Complete

Amieroh Abrahams

Contents


```r
print(getwd())
```

```
## [1] "/Users/ajsmit/Dropbox/R/students/Amieroh/Project_writeup"
```

Plagiarism Declaration

Declaration

Abstract

The South African coastline is comprised of distinct coastal regions, each varying in temperature but more importantly temperature characteristics vary among sites. Seawater temperature is an important driver affecting marine biodiversity and so understanding the factors affecting the variations of this is important. Here, I analysed temperature time series data from 18 different sites distributed along the South African coastline. These data were collected using underwater temperature recorders (UTRs), alcohol thermometers, and satellites, with the precision of the instruments varying from between 0.5 °C to 0.001°C. Using the minimum, maximum and mean temperatures I systematically grouped sites together in their distinct coastal regions and compared temperatures between regions. I further assessed the effects of wind and wave exposure on the variations of temperatures using coefficient of determination analyses. My results showed that wind and wave action per site were not significantly affecting temperature, achieving low R2 values, indicating that wave and wind action were not the predominant factors influencing coastal seawater temperature. Large scale oceanic processes such as coastal upwelling and the presence of major ocean currents, solar radiation or lower atmospheric temperature as well as anthropogenically induced factors are predicted to be the main drivers affecting temperature. This suggests that human interference may be indirectly influencing marine biodiversity via affecting ocean temperatures, and this insight could prove useful in aiding in conservation.

Keywords: Seawater temperature, climate change, coastal regions, code: R, variability

Acknowledgments

Special thanks go to my supervisor, Prof. AJ Smit, for the continuous motivation and guidance throughout my honours year. All of your contributions and efforts towards my academic career and experiences have been appreciated beyond measure. I would also like to thank Dr. Robert Schlegel and my co-supervisor, Dr. Robert Williamson for the help with my R analyses. I would like to thank KZNSB, DEA, DAFF, SAEON, SAWS, UWC and EKZNW for contributing the raw data allowing me to do this study. Without the data this thesis would not be possible.I would also like to thank my colleagues within Team Kelp who assisted me throughout this project. Their discussions and friendship has largely aided in the completion of this thesis. To my friends and family, thank you for providing me with the necessary support and encouragement. I would like to thank the entire Biodiversity and Conservation biology department at the University of the Western Cape. Lastly, I would like to thank the NRF for providing the necessary funding towards the completion of this project.

Introduction

Seawater temperature is a key indicator of environmental change in marine ecosystems (Pearce, Faskel, and Hyndes 2006), and yet little is known regarding the controlling influences of temperatures within coastal zones (with the coastal zone here defined as the region $\leqslant$ 400m from the shore). Coastal temperature observations are generally limited in their spatial and temporal coverage. Oceanic regions however are studied to great extent due to availability of long term datasets from moorings and satellites of monitoring ocean surface temperatures (Rouault et al. 2010; Beal et al. 2011; Tapia et al. 2014; Lee et al. 2018). Nearshore processes, such as wave action, coastal winds, and surface radiant heating, and the thermal properties of the substratum, are a few of the factors that have been implicated in affecting thermal variability across small spatial scales (Woodson et al. 2007; Davis et al. 2011; Fewings and Lentz 2011; Sinnett and Feddersen 2014). Given the significance of the temperature variation for the biogeographical limits of organisms, due to its effects on the reproductive, growth and survival limits of species (Hoek 1982; Breeman 1988; Pearce, Faskel, and Hyndes 2006; Broitman et al. 2008; Byrne et al. 2009; Smale and Wernberg 2009; Smit et al. 2013), it is imperative to understand how marine organisms may respond to climatic variation in coastal regions on both a global and local scale. Developing an understanding of the physical variables present within the coastal zone that are able to mediate thermal patterns and processes across small spatial scales and short temporal scales that are typically associated with nearshore processes will be instrumental in this understanding.

Temperature variability of the coastal region of South Africa, spanning approximately 3,100 km in distance (Smit et al. 2013), has not yet been studied in great detail at highly localised scales. At the broad scale, this region exhibits a large variation in seawater temperatures along its coastline (Mead et al. 2013; Smit et al. 2013) and is divided into four bioregions, each with contrasting temperatures. These bioregions are the Benguela Marrine Province (BMP), Benguela-Agulhas Transition Zone (B-ATZ), the Agulhas Marine Province (AMP) and the East Coast Transition Zone (ECTZ) (Smit, Bolton, and Anderson 2017). These regions display noticeable differences in seawater temperatures in comparison to each other, primarily due to the influences of the neighbouring ocean currents (Bolton et al. 2004; Mead et al. 2013; Schlegel and Smit 2016). These temperature gradients are associated with differences in ecosystem physiology, species distribution, and habitat structure (Smale and Wernberg 2009; Wernberg et al. 2010, 2011; Smit, Bolton, and Anderson 2017). As a result of the diverse habitats defined by thermal differences and exposure gradients along the coastline, species diversity is not uniformly distributed; consequently, the east and south coast has much higher species diversity and beta-diversity compared to the west coast (Mead et al. 2013; Smit, Bolton, and Anderson 2017).

On broad scales, the influences due to the the Benguela and Agulhas Currents greatly affect the thermal climatologies of the nearshore in the west and the east of the subcontinent, respectively. At an even broader scale, the Agulhas Current is driven by a wind stress curl between the southeast trade winds and the Southern Hemisphere westerlies (Beal et al. 2011), while the Benguela Current [AJS: add the broader-scale drivers of the Benguela here...]. Regionally, the Benguela Current assists in transporting cold water northwards from the Southern Ocean to the coast (Lüning 1990; Lutjeharms, Cooper, and Roberts 2000; Hutchings et al. 2009; Schlegel et al. 2017), whereas the Agulhas Current transports sub-tropical, warm water towards the tip of Africa (Schlegel et al. 2017). Together these two currents are responsible for the presence of a strong west-east thermal gradient occurring along the coastline of South Africa, with the west coast having significantly colder waters than the east coast (Smit et al. 2013; Smit, Bolton, and Anderson 2017). The south coast is unique as it is affected by both the Benguela and Agulhas Currents, with a strong overlap region from Cape

Agulhas to Cape Point (Smit, Bolton, and Anderson 2017), and it experiences a greater spatial and temporal variation in temperature compared to elsewhere along the coast (Lutjeharms and Van Ballegooyen 1988). At the localised scale, the statistical properties of temperature climatologies, such as the mean, minimum, and maximum of *in situ* coastal seawater temperature time series for the South African coastline, show distinct coastal variations (Schlegel and Smit 2016). The local influences acting on the water masses originating from the Benguela and Agulhas Currents can introduce thermal variation of up to 10°C within a 24-hour period (Schlegel et al. 2017), thus creating a highly dynamic nearshore environment.

Climate change is often understood as a long-term rise in the global mean temperatures and has resulted in an increased mean ocean temperatures over the past few decades (Stocker 2014). The seawater temperatures of the Benguela Current has been decreasing at a rate of approximately 0.5°C per decade whilst the Agulhas Current has been increasing by between 0.55°C-0.7°C per decade (Rouault, Penven, and Pohl 2009; Rouault et al. 2010). Overall, sea surface temperatures (SST) around South Africa have increased by approximately 0.25°C between 1903 and 2013 (DEA, 2013) and are still increasing at a rate of 0.12 °C per decade (Schlegel et al. 2017). Climate change is also leading to an increase in extreme atmosphetic heating (Easterling et al. 2000; Perkins and Alexander 2013) and a decrease in extreme cold events (Meehl and Tebaldi 2004). Human activities are largely responsible for these decadal trends (Rouault, Penven, and Pohl 2009; Rouault et al. 2010 ; Mead 2011; Mead et al. 2013).

