the seasonally varying threshold (usually the 90th percentile) by 2-3°C (Darmaraki et al., 2019a). Not only did this event last for more than a month, but it also caused variation in the composition of the corraligenous species community, the extinction of seagrass meadows, and the large-scale death of benthic invertebrates (Darmaraki et al., 2019b). In 2014-2016 a marine heatwave event occurred in the North Pacific 'Blob' and it was related to tropical-extratropical teleconnections providing strong evidence for the above statement (Benthuysen et al., 2020; Oliver et al., 2021). These different intensities, spatial extent, and periods of marine heatwave events have been connected to disruptive variations in marine ecosystems and commercial fisheries (Oliver et al., 2021). An example of the disruptive change in commercial fisheries is the recruitment of lobster fishery in the northeastern United States (Mills et al., 2013). When exposed to warmer temperatures in the ocean, the variability in the growth of individuals is reduced, which decreases the number of year classes contributing to annual recruitment (Mills et al., 2013). This ultimately makes the population more susceptible to overfishing (Mills et al., 2013).

Climate change is causing more frequent and severe marine heatwaves (Wang et al., 2022). Greenhouse gases trap more solar energy as the ocean absorbs more heat and the sea surface temperature rises (United States Environmental Protection Agency, 2023). According to Bakun's (1990) hypothesis, increased greenhouse gas emissions would cause significant alterations in land-sea pressure gradients, ultimately increasing the severity of upwelling over the oceans. Abrahams et al. (2021) evaluated Bakun's hypothesis and concluded that prolonged climate change may indeed allow enhanced upwelling in particular coastal locations, thus buffering ecosystems from climate change. As a result, this investigation does support Bakun's hypothesis (Abrahams et al., 2021).

Over the last two decades, assessments of notable marine heatwave occurrences have disclosed that they are typically induced by an association of atmospheric forcing or oceanic causes (Oliver et al., 2021). According to Gupta et al. (2020), two categories can explain the causes of marine heatwave events: i) continuous synoptic atmospheric systems, and ii) boundary current intensification (Gupta, 2023). Atmospheric factors are comprised of increased heat flow across the air-water interface, while ocean-driven events are caused by horizontal and vertical heat advection (Holbrook et al., 2019; Oliver et al., 2021). All these factors may be influenced by large-scale changes in climate, which may include remote sources through teleconnections (Oliver et al., 2021). They play a crucial part in marine heatwave events occurrence, maintenance, and termination (Holbrook et al., 2019). A mechanism involving severe air temperature, droughts, and atmospheric blocking gives insight into 60% of the events of marine heatwaves occurring in the ocean of the South Atlantic's western region (Costa and Rodrigues, 2021). The various phases of large-scale climate modes can either raise or decrease the likelihood of regional marine heatwave events (Oliver et al., 2021). Nonetheless, there have been record-breaking marine heatwave events where the atmospheric state is critical to their growth and duration (Li et al., 2022). An example is the 2016 marine heatwave event in the Yellow Sea (Li et al., 2022). Increased sea surface temperature (SST) is usually associated with less wind stress, clear skies, warm surface air temperature, and low surface level humidity (Holbrook et al., 2019).

The effects of the events of marine heatwaves differ between species and populations (Smith et al., 2022). Marine heatwaves negatively impact marine life. For example, marine heatwave events destroy coral reefs and kelp forests (Smith et al., 2022). There have been reports on marine heatwave events causing mass mortality in fish populations, often leading to detrimental algal blooms (Smith et al., 2022). In 2011, Western Australia suffered an intense marine heatwave that affected over 2,000 km of coastline for over ten weeks (Wernberg, 2021). During this unexpected occurrence, seawater temperatures rose above the physiological threshold (23°C) for total growth for kelp, *Ecklonia radiata*. As a result, kelp in that location experienced local extinction across 100 km of their northern (warm) range (Schlegel et al., 2017; Wernberg, 2021). Because of the extinction of these kelp forests, there were broad changes in species distribution among seaweeds, fish, and invertebrates (Wernberg, 2021), leading the way toward the tropicalisation of the ecosystem (Wernberg, 2021). The northern Pacific marine heatwave event from 2012 to 2015 had large-scale biological consequences (Frolicher and Laufkotter, 2018). This event increased the death of whales, sea lions, and birds, shallow ocean primary productivity, and a rise in the amount of warm-water copepod species which are found in northern California (Frolicher and Laufkotter, 2018). In 2016, approximately 90% of the Great Barrier Reef's observed reefs were bleached (Frolicher and Laufkotter, 2018).

Marine heatwaves have an impact on both marine life and human systems (Schlegel et al., 2017; Frolicher and Laufkotter, 2018). Fishing methods and harvest patterns are altered as a result of these MHW events (Frolicher and Laufkotter, 2018). This was observed following the northeast Pacific marine heatwave, which prompted the closure of both commercial and recreational fishing (Mills et al., 2013; Frolicher and Laufkotter, 2018). This resulted in a loss of millions of dollars for the fishing industry (Frolicher and Laufkotter, 2018). Several strategies for sustaining fisheries during marine heatwave occurrences have been identified (Mills et al., 2013), including improving management-relevant forecasting capacities and identifying adaptation needs in fisheries management.

There is evidence that atmospheric blockage during the austral summer was responsible for more than 50% of marine heatwave events in the western region of the South Atlantic Ocean from 1985 to 2016 (Rodrigues et al., 2019; Costa and Rodrigues, 2021). The atmospheric blocking is associated with an abnormally protracted anticyclonic circulation, suppressing the South Atlantic Convergence Zone (SACZ) (Rodrigues et al., 2019; Costa and Rodrigues, 2021). This is known as the primary cause of rainfall in eastern South America, triggering droughts (Costa and Rodrigues, 2021). Heat fluxes between the sea and the atmosphere varying regionally, known as air-sea heat fluxes, cause marine heatwave episodes in this area (Costa and Rodrigues, 2021). From 1982 to 2016, gridded SST data revealed increased frequency, intensity, and length of marine heatwave events (Costa and Rodrigues, 2021). However, the increases that occurred in the South Atlantic's subtropical areas were more moderate (Oliver et al., 2018). Between 2021 and 2050, marine heatwave occurrences are anticipated to increase in frequency, severity, duration, and length (Costa and Rodrigues, 2021). The SST in the South Atlantic is expected to reach its maximum by 2040 (Costa and Rodrigues, 2021). This will have major consequences for marine ecosystems because most species would find it difficult to adjust to the extreme variations in sea temperature (Oliver et al., 2018; Costa and Rodrigues, 2021).

South Africa's east and south coasts are hotspots for ocean warming (Popova et al., 2016). The Agulhas Current is known to be among the world's strongest currents, and it is known as the main characteristic of the South African hotspot (Popova et al., 2016). Previous research, however, has shown that climate change in South Africa will depend on the future of El Niño Southern Oscillation (ENSO) and climate change caused by humans (Mead et al., 2013). Ocean warming is a major issue in Namibia, particularly in the country's central and southern beaches, part of the Benguela Upwelling System (BUS) (Benguela Current Convention, 2022). Sardines off Namibia are falling due to latitudinal changes in marine species distribution caused by rising temperatures in the ocean (Potts et al., 2014; Namibian Chamber of Environment, 2021).

