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Documentary based evidence for sardine run events, east coast of South Africa: 1946-2012

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Abstract

The southern African sardine run is an annually recurring phenomenon involving vast schools of sardines travelling northwards along the east coast of South Africa. Climate change is assumed responsible for recently observed changes in the occurrence of sardine runs, yet data have been absent to quantify any phenological changes over time. The National Library of South Africa has extensive archives of Kwa-Zulu Natal based newspapers which were scrutinized to determine the annual arrival of sardines at specific places along the east coast between 1946 and 2012. In particular, 'The Natal Mercury', 'South Coast Herald' and 'South Coast Sun' newspapers were consulted. This yielded an uninterrupted sardine run record spanning 66 consecutive years. This is the first such study examining historical fish phenology in the southern Hemisphere.

A variety of environmental conditions is thought to influence the sardine runs and may include, oceanic temperatures, oceanic currents, visibility of the water, wind speed/direction and air temperature. We thus also demonstrate historical climate variability and change along the east coast for the period between 1936 and 2012, based on data obtained from the National Oceanic and Atmospheric Administration (NOAA) and the South African Weather Service. In particular, we examine the parameters: temperature, wind, the occurrence of westerly wave disturbances (i.e. cold fronts), the El Nino Southern Oscillation, and the Southern Oscillation Index. The sardine run data are then compared against the various climate parameters to ascertain which variables most influence their phenology. It is found that the sardine runs have become more temporally delayed during recent years, particularly since the late 1960s/early 1970s, and may be associated with considerable increases in Sea Surface Temperatures (SST) since that time.

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ENSO: El Niño Southern Oscillation
SST: Sea Surface Temperature
NOAA: National Oceanic and Atmospheric Administration
PSJ: Port St. Johns
PSH: Port Shepstone
EL: East London
DBN: Durban
IPCC: Intergovernmental Panel on Climate Change
USGS: United States Geological Survey
SAWS: South African Weather Service
KZN: Kwa-Zulu Natal
MEI: Multivariate El Niño Southern Oscillation Index

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Chapter 1: Introduction

1.1 Introduction

Over recent decades, climate scientists have drawn many conclusions about the earth's climate and the general consensus is that there has been recent accelerated warming owing, at least in part, to anthropogenic-related CO_2 emissions (Kutzbach et al., 2010; Fischer and Knutti, 2015). The global energy budget has increased and has brought about climatic changes the world over (Intergovernmental Panel on Climate Change [IPCC] 2013). This change in climate alters weather patterns and has made weather more variable during recent years (Stenseth and Mysterud, 2002; Fischer and Knutti, 2015). According to the IPCC (2013) reports, global surface temperatures have increased from the late 1900's onwards, which on average has increased by 0.85°C between 1880 and 2012. Moreover, strong evidence suggests that sea surface temperatures (SSTs) have warmed significantly at all latitudes. According to data sets from the last 40 years (1971-2010, the upper 700m of oceans have undergone strong warming (IPCC, 2013).

Southern Africa is particularly affected by climate change, of these impacts drought and flood have the most widespread and pronounced consequences on society and in particular the agricultural sector, which is dependent on reliable rainfall (Reason et al., 2006). Because climate change has hard-hitting outcomes for all inhabitants of the southern African region, it is therefore essential to understand these changes in climate in order to mitigate its effects. Thus, much climatic research has been undertaken to better understand these implications. Climatic research in southern Africa has focused on all spheres; terrestrial, atmospheric and oceanic, largely to determine how these systems have changed over time and to what extent their impacts have had on observed changes in climate across the region (Tyson and Whyte, 2000; Grab and Simpson, 2000; Rouault et al., 2009; Grab and Nash, 2010; Rouault et al., 2010; Weldon and Reason, 2014)

In southern Africa, extended instrumental records of climatic data are hard to come by, therefore climate data need to be observed using other forthcoming methods so as to extend the climate chronologies based only on instrumental records (Vogel, 1989; Nash and Grab,

2010). Proxy data sources such as diaries, newspaper articles memoirs and letters have proven to be an invaluable source of data to reconstruct past extreme weather events and climate chronologies (Vogel, 1989; Lindsay and Vogel, 1990; Nash and Endfield, 2002; Nash and Grab, 2010). These papers used historical documentary evidence to determine if any changes had occurred in rainfall patterns over time, or the seasonality of such rainfall patterns.

1.2 Setting the research scene: climate and phenology

Historical meteorological data have enabled scientists to better understand and explain likely drivers of climate change. The El Niño Southern Oscillation (ENSO) is a climate phenomenon which induces warming over the Pacific Ocean and is known largely to be responsible for dry conditions over central southern Africa (Mason and Joubert, 1997). Over the last 40 years it has been determined that El Niño events have occurred more frequently than La Niña events, the latter of which is synonymous with wet conditions over southern Africa (Mason and Joubert, 1997), and which have far reaching consequences for southern Africa. This is a result of atmospheric teleconnections caused by ENSO cycles, which have the ability to alter near surface air temperature, and in so doing can affect sea surface temperatures, salinity, and ocean currents (Alexander et al., 2002)

The surrounding coastal waters of southern Africa have also had an influence on the southern African climate. Moisture accumulated in the atmosphere over the Indian Ocean is responsible, in part, for the summer rainfall received over southern Africa (D'Abreton and Tyson, 1995). Understanding oceanic mechanisms and the relative oceanic and atmospheric interactions is therefore essential to detect changes in climate variability as a result in changes associated with oceanic mechanisms. Significant increases of temperature observed in the currents surrounding southern Africa have resulted in an influx of energy into the atmosphere which then plays a substantial role in the observed climate (and its variability) and associated marine ecosystems over southern Africa (Rouault et al., 2009).

Climate variability/change and the rapid changes it brings have had noticeable effects on terrestrial and aquatic species. Life cycle events and their timings are sensitive to climatic changes; therefore, they are regarded as important bio-indicators of how species are

responding to climate variables and change (Gordo and Sanz, 2005). By conducting research that extends many decades into the past, scientists have been able to improve their understanding of how these species have responded ecologically to the observed climate change (Stenseth and Mysterud, 2002; Matthews and Mazer, 2015). The scientific field of phenology, focusing on seasonal timings of life cycle events, has become more prominent in the field of climate change in recent times (Beaubien, 2011; Morelatto et al., 2016). Phenology, as a field in its own right, has become more prominent since the 1990s, most likely due to the rapid climatic changes that have occurred since then, having impacted on crop production in particular (Beaubien, 2011; Bjorkman et al., 2015; Cole et al., 2015; Matthews and Mazer, 2015; Morellato et al., 2016).

Phenology is the study of both faunal and floral seasonal response activities, based on certain environmental factors and conditions. Today, phenology is centralized around the study of how animals and plants are responding to observed climate change (Stenseth and Mystreud, 2002; Gordo and Sanz, 2005; Gordo, 2007; Matthews and Mazer, 2015; Morellato et al., 2016). Phenological studies to date have suggested that there is a noticeable trend of both animals and plants advancing their phenophases, such as the timing of flowering and breeding as a result of climate change (Walther et al., 2002; Mathews and Mazer, 2015; Wang et al., 2015). Based on this observation, the real question posed to scientists is how to interpret these observations; will it impose positive or negative influences on different species and will they be able to cope with these rapid changes? Positive responses could entail species adapting and coping to the noticeable changes in climate, or negative responses because climate is affecting phenophases of both plants and animals (Parmesan and Yohe, 2003). From an ecological point of view, the science of phenology is important because of the way species respond to mitigate challenges posed to them.

Phenological studies have been conducted as far back as the 1800's; one such study was pioneered by Wells W. Cooke in 1881. Cooke started the North American Bird Phenology Program in which more than 3000 people took part, recording more than 870 bird species' departure and arrival dates from 1881 to 1970 when the program terminated (USGS, 2013). In Japan, the Cherry blossom festival is a yearly reoccurring event because of its popularity and cultural significance. Because of this significance, records from festivals were kept by numerous sources; from which a record of the cherry blossom dates was constructed, which date back 1200 years (Primack et al., 2009). This extensive data set was thus used to

determine the effect that climate change has had on Cherry blossoming dates and it has been shown that due to recent climate warming, the cherries are blossoming up to 7 days earlier during the past 3 decades (Primack et al., 2009). Many phenological studies have been conducted worldwide focusing on bloom dates for important crops such as apples and pears (Grab and Craparo, 2011), citrus plants (Ramírez and Kallarackal, 2015; Kistner et al., 2016). and nuts (Pope, 2013; Guo et al., 2013). It is generally argued in these studies, that in response to recent climate change, blooming dates have advanced particularly during the growing season. The numerous research papers in this field is evident because plants are stationary organisms and easy to monitor, and in addition, because of their commercial importance, farmers usually keep records of when they bloom and produce fruit.

Animal phenology is more difficult to observe because they are not stationary and often migrate to new locations during particular seasons; their mobility aids them to cope with changes in climate and seasons, far more so than stationary species that are forced to cope with the observed changes *in situ*. However, records have been kept of when animals depart from a certain location, and when they arrive at their new locations. Such studies include the North American Bird Phenology Program and avian migratory patterns (Hüppop and Hüppo, 2003; Hurlbert and Liang, 2012). These studies all concluded that there is a noticeable trend in earlier arrival times for the bird species studied.

Marine species are challenging to monitor because they are constrained to depths under water and cannot be observed from the air and are not limited to one particular area of the ocean. Efforts have been made to determine the responses marine species are displaying as a result of climate change. Such undertakings have been conducted by Sims et al., (2004); Jansen and Gislason, (2010); Tseng et al., (2011) and Asch, (2015). In the studies mentioned above, all have concluded that the marine species concerned have been influenced by climate change and rising ocean temperatures, either changing their locations in search of favorable habitats or the timing of important life cycles have changed. Studies concerning marine phenology have only been undertaken in recent times, and the science in itself is still in its infancy. The importance of sustaining fish stocks is rudimentary and thus all research concerned with marine phenology is important because the positive and negative effects of rising ocean temperatures needs to be identified in order to preserve fish stocks by identifying the risks posed to fish by climate change and variability. The majorities of such research

initiatives stem from the northern hemisphere, and are becoming more prevalent as the need to conserve fish stocks is becoming a great concern on a global scale.

With regards to southern Africa, little published work exists on how climate change is impacting marine species around the southern African coast; in part this is potentially difficult to quantify given other possible factors such as over-fishing, increased recreation and commercial activities, and likely reduced food sources for many marine species.

Given this knowledge gap, an opportunity exists to investigate the possible impact of climate change on marine life in southern Africa. Thus, this Masters research project focuses on both climate change (Sea Surface Temperature changes) and phonological changes in the timing of the near annual sardine run up the east coast of South Africa, with a view to establish any possible associations.

1.3 Rationale

The annual southern African sardine run is said to be a poorly understood phenomenon and thus any research examining the nature of such events should be of value (O'Donoghue et al., 2010). Many of the sardines that eventually make it onto the beach along the KwaZulu-Natal coast line are harvested by the local communities, in what is described as a 'beach seine fishery'. Although the numbers harvested are relatively small compared to what is harvested in the Western Cape by commercial sardine fisheries, the harvesting of the sardines from the beach provides a great amount of excitement and entertainment (van der Lingen et al., 2010). The sardines are not only important to the local fisherman, but are also an important source of nutrition for fish, birds and other mammals. Many species time their migration and breeding patterns in accordance to sardine arrival times because they serve as a vital source of nutrition central to their life cycles (O'Donoghue et al., 2010). The sardine run has also attracted large historical film making channels such as National Geographic and Discovery Channel. Local and international divers regularly witness the sardine run and the accompanying predatory fish species along the east coast of South Africa. Scuba diving charters rely heavily on the sardine run as a major tourist attraction. Radio stations and even a hotline run by the KwaZulu-Natal Sharks Board report on the daily movement of the sardines and where they are on a daily basis (van der Lingen et al., 2010).

It has been observed that in some years, the sardine run does not take place (i.e. their movement along the coast goes unnoticed or they do not venture close inshore), but the causes are unknown and hence require an investigation. In 2013 and 2014, it was observed that the sardines did not make an appearance and have not been observed, apart from small bait balls (congregation of smaller bait fish that are preyed upon by other larger pelagic fish species and mammals [Clua and Grosvalet, 2001]) and other bait fish species (independent Online, 2013). It is believed that warm ocean temperatures are responsible for the sardines not migrating up the coast, inhibiting the movement entirely (independent Online, 2013). Estimating when the sardines might arrive, if the event might be diminished, or not take place in a given year, is important when planning for the attraction, also to inform stakeholders in advance. Being able to do this should aid the local economy and the tourism of KwaZulu-Natal. Research on the sardine run and investigating possible causes influencing its timing, is thus important.

1.4 Aim

The aim of this research project was to investigate whether there is any link between regional climate change/variability, and the timing of the South African Sardine Run. It was hypothesized that climate change/variability has influenced oceanic conditions and is continuing to do so, and thus the phenology of sardine migration along the east coast of southern Africa. However, the change in oceanic temperatures and oceanic mechanisms may not be the only variable that is influencing the annual timing and migration of sardines, thus all possible variables within climate systems were considered when the analysis was undertaken.

1.5 Research Questions

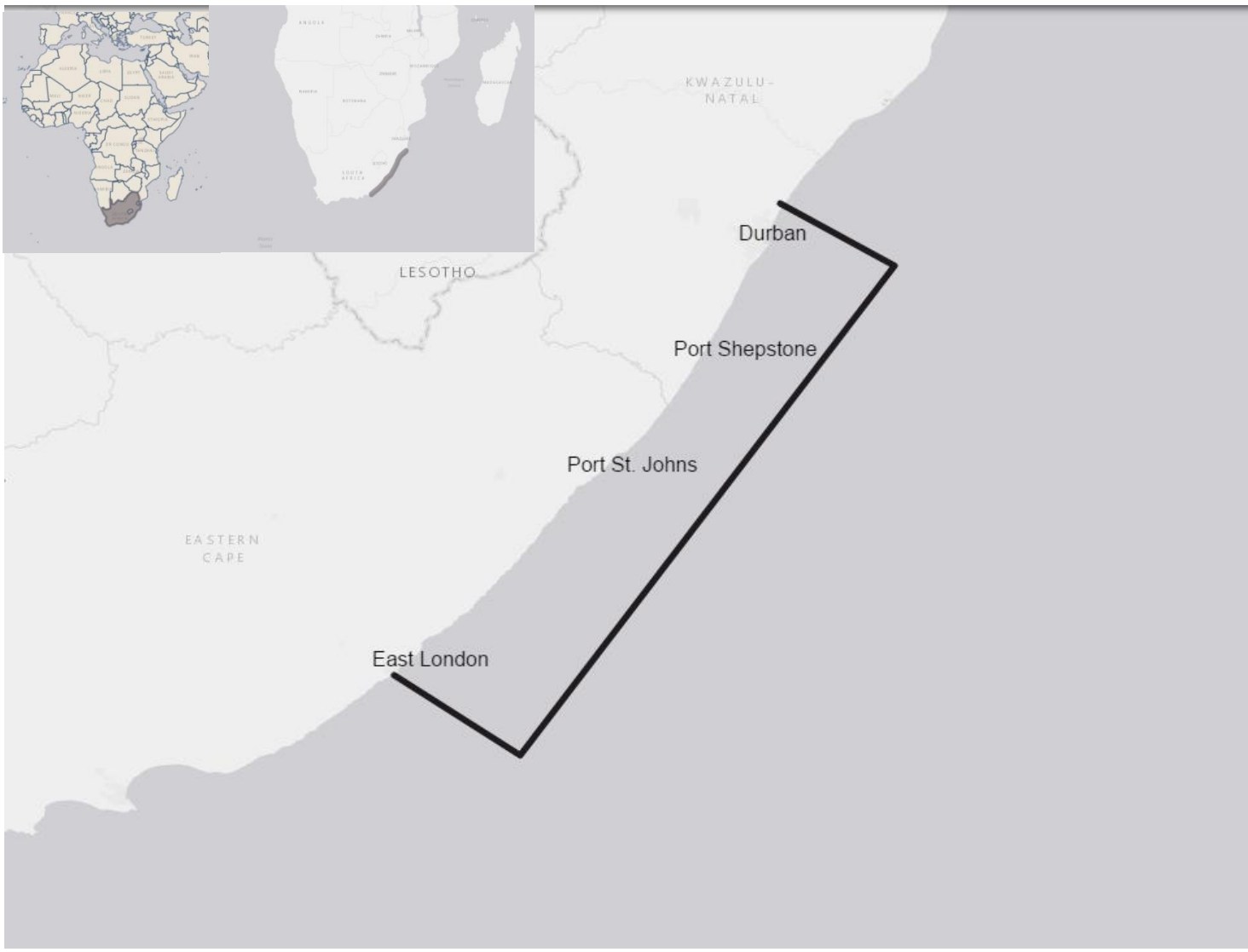
The sardine run is influenced by numerous environmental factors which are thought to be, but not limited to, ocean temperatures and oceanic mechanisms. Thus, to establish what might possibly influence the annual timing of the sardine run, these factors need to be taken into consideration. Due to the fact that the oceans surrounding southern Africa have been poorly surveyed, extended temperature records are not available. However, because ENSO influences oceanic mechanisms which are believed to aid the sardine run, historical ENSO records, along with other historical climatic data sets will be used to determine if any relationship exists with the sardine run. The MSc project will be investigating if there has been any change in the annual timing of the sardine runs using historical documentary evidence. This work aims to establish longer term trends (>50 years) in the sardine runs to better statistically establish any cyclic or other trends in comparison to climate and oceanic changes.