Over the last few decades, improvements in remote sensing technology have enabled researchers to map global sea surface temperature with a high level of accuracy (Zainuddin et al. 2006; Smale and Wernberg 2009). The National Oceanic and Atmospheric Administration's (NOAA) series of satellites have provided global SST datasets from the 1980s on both global and local scales (Pearce, Faskel, and Hyndes 2006). The NOAA dataset is critically important as it is often used to monitor changes in oceanic temperatures, and provide valuable information on both biological and physical parameters in the ocean (Demarcq et al. 2010). Furthermore, satellite-derived SST data play an important role in creating projections of the potential effects of climate change on coastal and oceanic marine biota (Müller et al. 2009; Wethey et al. 2011; Bartsch, Wiencke, and Laepple 2012). Satellite-derived data are not as reliable as *in situ* temperature measurements when used near the shoreline (Smit et al. 2013), but are often used as a proxy when these measurements are scarce or unavailable (Smale and Wernberg 2009). However, in South Africa, the local availability of an *in situ* collected coastal temperature data product provides a reliable source of accurate coastal seawater temperature data (Smit et al. 2013). The South African Coastal Temperature Network (SACTN) has collected SST data form the South African coastline from as early as 1972, with contributions from various organisations and governmental departments. This data set, used in combination with satellite-derived data that give a broader view, provides an opportunity to launch an investigation into the mechanistic underpinning for why the thermal *milieu* of the nearshore environment is so dynamic across short time scales and over short distances along the shore.

The intention of this study is to examine variations in temperature between selected sites along the South African coastline using seawater temperature data to better understand patterns of coastal temperature at a localised scale. The SACTN dataset used in this study consisted of *in situ* coastal seawater temperature measurements, allowing for comparisions between sites at a high temporal frequency. We also use co-located and overlapping satellite datasets, including that of SST, winds, and waves, to provide measurements of influential variables (i.e. as hypothesised drivers of the nearshore temperature field) representative of the wider regional scale. The aims of this study are to: i) examine whether there is homogeneity between the various sites sampled; ii) examine whether or not wind and wave action may contribute towards a variation in seawater temperatures along the South African coastline; and iii) to examine whether or not SST data collected via satellite may be affected by wind and wave action.

Methods

In order to compare abiotic variables such as wind and wave action along the South African coastline, large historical datasets for temperature, wave and wind were analysed and accessed.

Wave and wind data

Wind and wave action were important variables in this study as they were hypothesised to exhibit a direct influence on coastal water temperatures (Sinnet and Feddersen, 2014); consequently, they were investigated for their impact on seawater temperature at specific sites along the South African coastline. Wind and wave data were obtained from the South African Weather Service (SAWS), and were provided at three hour resolutions. Specific wind and wave characteristics were measured, namely, wave height (hs), wave period (tp), wave direction (dir), wind direction (dirw) and wind speed (spw). The data were then used to model short–crested waves, generated by the wind into the coastal environment, using the wave model Simulating Waves in the Nearshore (SWAN). SWAN enables the extraction of wave parameters from specific gridded locations in the nearshore. A resolution of 200 meters was modelled at both 7 and 15m contours.

In situ emperature data

The SACTN dataset was the primary source of temperature data used in this study. This dataset consisted of coastal seawater temperatures for 129 sites along the coast of South Africa, measured daily from 1972 until 2017. Of these, 80 were measured using hand-held thermometers and the remaining 45 were measured using UTRs. The duration and extent of the recordings per site were uneven, with the longest time series in the dataset being that of Gordons Bay, recorded by SAWS. Data collected for this region started on 13 September 1972 and concluded on 26 January 2017, with recordings still continuing daily. During the 1970s, a total of 11 time series began recording. A further 53 entries were added during the 1980s, 34 entries were added during the 1990s, and 18 entries were added during the 2000s. Recordings are still ongoing at many of these sites.

For this analyses, the data were combined and formatted into standardized comma delineated values (CSV) files which allowed for a fixed methodology to be used across the entire dataset. Prior to data analysis, all data points exceeding 35 °C and/or below 0 °C were removed as these were considered as outliers. These data points were then changed to NA (not available) so as to not interfere with analysis. All analyses were conducted in R software version 3.4.2 (insert the reference!!!). The data used within this study and comprehensive script used for data analyses, and production of figures can be found at https://github.com/AmierohAbrahams/HONOURSPROJECT.

Satellite SST data

This study made use of four satellite-derived SST datasets to compare with the SACTN *in situ* coastal seawater temperature and wave datasets. The AVHRR-only Optimally-Interpolated Sea Surface Temperature (OISST) was used to determine SST within the study region. The AVHRR datasets have been provided global SSTs for more than four decades (Reynolds and Smith, 1994; Pearce et al 2006). OISST is a global 1/4° gridded daily SST product that assimilates both remotely sensed and *in situ* sources of data to create a level-4 gap free product (Banzon et al., 2016). The Multi-scale Ultra-high Resolution (MUR) Sea Surface Temperature Analysis, the second dataset, is produced using satellite instruments with datasets spanning 1 June 2002 to present times (refs.). MUR provides SST data at a spatial resolution of 0.01° in longitude-latitude coordinates and is currently among the highest resolution SST datasets available. The third dataset, K10, is produced at the Naval Oceanographic Office (NAVOCEANO) on a 10km resolution, globally (refs.). The K10 analysis makes use of SST observations from the AVHRR, the Geostationary Operational Environmental Satellite (GOES) Imager and the Advanced Microwave Scanning Radiometer for EOS (AMSR-E). The CMC dataset constitutes the forth dataset and is a version 3.0 Group for High Resolution Sea Surface Temperature (GHRSST) Level 4 dataset with a 10km resolution constructed by the Canadian Meteorological Center (CMC; refs.). The CMC dataset combines infrared satellite SST at numerous points in the time series from the AVHRR, the European Meteorological Operational-A (METOP-A) and Operational-B (METOP-B) platforms, and microwave SST data from the Advanced Microwave Scanning Radiometer 2 in conjunction with *in situ* observations of SST from ships and buoys from the ICOADS program.

Site selection

In order to compare temperatures along the South African coastline at a localised scale, we selected appropriate sites from each of the major coastal regions. Since temperature data were not evenly recorded for each of the 129 sites representing South Africa's coastline, we firstly narrowed down the full dataset to only those sites that could be adequately compared. To do this a clustering analysis was perfomed using the `kmeans()` function in R, with multiple random seeds to identify a number of clustering solutions that grouped sites together based on their available temperature data. The mean, minimum, and maximum temperature values were used within the clustering algorithm to group sites with similar temperatures along each coastal region. The clustering analysis represented the most accurate and distinct site groupings based on temperature distributions and yielded distinct east, south, and west coast groupings. Eight clustering solutions along the South African coastline are shown (Figure 1). With the data now divided into eight distinct coastal regions, portions of overlapping time series (*i.e.* across the multiple sites per region) were selected of at least one decade in duration, but excluding those sites with temperature data collected deeper than 5m.

Once sites were clustered, we reduced the number of sites to a manageable but still representative sub-sample of the whole. This was done for two reasons. The first was to allow for the comparisons to be more readily interpretable by humans. Secondly, it was to allow for equal amount of sampling per coast. The east coast has previously been more heavily sampled than the rest, and such an imbalance needed to be addressed. The criteria considered for the sub-samples included selecting the longest time series within the region and including data from as many different sources (*i.e.* contributors to the SACTN) as possible. This process yielded three sites for each of the clusters along the South African coastline (Figure 2). The statistical characteristics of the temperature were used to guide analysis of the time series to produce an accurate assessment of temperature variation between sites that were grouped together.

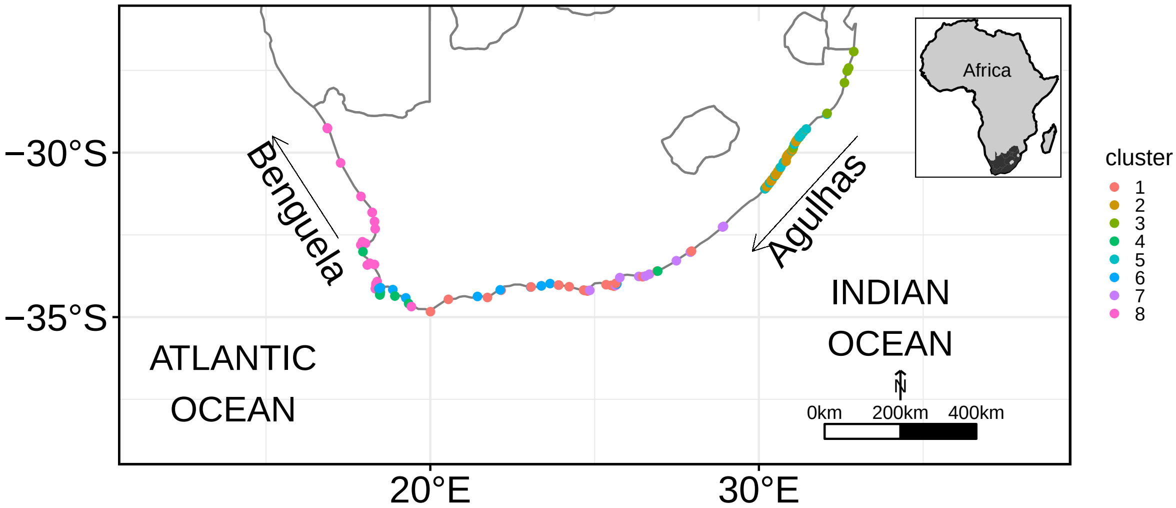

Figure 1: A map of the study area representing the 129 sites where *in situ* coastal seawater temperature was collected. These sites were grouped based on similar mean, minimum and maximum temperatures and as such each groups represents a unique colour variation.