The BUS response to marine heatwaves is uncertain (Varela et al., 2021). However, investigators discovered significant disparities in ocean warming between upwelling and non-upwelling zones (Varela et al., 2021). For 92% of the upwelling systems, there were fewer instances of increased temperature at the coast compared to in the ocean (Varela et al., 2021). In non-upwelling areas, the rate fell to 58% (Varela et al., 2021). Therefore, due to upwelling, oceanic warming seems to be mitigated in the ocean (Varela et al., 2021). As global warming increases, marine heatwave events are anticipated to grow more prevalent and severe (Varela et al., 2021). Because of the ecological richness in these areas, it is critical to understand how the BUS responds to marine heatwaves off South Africa and Namibia. South Africa, in particular, is rich in coral reef and kelp forest ecosystems (Blamey and Bolton, 2018). Marine heatwaves have been shown to cause irreversible damage and permanent harm to marine ecosystems (Schlegel et al., 2017; Wernberg, 2021).

Understanding the consequences of marine heatwaves in the BUS is critical for managing the fisheries and ecosystems of the region and predicting and mitigating future warming events. Continuing research in this area seeks to help improve our comprehension of the fundamental causes of marine heatwaves and their ecological consequences and to create solutions for adaptive management and conservation in light of climate change. In this study, I will look at how the BUS responds to patterns and trends in marine heatwaves off South Africa's western coastline and the Namibian coastline. I will use satellite-based, gridded data sets to conduct my research. I hypothesise that the intensity and occurrence of marine heatwave events will differ in the Benguela Upwelling system compared to non-upwelling locations.

METHODOLOGY

Study area

Sites along the BUS (Figure 1) which stretches from the tip of the west coast of South Africa to Southern Angola, were chosen for analysis. Bounding boxes were created to separate the areas that were focused on (South Africa and Namibia). The bounding box for South Africa included the region within (-35.50°S, 5°E, -30°S, 25°E), and that for Namibia (-28°S, 5°E, -17°S, 25°E). To properly understand how the Benguela upwelling system responds to marine heatwaves, we compared known upwelling and non-upwelling located regions off the coast of Namibia and South Africa's west coast in the BUS (Varela et al., 2021). The areas of upwelling are Paternoster (off South Africa's southwest coast) and Lüderitz (off the coast of southern Namibia). The areas of non-upwelling are Bloubergstrand and Strandfontein (off the southwestern coastline of South Africa).

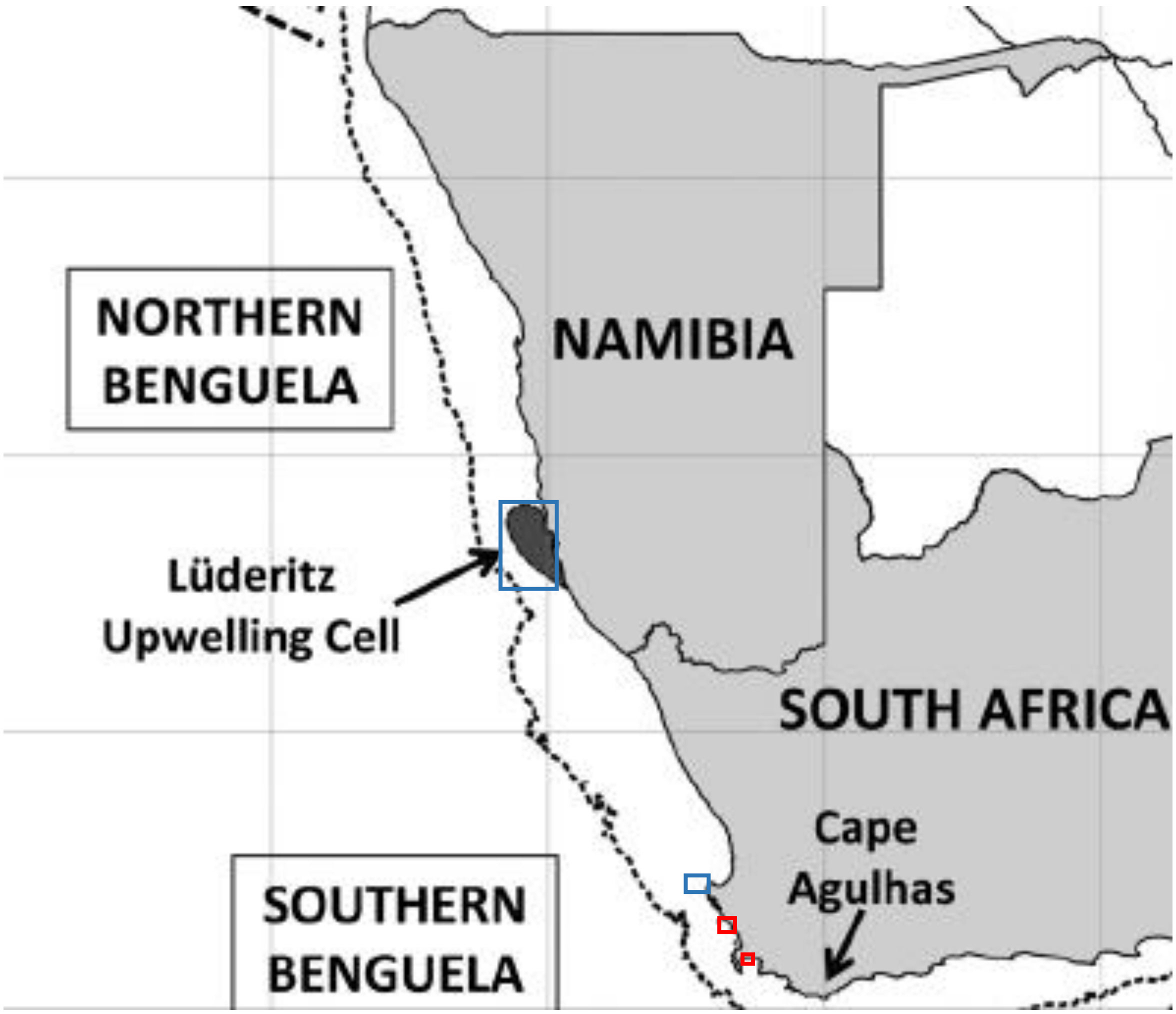

Figure 1: A map showing the Benguela system off South Africa and Namibia. The blue boxes represent the upwelling areas and the red boxes represent the non-upwelling areas used in this study (Taken directly from Roux et al., 2013).

Marine heatwave events

Marine heatwave events occur when there is an increase in sea surface temperature (SST), so much that it is higher than the seasonally changing threshold (90th percentile) and lasts for at least five days in a row. If the sea surface temperature dropped below the threshold for less than two days and then returned higher than the 90th percentile threshold, then the marine heatwave event was considered a single event. In this study, the heatwaveR package (available at: https://cran.r-project.org/web/packages/heatwaveR/citation.html) within R, which runs in the software 'RStudio' (v4.3.1) was used to analyse the data and provide results to show the trends in the occurrences and intensities of marine heatwaves. This package was developed by Schlegel and Smit (2018) and was used to determine percentile thresholds and average climatological SST for 38 years from 1984 to 2022. The heatwaveR package and its associated functions were created for use in the programming language, R, to specifically calculate the characteristics of MHW. This code is available at: https://robwschlegel.github.io/heatwaveR/articles/gridded_event_detection.html.

Datasets

We used gridded SST data from the NOAA (available at: https://www.noaa.gov/), publicly available on their website. The product of these daily mean global remote measurements of sea surface temperature (SST) has a ¼ degree, or 25 km x 25 km, resolution. This data product is an integrated dataset of Advanced Very High-Resolution Radiometer (AVHRR) satellite retrievals. Each marine heatwave event consisted of a unique set of characteristics, including how long each event lasted and numerous measures of intensity such as cumulative intensity, etc. Three time series with the most available data were selected from this data frame where the marine heatwave event lasted for 20 days (2005, 2016, and 2021). To ensure that there are no spatial or temporal gaps in the final result, these data were introduced and where practical, validated against a database of in-situ collected temperature measurements.

