Introduction_outline

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Chapter 1: General Introduction

Eastern boundary upwelling systems:

Globally, there are four major eastern boundary upwelling systems (EBUS). These are the Benguela Current off south-western Africa, the Canary Current off north-western Africa including its northern extension off the Iberian Peninsula of south-western Europe, the Peru-Humboldt Current off western South America, and the California Current off the western continental USA and north-western Mexico (Bakun et al, 2015; Pauly and Christensen, 1995). Each of these systems are characterized as vast regions of coastal ocean occurring along the western shores of continents bordering the Pacific and Atlantic Oceans. EBUS cover only 1% of the world's ocean surface, but despite these are among the most productive regions of the world (Pauly and Christensen, 1995). This is because these systems are subject to coastal upwelling, which is defined as the process whereby cold, nutrient rich, high CO2 concentrated, low pH, and low oxygen waters are pushed to the surface as a result of alongshore winds interacting with the earth's rotation (Huyer 1983). As a result of upwelling, diverse marine fauna and flora are able to thrive in these areas because of the abundance of nutrients and favourable temperatures.

Upwelling is primarily caused by alongshore, equator ward winds. These winds are caused by cross-shore atmospheric pressure gradients, and these gradients occur predominantly during heating periods. Bakun then proposed that if there is an increase in greenhouse gases, it will cause more heating during the day and more cooling during the night which cause the temperature gradient to increase and would result in a strong pressure gradient, and as we know the pressure gradient will affect the wind and therefore will affect upwelling. Several people have tried to model this using different datasets of SST and wind pattern data at various resolution and initially found that increases in gases, such as CO^2 causes a reduction in trade winds, and therefore a reduction in upwelling. However, these models were based on coarse data and when higher resolutions are used, such as for the Benguela EBUS, the models have shown that upwelling will intensify in accordance to the upwelling intensification hypotheses (eg, Hsieh and Boer 1992, Mote and Mantua 2002, Lima and Wethey's 2012).

Ecology and primary production within upwelling zones:

The duration and intensity of coastal upwelling are known to have a critical role in the phenology of key marine ecosystem processes. Similarly, changes in the characteristics of upwelling are shown to have cause large disturbances to ecosystems at several trophic levels (Wang et al., 2015). Cold, nutrient rich, low pH, and low oxygen upwelled waters fuels primary production as a consequence of the development of phytoplankton blooms (Ryther 1969, Cushing 1971, Payne 1987, McGillicuddy et al., 1998; Oschlies and Garçon, 1998). In these upwelling systems, the high productivity supports vast and diverse marine populations. Mesoscale and sub-mesoscale oceanic movements are key in managing the exchange and transportation of organic resources and marine organisms from the coastal zone to the open ocean. Most of the world's major fishing industries are dependent on upwelling, because this process brings nutrient rich waters into the euphotic zone, where it forms the foundation of a localized food web that ecologically differs from surrounding, non-upwelled regions (Bosman et al., 1987; Barshis et al., 2011). Whilst nutrients play a primary role in the survival of these systems, the cool temperatures of these waters are critical as well. There is an increasingly large body of research that has provided evidence showing that sea surface temperatures (SST) have and are continuing to increase. However, some regions still show a lower or non-significant increase, and in some cases cooling trends are evident (REFERENCES). Upwelling occurring along the Cape south coast is proven to have less of an economic importance in contrast to the west coast. Inshore regions and embayments that are protected from wind action may be subjected to intense episodes of primary production (Graham and Largier, 1997). Vander Wouder et al. (2006) found that these sites represent the highest levels of chlorophyll concentration. Biotic systems within the Benguela upwelling system may be negatively influenced by the changes in oxygen levels given their adaption to natural variable conditions (Capone and Hutchins, 2013).