With three sites per cluster, the haversine formula was used to calculate the geodesic distance between points specified by radians. Using this formula, the distances (km) between each of the sites along the coastline were determined. Thereafter, sites within the same cluster were matched based on the date that temperature was collected. This allowed for a comparison to test whether or not temperature variation exists between sites within the same cluster. Once the sites were matched, the means and standard deviations of temperatures between sites and clusters were determined. This highlighted the temperature variation between matched sites and allowed for seasonal comparisons within the same cluster.

Once the temperature variation between sites were carefully analysed, the seawater temperature data along with the wave and wind data were compared. The data were modelled for water depths of 7m and 15m. Since the wave and wind data were modelled at three hour resolutions, they were converted into daily data points in order to compare them with the temperature data. The `circular()` function in R software was then used to create circular objects around the wave data in order to calculate the daily wave and wind parameters.

With temperature and wave values now corresponding to their respective sites, depths and dates, the hypothesis regarding whether or not a relationship existed between wind/wave action and temperature was tested. To do this, linear models for each site were produced, reflecting temperature and wave variations at each depth. Linear models typically produce coefficients of determination R^2 as an output. The `purrr()` function within the **tidyverse** R package was used to simultaneously compare temperature and wave data across sites and depths. An ANOVA analyses was done compare one variable in two or more groups taking into account the variability of other variables. Hereafter, a wind rose diagram was constructed to determine the most predominant direction for a

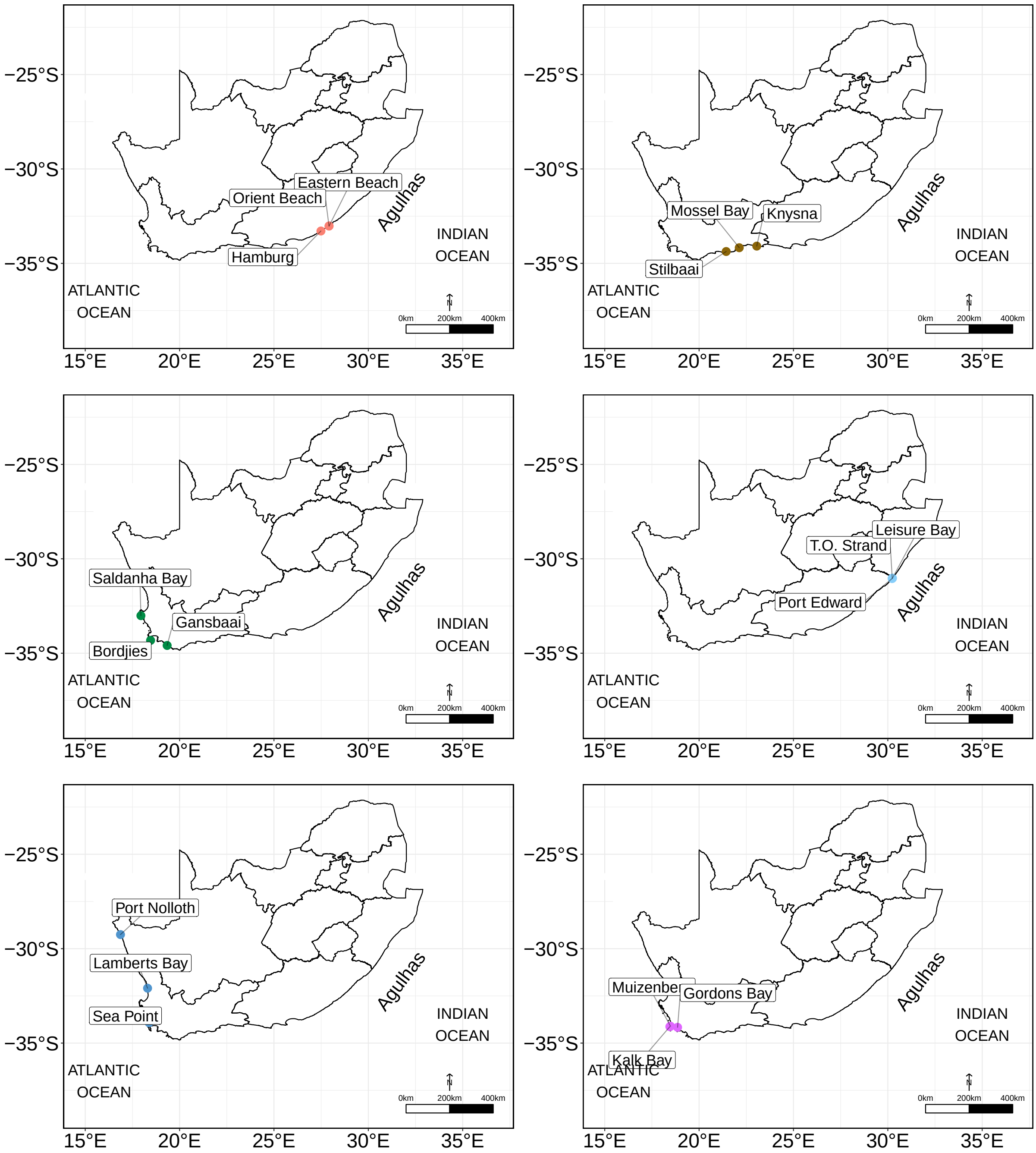

Figure 2: A map representing the three sites chosen within each of the six cluster along the South African coastline.

particular site. This was done to ascertain what the potential relationship between wind/waves and temperature was at each site during only the prevailing wind directions.

Satellite data analysis

SST measurements used in this study were obtained from four different sources: MUR, CMC, K10 and AVHRR. A time series of SST was determined by creating a bounding box which represented the region of extent at the latitudes (39.5°S, 25.5°S), and the longitudes (10.5°E, 39.5°E). The size of the pixel search area was set to a 5km resolution from each of the stations. The satellite datasets and the corresponding SACTN *in situ* collected dataset were matched based on the coordinates and the date at which temperature was collected. Some sites, however, shared the same satellite data due to their close proximities. Once the satellite data corresponded to the *in situ* collected data, linear models for each site were produced, reflecting temperature and wave variations at each depth. Linear models typically produce coefficients of determination (R^2 values) as an output, which is the statistic showing how much of the variance in a dependent variable is explained by the independent variable. This allows for us to test whether or not wave and wind direction may influence temperature at the various sites.

Statistical analyses

A series of ANOVA tests were used to compare the main effects of the chosen variables on a continuous variable. In this analysis the relationship between matched sites based on the mean temperature as a function of year and season were analysed; these analyses tested if significant differences occured between each pair of sites within each of the clusters. To determine the strength of correlation of temperature between sites found within the same clusters along the coast, boxplots were constructed. These plots enabled the visual identification of variations in temperature by summarising the descriptice statistics. To furthur analyse the temperature variation between sites line graphs were constucted. This plot allowed for visual identification of the variation in average temperature for each of the month and year for paired sites.

Results

Temperature variation

Seawater temperature was not uniformly distributed across the six clusters produced (Figure 3), with each set of sites having unique patterns of temperature variation. Within Cluster 1, along the south and east coast, comprising of Hamburg, Eastern Beach and Orient Beach, temperature varied from approximately 13°C to 22°C. Within this cluster of sites, Hamburg had the highest maximum temperatures and the lowest minimum temperatures of the three sites. Conversely, Orient Beach had the lowest range of temperature. Orient Beach and Eastern Beach had relatively similar ranges and distributions of temperatures, as evident by their box plots nearly overlapping completely.