1. Are the observed changes in the timing of the sardine runs a result of interdecadal variability of the sardine runs itself, or has the El Nino Southern Oscillation impacted on the timing of the sardine runs?
2. What are the possible implications of changing ocean temperatures on the sardine runs?
3. Will the increase of oceanic temperatures inevitably cause the sardine runs to cease in future years, as was noted in the sardine run of 2013 and 2014?
4. What are the other non-climatic variables that may impact the sardine runs?
5. Have there been any observed changes in the frequency of sardine runs taking place over the period observed?

1.6 Regional Setting

The sardine run is an annual reoccurring event that takes place along the east coast of South Africa during southern winter months, predominately between the months of June and July. The sardine run becomes evident once large shoals of sardines congregate offshore in the region of Port St. Johns where they begin their journey northwards to the south coast of Kwa-Zulu Natal. These fish events, in some cases, make their way as far north as Durban and surrounding areas and are known to have, on a few occasions proceeded as far north as Cape

Vidal (O'Donoghue et al. 2010; van der Lingen et al., 2010). However, in some years (e.g. 2013, 2014) the sardines do not venture on their annual migration, reasons for which are not fully understood, but it has been suggested that such cases may be due to adverse oceanic conditions, temperate oceanic waters, lack of nearshore (refers to the body of water that is in close proximity to landfall or the shore) counter currents and poor water visibility (O'Donoghue et al., 2010). Given this uncertainty, the current study aims to determine whether there may be a climate associated reason for non-run years.



Regional Map: Geographical reference map showing the regions of study of the research undertaking. Indicating the four main towns used in the analysis as well as the region where the sardine sightings were made.

Chapter 2: Literature Review

2.1 Southern African Climate Change

A significant amount of work has been conducted to determine the impacts of climate change in southern Africa, of which, largely investigate the causality between climate change and rainfall patterns (Reason et al,. 2006). This can be attributed due to the fact that the region is predominately agricultural and a large number of the population relies on rain-fed subsistence farming practices (Reason et al., 2006; Tibesigwa et al., 2015) and is why there is a substantial amount of research written on the subject. ENSO periods have been deemed largely responsible for rainfall variability experienced over much of the southern African region as evidence suggests significance between the correlation of wet periods with La Nina and dry periods with El Niño (Lindesay and Vogel, 1989; Reason et al., 2006; Weldon and Reason, 2014). Southern Africa is therefore subjected to pronounced periods of droughts and flooding (Reason et al., 2006). Apart from the rainfall variability, evidence has been brought forward to depict significant changes in temperature increases for many regions in South Africa (Reason et al., 2006; van Wilgen et al., 2015). Despite all the research conducted to determine the impact climate change has on agricultural practices, natural disaster, risk and mitigation, little research has been done to determine the impact of climate change on animal species in southern Africa as Erasmus et al., (2002) report this subject has been poorly documented. Therefore, all research concerning fauna and marine species is now fundamentally important.

2. 2 Observed Changes in the Coastal Waters of Southern Africa

The change in water temperatures has been described as one of the most innate indicators of change in a marine environment concerning global climate change (Bailleul et al., 2012), therefore, special emphasis on the change of oceanic temperatures where the sardines are found, need to be investigated to determine if any such change exists in their given marine environment. The Agulhas current is known to be very influential with regards to the weather and climate of southern Africa and is key to marine species and ecosystems (Lutjeharms, 2007). Therefore, it is important to comprehend the ways in which the system has changed, so as to enable further understanding on how they may possibly impact marine species and

how these species are likely to respond to such systems changes. Rouault et al., (2009) have reported noticeable changes in the coastal waters surrounding South Africa. One of the changes which are of importance to this study is that the Agulhas current has warmed since the 1980's. The Agulhas current has undergone significant increases in sea surface temperature; this has been a result of the intensification of the currents' transport brought about by an increase in wind stress curl over the southern Indian Ocean (Rouault et al., 2009; 2010). As a result, more energy is released from the oceans into the atmosphere and this has led to increased eddy kinetic energy which affects the migration of the sardines (Rouault et al., 2009; 2010). The Agulhas current is also responsible for changes in upwelling which has been positively linked to ENSO cycles. El Niño years negatively impact the upwelling, while La Niña influences upwelling positively, ENSO cycles have been statistically linked to episodes of warm and cool events present in SST (Rouault et al., 2009; 2010). Both oceanic temperatures and oceanic mechanisms have been known to be influential with regards to the sardine runs, therefore it is of importance to determine this change and investigate possible implications it has on the sardine run, this is discussed further in the later part of this chapter. The coastal waters of southern Africa are known to be poorly surveyed and hence the greatest challenge this research initiative faces is finding useable data to determine any possible implications the change in coastal waters have on the sardine run.

2.3 Phenology

Phenology can be described as the scientific study of the influence that climate change has on inter annual or seasonal life cycle events of animals and plants, such as budding and migrations (Parmesan and Yohe, 2003).). Research focusing on global ecosystems and species that occupy them, has found that anthropogenic climate change has impacted such ecosystems; this is now well understood given global metadata analyses which provide high confidence in findings made (IPCC, 2013; Parmesan et al., 2013). Numerous studies have shown that animals and plants are shifting their ranges as well as the onset of important life cycle events such as flowering, reproducing and migrating, due to an increase in global temperatures (Hurlbert and Liang, 2012). A noticeable trend has been observed at a global scale concerning numerous different species of fauna and flora, in particular the onset of earlier arrival of important life cycle events which is rooted in a rise in global temperature. The current research dissertation may be classified as the phenological study of the South

African sardine run, because the objective was to investigate how climate change/variability has potentially influenced ocean currents, oceanic drivers, ocean temperature and ultimately the annual sardine migration along the east coast of South Africa. It has been observed that migrant organisms await seasonal cues that set them off to their new destinations or breeding grounds; these seasonal cues can be temperature related or can be photoperiods (Schwartz et al., 2006). Photoperiodism can be described as the response that organisms, both plants and animals, have to the length of day and night. Both the above mentioned seasonal cues are important for migrants to reach their destination in time for important life cycles. Other factors also contribute to changes in arrival dates for different species, one of these factors is migration distance. Species that have a shorter distance to travel and migrate, have a better capacity to assess conditions of their migration route and therefore such species tend towards an earlier migration pattern (Gordo, 2007).

Seemingly, some birds have shifted their migration dates and arrival dates by 0.8 days earlier for every 1°C increase in temperature, while other bird species have shifted their range by as much as 3 to 6 days earlier per 1°C increase, the difference in arrival times may be a result of species characteristics of different birds (Hurlbert and Liang, 2012). It can be inferred from the readings that both plants and animals are being significantly influenced by climate change, in particular the timing of their phenophases.

Being able to understand how different species and ecosystems respond to changing environmental conditions is crucial to foresee future changes as a result of continuing and forthcoming climate change, thus enabling researchers to pinpoint those species that will be most adversely affected by climate change (Hurlbert and Liang, 2012). It is of great importance that animals and plants time their movements or life cycles. Arriving late may leave the animal in competition for space or food, while blooming too early or late will also have consequences such as not being pollenated by insects at the correct time when they are present (Mauseth, 2003).

2.4 Fish Phenology

This subsection will present research on marine species of fish and the impacts climate change has had on their phenology and onset of life cycle events. Because research on this topic is sparse in the southern hemisphere and especially Africa, most of the literature presented is focused on northern hemisphere fish species. Nevertheless, their responses can shed light on important facets that may also be observable within the sardine run.

Whilst much research has focused on how increases in mean global temperatures are affecting terrestrial plants and animals, not many studies have examined their aquatic counterparts, specifically in southern Africa. Changes in global climate have affected the life history of fish species that are an important food source. To sustain this food source, the relationship that exists between the life history of fish species and the change in temperature needs to be explored (Graham and Harrod, 2009). It does hold constraints given that marine life is extremely difficult to monitor because much of it occurs at depth underwater, and this is difficult to observe and measure. Recent advances in technology, such as bathymetry (the scientific study involving the below surface mapping of waterbodies (Thurman, 1997) derived from sonar side scanning are assisting in overcoming some of these challenges by identifying schools of different fish species (Pittman et al., 2009).

The North Sea Mackerel is a migratory pelagic fish species and a study has been conducted exploring its migration patterns in relation to temperatures during their annual migration into the northern North Sea during autumn and winter months (Jansen and Gislason, 2011). A strong relationship was found between sea surface temperature and the timing of pre and post spawning migration. The arrival of the mackerel was very closely related to the temperature during the start and peak of the spawning period and it was noticed that warmer and colder years could produce up to a two month difference in the arrival time of the mackerel (Jansen and Gislason, 2011). The results suggest that with the current trend of increasing temperatures, the North Sea Mackerels' important life cycles would change, as well as impacting their growth, reproduction and migration patterns (Jansen and Gislason, 2011).

Another pelagic fish species that is influenced by sea surface temperatures is that of the Pacific Saury. Like sardines, they are found in large schools and prefer cooler water temperatures, the Pacific Saury are found in the coastal waters near the Japanese island of

Hokkaido (Tseng et al., 2011). The saury is a very important species of fish to many economies and had a net worth of one to three billion New Taiwan Dollars between 2007 and 2010 (Tseng et al., 2011). Although the sea surface characteristics (e.g. temperature) are not the only determining influential factor on the habitat of the saury, others, such as food availability and below surface water column temperatures are also influential, however, it does play an important role in predicting the habitat that the saury occupies (Tittensor et al., 2010). Commercial fisherman, therefore, use newly gathered sea surface temperature data to determine potential fishing grounds of the Pacific Saury (Tseng et al., 2011). It was observed that there has been a noticeable poleward shift of the Pacific Saury in order to find favorable ocean temperatures/habitats and this has been hypothesized to be due to climate change (Tseng et al., 2011).

The Beluga whale's migration phenology was studied in the eastern Hudson Bay of Canada and an attempt was made to determine the impact climate change has had on their annual movements. It was established that the SST's were related to the movement and migration of the Beluga whales and was a useful indicator in predicting their migration timing (Bailleul et al., 2012). However, it was apparent that uncharacteristic behavior displayed by some whales was indicative that external environmental characteristics and the animal's instinctive nature could also be responsible for initiating their migration (Bailleul et al., 2012). This is an important factor to consider when analyzing the sardines response to the change in coastal water temperatures. Although it might be apparent that the water temperature influences when they migrate and the movement they follow in search of a favorable habitat range, external environmental factors and intrinsic instinctive behavior could explain their migration patterns further.

Fisheries form part of large sectors within the global economy that have a monetary value of 217 billion Dollars, as estimated in 2010 by the Food and Agriculture Organization of the United Nations (FAO, 2010), and therefore need to be managed effectively, placing emphasis on how important climatic research on marine environments is. The English flounder has been observed to migrate from its estuarine habitats into the oceans to spawning grounds upon favorable ocean temperatures (Sims et al., 2004). In years recording up to a 2°C difference in ocean temperatures, the flounder was found to migrate to spawning grounds between 1 to 2 months earlier. This is indicative that the flounder is sensitive and responsive

to temperature changes. Apart from this, it was found that the North Atlantic Oscillation had significant effects on the timing of peak abundance of fish populations (Sims et al., 2004).

2.5 Climate Change and Phenology

The general conclusion that can be drawn from phenological studies and the influence climate change has had on numerous fauna and flora, the ecosystems they inhabit, and how these systems have depicted change, is that anthropogenic influences on accelerating climate change have indeed impacted biota (Parmesan et al., (2013). For instance, studies have found an early onset of avian migration patterns (Hurlbert and Liang, 2012; Hüppop and Hüppo, 2012), changes have been depicted for the North Sea mackerel's life cycle events in response to rising ocean temperatures (Jansen and Gislason, 2011), and the Pacific saury have changed their habitat range in response to rising ocean temperatures by moving poleward in search of cooler oceanic temperatures (Tseng et al., 2011). Further, many studies have reported an advance in the onset of fruit tree blossoming dates in response to climate change and variability (e.g. Primack et al., 2009; Grab and Craparo, 2011; Pope, 2013; Guo et al., 2013; Ramirez and Kallarackal, 2015). Poloczanska et al. (2013) investigated 1735 marine biological responses as result of climate change and found 81-83% of all observations where consistent with expected impacts of climate change, some of the impacts included distribution, phenology, abundance and demography. The phenological responses of taxa studied had rates comparable to or greater than terrestrial systems. Marine ecosystems are experiencing population wide phenological shifts because the new environments pose physiological intolerances that species cannot cope with (Doney et al., 2012). A further recent study by Ge et al. (2014) investigated phenological responses of 112 species in China, which were made up of numerous fauna and flora containing data sets extending beyond the past 20 years. This study found that 90.8% of all spring/summer phenophases show earlier trends with a mean advance of 2.75 days across all species observed. Marine environments have changed as a result of changes in atmospheric concentrations of CO_2 and associated climate change, which have consequently brought about oceanic acidification, nutrient input fluctuations, changes in temperature circulation and current shifts, all of which have caused the observed responses in marine taxa phenology and habitat distribution (Doney et al., 2012). With new evidence and research methods emerging, important observations are being made in both terrestrial and marine ecosystems as to how species are responding to climate change and what consequences may be expected.

2.6 Sardine Run Theories and Possible Causes

Because the sardine run is a relatively poorly understood phenomenon, there have been many attempts to explain the exact purpose and reason of the migration. In the subsection bellow, some of the theories proposed and published will be further discussed. As theories progress through time, new evidence is brought forward, which, starts to strengthen ones grasp and understanding as to why they migrate northwards in the case of southern Africa. More recent theories begin to agree on a common reason as to why they migrate northwards, with focus being directed to other mechanisms associated with the run, explaining further how they migrate northwards and what factors are detrimental to their movement.