For several decades, regime shifts have become an important factor of marine research. Regime shifts are often defined as a shift from one stable ecosystem state to another. This process affects several species within a short period of time (deYoung et al., 2004; Cury and Shannon, 2004; Jarre et al., 2006, Blamey 2012). Regime shifts are thought to be driven by abiotic processes such as climate change (Polovina, 2005, Blamey 2012). The southern Benguela upwelling system supports a wide variety of commercially-exploited fish species and exhibits substantial variability in both oceanographic and biological components. Over the past 3 three decades, a number of species occurring within this region have undergone shifts in their distributions and Roy et al. (2007) linked these shifts to cooling waters along the inner shelf of the Agulhas bank on the south coast, east of Cape Agulhas (Blamey, 2012). This coast is associated with high levels of harmful toxic algal blooms, which negatively impact commercial and recreational interests along the coastal region. These harmful blooms are often attributed to flagellated species with the red tide representing dinoflagellate blooms (Pitcher et al. 1993A, Pitcher 1998). Formations of red tides are often related to the prevailing winds of the southern Benguela which govern most hydrodynamic processes on the continental shelf. Red tide events are greatest during the latter part of the upwelling season during transitions in the synoptic weather patterns which result in diminished upwelling activity and increased thermal stratification (Pitcher et al. 1993a).

Atmosphere:

Throughout region surrounding the Benguela EBUS, the atmosphere is dominated by anticyclonic high pressure cells with quasi-stationary positions. The South Atlantic Ocean High is situated along the west, drawing cool, dry air onto the west of the subcontinent (Van Heerden and Hurry, 1998). Solar heating during summer may result in the development of low pressure cells, known as heat lows. These cells are absent during winter time (Tyson and Preston-Whyte, 2000). When the anticyclones shift north, during winter months, the cold westerlies have a substantial impact on the weather of the southern tip of the South African subcontinent (Van Heerden and Hurry, 1998). The atmospheric temperatures along the coastline are largely influenced by the Benguela Current (Van Heerden and Hurry, 1998). However, upwelling systems may be forced by various atmospheric conditions (Lutjeharms et al., 2003; Roberts, 2005; Hutchings et al., 2009).

Sea surface temperature and data collection:

Water temperature affects the survival, abundance, distribution and growth of marine species (REFERENCE). As such, a clear understanding of the relationship between marine ecosystems and their thermal tolerance is necessary for conservation and management planning. Future predictions in biogeographical patterns and ecosystem functioning may also be estimated based on various climatic behaviours. Regardless of the objectives, whether it be studies based on climate change, extreme events or ecosystem functioning, it is important that the research is conducted through accurate, reliable datasets. Unfortunately, not all data are created equally and under the same conditions and as such not all datasets are usable for a particular task.

Remotely-sensed satellite SST products are produced and maintained by a number of organisations worldwide. In order to obtain these SST data, advanced technology is launched into space, in order to obtain infra-red light being emitted by the ocean. This irradiance is then taken as a proxy for SST. Due to the distance at which these SST are being collected, certain coarseness within the datasets are unavoidable. Satellite SST products undergo a range of quality control processes that are well researched and tested (Reynolds and Smith, 1994; Brown et al., 1999; Martin et al., 2012), making their use more reliable. However, Smit et al. (2013) have shown that SST data are not particularly reliable for coastal regions and should be used cautiously as they can be prone to both warm and cold bias. Nevertheless, satellite data products are extremely useful when investigating the ocean at broad scale and can provide important SST data.

In situ data

Having coastal, in situ seawater temperature data is a rare privilege to researchers. Most biological and ecological research requires coastal temperature data. The South African Coastal Temperature Network (SACTN). The availability of the in situ collected coastal temperature data products for several decades and provides a reliable source of accurate coastal seawater temperature data (Smit et al. 2013). SACTN has collected coastal seawater temperature along the South African coastline from as early as 1972, with contributions from a total of seven different organisations and governmental departments. At present, this dataset contained temperature of 129 sites along the three distinct coasts of the South African coastline. Temperature recordings are still ongoing at many of these sites, but unfortunately, the durations and extents of these are uneve per site. 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.