Along the south coast, within the cluster comprised of Mossel Bay, Stilbaai and Knysna, temperatures ranged from approximately 12 °C to 27 °C, with most box plots being relatively long indicating a large amount of variation. Stilbaai had the widest range of temperature variation among the three sites but despite the apparent differences in temperature ranges between these sites, the average temperatures were relatively similar. Average temperatures were nearly identical within this cluster, with very few outliers present within the temperatures ranges of these sites.

Sites located within the third cluster had slightly lower temperatures than the previous two clusters. This cluster comprised of Bordjies, Saldanha, and Gansbaai and temperatures within here ranged from approximately 11 °C to 21 °C, with an average median temperature being close to 15 °C across all three sites. Gansbaai had relatively low variation in temperature as it had a comparatively short box plot. Conversely, Saldanha had a long box plot representing high variation and relatively evenly distributed temperatures by showing little skewness. These sites were similar in terms of their temperature, as their box plots were largely overlapping with few differences between them. There were however, several outliers present within the temperatures of these sites.

The fourth cluster which was located along the east coast, comprised of Port Edward, Leisure Bay, and T.O. Strand. Overall, the temperatures of these sites were higher than those of the sites within the other clusters, with a range of 15 °C to 25 °C. The box plots for these sites were all decidedly long, representing a low variation of temperature with little skewness across sites. Temperatures are they identical between these three sites with each box plot overlapping very well . The median temperature for each of the sites within this cluster is 20.5 °C.

Sites within the fifth cluster had overall lower temperatures than those within the remaining clusters. This cluster comprised of Port Nolloth, Lamberts Bay, and Sea Point, here sharp declines in average temperatures were observed throughout. Temperatures within this cluster ranges between 8 °C and 18 °C, with an average temperature being close to 13 °C. Port Nolloth had low variation in temperature as it had a comparatively short box plot with relatively evenly distributed temperatures. Lamberts Bay and Sea Point were similar in terms of temperature variances, as their box plots were largely overlapping with little differences between them. Several outliers were present within the temperatures of these sites.

In the cluster comprising of Kalk Bay, Muizenberg, and Gordons Bay the temperatures of these sites ranged from 8 °C to 24 °C, with most box plots being short. Muizenberg had the widest range of temperature variation of the three sites. Gordons Bay and Kalk Bay had identical temperature ranges. Similarly to the second cluster, despite the apparent differences in temperature ranges between these sites, the average temperatures across them were relatively similar and nearly identical.

On a monthly basis, large differences of average temperatures was seen between sites within cluster 1, comprising of Eastern Beach, Orient Beach and Hamburg. These differences largely occured during the summer and spring months of 1995 to 1997 (Figure 4). For the remaining sites however, differences in average temperatures were lower during autumn. It was also evident that the average temperature between Hamburg and Orient Beach varied largely on an apparent seasonal basis. Small monthly average temperature differences existed between Eastern Beach and Orient Beach throughout the different seasons.

Converse to the first cluster, the cluster containing Mossel Bay, Knysna and Stilbaai, the largest differences in average temperatures were observed during spring. In this cluster large differences in average temperatures were present between Mossel Bay and Knysna, with the differences increasing annually from 1985 to 2017. Similarly, differences in average temperature also increased slightly between Stilbaai and Knysna during winter and spring. During summer months little differences in average temperature were seen between all three sites within this cluster.

Differences of average temperatures between sites within cluster 3 (Bordjies, Gansbaai and Saldahna Bay) varied on a seasonal basis. During the summer months, large differences in average tempera-

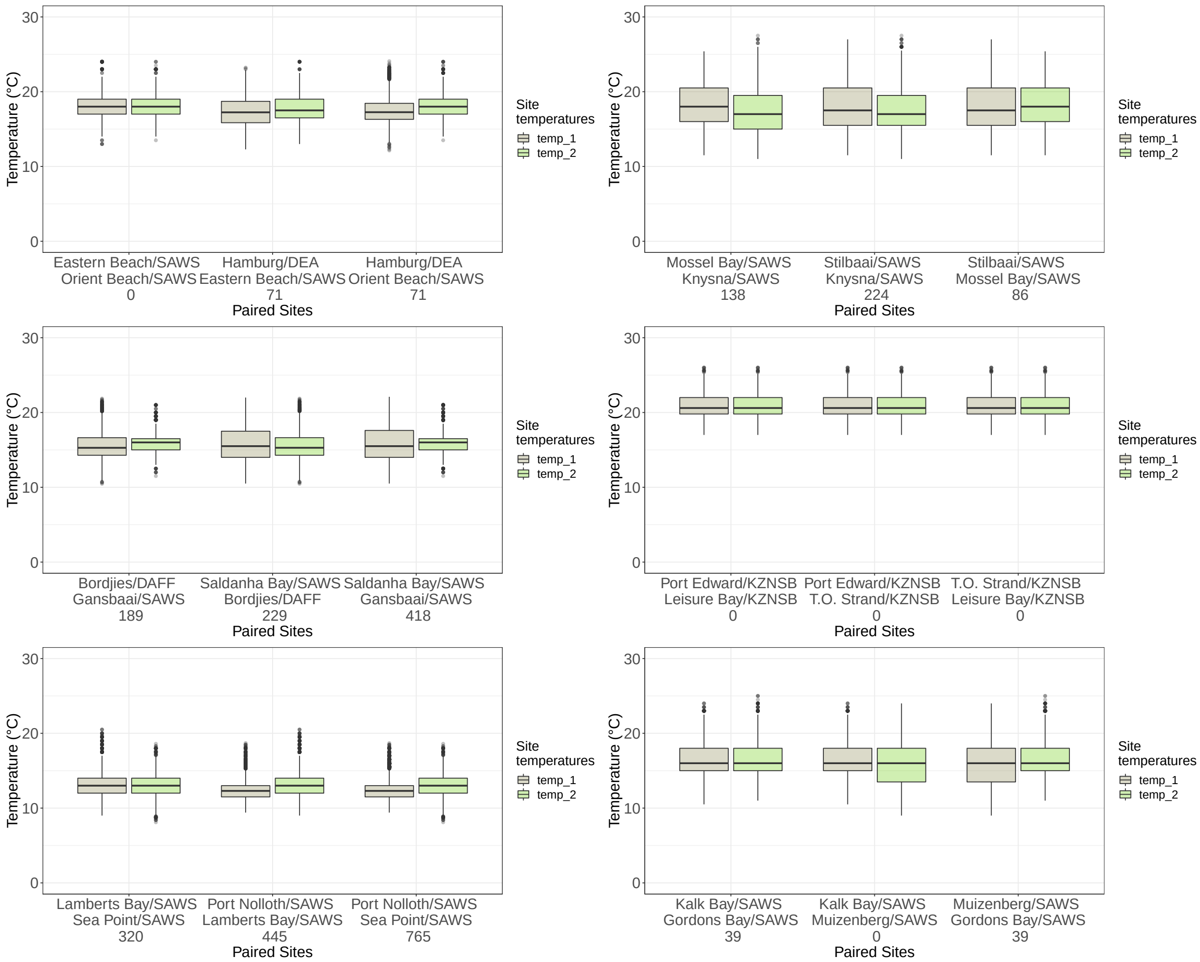

Figure 3: Boxplots representing the seawater temperature of paired sites within each cluster along the South African coast with the values representing the distance (km) between paired sites.

tures exist between Bordjies and the remaining twonsites, with an increase in differences of average temperature between Saldanha Bay and Gansbaai throughout autumn, winter and spring.

In the fourth cluster, which comprised of Port Edward, Leisure Bay and T.O. Strand, small changes in the differences of monthly average temperatures were noticed between sites between 1980 to 2017. Here, the large differences in temperatures were observed towards the end of spring and during summer months. Temperatures were relatively stable throughout winter and the beginning of spring across all three sites found within this cluster.

In the cluster comprising of Lamberts Bay, Port Nolloth and Sea Point, large differences in average temperatures existed between sites at selected months between 1972 and 2017. During summer and autumn months, differences in average temperature were observed between Lamberts Bay and the remaining sites increased. During the months of autumn Lamberts Bay and Sea Point showed large differences in average temperature variation. For the remaining sites, differences in average temperatures were relatively low throughout each month for the same time period.