I aimed to identify the response of the BUS to marine heatwave events off South Africa's western coastline and the Namibian coastline. The plots best for showing long-term patterns in MHW events on relatively small axes are the horizon and Hovmöller plots. These plots were created in R to show the intensity of the marine heatwave events over time and along a region (from south to north). For each of these areas, horizon plots were created to display the trends in the events from 1982 till the present year (2023). This gives sufficient information on whether upwelling mitigates the intensity of marine heatwaves in upwelling areas as compared to non-upwelling areas.

RESULTS

The results presented below include horizon plots and Hovmöller plots. These plots provide detailed information on marine heatwave events such as the intensity of the events, how long each event lasted, and the number of events that occurred. The horizon plots (Figures 2 and 3) display the occurrence of marine heatwave events over time from 1982 to the present. The Hovmöller plot (Figure 4) shows the occurrence of marine heatwave events along selected latitudinal points. In this case, the latitudinal points consist of the latitude coordinates of the Benguela, which is along the coastline of Namibia and South Africa's west coast. For an event to be considered extreme its temperature would have to be 2-3°C above the threshold (90th percentile).

Extreme temperature timeline for South Africa

The duration, number of events, and severity of marine heatwave events from 1982 till the present have increased (Figure 2). It's clear that historically there have been extreme marine heatwave events. However, from 2016 onwards there has been an increase in extreme and severe marine heatwave events, unlike any that have historically taken place. Furthermore, the frequency and duration of these events are seen to be a lot more consistent and extreme in their nature when compared to previous years. The spikes of the extreme marine heatwaves from 2016 to the present are much higher than in the past.

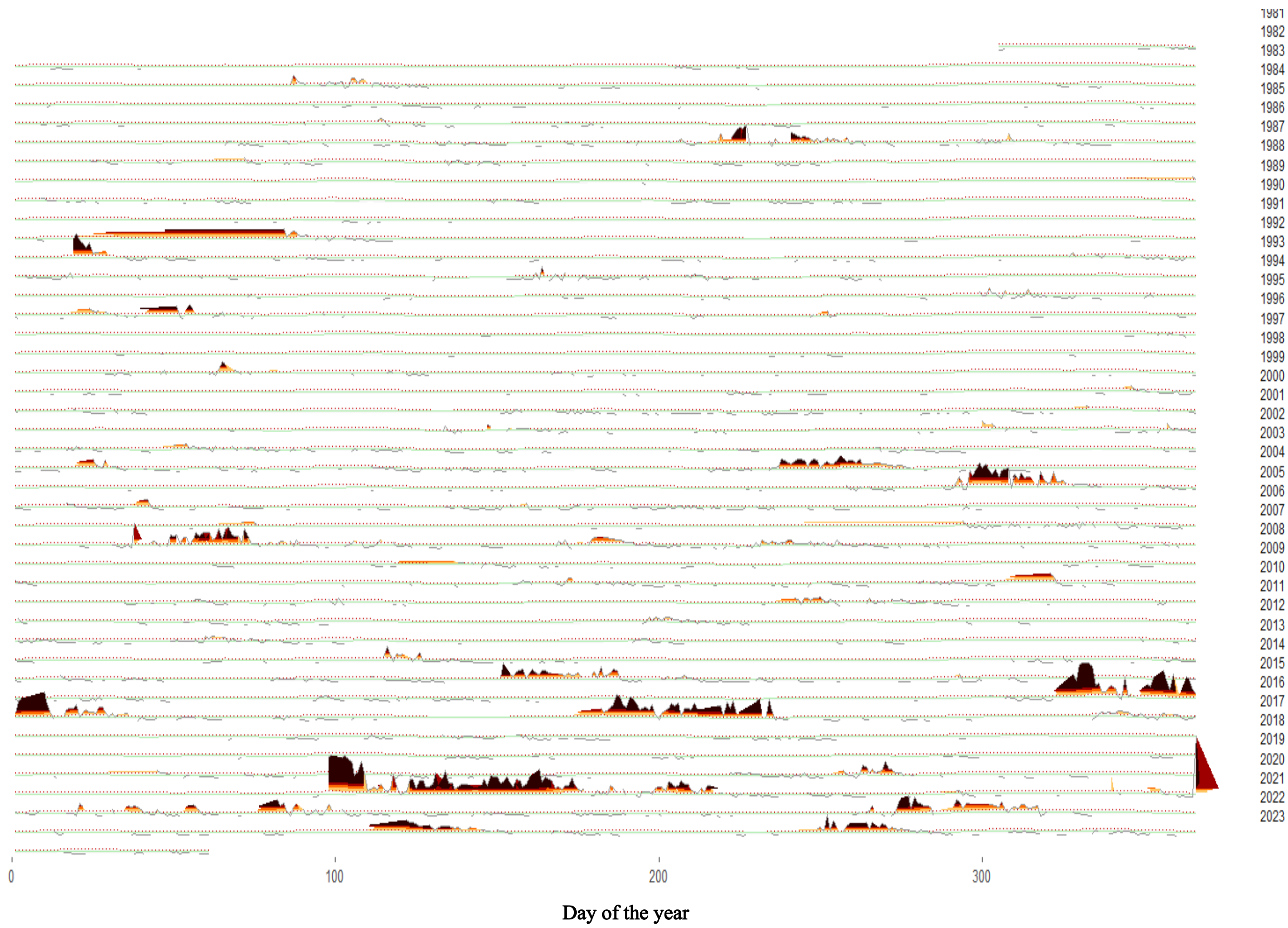

Figure 2: A Horizon plot showing the intensities, frequency, and duration of marine heatwave events off South Africa's west coast from 1982 to the present. Black represents an extreme marine heatwave event, maroon represents a severe marine heatwave event, orange represents a strong marine heatwave event and yellow represents a moderate marine heatwave event. The green line presents the climatology, and the threshold (90%) is represented by the dotted red line.

Extreme temperature timeline for Namibia

Below in Figure 3, it is noticeable that Namibia has a history of moderate to extreme events. The first marine heatwave event started in 1984 and was moderate to strong. After that, there have been multiple occurrences throughout the years, where marine heatwave events happened. However, it is important to observe that the increase in intensity of marine heatwave events occurs mainly from 2018 onwards. Historically, there have been more extreme marine heatwave events in the second half of the year (August, September, etc.). In contrast, recently, extreme marine heatwave events have occurred during the beginning of the year (January, February, etc.).