Earlier research had shown that sardines were not a resident population of KZN, but were migrants from the Agulhas Banks offshore of Cape Town (Baird, 1971). From the main shoal located near the Agulhas Banks, a smaller shoal separates, and migrates from the Cape waters to KZN (Baird, 1971). Previous studies have concluded that the Agulhas Banks of the southern Cape are the main breeding grounds for the larger population, which is why Baird's, (1971) theory was a strong possibility. The northward movement of the sardines along the coast could occur because of a counter current originating from the Agulhas banks that flows alongside the Agulhas current and enables the sardines to move up along the coast (Baird, 1971; van der Lingen et al., 2010). Heydron et al., (1978) also agreed that the sardines migrated from the Agulhas banks up the coast, but were indeed skeptical of such a large counter current that allows the sardines to migrate up the coast. These authors posited an oceanic mechanism that developed advection pockets of cooler water that moved in a northerly direction, enabling the sardines to move along the coast (van der Lingen et al., 2010). Both Baird, (1971) and Heydron et al., (1978) theorized that the sardines migrated from the Agulhas banks but they used different oceanic mechanisms to explain the migration up the coast. Baird, (1971) also suggested that no evidence could be found as to why the sardines would migrate to KZN; and found no evidence of spawning grounds for the sardines. It was thus theorized that they had no apparent reason to migrate northwards along the coast.

Armstrong et al., (1991) proposed that the sardine run occurred because of conditions that extended their preferred habitat. Usual timings of the annual sardine run confirmed the theory that seasonal variations such as temperature were more influential to the sardine run than

other abiotic factors such as counter currents (van der Lingen et al., 2010). It could be said that the theory by Heydron et al., (1978) was more correct, that there were advection pockets which allowed the sardines to migrate because it extended their preferred habitat. This compares favorably with research findings by Tseng et al., (2011) who found that the saury moved to different locations in search of their preferred habitat range and because of this, could be monitored by predicting where their favorable ranges occur.

Studies conducted by Van Der Byl, (1978) and Connell, (2001; 2010) both concluded that sardine eggs and larvae were present in the waters of KZN, and the work of Freon et al., (2010) suggest that the sardine run is an annual spawning migration. Connell, (2010) found a strong pattern in the study that took place during the period 1987-1998 where sardine and egg larvae where present in the study area. This could dismiss the idea that the sardines migrate along the coast for no apparent purpose. A strong connection was also found that the sardines would pass the particular area were the samples were collected at the start of the sardine run, which would indicate the possibility of spawning in the area. Connell, (2010) also theorizes that after the run takes place, usually the sardines disappear from sight from observors both on land and in the air, this is typically in response to an increase in water temperatures brought on by seasonal changes, which forces the sardines into deeper waters and towards a more southerly direction (van der Lingen et al., 2010). The findings of both Van Der Byl, (1978) and Connell, (2010) contest the theory of Baird, (1971), and it can be said that indeed the waters of KZN act as a nursery ground for the sardines; it is also believed that the KZN breeding grounds replenish Eastern Cape waters with sardines (van der Lingen et al., 2010). Spawning grounds could be a potential driving factor as to why the sardines migrate to the warmer KZN waters, but other environmental factors such as predators and abiotic factors such as temperature force them inshore (O'Donoghue et al., 2010).

O'Donoghue et al., (2010) state that the sardines prefer a water temperature of between 14 – 20° C; the nearshore water of the KZN coastline cools down to these temperatures during the South African winter months as well as the result of the formation of northward counter flowing currents which are typically cooler than the Agulhas current (Roberts et al., 2010). Winter conditions and the onset of cooler ocean temperatures extend the sardines' preferred habitat range and would enable them to migrate to new breeding grounds, which coincides with the previous views that their preferred habitat range increases and thus they would migrate to these new areas. Another oceanic driver that may influence the sardines moving

northwards along the shore is a cyclonic gyre called the Durban eddy (O'Donoghue et al., 2010; Roberts et al.,2010). The gyre forces warm water from the Agulhas current to flow onshore-wards across the coastal shelf with an increase in SST measureable within 300m of the shoreline and force the sardines into cooler waters which arise from nearshore current that flows from south to north (O'Donoghue et al., 2010). It is along this part of the coastline that sardines are found closest to the shoreline, probably because they are being forced shoreward by the warm water

2.7 Other Variables Influencing the Sardine Run

As previously stated, other environmental factors which may influence sardines, need to be considered. These factors include a calm wind factor, favorable prevailing oceanic currents as well as higher minimum atmospheric temperature, and an increased atmospheric pressure. When present, these factors resulted in a much larger sardine presence. An increase in sea surface temperatures, oceanic currents moving in an opposite direction to which the sardines are traveling, reduced water visibility and large ocean swells, all have been associated with a reduced presence of sardines (i.e. it had a negative impact) (O'Donoghue et al., 2010). Armstrong et al. (1991) noted sardine presence in water temperatures above 20°C and suggested that other variables apart from temperature may act as controlling mechanisms for the sardine movement, such as predation. However, O'Donoghue et al., (2010) argue that environmental variables significantly influence the sardine runs. Environmental factors are said to offer a valuable understanding of what conditions are favorable for the sardine presence (O'Donoghue et al., 2010). Water temperature was found to have a highly significant influence. The observation of sardine presence during winter months is higher during periods between the passage of cold fronts, which creates favorable conditions for the sardines, while the presence of a cold front itself creates unfavorable conditions (O'Donoghue et al., 2010). These contributing factors and variables need to be included in the analysis, as they control conditions which might delay, hinder or even deter a sardine run from being observed.

The nearshore counter currents that arise from upwelling cells that occur between Port Alfred, East London and Port St. Johns, coined the Natal Pulse and Durban break away Eddy, are believed to assist the sardines to move up along the coast and the Agulhas current (van der Lingen et al., 2010; Roberts et al., 2010). Once the sardines reach Waterfall Bluff, they

rely on a Durban break away eddy to move south, which is the last oceanic driver required to assist them to move up the coast. These oceanic mechanism works in unison to assist the northward migration of the sardines as well as enabling them to overcome their habitat restrictions (Roberts et al., 2010) this theory is termed the Waterfall Bluff Gate hypothesis (van der Lingen et al., 2010). Oosterbaan et al., (2013) tested this theory respectively for the sardine runs that occurred in 2003, 2004 and 2005. Their findings were conclusive in proving that this theory is valid and the runs were responsive to their presence or lack thereof. However, historical data for the respective oceanic gyres do not exist and do not extend as far back as the historical chronology of sardine runs acquired for this research study.

Predation is also a determinant with regards to the sardine run migration, as many predators time their life cycle events and migration patterns in relation to the sardine run arrival, and thus are an influential aspect to the migrations (O'Donoghue et al., 2010). Predators may hasten their northward movement which may skew first sightings, in addition the large schools may be broken up into smaller schools. Hence, being able to distinguish between the main shoals and pilot shoals may present challenges. However, as previously stated, O'Donoghue et al., (2010) propose that environmental factors are more influential with sardine movement and presence than external biotic factors.

From such publications, it can be deduced that there are indeed many factors and facets that contribute to the sardine run. Thus, all these factors have to be taken into account when attempting to determine whether or not climate variability is influencing the sardine run, and if so, to what extent.

2.8 Historical Documentary Evidence

To build a historical chronology of historical sardine run events, the aid of documentary material was required to accomplish this because historical sardine run data sets do not predate the 1980's. The same can be said of historical climatic data which are relatively incomplete before the 1950's in southern Africa. This was largely due to a lack of instrumental data sets and technological constraints during the early 1900's and prior. To overcome the lack of continual data sets innovative approaches were therefore required to complete the missing entries. Such innovative approaches were also utilized by Lindsay and Vogel, (1990); Nash, (1996); Shaw and Nash, (1998); Nash and Endfield, (2002); Nash and Grab, (2010), These research efforts sought to reconstruct past climates and by analyzing rainfall and cold season weather phenomenon amongst others. This was made possible by using documentary evidence to build a relative climate chronology. Letters, journals, diaries, reports written by missionaries and newspapers, were used to reconstruct past climates (Nash and Grab, 2010). Thus, the climate could be analyzed to note any variability or change that occurred in the past where no statistical or instrumental data were present. Documentary evidence often records the occurrence of natural disasters and extreme weather events as they have direct implications on social and economic spheres (Pfister et al., 2009). Because the sardine run is a great natural reoccurring phenomenon, the probability of it being recorded in historical newspapers was high. However, more resolute documented evidence of past sardine runs was not readily available, the likes of past catch record sightings from local residents were mentioned in news articles but were never archived. Nonetheless, because of the interest received from the annual reoccurring runs, the subject was well documented and reported on in all the years analyzed,

Chapter 3: Data Capture, Analysis and Methods

3.1 Climatic Data

Historical temperature data, necessary for this dissertation, were acquired from the South African Weather Service (SAWS). Digital data archived by the SAWS generally only extends back to the early and late 1950's, therefore to extend the historical climate data sets to the appropriate dates required sourcing hard copies of annual weather reports. The National Oceanographic and Atmospheric Administration (NOAA) have complete climatic records dating back to 1920, and are based on records for each year from the former Meteorological office in South Africa; they are, however, hard copies and require digitization. The climatic regions that are of interest to this dissertation include two provinces and two weather stations from each respective province. East London (EL) and Port St. Johns (PSJ) were selected for the Eastern Cape while Durban (DBN) and Port Shepstone (PSH) represented the KwaZulu-Natal (KZN) province. The two weather stations that are of key interest to this study are PSH and PSJ, as they are central to the sardine runs. In addition, data from DBN and EL were analysed to confirm the trends recorded for the two main sites, therefore strengthening the observations made for establishing climatic trends. The four stations were also analysed for any overarching trends that may well be present and indicative of similar climatic changes occurring along the eastern seaboard of South Africa.

The temperature records obtained for DBN began in 1937 and continue to present; regrettably records do not extend back to the 1920's for DBN, the reason being that readings were recorded from numerous weather stations located in different areas around DBN and continuous data from one station were not available. Hence these station records were not continued once initial readings were taken from the Durban Airport or Aerodrome. Weather readings were taken from the DBN airport from 1937 to 2012, which yields a 75 year climatic data set. Readings at the PSH weather station started in 1926 and continue to 2012, yielding an 86 year climatic data set. The weather stations at both EL and PSJ both began recording in 1921 and continued to present, apart from PSJ which discontinued weather readings in 2010, yielding a 92 and 90 year climatic data set respectively.

Data obtained from the respective weather stations consisted of monthly mean maximums, mean minimums and monthly averages. Monthly maximum, minimum and average temperatures were calculated and graphically presented for the period between 1920 and

2012. To analyse the data at a finer resolution, temperature change was investigated seasonally. The year would be sub-divided into 4 seasons consisting of 3 months each. December of the previous calendar year would be included in the next years' summer seasonal analysis, therefore, on a seasonal basis, the temporal scale began in 1921 and ended in 2012 with DBN starting in 1938 and PSH starting in 1927. The austral summer would consist of December, January and February; the autumn months of March, April and May; the winter months of June July August; and the spring months of September, October and November. The seasons most important for the analysis would be the periods leading up to the winter months when the sardine runs occur, and thus most emphasis is placed on such months. Each region's data are graphically depicted, showing seasonal changes in the mean maximum, mean minimum and average temperature for their respective temporal scales. Specific monthly temperatures were also statistically tested against historical sardine runs to determine if the sardines are more responsive to one month's temperature than another. Summer and autumn months occurring before the sardine runs were specifically analysed as these are believed to be more influential than months succeeding it.

Historical air temperatures were selected for this study as they are the only records that extend far enough into the past and which may be considered as the closest substitute to oceanic temperatures required for this study. Recent warming observed in the Indian Ocean temperatures derived from satellite data, have shown that oceanic water temperatures are following a similar trend to that of atmospheric temperatures (Rouault et al. 2009; 2010).

3.2 Sea Surface Temperatures

The surrounding oceanic waters of southern Africa are poorly surveyed, with many regions having no continuous historical data sets available. The most commonly used continuous extended data sets are sea surface temperatures (SST) derived from satellite images. However, these data sets have constraints; the sardine runs are found close inshore, often where the coastal bleed occurs in the images where temperatures cannot be determined. In addition, Smit et al., (2013) found large biases between satellite derived data and *in situ* recorded data which may distort the findings and results. Therefore, to acquire oceanic temperature data suitable for this study, these would have to be available as instrumental data. The KwaZulu-Natal Sharks Board took temperature readings when inspecting the shark nets along various beaches along the KZN coast line. However, the limitation of this data set is that, whenever the sardines were in the vicinity, the nets would be lifted to prevent any

predatory fish being caught, and thus no recordings would be made (O'Donoghue et al., 2010). Pending the creation of data sets that would be of enhanced use for this study, oceanic temperatures were substituted by atmospheric temperatures which are continuous and extend back as far as the historical sardine run records. Nevertheless, SST's are of importance with regard to this study because it may show thermal changes in the oceanic waters surrounding the eastern coast of southern Africa. NOAA has an extended reconstructed SST database that begins in 1854 and extends to the present. This data set was used to indicate changes occurring in the oceanic waters of the east coast from 1854 to present. This was used to establish whether the oceanic temperatures are following similar trends to those of atmospheric temperatures. The SST's were graphically depicted using different temporal scales, including annual and for the winter months (June, July and August). This data set was included in the statistical analyses to determine if, on a larger scale, any relationship exists, irrespective of the shortcomings of the data.

3.3 Mid Latitude Cyclones

Data on the occurrence of mid latitude cyclones were obtained from Daily South African Weather Bulletins. Records of these bulletins started in 1950 and yielded a 62 year record of frontal depressions. KZN being the study region, was analysed for the number of cold fronts passing over in a given year. Autumn and winter months from April to August each year are analysed for frontal depression occurrences, the total number per month and year were noted and graphically presented. Frontal depressions play an important role in the weather experienced along the KZN coast, and decrease the ambient temperature sufficiently for the sardines to migrate northwards. Numerous sardine runs have occurred subsequent to a frontal depression having passed. Because of their importance, their change in occurrence over time are statistically analysed with the historical sardine runs to note if changes observed in these systems have any influence in annual timing of the runs. In addition, their occurrence would be analysed in relation to atmospheric temperature of the different regions to note the effect it has on them.

3.4 Wind Data

Wind conditions have also been known to influence the sardine runs (O'Donoghue et al., 2010). Poor weather conditions, depending on wind speed on the Beaufort scale, may cause detrimental oceanic conditions on sardine presence and occurrence. Mention was made in historical news reports when wind played a negative effect in a particular years' run, the

sardines would migrate up the coast, irrespective if the wind conditions were favourable or not, therefore sightings could still be made. The negative effect would be that the sardines do not come in close enough inshore to be netted, but rather pass out far to sea and depending on the direction of the wind, impede their movement along the coast. Consequently, wind was also taken into consideration to analyse whether or not favourable and unfavourable wind conditions have changed over time. Wind data were obtained from the SAWS for PSH from 1960-2012; unfortunately prior to 1978 there were irregularities in the data captured as no wind speeds were recorded above a category 3 on the Beaufort scale, and thus the wind analysis only begins in 1978 and continues until 2012. PSH was again selected as the weather station of importance because this is the region where data of first sightings are captured along the lower south coast. The wind data were categorized according to the Beaufort scale and 16 points of direction used. The data consisted of an average wind speed and the dominant direction for each respective day for every year analysed.