In the cluster comprising of Kalk Bay, Gordons Bay and Muizenberg, the largest differences in average temperatures were observed during mid autumn and winter months. In this cluster large differences in average temperatures were seen between Muizenberg and the remaining sites, with the differences increasing annually throughout 1972 and 2016 during winter. Similarly, differences of average temperatures also increased between Kalk Bay and Muizenberg during these same months. In the summer and spring months little differences in average temperatures between sites, with minimal differences in the rates of these changes. These rates increased during spring.

Average temperature of clustered sites

In the first cluster of sites, the results of a one way ANOVA tests it was found that there was a significant (p<0.05) differences in average temperatures between paired sites (F=12.07, SS=15.28, p<0.001). These differences were present across season (F=3.44, SS=13.07, p<0.002) but were not present yearly between individual sites and paired sites (F=1.38, SS=1.75, p=0.25). Similarly, paired sites within the second cluster also a significantly differed in average temperature (F=166.84, SS=418.6, p<0.001). Conversely to first cluster however these differences were present yearly (F = 33.21, SS = 41.7, p < 0.001) and seasonally (F=16.72, SS=125.9, p<0.02) between individual and paired sites. In the third cluster of sites, ANOVA tests revealed that there were no significant differences in average temperatures between paired sites (F=1.17, SS=2.9, p=0.31), but temperatures varied seasonally and yearly between individual sites. In the fourth cluster there were again no significant difference of average temperatures between paired sites (F= 0.73, SS=2.9, p=0.48). Significant differences were also absent across seasons (F=0.75, SS=0.0042, p=0.52) and years (F=0.495, SS=0.0009, p=0.48) between both individual and paired sites. Sites within the fifth cluster were significantly different in average temperatures between paired sites (F = 77.10, SS = 196.7, p < 0.002), with these differences being present yearly (F=172.80, SS=220.4, p<0.001) and seasonally (F=77.10, SS=29.92, p<0.002) for both paired and individual sites. Finally, sites within the sixth cluster also significantly difference in average temperatures between paired sites, yearly and seasonally (F=132.044, SS=419.7, p<0.01).

The impact of wind and wave action on temperature

The coeffcient of determination was calculated to analyse how differences in one variable can be explained by a difference in the second variable. Here, the relationship between temperature and

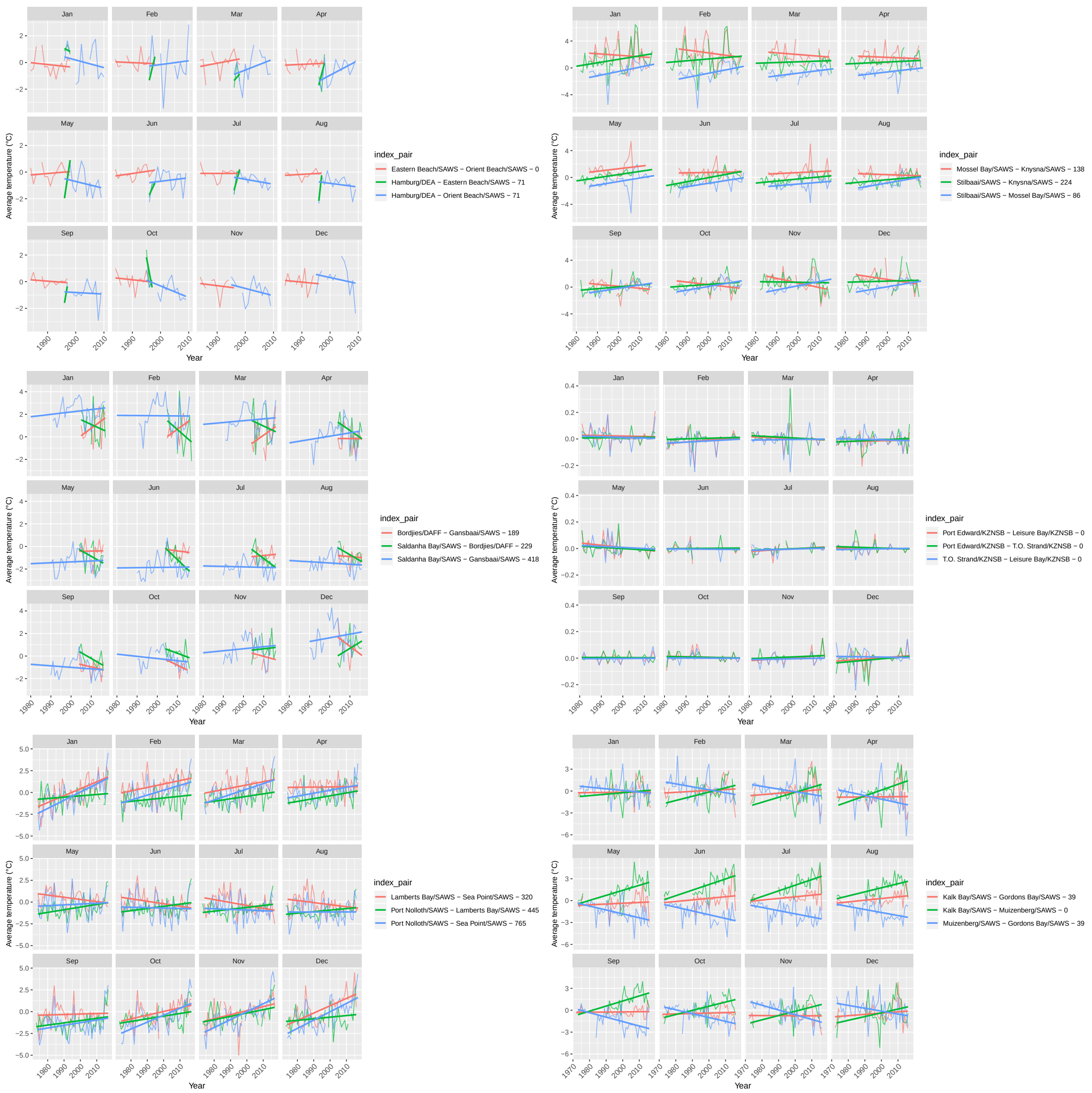

Figure 4: Line graph representing the variation in average seawater temperature for each of the month and year for paired sites along the South African coastline with the values representing the distance (km) between paired sites.

several variables including wind direction and speed as well as wave height, period, direction and speed was determined for all 18 sites. The results obtained from the SACTN temperature dataset showed little variation in environmental factors and temperature for each of the sites. Wind and wave direction influenced temperature at 0–3%. The most significant relationships were found in Muizenberg, Kalk Bay and Mossel Bay where the R^2 values indicated that wave period had a 6-7% influence on temperature. Overall wind and wave action had no significant impact on temperature differences along the coast.

Upon examining the impact of wind and wave action on seawater temperature of the AVHRR temperature dataset, it was seen that wave and wind direction had a minimal effect on temperature variation with its R^2 values ranging between 0-3%. The results also indicated that wave height influenced temperature at some of the sites. This was evident in Gaansbaai and Lamberts Bay where wave height had a 9% impact on temperature variation. The results obtained from the MUR dataset continued to show little variation in regards to the influence of wind and wave action on temperature. At many of the sites, both wind and wave direction had a 0% impact on the temperature, however, it was seen that wave height and wave period had the greatest impact on temperature at some of the sites, with Gordons Bay and Gaansbaai indicating an 8% and 10% impact of wave height on temperature variation respectively. The results obtained from the CMC temperature dataset indicated that wave and wind direction as well as wind speed showed the least significant impact on temperature variation with R^2 values ranging between 0-3%. Wave height continued to show the largest impact on temperature variation at some of the sites. Gaansbaai and Gordons Bay indicated the highest R^2 values of 12% and 9% respectively. Upon comparing the impact of various environmental factors on temperature variation for the K10 data, the results indicated that the each of the above-mentioned variables had no impact on the temperature variation at Hamburg. The impact of wind direction on temperature is highest at Gansbaai, representing an R^2 value of 4% while wave height still repersented the greatest influence on temperature occurring at these sites.

Wind rose diagram

Wind and wave diagrams help visualise the patterns present at a particular site. As you move outward on the radial scale, the frequency associated with wind and waves coming from a partiular direction increases. The predominant wind direction along the south coast 105°. The predominant wind direction of sites located along the east coast such as T.O. Strand and Orient Beach occured at 45°. Leisure Bay, also located along the east coast however indicates a predominant wind direction of 15°. Port Nolloth, located along the west coast, indicates a predominant wind direction at both 135° and 165°.