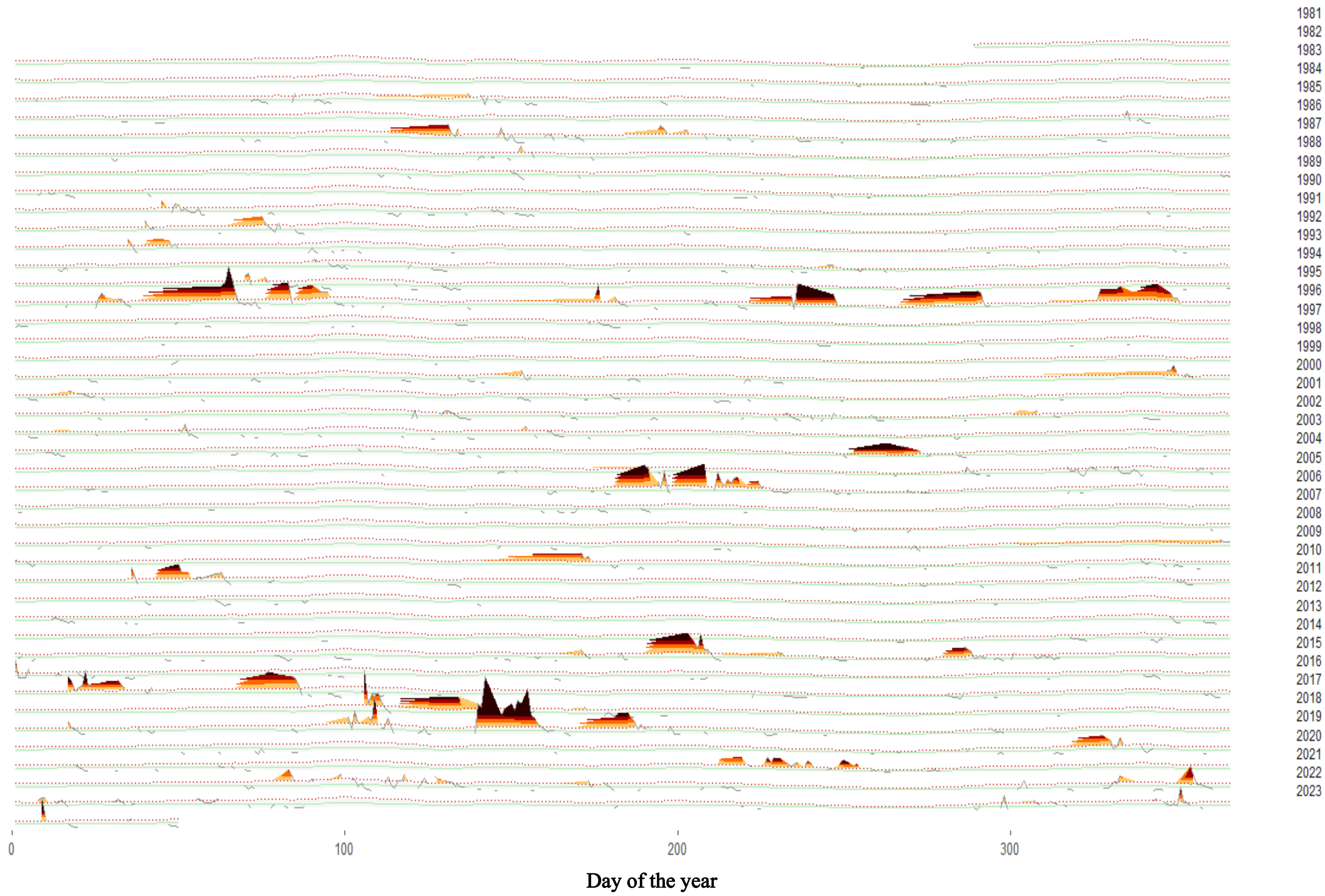

Figure 3: A Horizon plot showing the intensities, frequency, and duration of marine heatwave events along the coast of Namibia from 1982 to the present. Line types and colours as per Figure 2.

Extreme temperature timeline along the west coast of Africa in 2005

Figure 4 shows that during 2005 there were more marine heatwave events in the northern than southern regions. However, the marine heatwave events range between moderate and strong intensity. There were no occurrences of extreme marine heatwave events. These events occurred from July till September.

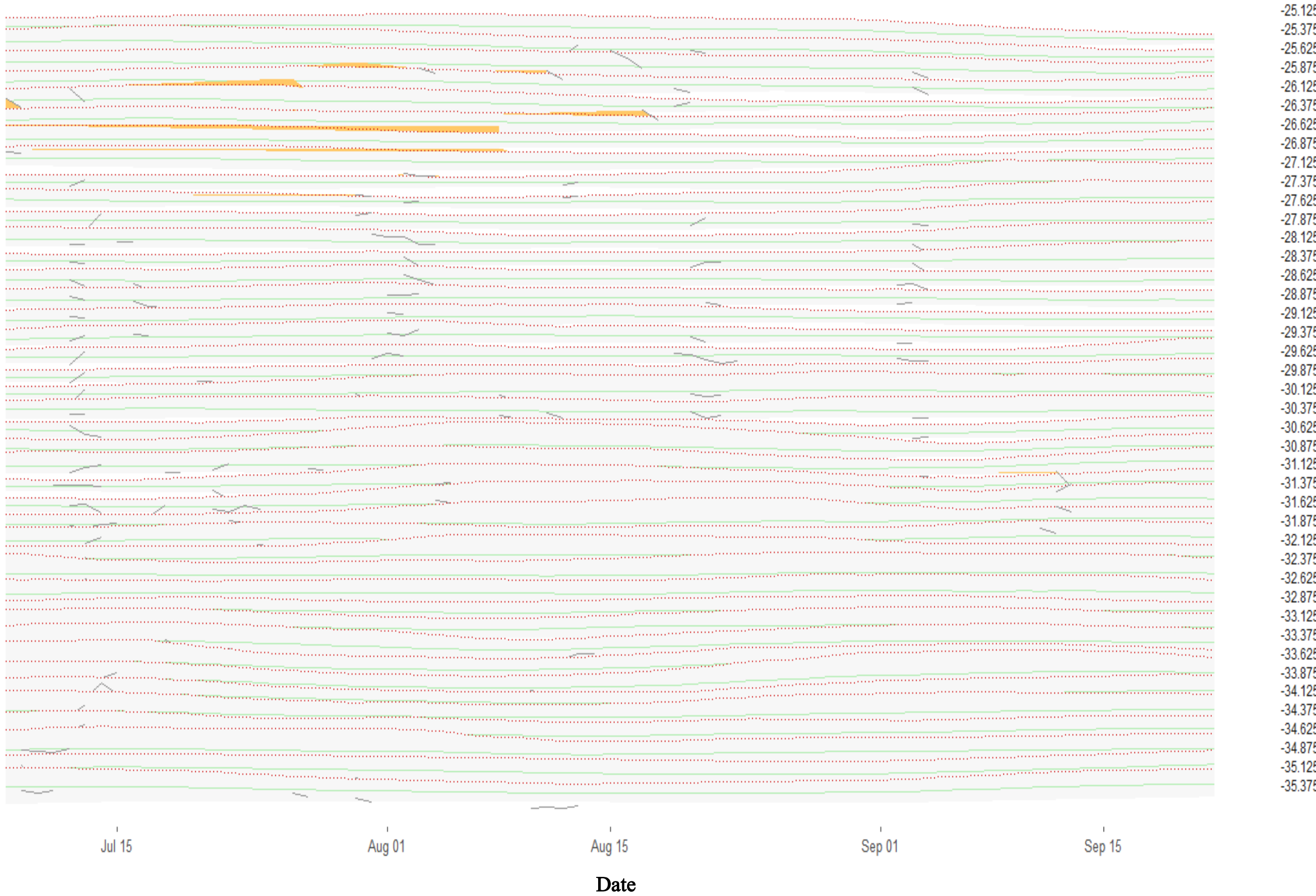

Figure 4: A Hovmöller plot showing the severity, frequency, and duration of marine heatwave events along the Benguela in 2005. The timeline is from the 15 July to the 15 September. Line types and colours as per Figure 2.

Extreme temperature timeline along Africa's west coast in 2016

Figure 5 shows that the southern region has very few marine heatwave events, mostly moderate to strong, and only occurs during January. The southern region has short periods of moderate to strong marine heatwave events between 15 January and 1 February. In the northern region, there are shorter durations of strong marine heatwave events that occur occasionally. However, there is an increase in the duration of more severe events moving further south.