Beaufort Scale	Meters per second	Kilometres Per hour
0	**0-0.3**	**0-1.08**
1	**0.4-1.5**	**1.44-5.4**
2	**1.6-3.3**	**5.76-11.88**
3	**3.4-5.4**	**12.24-19.44**
4	**5.5-7.9**	**19.8-28.44**
5	**8.0-10.7**	**28.8-10.7**
6	**10.8-13.8**	**38.8-49.68**

Table 1: Beaufort scale with associated wind speed values

Wind evaluating software from Enviroware 2013 was used to analyse the different wind directions and the prevailing wind speed from them. Wind roses and graphs were generated to depict the occurrence of different wind events for PSH. Changes in certain categories of the Beaufort scale were also plotted to determine any change in favourable and unfavourable wind speed events.

3.5 Multivariate ENSO Index

ENSO (El Nino Southern Oscillation) data date back to 1946, enabling this study to analyse the multivariate ENSO index (MEI) data set for a period of 66 years. ENSO is an oceanic derived index and therefore can be used as a substitute for oceanic temperatures in addition to the atmospheric temperatures already discussed. Apart from being temperature derived, ENSO also influences oceanic drivers which are hypothesised to be more influential to the sardine runs than temperature itself (Alexander et al., 2002). ENSO was included in this study to determine if any of the intensities of past ENSO cycles may have had a contributing influence to the sardine arrival times based on its influence on the atmospheric teleconnections and the resulting influence that it has on oceanic mechanisms, currents and SST. Statistical analyses were utilised to determine any relationship between arrival times and ENSO intensities.

3.6 Historical Sardine Run Events

Historical sardine run events were regrettably never recorded by one specific authority and therefore a historical chronology needed to be built from numerous sources. Ledgers, journals and catch records that contain dates of these events are available, however, their location is not known and could not form part of the historical chronology. An article found in the South Coast Herald written by a Mr Ronnie Cooper in 1960 is the only historical evidence of past sardine runs predating and running congruently with data captured by this study. His article thus made it possible to further extend the chronology of past runs. It is assumed that residents of KZN and the KZN coastline started noticing the sardine runs that occurred annually in the late 1800's and early 1900's. Mention of past sardine runs before the First World War and records thereof were observed from historical documentary evidence. The first known reporting of a sardine run occurred on the 2nd of August 1853 at Back Beach, Durban, reported in the Natal Mercury:

"*Shoal of Mackerel:* o*n Tuesday the 2nd August 1853, a shoal of mackerel chased by sharks and other large fish, took refuge close to shore this stranding of fish has not been remembered to have occurred beforehand."* (Natal Mercury, 1853)

It is apparent that sardine runs were not recorded or mentioned in documents prior to that day, and for many years thereafter no other mention was made of the sardine run again.

To reconstruct a historical chronology of sardine run events, documentary evidence was sought to undertake this endeavour. The excitement the sardine run produced on an annual basis lends itself to being a well reported phenomenon; therefore, it features in numerous newspapers, from which, it was sought to compile this data set. The National Library of South Africa contains archives of several South African based newspapers. Specific newspapers originating from the South Coast of KZN and DBN were considered because of their close proximity to the location of the sardine run events, which would make reporting on the subject relevant. Three newspapers were used to reconstruct past sardine runs; The *South Coast Sun* 1999-2006, *South Coast Herald* 1949-1998; 2006-2012 and *The Natal Mercury* 1852-1949. The main source of sardine run data came from the *South Coast Herald*, it is the oldest and most continuous of the South Coast newspapers. *The Natal Mercury* predates the *South Coast Herald*, however, Durban is considered to form part of the north coast. For the 66 years of sardine run event data presented in this dissertation, the *South Coast Herald* provides information for 55 of these years, *The South Coast Sun* 8 and *The Natal Mercury* 3. Combined, the newspapers offered a continuous data set that started in 1946 and continued through to 2012. Newspapers found in the archive end in 2012, however, news reporting related to the sardine runs after 2012 can be found electronically from a number of different sources. To keep the analysis consistent, only those records for the years leading up to 2012 will be statistically analysed. The years of 2013 and 2014 did not experience a sardine run. Prior to 1946, reporting only occurred in the DBN based *Natal Mercury* and became very sporadic since no other South Coast newspaper predated the *South Coast Herald*. Thus, to limit noise in the data set, it was decided to analyse the sardine run events between the years 1946-2012. The *South Coast Sun* was substituted for the *South Coast Herald* during the period between 1999-2006, the reason for this being that the newspaper archives did not have records for the Herald during that time period.

The respective newspapers were analysed from a period that began in April of each year, until no further news reports were found concerning the sardine runs; this generally occurred late in July or August. Often, if no run occurred during a given year, news reports would include probable reasons as to why this may be the case; these more often than not were weather related factors that deterred sardine runs from occurring. For the duration of the study (1946-2012), there were no occasions where sardine related articles could not be found. Therefore, all sardine run related news reports were documented by using the following criteria: paper date, page number, sighting dates if relevant, authors if available, and text exerts of the

article. As this study is concerned with annual arrival times of the sardine runs, first sightings along the coast were of primary interest, however, additional information was recorded for the possible use in future analyses. Generally, the first news reports often came from sightings of sardine schools either in the vicinity of EL or PSJ made by the lighthouse keeper, fishermen, boats and ships - these dates were also documented. However, the primary focus of this study is to determine the sardine arrival times along the lower South Coast of KZN.

Two distinct schools of sardines were the focus of writing, namely advance elements of the main shoal or pilot shoal as it is generally termed, and the main shoal. The newspaper reports could distinguish the shoals quite effectively and could refute falsified claims of sightings as other bait fish schools, commonly ascertained by ski-boat fisherman or local beach seine netters. Descriptive terms such as the 'main body', 'accompanied by thousands of gulls', 'vast', 'massive', and 'huge shoals' would be used to describe the main shoal in news reporting, whereas 'advance elements', 'small pocket', 'isolated pockets' and 'small shoal moving rapidly' were used to describe or identify the pilot shoals. The categories were based and formatted on adjectives used to describe the sardine shoals, such as: *"the sardines are definitely in the area, huge shoal spotted"*(South Coast Herald, 15 June 1990); *"Pockets of sards passed the coast daily, but have been out to sea and have not been driven inshore"* (South Coast Herald, 9 July 1965); *Hundreds of cars from far and wide poured in and out Port Edward looking for sardines, huge shoals and thousands of birds spotted at Port Edward on Sunday"* (South Coast Herald, 30 June 1961); *"Two pilot shoals driven into the surf at Port Shepstone this week"* (South Coast Herald, 13 June 1958); *"Our photographer was at Portobello beach last weekend when the mammoth 1971 sardine run began, already it has been the biggest sardine run in 8 years say some experts, others claim there haven't been so many of the fish since 1959"* (South Coast Herald, 25 June 1971)

Main Shoal	Pilot Shoal
Main body	Advance elements
Thousands of gulls	Small pocket
Vast, massive	Isolated pockets
Huge shoals	Small shoal moving rapidly

Table2: Classifying terminology used to distinguish between the main and pilot shoals described in the newspaper reporting's.

The pilot shoals would often arrive well in advance, compared to the main shoals that would be stationary in the vicinity of PSJ or the Eastern Cape coastline, generally they would differ from a couple of days to a week in some instances. The most common explanation of this cause are the biotic external factors which are more often than not consist with predatory fish and mammals that pursue the shoals, hastening their passage along the coast. Therefore, their arrival is often in advance to the main shoal (O'Donoghue et al., 2010), but the pilot shoal arrival times were also documented. After the arrival of the pilot shoals, the main shoals would typically reach the lower South Coast. The date of their arrival, time if mentioned, indicated size and location in relation to towns along the south coast and if they were close to the beach or far out to sea, would be captured. It was found that in some cases the runs would occur contrarily, pilot shoals would arrive with the absence of a following main shoal which resulted in a non-run and in other instances the main shoal would arrive without any sightings of the pilot shoals.

All sightings and other relevant information such weather and ocean conditions, predatory animal behaviour and sightings, associated runs, angler activity and netting efforts, were documented. The first analysis that was conducted involved the first sightings of the pilot or main shoals, whichever arrived first along the lower South Coast. The respective date was taken for that calendar year and was graphically depicted along with the other years to determine if any change existed in arrival times over the study period. Subsequently, other analyses looked at separating the pilot shoals from the main shoal arrival times, bearing in mind that in some years either the pilot or main shoal was absent from any sightings.

Graphically depicting the first arrival time of the pilot and main shoal will illustrate any linear trends of their migration phenology.

Since the data set consisted of 6 decades worth of sardine run data, a decadal trend analysis was utilised to determine whether or not the occurrence of the runs were in fact varying. Therefore, each year had to be classified as a hit/miss and run/non-run year, certain criteria, such as any information leading to the fact that no apparent sighting of the main shoal was noted, were used to determine the nature of each year's sardine run. It was therefore essential to distinguish between the two shoals to enable an effective analysis. A non-run was classified as no reported sightings of the main shoal for a given year (i.e. they did not appear along the lower south coast), the second criteria used for discerning a run from a non-run was if the sardines travelled well out to sea without venturing close inshore due to adverse weather conditions. This, however, did not influence the recordings of first arrival times, as was noted when the sardines passed a particular area even if well out to sea. It was evident from the newspapers that the term "poor run" was used to describe a run in which the main shoal failed to appear along the LSC, or they passed well out to sea. Sardine runs, on the contrary, were discerned from non-runs when the sardines arrived along the LSC and were harvested. Terms such as 'good run', the 'best run in years', 'mammoth run' and the 'main shoal arrived' were all terms used to classify a run. The total amount of runs per decade was graphically depicted to illustrate any trends in occurrence of sardine runs.

Statistical analysis is performed to determine whether or not any correlation or significance exists between the data sets of climate and those for the first arrivals of the main shoal, ultimately illustrating their influence on the sardine run arrival times. The sardine run arrival times were evaluated using an Anderson-Darling test to determine whether or not the data are normally distributed or not, thus determining what form of subsequent statistical analysis to best perform. The tests would be either a multiple regression analysis if the data were found to be normally distributed, or Mann-Whitney u test for non-normally distributed data. In all cases the sardine run arrival times of the main shoal were used as the dependent variable and all other climatic data formed part of the independent variables. Correlation statistics were utilized to determine if any correlation existed between the independent variables as well as if any relationship existed between the dependant variable and each of the independent variables, highlighting any relationships that exists between the variables and determining which variables are more influential.

Chapter 4: Results and Discussion

4. 1 Climatic Data

The overarching trend observed in the four climatic regions (PSJ, PSH, EL and DBN) analysed is that the temperature has indeed changed over the period investigated. All four regions display similar trends of increased air temperatures. The four regions also display similar periods of increased and decreased temperatures, confirming that there are no abnormalities within the data. DBN, PSH and EL have strong linear trends and this is true for mean maximums, mean minimums and averages. Over the 75 year period 1937-2012, DBN recorded an average increase of 1.21°C during summer months and 0.84°C during winter months, EL recorded an average increase of 1.11°C during summer months and 0.54°C during winter months, PSH recorded an average increase of 0.76°C during summer months and 1.40°C during winter months. However, the temperature records observed for PSJ, have a weak linear trend and depict inter-annual variability, PSJ has experienced an average increase of 0.37°C during summer months and 0.10°C during winter months. Upon examining this further, it was observed that changes in temperatures for PSJ only began to show a change in the late 1950's to early 1960's, therefore the general trend was weaker, whereas the other regions experienced warming trends from an earlier onset date. A possible cause for this is because of the numerous oceanic currents present in the area, primarily a consequence of gyres and upwelling cells, which over time, may have induced variable temperature controls on adjoining coastal regions, once again placing emphasis on the importance of PSJ in the migration of the sardines.

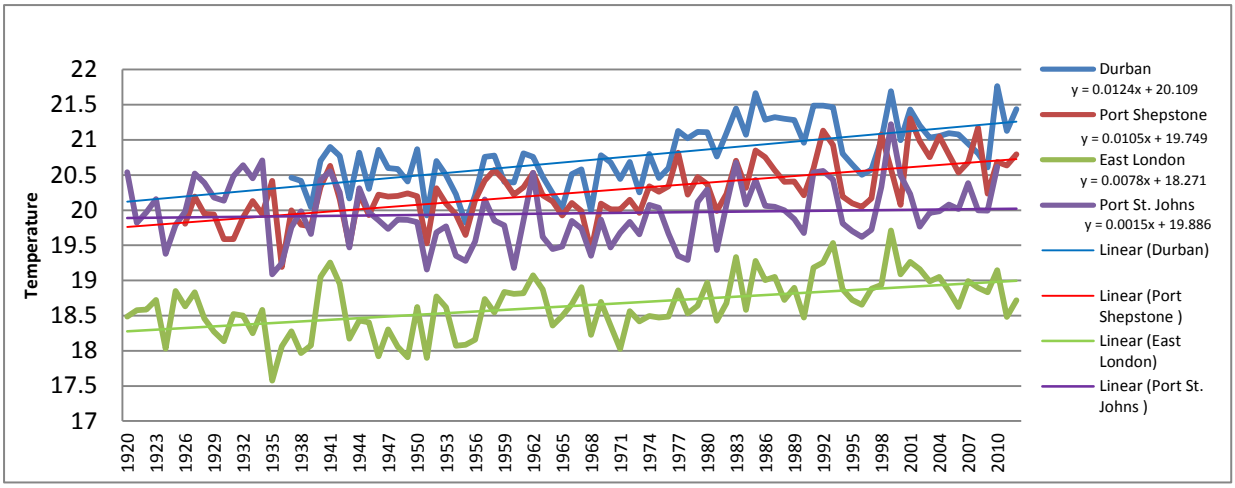


Figure 1: Annual average long term temperatures trends for the four climatic zones with a running mean of 11 years

Once the general trends were observed and confirmed for all regions studied, the temperature variability was analysed at a finer temporal scale. The seasonal temperature changes of the four regions were observed and once again similar trends to the general temperature changes were detected.

	Durban	East London	Port Shepstone	Port St. Johns
Summer	1.21	1.11	0.76	0.37
Autumn	0.95	0.90	0.85	0.22
Winter	0.84	0.54	1.40	0.10
Spring	0.70	0.25	0.30	0.027

Table 3: Average temperature increases in degrees Celsius for the four climatic regions during the entire study period. DBN was analysed over a period of 75 years, EL a period of 91 years, PSH a period of 75 years and PSJ a period of 89 years.

Table 1 displays the seasonal long term temperature trends of the four climatic regions based on linear trends. It was generally observed that the months that experienced the greatest long term warming trends were summer and autumn for DBN, El and PSJ, however for PSH it was found that winter, summer and autumn months experienced the strongest long term temperature trends. PSJ was found to have experienced the weakest long term temperature trend over the last 89 years.