The impact of predominant wind and wave action on seawater temperature

The results indicated that wind speed, wind height, wind and wave direction as well as wave period had no significant impact on *in situ* temperature variation at the various sites along the coastline (Figure 6). Eastern Beach however, showed that wave period and wave height appear to have the largest effect on temperature variation, this however varied between sites. Hamburg and Gordons Bay show that wave direction explained 4% of the temperature variation. Muizenberg, representing the largest value of 5% influence of wave height on temperature variation. Cluster two comprising of Stilbaai, Mossel Bay and Knysna, wind and wave action had very little impact on temperature variation, with all three graphs representing similar results. In the cluster comprising of Port Edward,

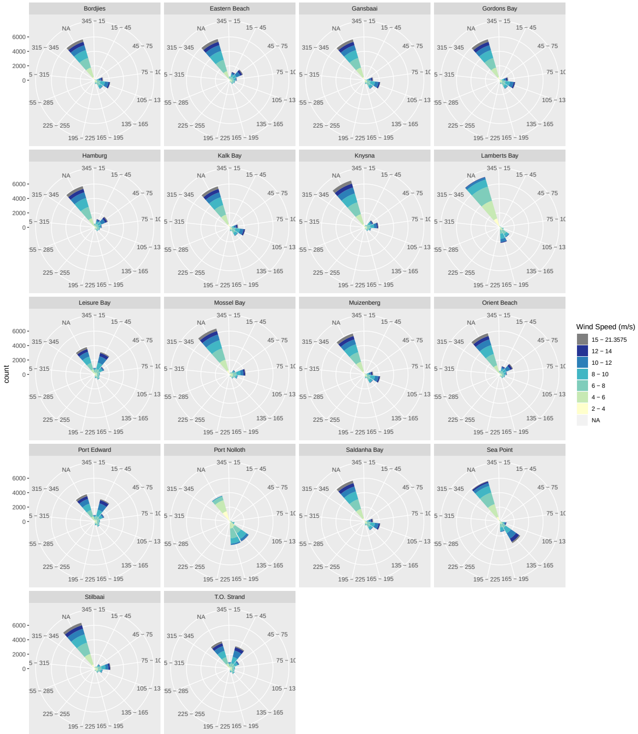

Figure 5: Wind rose diagrams representing the the most predominant wind direction for each of the sites. Each spoke is divided by color into wind speed ranges. The radial length of each spoke around the circle is the time that the wind and waves comes from that direction

Leisure Bay and T.O Strand, wave height is seen to have a minor impact on temperature variation with an r-squared value variating between 1-5%. Overall it is seen that predominant wind and wave direction have no significant impact on the seawater temperature variation along the coast.

Discussion

why was it expected that wind and wave may influece tempeature

This study aimed to investigate how wind and wave action influenced variation in coastal seawater temperature along the South African coastline. As seawater temperature is known to have large influences on species distributions (Bolton 2010; Smit et al. 2013), it is important to understand not only how temperatures vary along the coastline, but the factors driving these variations as well. Sinnett and Feddesen (2014) proved that various environmental factors such as solar radiation, air temperature, humidity and wave energy is responsible for temperature variation within the coastal region. Here, It was confirmed that there were statistically significant differences in the *in situ* seawater temperature between 18 sites along the coastline of South Africa, with temperatures contrasting between coasts, and among sites along the same coasts. Overall, sites located along the west coast had lower temperatures than those along the south and east coasts. It was discovered that the east coast had overall, little variation in temperatures between sites, whereas the south coast varied more frequently (Schlegel and Smit 2016).

The results in this study confirmed that there were significant differences in temperatures between sites along the coastline, annually and seasonally, but did not provide evidence of which factors were driving these. Across each of the 18 sites that were assessed, it was found that wind and wave

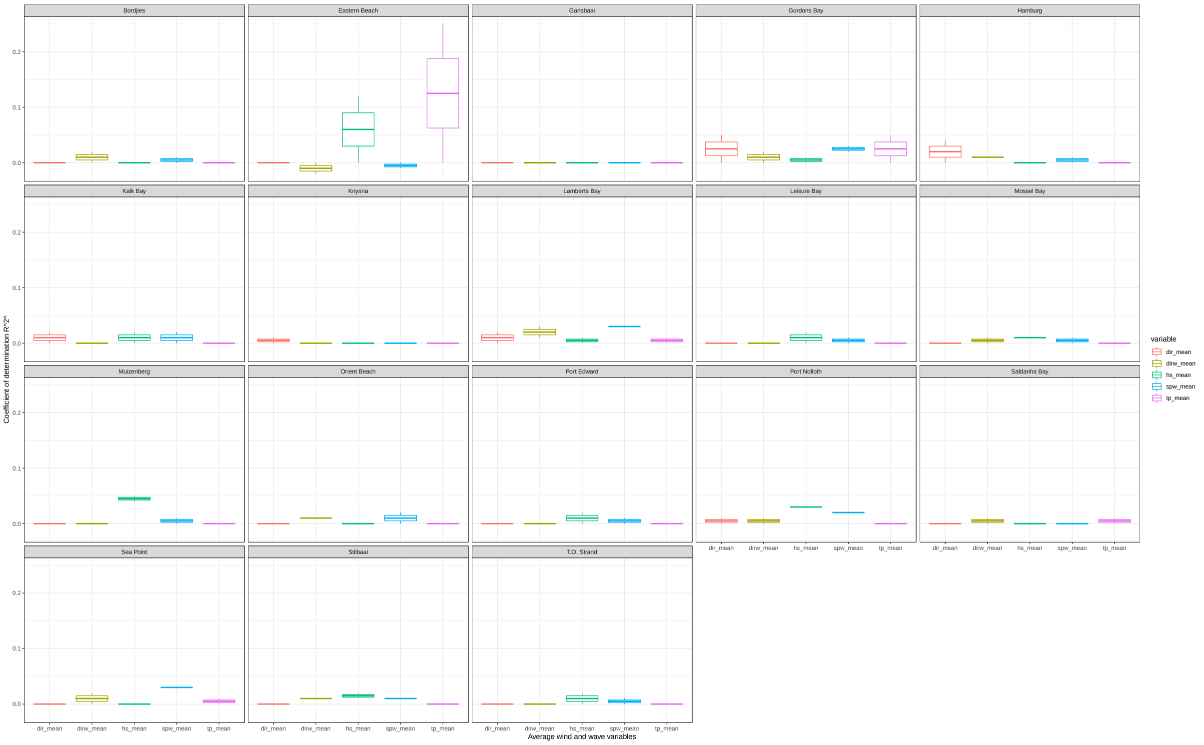

Figure 6: Boxplot representing the R^2 value each of the environmental variables at the most predominant wave and wind direction for each of the sites.

action did not significantly influence both satellite and *in situ* SSTs. Differences in temperature between sites at different locations along the coastline were therefore not caused by variations in wind or wave action, suggesting that other factors were responsible for the observed patterns of temperature variation. These findings were consistent across six different datasets from various sources, with each of these providing minimal evidence of a relationship between wind or wave action and the SST of a site. It must be noted however, these analyses consisted of a combination of satellite and thermometer data, which varied in their measurements and time series.

Theron et al. (2014) discusses how the wave data set, from which the current study data was extracted from, was created and validated. However, despite the validation, discrepaancies may arise as a result of the assumptions made in the assumptions of the SWAN model. Quasi-stationary SWAN computation were performed under the assumption that the boundary conditions were fluctuating at a much slower tempo compare to the time it took for those conditions to propagate towards the coastline. This may ultimately result in the wind driven wave components to be overestimated as the duration limited effect of the wind was thus neglected and computed towards a converging wave condition during each quasi-stationary time step.

The SWAN model usually overestimates the energy of developing waves with low frequencies (long periods) for very short distances from the shore. This is because wave conditions are simplified by using an a priori wave spectrum (Booij, Ris, and Holthuijsen 1999; Thomas and Dwarakish 2015). For most modelled areas, these assumptions are reasonable to make because most of the South African coastline is exposed and agree to the requirements of these assumptions (Joubert et al. 2013).