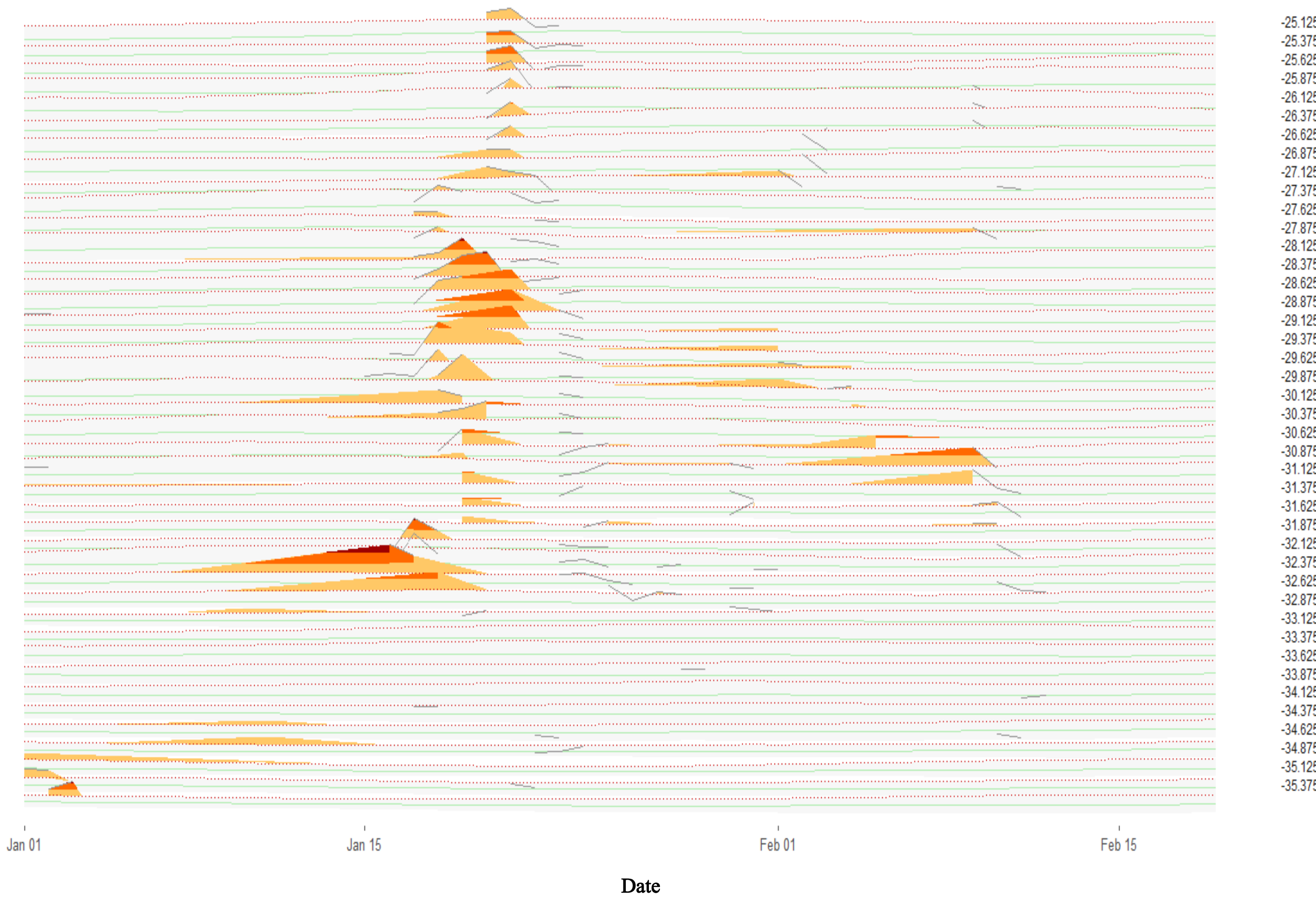

Figure 5: Hovmöller plot showing the intensities, frequency, and duration of marine heatwave events along the Benguela in 2016 from 1 January and 15 February. Line types and colours as per Figure 2.

Extreme temperature timeline along the west coast of Africa in 2021

Interestingly, Figure 6 shows that during 2021, there were more marine heatwave events in the northern region, with an extended marine heatwave event in the central region and little to no marine heatwave events in the southern region. All of these marine heatwave events during this year are moderate events. The events in the northern region happened at the start of the year. However, the event in the central region occurred from February to March.

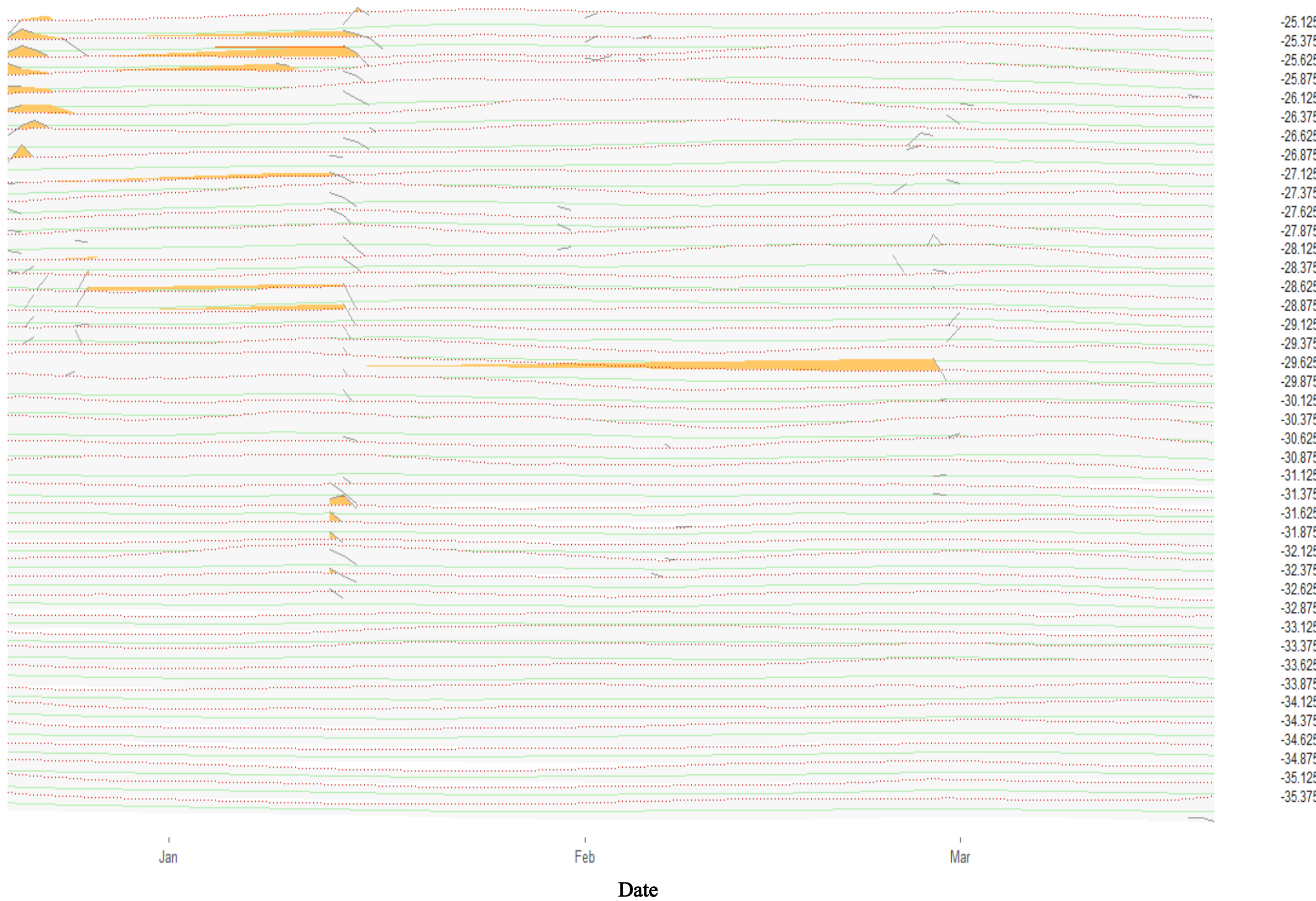

Figure 6: A Hovmöller plot showing intensities, frequency, and duration of marine heatwave events along the Benguela in 2021. This timeline starts from January till March. Line types and colours as per Figure 2.