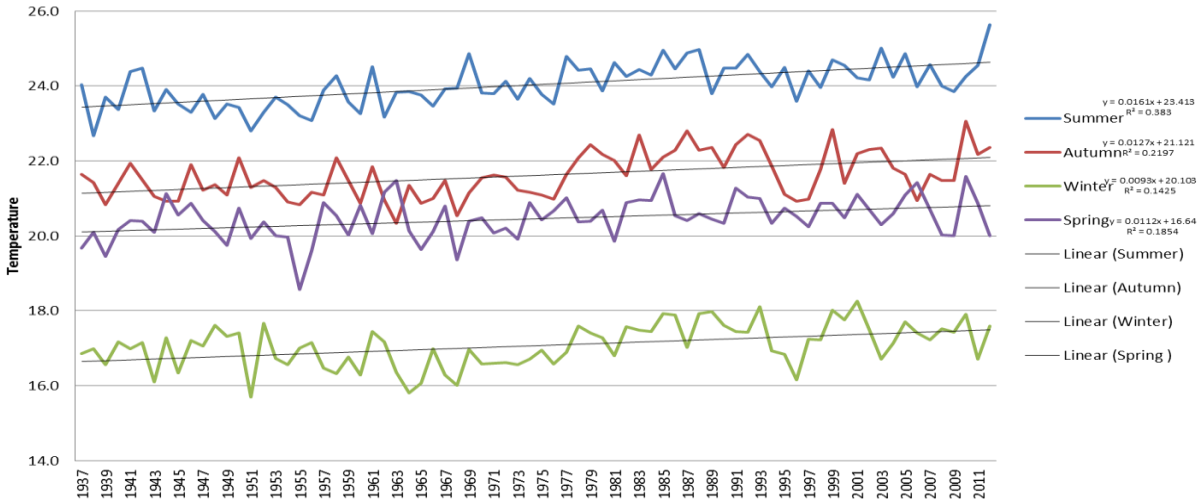


Figure 2: Seasonal changes in average temperature for Durban for the period between 1937 and 2012,

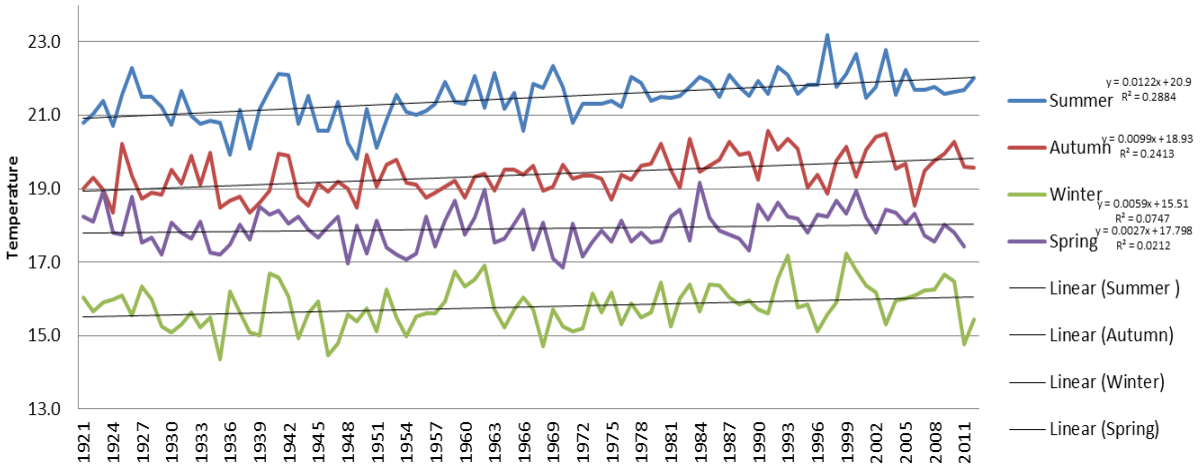


Figure 3: Seasonal changes in average temperature for East London for the period between 1921 and 2012,

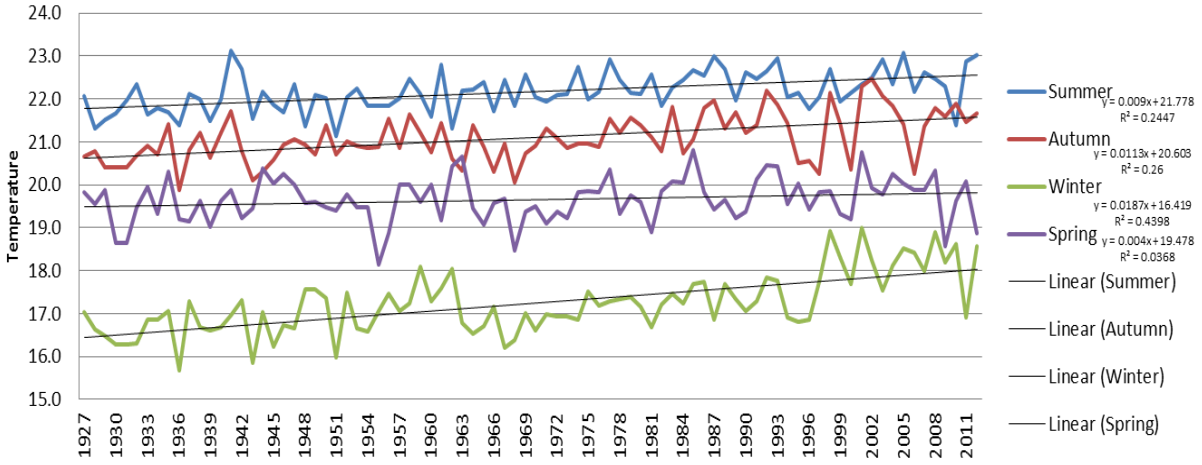


Figure 4: Seasonal changes in average temperature for Port Shepstone for the period between 1927 and 2012, with a running mean trend of 11 years.

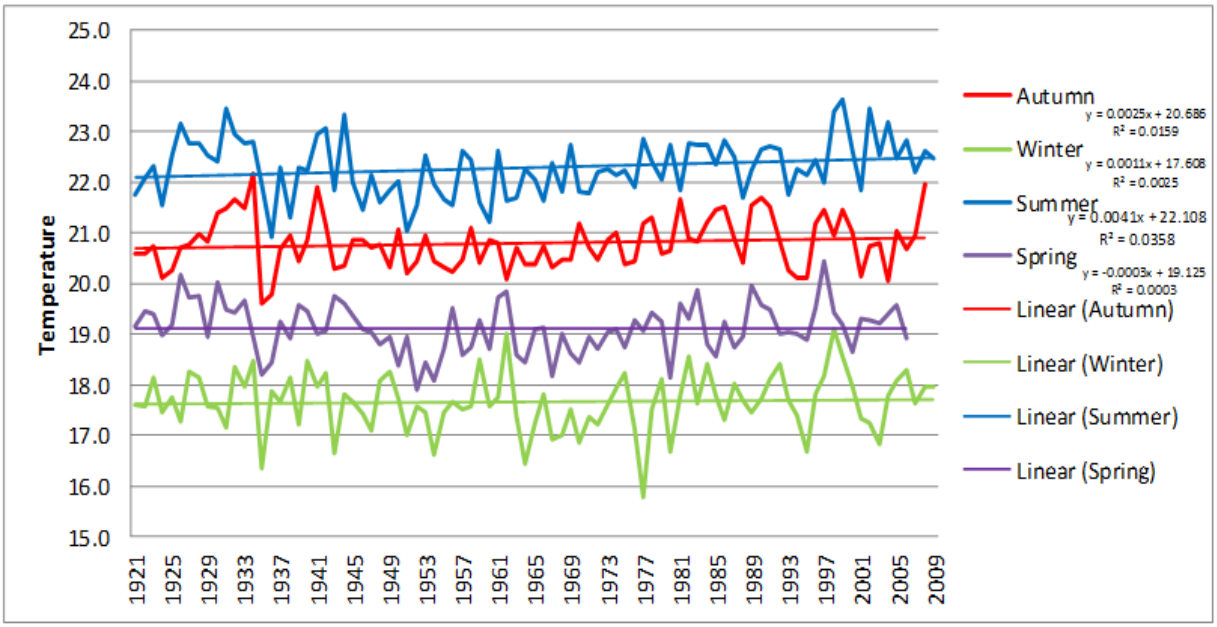


Figure 5: Seasonal changes in average temperature for Port St. Johns for the period between 1921 and 2012

Figures 2-5 display graphical representations of seasonal temperatures for DBN, EL, PSH and PSJ. Once again, the trends displayed are all similar with regards to temperature variability. Additionally, a particular period beginning in the late 1950's and early 1960's displayed a rapid increase in temperature for all analyses, this increase has continued for the remainder of the study period although not as rapidly as the period mentioned. The temperature analysis for a large region of the eastern seaboard of southern Africa has thus constituted evidence for a change in temperature variability which is conclusive to other climatic studies of similar origin.

4.2 Reconstructed Sea Surface Temperatures

The NOAA reconstructed SST database was utilized to determine whether or not the surrounding waters along the east coast of southern Africa are undergoing the same temperature variability as the mean air temperature variability

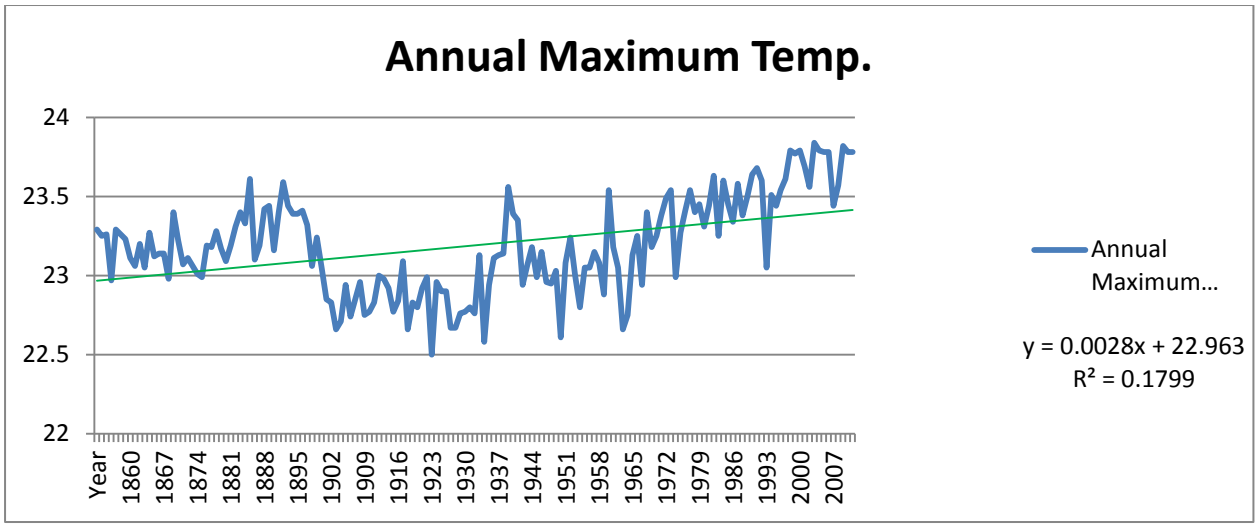


Figure 6: SST annual maximum decadal trends for the southern African East Coast 1912-2012

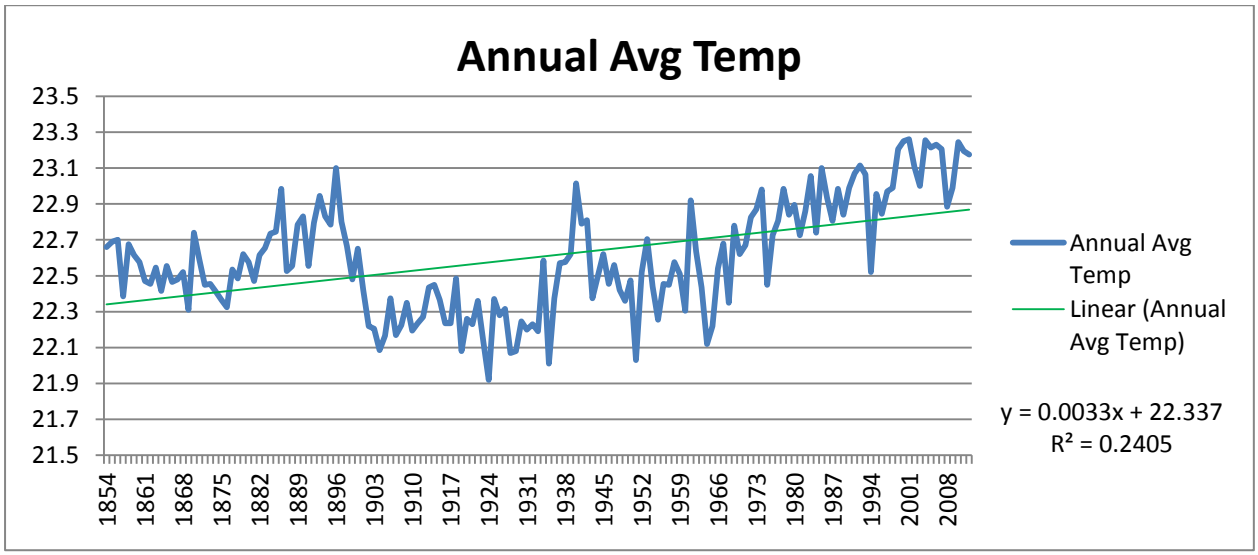


Figure 7: SST annual average decadal trends for the southern African East Coast 1912-2012

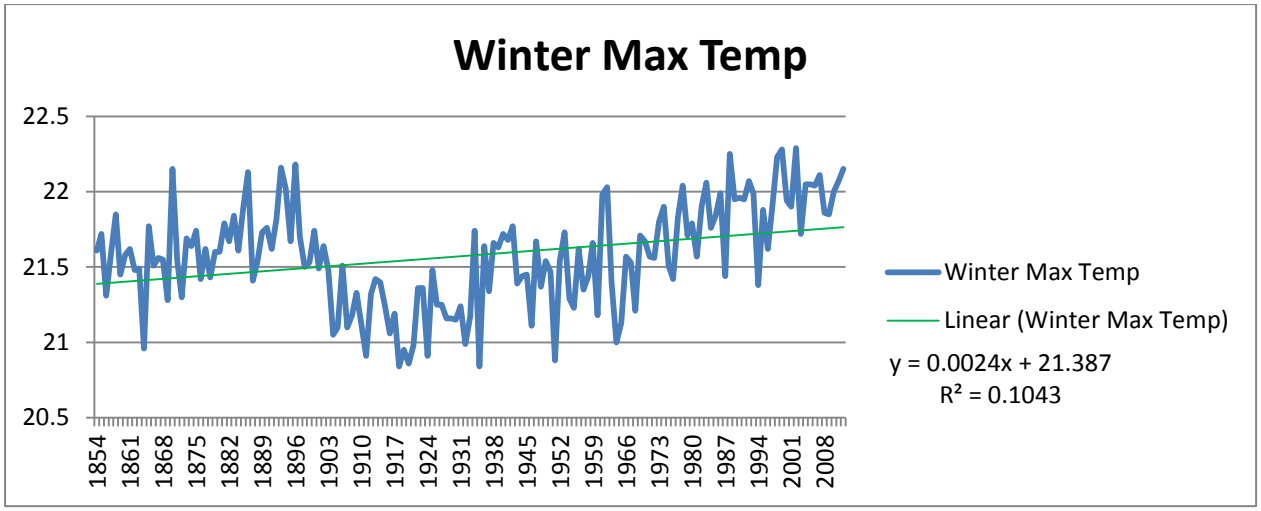


Figure 8: SST winter maximum decadal trends for the southern African East Coast 1912-2012