The uneven and inconsistent nature of the SATCN dataset can be attributed to several factors. For instance, these may be as a result of variances in the equipment used by the various organisations and governmental bodies who recorded the data. One problematic outcome of this sampling methodology is that due to specific work of the South African Weather Service (SAWS) and Kwazulu Natal Sharks Board (KZNSB), two thirds of the SACTN data that were sampled were obtained with hand-held thermometers and records at a data precision of 0.500 $\circ$ C. However, the current global standard is to make use of underwater temperature recorders (UTRs), which have a data precision of 0.001 $\circ$ C (Jarraud, 2008). Because of these inconsistencies, this dataset required verification from an independent source before its use within research. Smit et al. (2013) thoroughly compared the temperature data within the SACTN dataset to those of several remotely-sensed SST products and found bias results. Using these in situ collected temperature data along with remotely sensed SST data requires a clear understanding in the characteristics of the contributing data sources in order to understand how accurate, reliable and useful these long term measurements are for use in climate change studies.

It must also be acknowledged that most of the time series within the SACTN dataset do not have meta-data records that meet the international climate change research requirements (Aguilar et al., 2003). Specifically uncertainty lies in the drift of the instrument, who was sampling and where the exact sampling locations were collected throughout the collection period. We are however certain that all of the thermometer time series were collected by thermometers and that the UTR time series were collected by UTRs. Given these issues associated with the mete-data, recent work has been started to develop a nation wide standard.

For this analysis, the seawater temperature data, obtained from the seven different sources, were combined and formatted into standardized comma delineated value (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 (http://www.r-project.org/). 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/MASTERSPROJECT.

Global warming and climate change:

Climate change as a result of anthropogenic activities is now established as a global concern for both scientific and political importance. As the human population grows, the rate of global warming increases, resulting in profound effects on marine and other ecosystems. Climbing temperatures create a host of additional changes to marine systems, such as rising sea levels, increased ocean stratification, decreased sea-ice extent, and altered patterns of ocean circulation and precipitation (Doney et al., 2011). Furthermore, direct effects on ocean temperature changes and chemistry may alter the functioning and behaviour or marine organisms. In turn, these changes lead to a change in species integration and trophic pathways.

Significant research studies accept the climate change and variability have great impacts on marine ecosystems (Stenseth et al. 2002, Harley et al. 2006, Hoegh-Guldberg & Bruno 2010). The Intergovernmental Panel on Climate Change (IPCC) predicts future projections with a mean increase in air temperature of 1.1°C by the 2020's and 1.8°C by the 2040's as a result of greenhouse gas concentrations (Solomon et al. 2007). A large amount of this heat will be absorbed by the world's ocean. In current years, as a result of changes in air temperature, the heat content of the ocean has increased largely. Given ocean warming in association with their physical changes such as sea level rise and declines in sea ice, marine life is expected to intensify in future decades. Global warming represents distinct warming and cooling periods throughout the 20th and 21st century (IPCC, 2007). Global warming however is not evenly distributed across the global ocean thus presenting regions warming much faster or slower than then the global average (Levitus et al., 2000; Palttridge and Woodruff, 1981; Santos 2012). In particular, the Atlantic Ocean contributes most to the increase of the heat content (Nerem et al., 1999; Levitus et al., 2000; Strong et al., 2000).

As a result of climate change, research studies provide significant evidence on the increase in warming of the ocean surface. This warming slowly propagates down through the water column and in turn increases the thermal stratification (Gruber, 2011). Strong stratification limits the depth at which water is upwelled and hence controls the amount of nutrients brought up (Chhak and Di Lorenzo, 2007; Jacox and Edwards, 2011; Jacox et al., 2015). The interplay between upwelling winds and stratification determine the amount of nutrients present within the system and thus is strongly linked to biological productivity. Globally, as a result of climate change, stratification of the water-column between 0 and 200 m has increased by an estimated 4% between 1971 to 2010 (Stocker et al., 2013). Increased ocean stratification as a result of surface warming may reduce the ventilation of deep-water masses. As the deep water is being up welled to the surface, decreases in oxygen and pH levels are predicted along with an increase in nutrient levels (Rykaczewski and Dunne, 2010). Generally, regional ocean climate oscillations like the Benguela Niño for the Benguela Current System impose considerable variability on temperatures and complicate attempts to assess long-term trends (Demarcq, 2009). It is predicted that these climate oscillations may increase the variance with climate change (Timmermann et al., 1999; Kuzmina et al., 2005; Sydeman et al., 2013; Cai et al., 2015) which will further result in unusual trends.