Upwelling regions

Extreme temperature timeline for Paternoster

Figure 7 shows that the severity and duration of marine heatwave events increased over time. There has been a significant increase since 2003. The severity and occurrence of marine heatwave events continued to grow until present. The majority of these events occurred in the middle of the year and very few occurred towards the end of the year. The events that occurred after 2003 are more extreme and longer lasting. There are also more than one heatwave event occurrences in a year (2021). There was a small and isolated heatwave event that was strong to extreme that occurred in 1984.

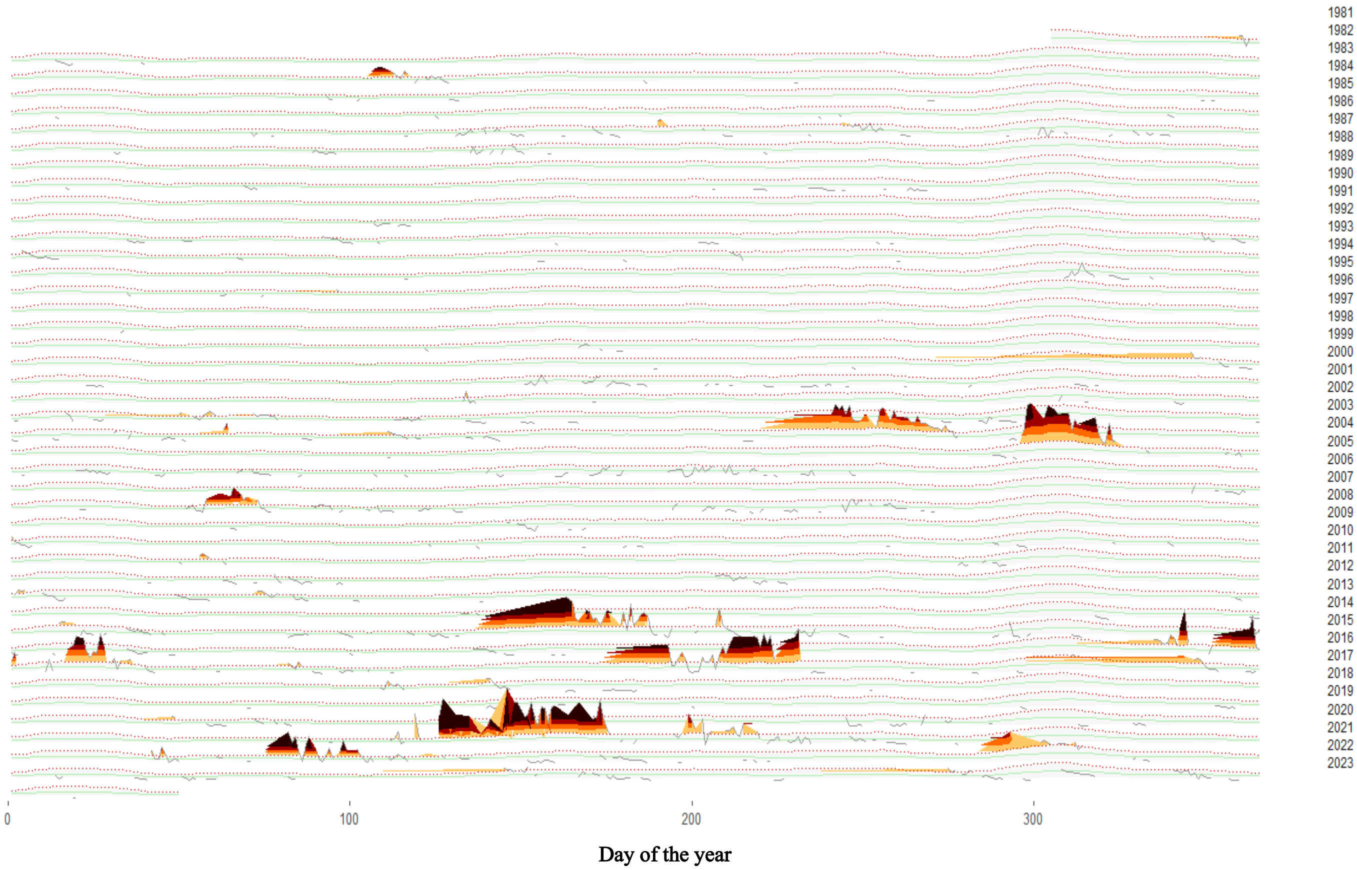

Figure 7: A Horizon plot displaying the frequency, severity and duration of marine heatwave events in Paternoster where upwelling occurs from 1982 to the present. Line types and colours as per Figure 2.

Extreme temperature timeline for Lüderitz

Figure 8 shows that this region has a history of marine heatwaves starting in 1984. However, marine heatwave events' occurrence, duration, and intensity increased over time. From 2003 to the present, there have been numerous extreme marine heatwave events, some of which spiked higher than usual. At times there was more than one event in a year. These events were spread out throughout the year. In 1996, there were numerous occurrences of marine heatwave events in the year, and there were three events that reached extreme.