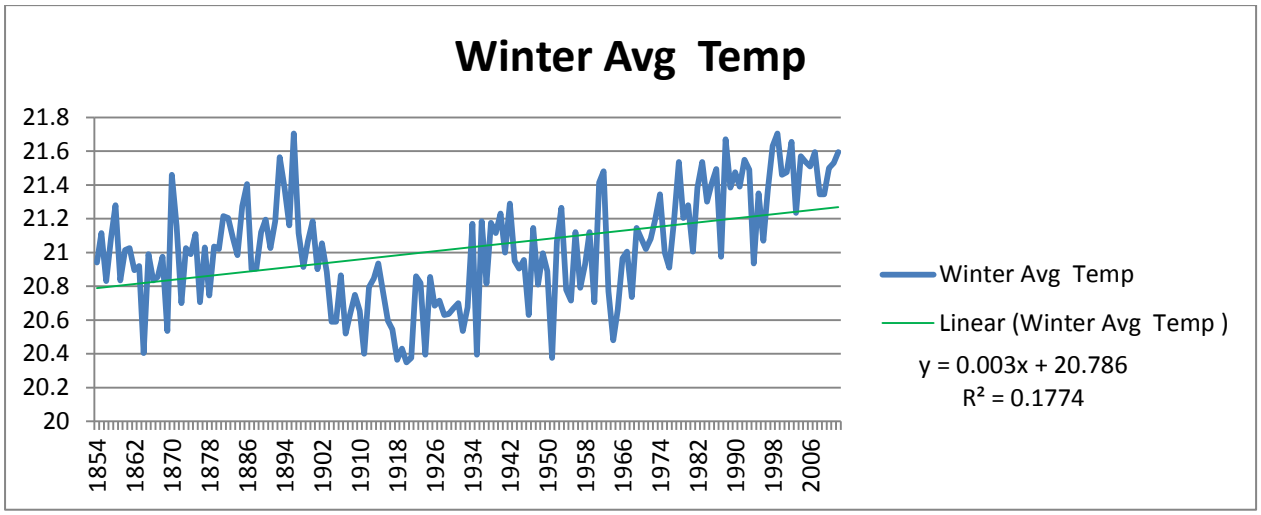


Figure 9: SST winter average decadal trends for the southern African East Coast 1912-2012

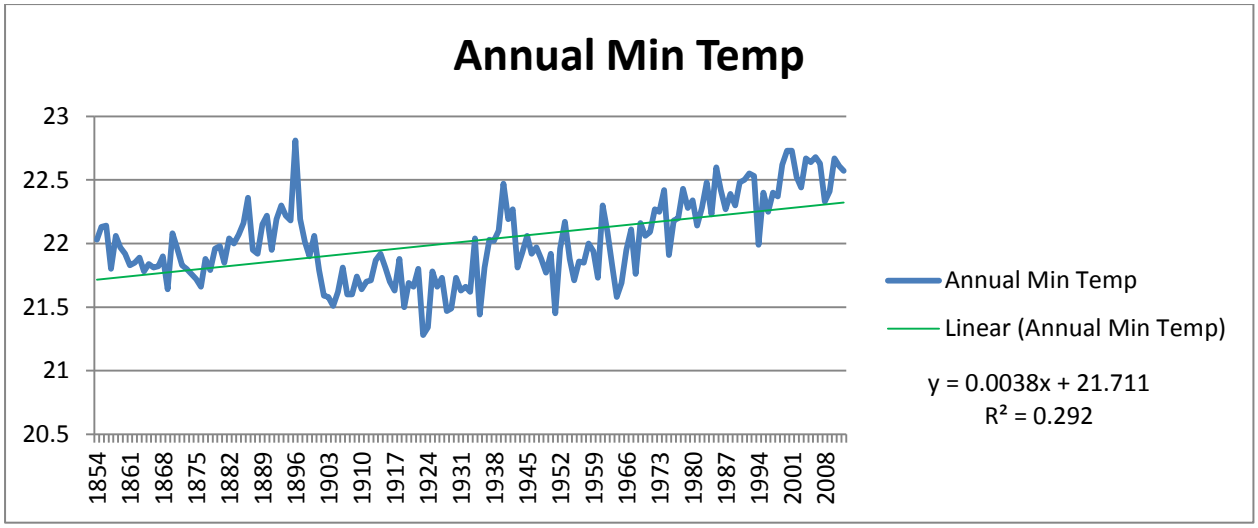


Figure 10: SST mean maximum decadal trends for the southern African East Coast 1912-2012

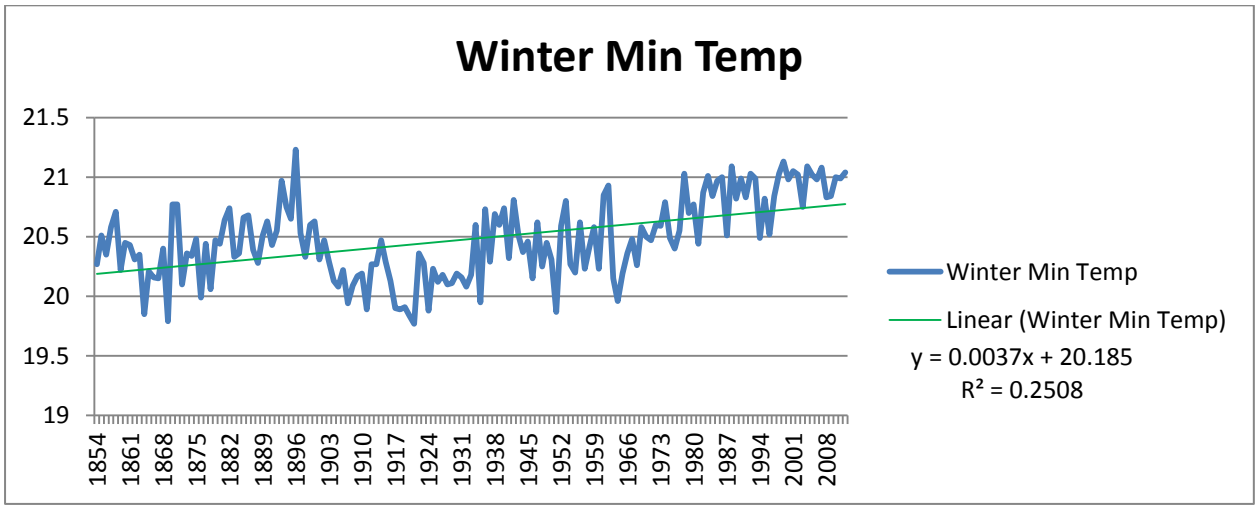


Figure 11: SST mean minimum decadal trends for the southern African East Coast 1912-2012

Figure 6 and 11 graphically represent minimum SST temperatures for PSJ where the minimum temperatures have displayed the greatest temperature increase from 1854-2012, annual minimum SST have increased by 0.038°C/decade and 0.60°C over 158 years. Winter minimum SST has increased by 0.037°C/decade and 0.58°C over 158 years. Annual mean, maximum and winter mean and maximum SST analysis both reveal similar trends in ocean temperature variability as depicted by Table 2 below. The results indicate that SST are experiencing similar increases to those of air temperatures analysed. A link therefore can be made between SST and atmospheric temperatures, as Alexander et al., (2002) report that atmospheric temperature has the ability to influence SST as well as ocean currents, due to surface heat momentum. However, in all the SST's analysed in this study, a particular period

of interest is observed in Figures 6-11, namely the 1880's. A period of similar SST increase to that more recently, was detected; thereafter a rapid decrease in SST was observed in the late 1890's, which continued into the early 1900's. The same periods of increases and decreases noted in Figures 6-11 were evident in a study utilizing coral records from the Ishigaki Island in Japan (Mishima et al., 2010).. It was reported that coral records depicted a rapid shift towards cooler conditions between 1900 and 1905, which were supported by SST and climatic records (Mishima et al., 2010). Subsequently, gradual increases in SST have been recorded, with inter-annual variability present, however, the general conclusion is that SST's have continued to increase during the period from1820 to 2000 when the study ended (Mishima et al., 2010).

	Annual		Winter	
	Per Decade	Entire Study	Per Decade	Entire Study
Max	0.028	0.44	0.024	0.38
Min	0.038	0.6	0.037	0.58
Avg	0.03	0.47	0.03	0.47

Table4: Displays the change in SST temperature in Degree Celsius for the PSJ region from 1854 to 2012

Based on ocean atmospheric interactions, it was assumed that the analysis would yield similar trends. Therefore, the *in situ* air temperature data recorded at strategic points along the coastline where the sardines pass would serve as the closest and most accurate temperature recorded available for use in this study, unless new complete historical data sets of oceanic water temperatures become available. From Figure 10 and 11 it is observed that winter oceanic temperatures and annual oceanic temperatures have increased by between 0.38°C and 0.60°C over the 158 years analysed- this may impact the sardine's favourable habitat range, since they prefer a water temperature within a certain range which is between 14°C and 20°C (Barange and Hampton, 1997; O'Donoghue et al., 2010).

4.3 Mid Latitude Cyclones

The 62 year period used to study the occurrence of frontal depressions during winter months (April-August) over the southern KZN coast revealed that there is a slight decrease in the average number of cold fronts passing over KZN. It was determined that the numbers of cold fronts were decreasing by an estimated 0.08 per decade and 0.52 over the entire study period. Cold fronts, as previously mentioned, are of importance with regards to the sardine runs, as they decrease the ambient temperature, increasing the favourable range of the sardines and

allowing them to move up along the coast. A decrease in the incidence of cold fronts reaching the KZN region may thus have a negative implication on sardine presence in the area.

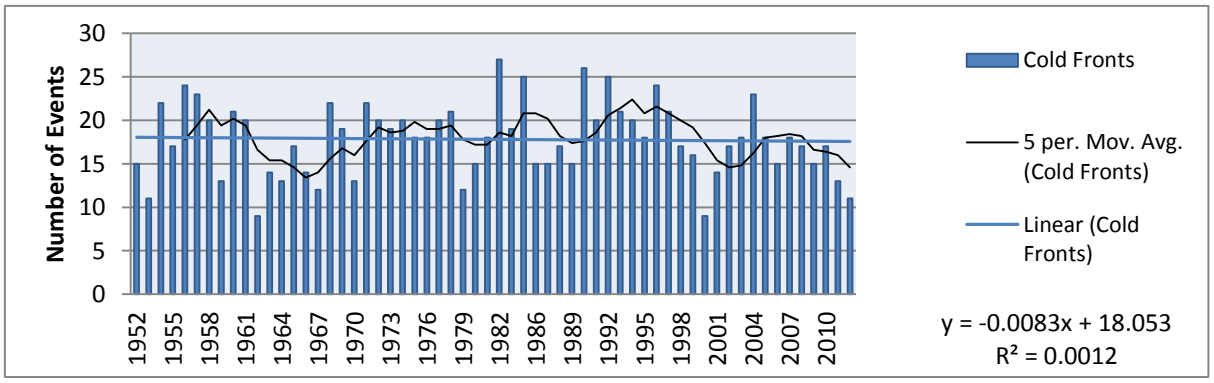


Figure 12: Total amount of mid latitude disturbances of each winter period from 1952-2010

Upon investigating the occurrence of mid latitude disturbances at a finer resolution, it was determined that the months preceding the sardine runs, namely April and May, are experiencing a decrease in the frequency of frontal depressions passing the region. April has experienced a decrease of 0.13 fronts/decade or 0.78 over the study period. Similarly, May has experienced a decrease of 0.15 fronts/decade and 0.92 over the entire study period. However, the decrease is very minimal and is not statistically significant; such that the effects are deemed negligible. Conversely, the months of June and July have experienced an increase in the frequency of frontal depressions passing that region, June has experienced an increase of 0.11 fronts/decade (or 0.68 over the study period), while July has experienced an increase of 0.0172 fronts/decade (or 0.45 over the study period). However, again these figures show a negligible increase. June was determined to be the most significant month with frontal occurrence and sardine arrival times. The month of June is generally the first time the sardines are sighted each year; the statistical regression analysis of frontal occurrence and first arrival times suggest that fronts explain 0.29% of the variance in arrival times of the sardines. The results are statistically significant, although not strong, and represent a p value

of 0.04. This result reaffirms the theory and observation that often people along the lower south coast will wait for a frontal system to decrease the ambient temperatures sufficiently to stimulate the sardine migration. This was recorded in the newspaper articles when nearshore ocean temperatures were often too warm to allow the sardines to migrate northwards along the coast "In my opinion they should arrive after the present or next cold front passes over" – Barry Smith *South Coast Herald* 4 July 1986.

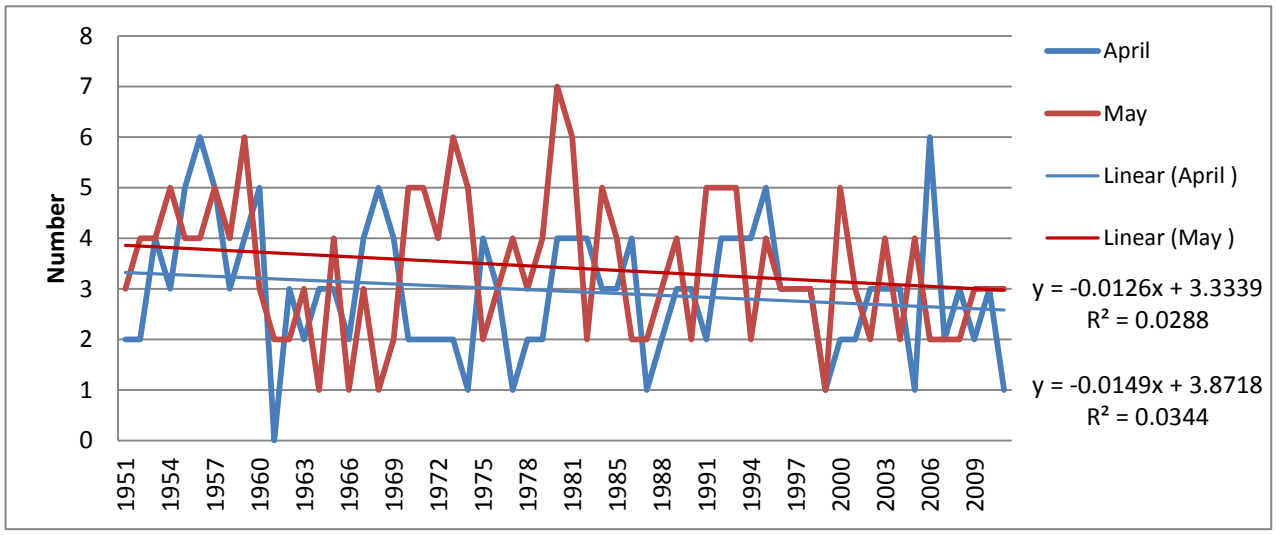


Figure 13: Occurrence of cold fronts in the KZN region during April and May 1951-2011

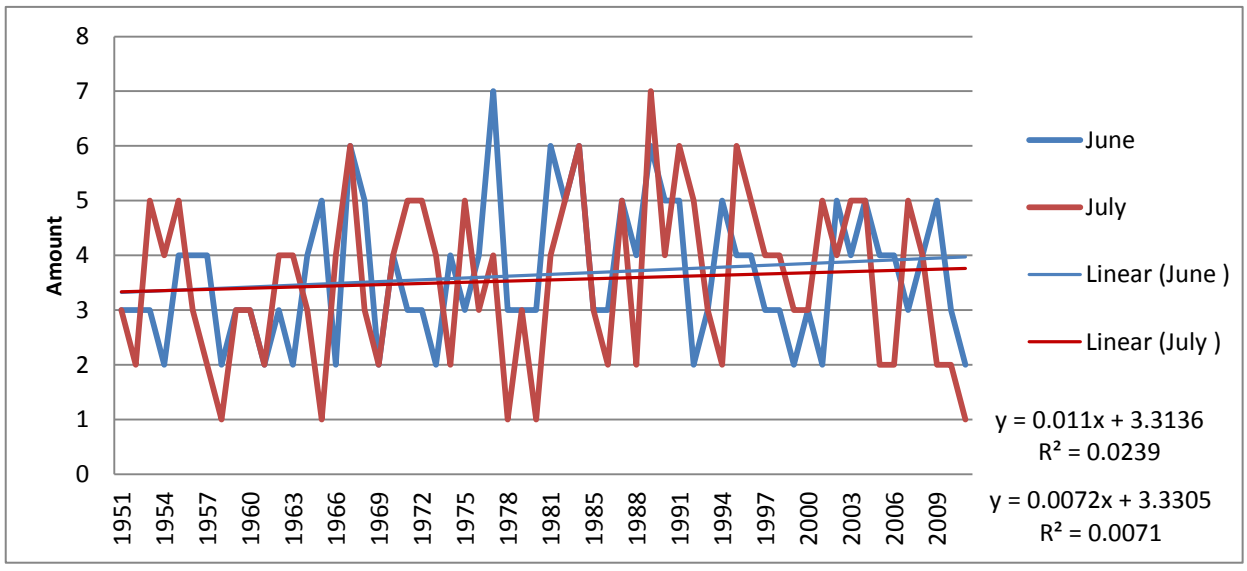


Figure 14: Occurrence of cold fronts in the KZN region during June and July 1951-2011

The change of frontal depression frequency and occurrence in the months prior to and during the months of sardine run incidence could also have implications on their annual arrival times, because they have an influence on weather conditions and are responsible for rapidly decreasing coastal water temperatures. Frontal depressions may have no statistically significant implications to the sardine arrival times over a large temporal scale, however, frontal depressions may be responsible for runs to start by decreasing coastal water temperatures, or disrupt the runs with adverse conditions causing non-runs.