Previous studies suggest that a longer time series containing more data would have greater accuracy in detecting subtle changes in temperature differences obtained from variable coastal regions such as the South African coastline. Schlegel and Smit (2016) suggested that having a time series of greater than 30 years for sites with a low variance results in increased ability to detect changes. They showed that high quality time series datasets have frequent measurements with minimal missing (NA) values present. Furthermore, low quality datasets (i.e. those with more than 5% of NA values) have a higher chance of detecting variation where none exists.

The SACTN dataset containing temperature information are inconsistent. Temperature collection along the South African coastline started in the 1970s, and has been inconsistent in terms of instruments used, modifications to styles and methods, calibration, and site locations (Smit et al. 2013; Schlegel and Smit 2016). Additionally, older records within some datasets, such as the SACTN dataset, may have been lost or are unreliable since the metadata for these are unavailable. These metadata are essential as their absence prevents the understanding of the influence that the instruments had on temperature recordings. Some measurements may therefore not represent accurate temperatures due to the instrumentation used however, have an accurate indication of which recordings were measured with thermometers and which were with UTRs is available.

The UTRs used to collect data in the SACTN dataset appeared to express a lower number of NA values compared to the data collected with hand thermometers. As such, this may have influenced the overall time series dataset (Schlegel and Smit 2016). The level of precision at which data was collected also influenced the length of the time series needed. Time series in which temperature were collected at a precision of 0.5 °C may require another 24 months of recordings to precisely detect long term variation (Schlegel and Smit 2016). The average length of the thermometer time series component of the SACTN dataset was 346 months whereas the average length of UTR time series was less than half of that. With the extent of these differences in length being so severe, even once correcting for potential negative effects on the measurement precision of the thermometer collected time series, it was clear that thermometer data were more useful than that of UTRS.

Satellite acquired SST records are useful to modern marine scientists. These data are often used to model and predict a wide range of oceanic and biological processes in the open ocean but have only recently been used to study temperature variations influencing benthic organisms (Pearce, Faskel, and Hyndes 2006). Here, both satellite SST data, and in situ thermometer data were correlated with wind and wave data along the coastal environment at a depth of 7 and 15 meters respectively. SST data acquired by satellites are obtained from a thin boundary layer at the air-sea interface (Smale and Wernberg 2009) and at different locations and thus deviated from coastal in situ collected seawater temperatures. These deviations may have affected the outcomes of the analyses thereby inhibiting the findings. Upon assessing the impacts of wind and wave action on satellite and in situ collected seawater temperature data it was found that wind and wave action had insignificant impacts on the temperature variation along the South African coastline.

My findings were surprising but not unexpected. Along the coastline of South Africa, there is a known east-west thermal temperature gradient that may have caused some interesting results (Smit et al. 2013). This is caused by major oceanic processes such as coastal upwelling, thermohaline circulation, solar radiation, atmospheric temperature (**???**) and the presence of major ocean currents, which cumulatively influences the temperatures along this coastline (Walker 1990; Schlegel and Smit 2016). While it was reasonable to assume that surface level environmental factors like wind and wave action would affect sea surface temperatures, it is not completely unexpected that they would have little effect given the prevalence of the major processes mentioned above. However, this is unlikely as the 'West Coast' system is considered wind driven and there are multiple wind driven upwelling cells along the south coast. Those processes are of the largest drivers behind coastal temperature variation and may simply be overpowering the effects of other environmental factors. Other factors such as latent heat flux and wave energy flux were also proven to heat and cool coastal seawater temperatures (**???**).

Alternatively, it is possible that factors other than wind and wave action are influencing temperatures across the South African coastline. For example, whilst rainfall can have large influences on coastal SST (Reason and Mulenga 1999) other, non-climatic, factors could be playing a greater role. Coastal regions are highly impacted by human mediated pressures (Mead et al. 2013). These pressures are predicted to drive change over a spatial and temporal scale and is often a cause of temperature variation (Griffiths, Mead, and Zietsman 2011). Additionally, evidence indicates that human driven climate change on both a local and global scale largely influence seawater temperatures, wind regimes, and wave action (Rouault, Penven, and Pohl 2009; Rouault et al. 2010; Mead et al. 2013). These pressures are present along the South African coastline in the form of pollution, coastal runoff, invasive species, resource exploitation, and coastal mining, which directly and indirectly influences air temperature, wind, seawater temperature, and rainfall (**???**; James and Hermes 2011; Mead et al. 2013). These anthropogenic factors may be cumulatively playing an important role in affecting SST along the coastline, but the full extent of these factors are unknown.

Within marine environments, coastal temperature variation allows for a variation in the spatial arrangements of marine biodiversity. Whilst wind and wave action may not be directly affecting ocean temperatures, Blamey and Branch (2008) have found that wave action has a profound influence on species distributions along the coastline. The presence or absence of marine species are determined by a variety of factors and whilst those factors may not be influencing each other as was the case here, they collectively play important roles in affecting the marine life of the South African coastline and identifying those roles can aid in improving our understanding of nearshore dynamics, thereby providing greater knowledge to be used for conservation.

This study has shown that wind and wave action are not directly affecting seawater temperature variation along the South African coastline, However, other factors may be. Future research could aim to examine the effects of air temperature and rainfall on the coastal seawater temperature for the 18 sites being assessed. Additionally, other factors such as the amount of sunlight penetrating the ocean or site exposure could also be tested, as well as assessing the optimal locations for data collection. Further studies should also consider examining how chlorophyll concentrations and salinity varies with temperature in order to assess the effects of seawater temperature on marine plant life. Homogenous coastlines with distinct temperature gradients such as in South Africa provide a model environment for temperature analyses at fine-resolutions. These data could provide critically important information that can be used to assist in conserving marine biodiversity within these waters and should be given greater priority within marine research in the near future.

Bartsch, Inka, Christian Wiencke, and Thomas Laepple. 2012. "Global Seaweed Biogeography Under a Changing Climate: The Prospected Effects of Temperature." In *Seaweed Biology*, 383–406. Springer.

Beal, Lisa M, De RuijterWilhelmus PM, Arne Biastoch, Rainer Zahn, Meghan Cronin, Juliet Hermes, Johann Lutjeharms, et al. 2011. "On the Role of the Agulhas System in Ocean Circulation and Climate." *Nature* 472 (7344): 429.

Bolton, JJ, Frédérik Leliaert, De ClerckOlivier, RJ Anderson, H Stegenga, HE Engledow, and Eric Coppejans. 2004. "Where Is the Western Limit of the Tropical Indian Ocean Seaweed Flora? An Analysis of Intertidal Seaweed Biogeography on the East Coast of South Africa." *Marine Biology* 144 (1): 51–59.

Bolton, John J. 2010. "The Biogeography of Kelps (Laminariales, Phaeophyceae): A Global Analysis with New Insights from Recent Advances in Molecular Phylogenetics." *Helgoland Marine Research* 64 (4): 263.

Booij, NRRC, RC Ris, and Leo H Holthuijsen. 1999. "A Third-Generation Wave Model for Coastal Regions: 1. Model Description and Validation." *Journal of Geophysical Research: Oceans* 104 (C4): 7649–66.

Breeman, AM. 1988. "Relative Importance of Temperature and Other Factors in Determining Geographic Boundaries of Seaweeds: Experimental and Phenological Evidence." *Helgoländer Meeresuntersuchungen* 42 (2): 199.

Broitman, BR, CA Blanchette, BA Menge, J Lubchenco, C Krenz, M Foley, PT Raimondi, D Lohse, and SD Gaines. 2008. "Spatial and Temporal Patterns of Invertebrate Recruitment Along the West Coast of the United States." *Ecological Monographs* 78 (3): 403–21.

Byrne, Maria, Melanie Ho, Paulina Selvakumaraswamy, Hong D Nguyen, Symon A Dworjanyn, and Andy R Davis. 2009. "Temperature, but Not pH, Compromises Sea Urchin Fertilization and Early Development Under Near-Future Climate Change Scenarios." *Proceedings of the Royal Society of London B: Biological Sciences* 276 (1663): 1883–8.

Davis, KA, SJ Lentz, J Pineda, JT Farrar, VR Starczak, and JH Churchill. 2011. "Observations of the Thermal Environment on Red Sea Platform Reefs: A Heat Budget Analysis." *Coral Reefs* 30 (1): 25–36.