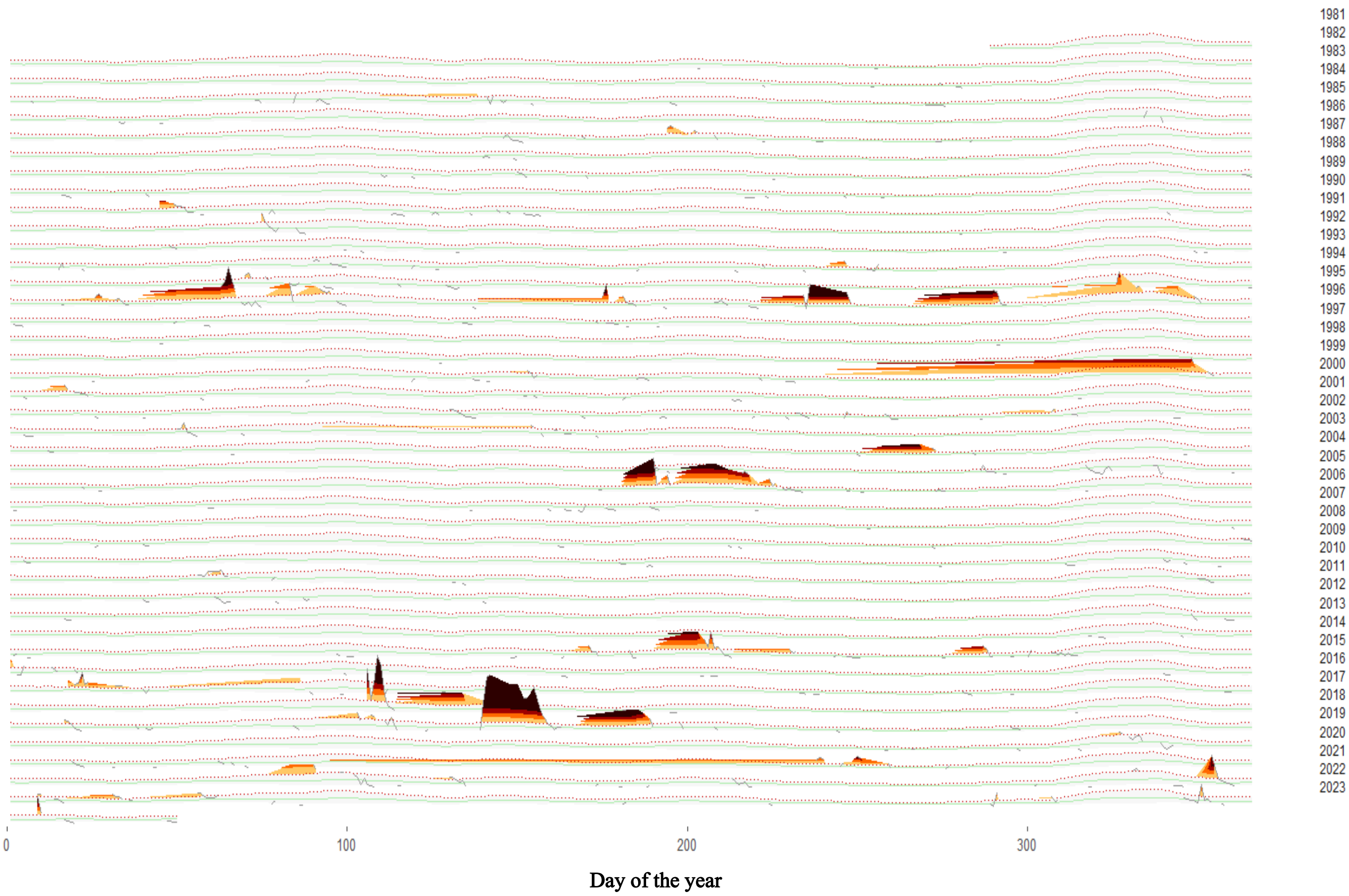

Figure 8: A Horizon plot displaying the intensities, frequency, and duration of marine heatwave events in Luderitz where upwelling occurs from 1982 to the present. Line types and colours as per Figure 2.

Non-upwelling regions

Extreme temperature timeline for Bloubergstrand:

Figure 9 shows that there have been numerous occurrences of moderate to extreme marine heatwave events from 1984 till present. However, the number of events occurring each year has increased over time. Recently, in 2020, there has been more than one occurrence of marine heatwave events, and the times they each occurred were not that far apart. In this area, multiple extreme marine heatwave events have occurred in more than one year.

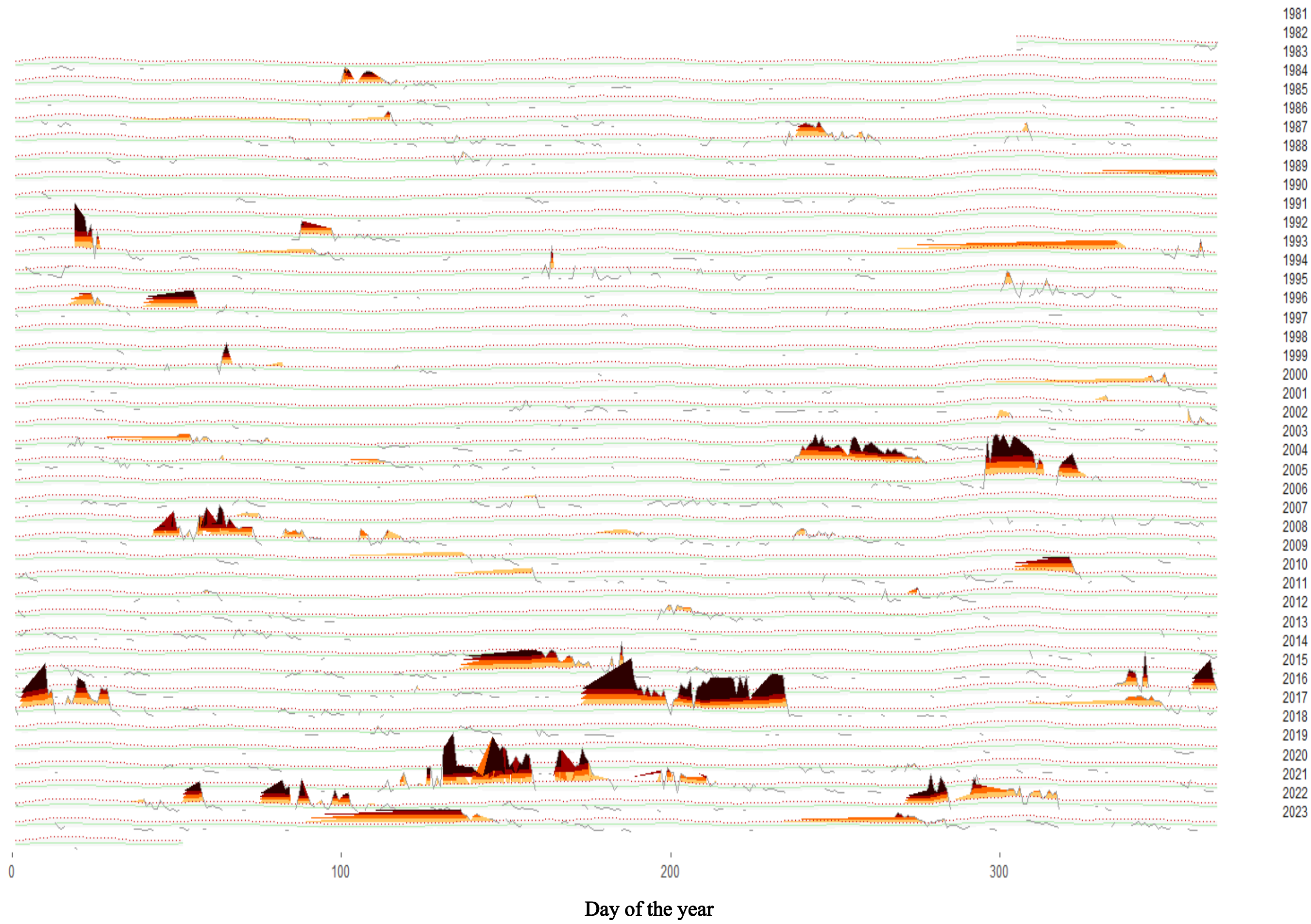

Figure 9: A Horizon plot displaying the duration, intensities, and frequency of marine heatwave events in Bloubergstrand where non-upwelling occurs from 1982 to the present. Line types and colours as per Figure 2.

Extreme temperature timeline for Strandfontein

Extreme marine heatwave events have been widespread in this region as seen in Figure 10. However, extreme marine heatwave events have increased from 1984 till the present. In 2020 more than one extreme marine heatwave event occurred during the first half of the year. In 1988, a moderate to marine solid long-lasting heatwave event happened during the year’s second half. The event in 1988 remains the longest-lasting marine heatwave event in this region. With time, marine heatwave events seem to be becoming shorter and more severe.