4.4 Wind Trend Analysis

Wind trends were analysed from 1978-2012, as previously mentioned these dates had the most reliable data to use in an analysis. On an annual basis, PSH has four dominant winds that occur and they are a south westerly, north easterly, north westerly and northerly wind respectively. The south westerly, south easterly and north easterly wind directions generate highest wind speeds, which on average are higher than 5 meters per second. Category 2 wind events on the Beaufort scale are the most dominant in the region, occurring 44.3% of the time, category 3 wind events occur 32.7% of the time, category 4 wind events 14.9% of the time and, category 1 wind events 8.0% of the time. During the winter months, which is of importance for this study, the wind trends are dissimilar than annual trends.

During winter months it is observed that northerly and north westerly winds dominate, however, wind speeds generated from these directions are not strong compared to winds generated from other directions. The highest wind speeds occur from a south westerly and south easterly direction and are often on average greater than 5 meters per second, largely as a result of frontal depressions moving over the area. During winter months, category 2 on the Beaufort scale is still the dominant wind event with 40.3% of the events occurring, category 3 with 31.1% of the events occurring, category 4 with 11.6% of the events occurring, category 1 with 7.3% of the events occurring and category 5 with 1.6% of the events occurring. It has been observed that winter months have the occurrence of greater wind speed events than summer, the reason being due to mid latitude cyclones passing the region and creating these events.

It is known that different wind speed events may have a positive or negative effect in relation to sardine presence (O'Donoghue et al., 2010), therefore each wind speed category was analysed to determine whether or not any variability existed. It was determined that during both annual and winter months, wind speeds have been variable over the course of 34 years.

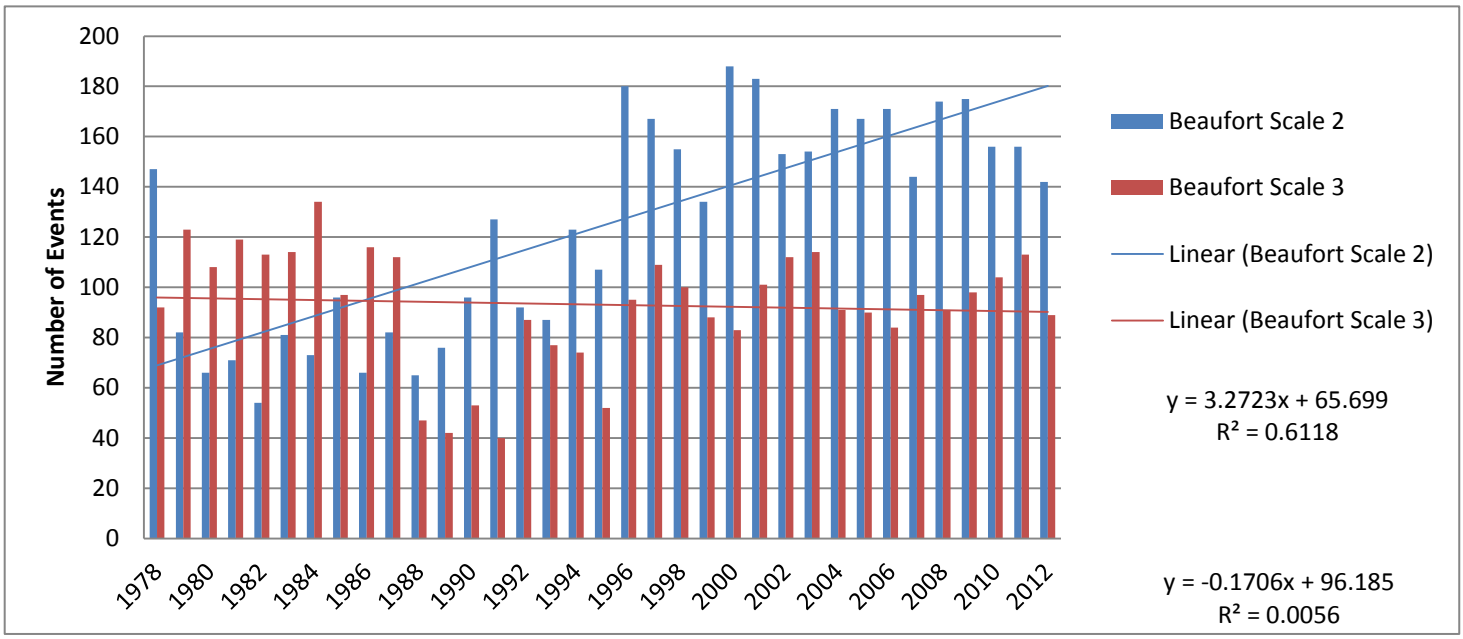


Figure 15: Category 2 and winter wind speed variability, Port Shepstone 1978-2012

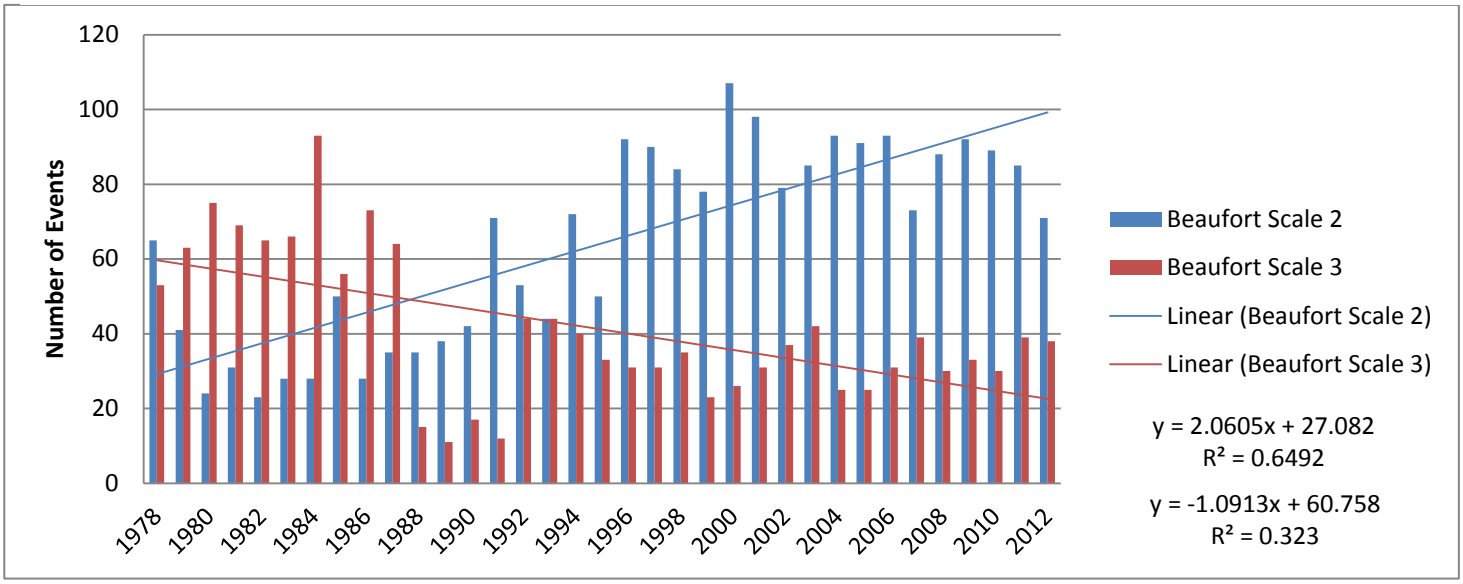


Figure16: Category 2 and 3 annual wind speed variability, Port Shepstone 1978-2012

It is evident from Figures 15-16 that for both annual and winter scales, category 2 wind speed events have increased in occurrence while category 3 wind speed events have decreased in occurrence. Wind speeds of a magnitude 3 on the Beaufort scale have been described as favourable conditions for the presence of sardines along the KZN south coast, anything above a scale of 4 have been described as unfavourable (O'Donoghue et al., 2010). Although the wind data set does not extend as far back as the other data sets, an assumption can be made that favourable wind conditions are becoming more prevalent along the KZN south coast, inducing calmer seas and currents that are more favourable for the passage of the sardines.

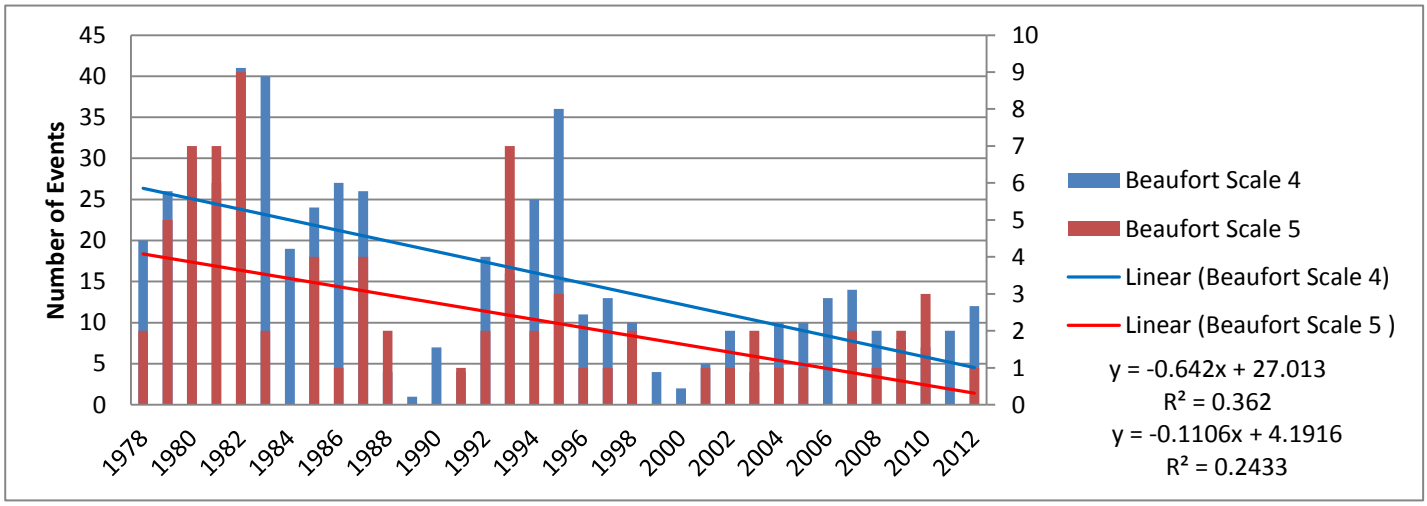


Figure 17: Category 4 and 5 annual winter wind speed variability, Port Shepstone 1978-2012

Similarly, the occurrence of scale four and five wind speed classes have decreased, these wind speeds are classified as being unfavourable for sardine presence. The decrease in the following categories may also give an indication of a decrease in mid latitude cyclone frequency, as the cold fronts are often responsible for the strong winds received from a south westerly direction. It may, therefore, be conceptualised that favourable wind conditions are increasing during the arrival times of the sardines, and strong wind speeds are decreasing in their occurrence.

4.5 Sardine run analysis

The first sardine arrival times were graphically plotted to analyse each element of the sardine runs, namely the advanced elements or pilot shoals, main shoal and the combined arrival times of the main and pilot shoals. From the graphs, any linear trends that exist could thus be noted and interpreted based on the observed trend.

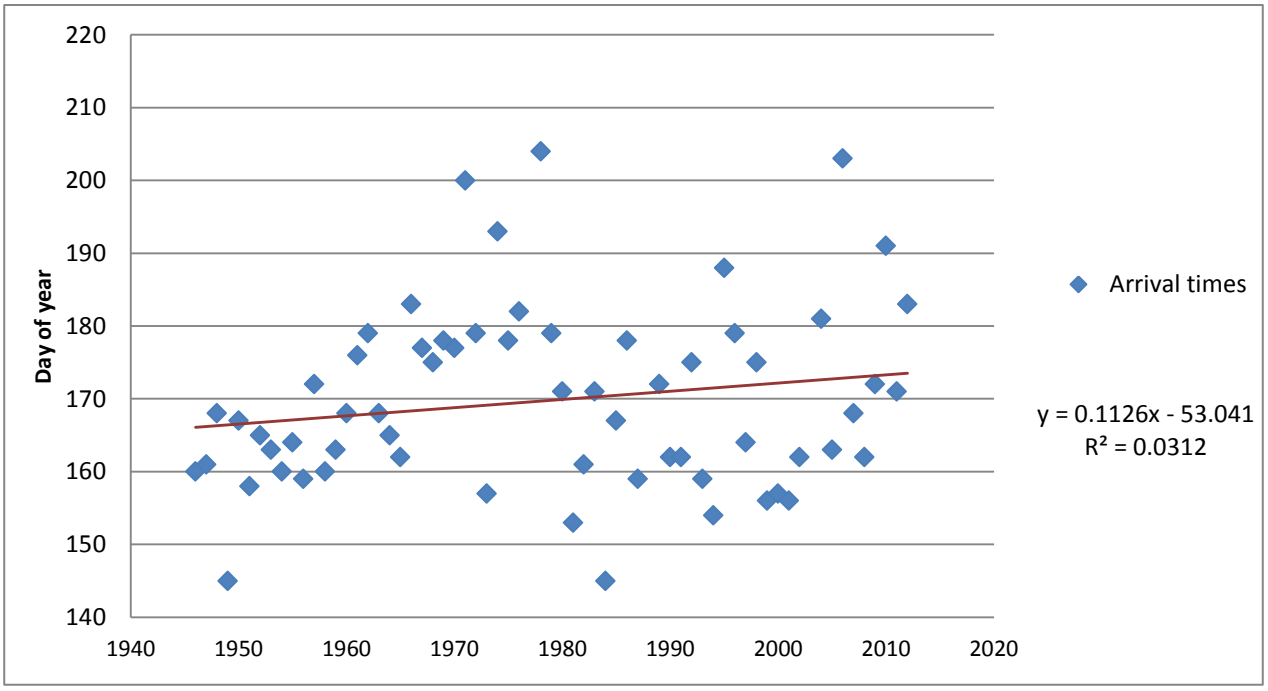


Figure 18: Graphical representation of the first arrival times of the sardine shoals that include the main and the pilot shoals. The runs were examined over a period of 66 years and started in 1946 and ended in 2012. The dates were selected based on which shoal arrived along the south coast of KZN first, whether it was the pilot or the main shoal and thus graphically depicted.

Figure 18 depicts a slight increasing linear trend, which suggests that the arrival times are becoming more delayed; therefore, an assumption can be made that the two shoals combined are showing evidence of a delayed response with regards to their arrival times. Possible influencing factors of this trend will be addressed in the later part of the discussion. From the linear trend, it seems that the arrival date is varying on average by 0.11 days a year, 1.12 days a decade and the total average delay in arrival times for the 66 year period is 7.4 days. However, the pilot shoals are subject to external factors influencing the speed at which they travel along the east coast, and therefore the depicted arrival times may be influenced by external factors, therefore, the arrival times of the two shoals need to be analysed in finer detail to determine if such an influence is evident.