As previously mentioned, upwelling winds in EBUSs are generated by pressure differences between continental thermal lows and oceanic highs. As warming intensifies, pressure gradients between land and sea increases, resulting in a greater intensity of upwelling winds (Bakun et al. 2010). In rare cases, projected upwelling increases may overcome the countervailing effects of upper-ocean warming and stratification to cause regional cooling (Auad et al.2006). Research studies reveal declines in ocean oxygen levels as a result of ocean warming and reduced ventilation from stratification and circulation changes (Keeling et al. 2010). Similarly, low oxygen levels are also possible because of shifts in the composition of sinking organic material (Hofmann & Schellnhuber 2009, Doney et al., 2011).

Problem statement:

With global warming continuing at a rapid pace the amount of greenhouse gases within the atmosphere are going to increase in the future. This increase will undoubtedly have an impact on the world's oceans and the marine life within, both directly and indirectly. The oceanic process of coastal upwelling is one aspect that is likely to be affected as changes in global temperature will affect temperature and pressure gradients, and in turn affect alongshore winds which are responsible for driving this process within EBUS regions. Because upwelling is important for productivity within coastal systems, a decrease in this process will negatively impact on marine fauna and flora, and on human activities such as fishing. To assess changes in upwelling events, here I aim to use SST, wind, chlorophyll data etc. to monitor durations and intensities of upwelling within one of the EBUS.....

Study Area:

This study focusses on the Benguela EBUS. The Benguela EBUS is unique in that it is bounded at both the equator ward and pole ward ends by warm water regimes. These currents are forced locally by the wind stress field off South-West Africa (Nelson and Hutchings 1983; Fennel 1999). This upwelling system stretches along the south-western coast of Africa from southern Angola to Cape Agulhas (Cole, 1999). Water is coldest and most persistent off the Namibian coast at 25°S and weakest at 17°S (Lutjeharms and Meeuwis, 1987). The main upwelling period in the Benguela north of 25°S extends mainly from March to November, peaking during August (Shannon, 1985), but upwelling persists throughout the year. Upwelling season in the northern Benguela extends between September and March, with very little upwelling taking place during winter (June-August). In the central Benguela and also at Cape Frio upwelling is continuous throughout the year (Shannon, 1985). The cold Benguela waters are bound in the south by the warm Agulus retroflexion region and in the north by the southward flowing Angola current. The flow of the Benguela is often considered to be topographically guided (Nelson and Hutchings, 1983; Barange et al. 1991a and 1991b). The Benguela system is split into northern and southern systems by a zone of intense perennial upwelling activity in the Luderitz region within the Namibian region (Shannon 1985; Cole 1999).

Upwelling in the northern Benguela is in phase with the seasonal insulation cycle, whereas in the southern Benguela it is not. The result is that there is a pronounced seasonal cycle in SST in the north while in the south there is no clear SST cycle. The seasonal warming occurring during the late summer season off northern and central Namibia is a regular occurrence and is associated with warmer, higher salinity water of Angolan origin into the region (O'Toole, 1980; Shannon, 1985). There have been a number of warm and cool periods documented in the northern and southern Benguela (e.g. Stander and De Decker, 1969; Walker et al.1984; Shannon et al., 1984; Boyd and Thomas, 1984; Shelton et al. 1985; McLain et al.: 1985). Walter (1937) found a major climatic event in the northern Benguela region of anonymously warm water. This unusual warm water may have resulted due to reduced upwelling or an increase southward advection of warm water. Another warming event occurred during the summer and autumn months of 1984 (Shannon et al, 1986). The presence of this anomalous warm water during 1984 followed two cooler than normal years in the northern Benguela. Shannon et al. (1986) illustrated the warm (21-23°C) water near Walvis Bay as a large warm water patch offshore west of Luderitz. The absence of upwelling between Walvis Bay and north of Luderitz is evident however, the upwelling centre in the Benguela system (Shannon, 1985), and upwelling was minimal. Interestingly, in the southern Benguela region, there was no evidence of any unusual patterns in temperature distributions. The seasonal temperature pattern within the northern Benguela is somewhat similar to that in the eastern equatorial Atlantic and the regular southward intrusion of warm water into the northern Benguela during the summer season. During these warming periods the equator ward wind stress over the northern Benguela region was stronger than normal; yet upwelling was suppressed by the southward movement of warm saline waters from the Angolan region.