Easterling, David R, Gerald A Meehl, Camille Parmesan, Stanley A Changnon, Thomas R Karl, and Linda O Mearns. 2000. "Climate Extremes: Observations, Modeling, and Impacts." *Science* 289 (5487): 2068–74.

Fewings, Melanie R, and Steven J Lentz. 2011. "Summertime Cooling of the Shallow Continental Shelf." *Journal of Geophysical Research: Oceans* 116 (C7).

Griffiths, CL, A Mead, and L Zietsman. 2011. "Human Activities as Drivers of Change on South African Rocky Shores." *Observations on Environmental Change in South Africa, Sun Media, Stellenbosch, South Africa*, 242–6.

Hoek, C van den. 1982. "The Distribution of Benthic Marine Algae in Relation to the Temperature Regulation of Their Life Histories." *Biological Journal of the Linnean Society* 18 (2): 81–144.

Hutchings, L, Van der LingenCD, LJ Shannon, RJM Crawford, HMS Verheye, CH Bartholomae, Van der PlasAK, et al. 2009. "The Benguela Current: An Ecosystem of Four Components." *Progress in Oceanography* 83 (1-4): 15–32.

James, Nicola Caroline, and Juliet Hermes. 2011. *Insights into Impacts of Climate Change on the South African Marine and Coastal Environment*. SAEON.

Joubert, JR, JL van Niekerk, J Reinecke, and I Meyer. 2013. "Wave Energy Converters (Wecs)." *Centre for Renewable and Sustainable Energy Studies, Centre for Renewable and Sustainable Energy Studies, Faculty of Engineering*.

Lee, Kate Asha, Moninya Roughan, Hamish Malcolm, and Nicholas Otway. 2018. "Assessing the Use of Area-and Time-Averaging Based on Known de-Correlation Scales to Provide Satellite Derived Sea Surface Temperatures in Coastal Areas." *Frontiers in Marine Science* 5: 261.

Lutjeharms, JRE, J Cooper, and M Roberts. 2000. "Upwelling at the Inshore Edge of the Agulhas Current." *Continental Shelf Research* 20 (7): 737–61.

Lutjeharms, JRE, and Van BallegooyenRC. 1988. "Anomalous Upstream Retroflection in the Agulhas Current." *Science* 240 (4860): 1770.

Lüning, Klaus. 1990. *Seaweeds: Their Environment, Biogeography, and Ecophysiology*. John Wiley & Sons.

Mead, A, CL Griffiths, GM Branch, CD McQuaid, LK Blamey, JJ Bolton, RJ Anderson, et al. 2013. "Human-Mediated Drivers of Change—Impacts on Coastal Ecosystems and Marine Biota of South Africa." *African Journal of Marine Science* 35 (3): 403–25.

Mead, Angela. 2011. "Climate and Bioinvasives Drivers of Change on South African Rocky Shores?" PhD thesis, University of Cape Town.

Meehl, Gerald A, and Claudia Tebaldi. 2004. "More Intense, More Frequent, and Longer Lasting Heat Waves in the 21st Century." *Science* 305 (5686): 994–97.

Müller, Ruth, Thomas Laepple, Inka Bartsch, and Christian Wiencke. 2009. "Impact of Oceanic Warming on the Distribution of Seaweeds in Polar and Cold-Temperate Waters." *Botanica Marina* 52 (6): 617–38.

Pearce, Alan, Fabienne Faskel, and Glenn Hyndes. 2006. "Nearshore Sea Temperature Variability Off Rottnest Island (Western Australia) Derived from Satellite Data." *International Journal of Remote Sensing* 27 (12): 2503–18.

Perkins, SE, and LV Alexander. 2013. "On the Measurement of Heat Waves." *Journal of Climate* 26 (13): 4500–4517.

Reason, CJC, and H Mulenga. 1999. "Relationships Between South African Rainfall and Sst Anomalies in the Southwest Indian Ocean." *International Journal of Climatology: A Journal of the Royal Meteorological Society* 19 (15): 1651–73.

Rouault, Marjolaine J, Alexis Mouche, Fabrice Collard, JA Johannessen, and Bertrand Chapron. 2010. "Mapping the Agulhas Current from Space: An Assessment of Asar Surface Current Velocities." *Journal of Geophysical Research: Oceans* 115 (C10).

Rouault, Mathieu, Pierrick Penven, and Benjamin Pohl. 2009. "Warming in the Agulhas Current System Since the 1980's." *Geophysical Research Letters* 36 (12).

Schlegel, Robert W, Eric CJ Oliver, Sarah Perkins-Kirkpatrick, Andries Kruger, and Albertus J Smit. 2017. "Predominant Atmospheric and Oceanic Patterns During Coastal Marine Heatwaves." *Frontiers in Marine Science* 4: 323.

Schlegel, Robert W, and Albertus J Smit. 2016. "Climate Change in Coastal Waters: Time Series Properties Affecting Trend Estimation." *Journal of Climate* 29 (24): 9113–24.

Sinnett, Gregory, and Falk Feddersen. 2014. "The Surf Zone Heat Budget: The Effect of Wave Heating." *Geophysical Research Letters* 41 (20): 7217–26.

Smale, Dan A, and Thomas Wernberg. 2009. "Satellite-Derived Sst Data as a Proxy for Water Temperature in Nearshore Benthic Ecology." *Marine Ecology Progress Series* 387: 27–37.

Smit, Albertus J, John J Bolton, and Robert J Anderson. 2017. "Seaweeds in Two Oceans: Beta-Diversity." *Frontiers in Marine Science* 4: 404.

Smit, Albertus J, Michael Roberts, Robert J Anderson, Francois Dufois, Sheldon FJ Dudley, Thomas G Bornman, Jennifer Olbers, and John J Bolton. 2013. "A Coastal Seawater Temperature Dataset for

Biogeographical Studies: Large Biases Between in Situ and Remotely-Sensed Data Sets Around the Coast of South Africa." *PLoS One* 8 (12): e81944.

Stocker, Thomas. 2014. *Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Tapia, Fabian J, John L Largier, Manuel Castillo, Evie A Wieters, and Sergio A Navarrete. 2014. "Latitudinal Discontinuity in Thermal Conditions Along the Nearshore of Central-Northern Chile." *PLoS One* 9 (10): e110841.

Thomas, T Justin, and GS Dwarakish. 2015. "Numerical Wave Modelling–a Review." *Aquatic Procedia* 4: 443–48.

Walker, ND. 1990. "Links Between South African Summer Rainfall and Temperature Variability of the Agulhas and Benguela Current Systems." *Journal of Geophysical Research: Oceans* 95 (C3): 3297–3319.

Wernberg, Thomas, Bayden D Russell, Pippa J Moore, Scott D Ling, Daniel A Smale, Alex Campbell, Melinda A Coleman, Peter D Steinberg, Gary A Kendrick, and Sean D Connell. 2011. "Impacts of Climate Change in a Global Hotspot for Temperate Marine Biodiversity and Ocean Warming." *Journal of Experimental Marine Biology and Ecology* 400 (1-2): 7–16.

Wernberg, Thomas, Mads S Thomsen, Fernando Tuya, Gary A Kendrick, Peter A Staehr, and Benjamin D Toohey. 2010. "Decreasing Resilience of Kelp Beds Along a Latitudinal Temperature Gradient: Potential Implications for a Warmer Future." *Ecology Letters* 13 (6): 685–94.

Wethey, David S, Sarah A Woodin, Thomas J Hilbish, Sierra J Jones, Fernando P Lima, and Pamela M Brannock. 2011. "Response of Intertidal Populations to Climate: Effects of Extreme Events Versus Long Term Change." *Journal of Experimental Marine Biology and Ecology* 400 (1-2): 132–44.

Woodson, CB, DI Eerkes-Medrano, A Flores-Morales, MM Foley, SK Henkel, M Hessing-Lewis, D Jacinto, et al. 2007. "Local Diurnal Upwelling Driven by Sea Breezes in Northern Monterey Bay." *Continental Shelf Research* 27 (18): 2289–2302.

Zainuddin, Mukti, Hidetada Kiyofuji, Katsuya Saitoh, and Sei-Ichi Saitoh. 2006. "Using Multi-Sensor Satellite Remote Sensing and Catch Data to Detect Ocean Hot Spots for Albacore (Thunnus Alalunga) in the Northwestern North Pacific." *Deep Sea Research Part II: Topical Studies in Oceanography* 53 (3-4): 419–31.