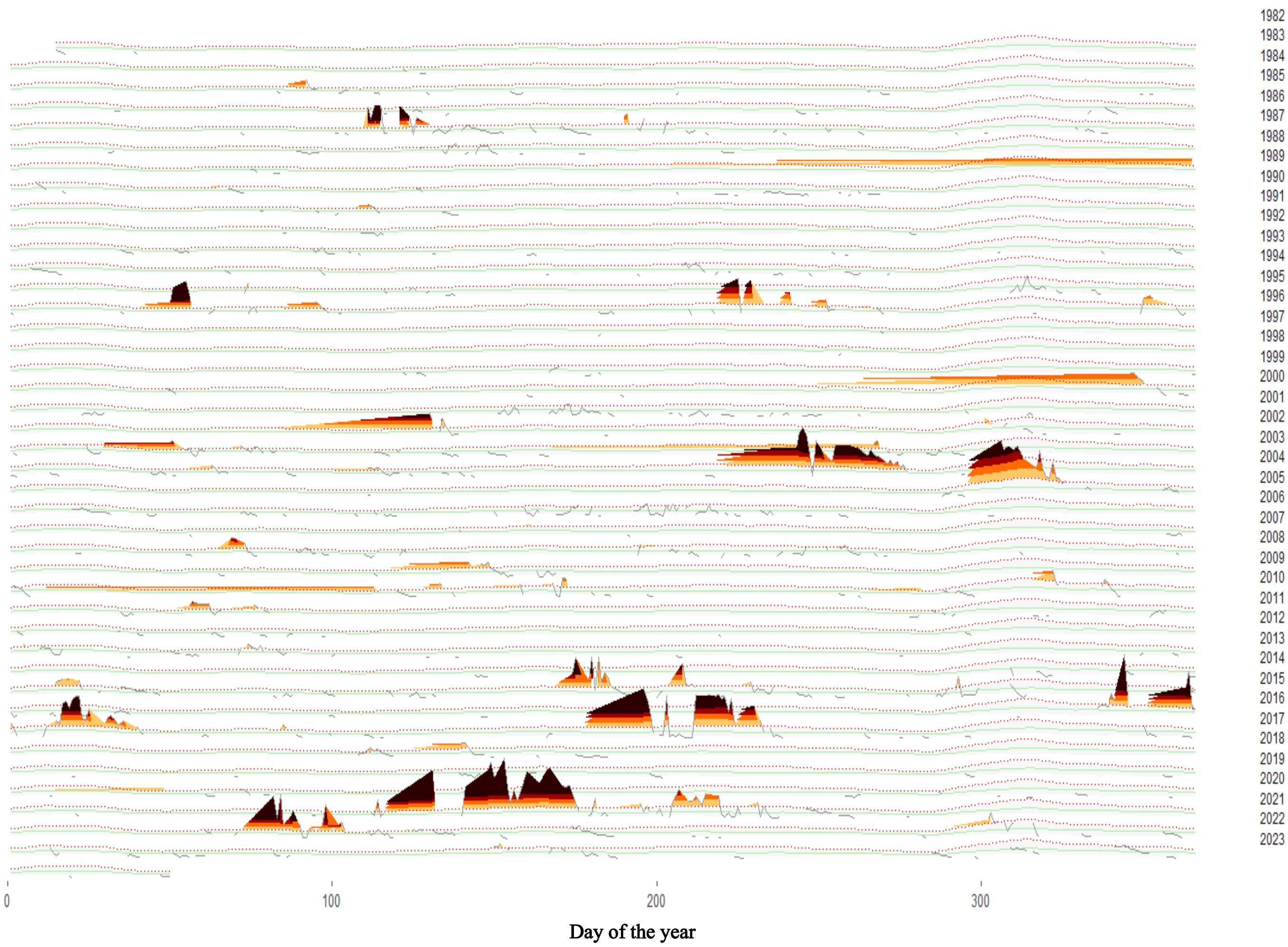

Figure 10: A Horizon plot displaying the intensities, duration, and frequency of marine heatwave events in Strandfontein where non-upwelling occurs from 1982 to the present. Line types and colours as per Figure 2.

DISCUSSION

There is no doubt that the number of marine heatwave events has increased over time across all regions studied here. Interestingly, the severity and duration of marine heatwave events along the west coast of South Africa and the coastline of Namibia have increased. When comparing upwelling and non-upwelling areas, it is clear that non-upwelling areas experience more extreme heatwave events than upwelling areas. This could support the suggestions that upwelling moderates the severity of marine heatwaves making the events less extreme/severe (Varela et al., 2021). While looking at the southwest coastline of South Africa and the coastline of Namibia, it is evident that the northern region of Benguela experiences much more heatwave events than the southern region. During El Niño Southern Oscillation (ENSO) events the northern Benguela is colder due to more upwelling and the southern Benguela is warmer due to less upwelling because the South Atlantic Anticyclone varies in latitude (Rouault and Tomety, 2022). During La Niña events, the southern Benguela is colder due to more upwelling and the northern Benguela is warmer due to less upwelling (Rouault and Tomety, 2022). Therefore, we can say that ENSO events increase the frequency of marine heatwaves.

Climate change is a major factor influencing the functioning of the BUS as it can affect the strength of upwelling (Bakun et al., 2015). The southern Benguela system has been recognised as a climate change hotspot due to the rapid warming of its eastern region (Ortega-Cisneros et al., 2018). As a result, climate estimates have shown that the southern Benguela system is expected to rise in sea surface temperature (Popova et al., 2016; Ortega-Cisneros et al., 2018). Increased carbon dioxide emissions cause ocean warming which has numerous effects on various aquatic organisms (Ortega-Cisneros et al., 2018; Finkel et al., 2010). Bakun (1990) suggested that there would be more upwelling winds in the EBUSs when there is an increase in greenhouse gas concentrations in the atmosphere. Because of global warming, atmospheric temperature would increase, resulting in intensified continental thermal lows alongside upwelling regions (Sylla et al., 2019). The intensified continental thermal lows cause an increase in onshore and offshore atmospheric pressure gradients and winds alongshore, ultimately causing an increase in coastal upwelling (Sylla et al., 2019). This could explain why there are fewer extreme marine heatwave events in the Benguela system's southern region than in the northern region.

The strongest point of upwelling in the BUS is located at Lüderitz (Tim et al., 2015). This area separates the BUS into the southern Benguela (includes South Africa's west coast and a small region of the south of Namibia) and the northern Benguela (includes Namibia except its southern tip) (Tim et al., 2015). Non-upwelling areas along the coast are areas where the coastline changes direction resulting in there being no orientation between the coastline and winds (National Oceanic and Atmospheric Administration, 2017). The results presented in this study support that there are more occurrences of marine heatwaves and the events of marine heatwaves are more extreme in non-upwelling areas. This is because there are no winds that are welling cold water to the surface to mitigate events of marine heatwaves (Izquierdo et al., 2022). It is evident that the BUS does have an impact on marine heatwaves because areas that experience upwelling have proven to have less extreme marine heatwave events as compared to areas that do not experience upwelling.

There is evidence that ENSO has an impact on the BUS in southern Benguela (Tim et al., 2015). The occurrence of El Niño events typically weakens upwelling as it makes it difficult for water to well up as the southeasterly winds become weaker, resulting in much warmer sea surface temperature along the coast (Tim et al., 2015; Rouault and Tomety, 2022). Along the Benguela from the northern region of Namibia, to South Africa’s southwest coastline, there is an increase in marine heatwave events, and the intensity of the events is becoming more extreme now than in the past. Therefore, I would recommend that future studies look into the strength of the BUS as it would provide better results and understanding when investigating marine heatwaves between upwelling and non-upwelling regions.

CONCLUSION

The results from this study show that the BUS positively responds to marine heatwaves off South Africa and Namibia. This means that the BUS does in fact mitigate marine heatwaves. In areas of upwelling, there are fewer marine heatwaves, and the marine heatwaves that occur are moderate to extreme. However, there are fewer extreme events in upwelling regions than in non-upwelling regions. Marine heatwave events in non-upwelling areas were mainly strong to extreme events that lasted for long periods and occurred more than once a year. This is important to know as it will allow us to create solutions for marine ecosystems that could be in danger and the economy in non-upwelling areas.

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