Northward, the Benguela Current Upwelling system is linked by the Angola Benguela Front which converge between the Benguela current and the Benguela coastal current as well as the warm saline waters of the Angola Current (Peterson and Stramma, 1991). Research done by Yamagata and Iizuka (1995) discovered slight indication that coastal Kelvin waves, originating from equatorial Kelvin waves, carry the down welling process southward. Southward, the coastal upwelling system is bounded by the Agulhas Bank. South of the African coast the warm Agulhas Current, western boundary current, flows in from the Indian Ocean and returns eastwards while generating warm eddies that spin off in a north-westerly direction in the Benguela current (Duncombe, 1991). The region surrounding the Benguela experiences a persistent along shore wind. This wind is associated with the St. Helena high pressure system. Lutjeharms and Meeuwis, (1987) also found a strong relationship between the intensity of upwelling events and the strength and direction of prevailing winds. These favourable upwelling equatorial winds represent a maximum at 25°S and decrease towards the northern and southern boundaries of the Benguela upwelling system. Continental shelf bathymetry and upwelling favourable winds provide a large-scale upwelling mechanism in the southern Benguela, whereas local topography and meteorology create an alternating pattern of active and passive upwelling circulations along the coast. Winds occurring within the southern regions represent a seasonal variation, reaching a maximum during spring and summer months (Boyd 1987; Shannon and Nelson 1996; Fennel 1999). Winds occurring within this region tend to show increasing patterns away from the coast whereas, winds occurring in the northern region exhibits relatively less seasonal variation (Shannon 1985. Pitcher et al. 1992). Upwelling occurring along the South Coast of the Cape Province within South Africa, specifically along the coastline is generated by local wind. The wind increases somewhat away from the coast. This facilitated the idea of wind stress curl, as discussed in Bakun and Nelson (1991) and Shannon and Nelson (1996).

Extreme events

Extreme thermal events have a range of broad scale definitions, but they can each be classified into two categories, namely, cold-spells (e.g. Gunter, 1941; Lirman et al., 2011; Boucek et al., 2016) or heatwaves (e.g. Gordon et al., 1988; Stott et al., 2004; Perkins-Kirkpatrick et al., 2016). These events occur rapidly, and unexpectedly and they profoundly impact on species diversity, distributions, growth and survival where they take place. These events are often undetected but studies have found that extreme events have occurred as recently as approximately four decades ago. Jentsch et al. (2007) were the first to discuss this mode of climate change and brought it to focus. Steps have since been taken towards understanding the drivers, impacts and consequences of these events. Subsequently, research has predicted an increase in the occurrence of these extreme events as a result of long-term warming of the planet via the process of global warming (REFERENCE). Extreme events are often associated with toxic algal blooms, shifts in species distribution, and the bleaching of coral reefs (McCabe et al., 2016; Harley and Paine, 2009; Schoepf et al., 2015).

Little is known about extreme events occurring within the South African region. Very little South African researchers spend their time and careers on studyig extreme events within this region. During the 1980s, a study done by Birkett and Cook was the only study done where they anaylsed the impact of extreme warming events on the life cycle of white muscles,Donax serra Röding. However, more recently studies done by Schlegel et al, (2017,2018) examined the relationship between the nearshore and offshore occurances of marine heatwaves and cold-spells as well as the influence of predominant atmosphetic and oceanic patterns during Coastal Marine Heatwaves. It is now becoming accepted that extreme events are a threat to several ecosystem (Thompson et al., 2013).

Cold spells

- Definition
- Impact -Major cold spells

Aims and approach:

In this thesis I aim to…