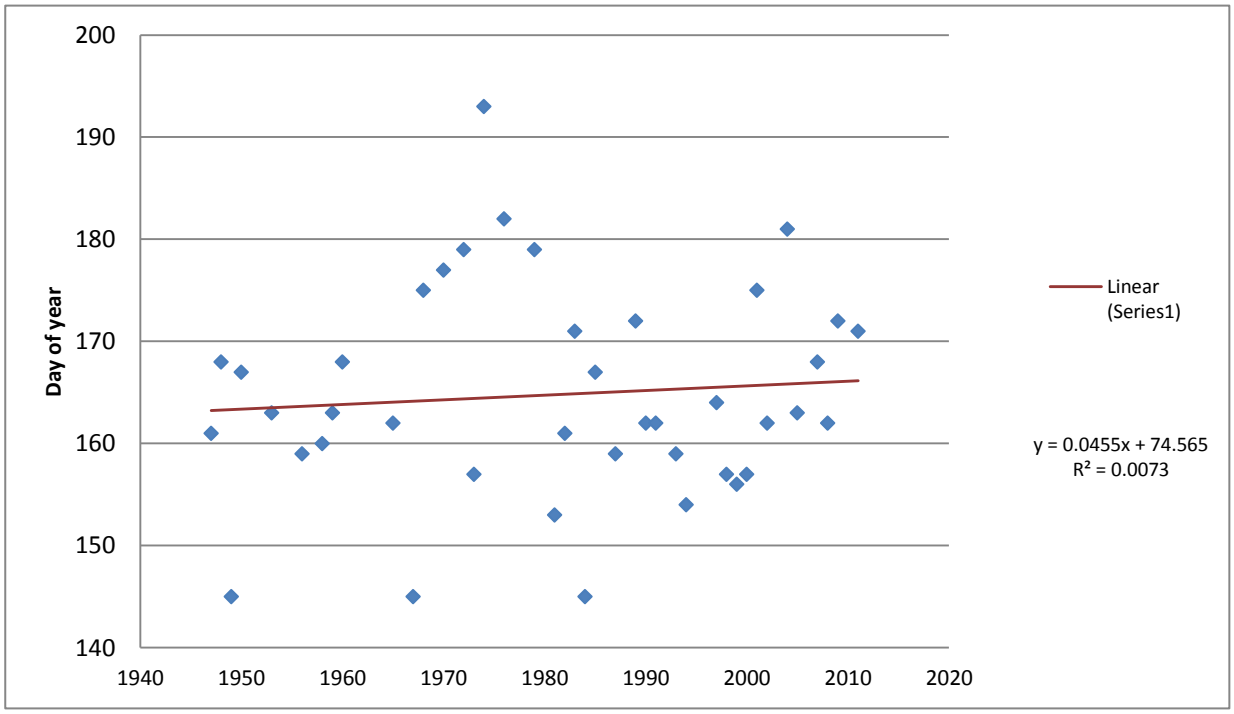


Figure 19: Graphical representation and linear trend of the pilot shoals first arrivals along the south coast of KZN from 1946 to 2012. It is essential to bear in mind that in some years they pilot shoals are absent from a main shoal therefore the points are fewer than figure 16.

Similarly, a slight increase of 0.5 days/decade is evident in a delayed response of arrival times (Figure 19); it is, however, not as considerable as the previous linear trend, on average the delay in arrival times can be narrowed down to three days. Therefore, it can be stated that there has been no significant observed change in pilot shoal arrival times presented by an R^2 value of 0.0073, and because such a weak linear trend is apparent in Figure 19, it provides further evidence that pilot shoals are indeed influenced by external factors influencing their movement. Therefore, pilot shoal arrival times should be excluded from the analysis to prevent noise in the results. The main shoal was thus the central focus of the study and the arrival times of the main shoal were regarded as the only element that had the potential to indicate change in their phenology. The main shoal arrival times are herewith used as the indicating factor of change and were analysed in conjunction with all other climatic data to determine any existing relationships.

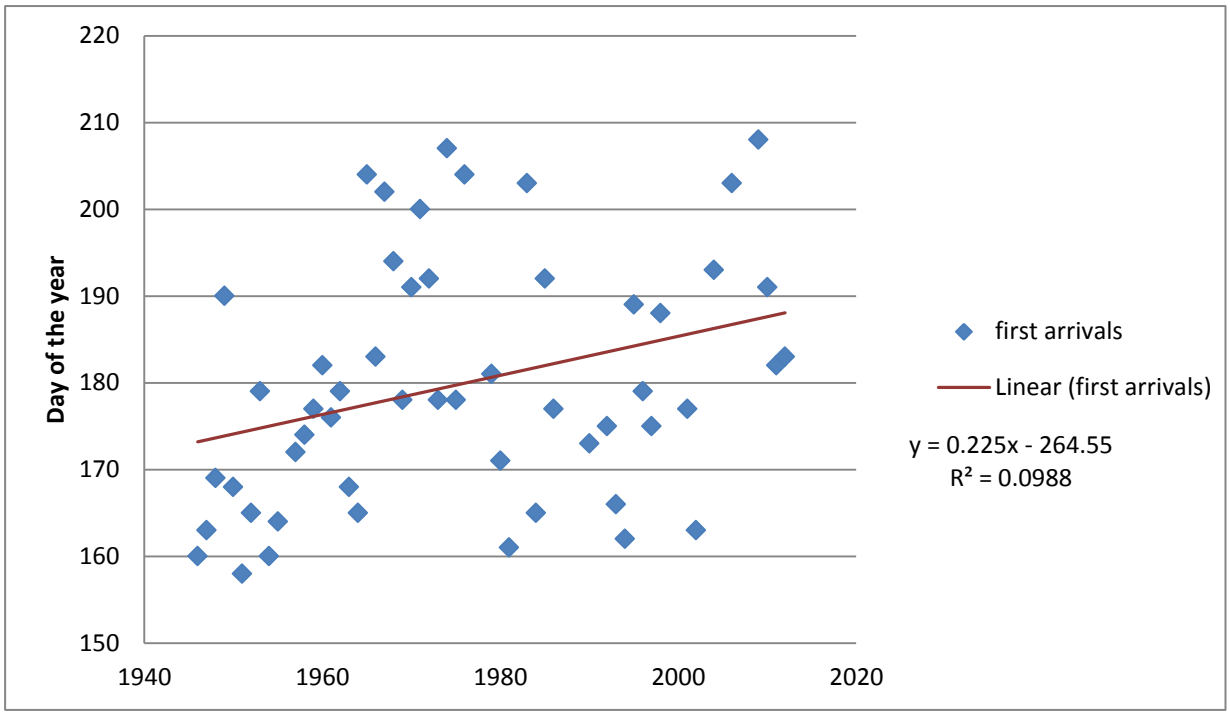


Figure 20: Graphical representation of the first arrival times of the main shoal on the lower south coast of KZN, the period observed was between 1946 and 2012. Similarly to figure 17 in some years the main shoal failed to appear along the lower south coast and therefore were classified as a non-run, therefore there are fewer listed points as in figure 16.

Furthermore, a more apparent increasing linear trend is observed in Figure 20, providing evidence of a delay in arrival times for the sardine runs in the 66 year period examined. On a decadal scale, the arrival times have on average advanced by 2.25 days/decade, whereas the entire study period has resulted in an average 14.85 day delay in arrival times. It is therefore suggested that the sardine runs annual first arrival times have undergone a change due certain contributing factors. As theorised, the main shoal of sardines are less influenced by external factors that hasten their travel along the coast, the main shoal on the contrary is more susceptible to external factors such as wind, water temperature, swell and water clarity (O'Donoghue et al., 2010). Climatic factors that influence favourable conditions for the sardine runs were then regarded as significant to the study and were analysed against arrival times of the main shoal.

Documented arrival dates predating the arrival times used in this study were recorded by Ronnie Cooper in the South Coast Herald in 1960. The dates captured by Ronnie Cooper began in 1928 and ended in 1960 when the article was published. These dates, regrettably, could not be used in the historical chronology of sardine run events as they made reference to when the sardines arrived in certain months and not a given year when they arrived. However, these dates could be utilized to calculate a mean which could be compared to the dates collected by the study.

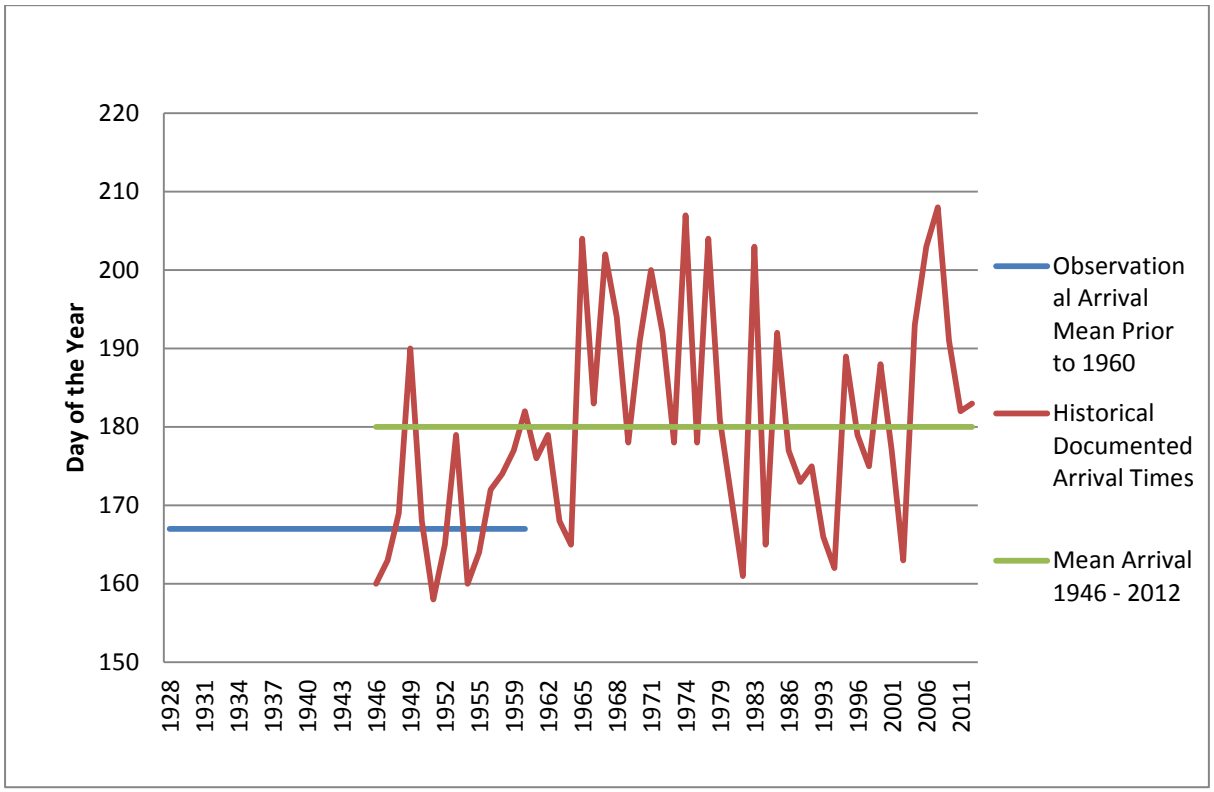


Figure 21: Documented and observed arrival times of sardine runs 1928-2012. Observational arrival time means calculated from arrival dates published by Ronnie Cooper

Figure 21 graphically presents the historical chronology of sardine run events collected from newspaper reports as well as the average arrival dates provided by Ronnie Cooper. The observational arrival mean falls well below the mean of the historical data collected. From such an observation it can be assumed that the general delay in arrival times noted over the course of the study period began well before the first arrival date collected in this study, suggesting environmental factors were already impacting the arrival times of the sardine shoals.

Apart from the delay in arrival times of the sardine shoals, it was also discovered whilst constructing the historical chronology of arrival times, that as the years progressed, the years in which non-runs occurred became more prevalent. Therefore, the frequency of sardine runs was analysed to determine whether or not this has changed over time. The absence of sightings of the main shoal of sardines along the south coast was considered to be the constitution of a non-run event. This analysis was carried out over a decadal scale (i.e. the number of runs and no runs were documented for each decadal period starting in 1955 and ending in 2015, and is presented graphically. The years of 2013, 2014, and 2015, although not forming part of the historical chronology and statistical analysis in this study, were used to determine changes in frequency as 2013 and 2014 were considered as non runs and 2015 witnessed a run.

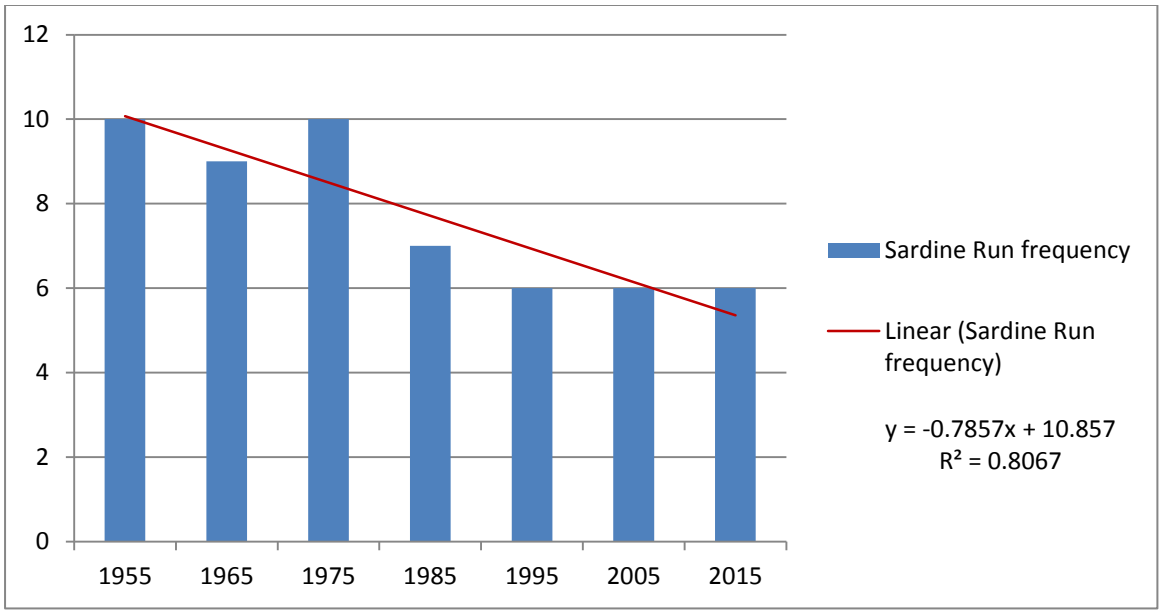


Figure 22: Decadal sardine run occurrence 1955-2015

It is evident from Figure 22 that there has been a noticeable decrease in the frequency of sardine events taking place on a decadal scale. The sardine run frequency is decreasing by 0.79 runs/decade and has decreased by 5.49 runs over 7 decades. Not only is a delay evident, but a decrease in frequency of events is taking place. It therefore provides further evidence that environmental factors or secondary external factors are influencing the sardine run events.

4.6 Descriptive Statistics Results

The first arrival dates of the main shoal were tested to determine whether or not the data obtained were normally distributed, and based on these results, a suitable statistical analysis was selected that would yield appropriate results for the study. The sardine arrival times were deemed to be normally distributed by utilising an Anderson-Darling test within 95 percentile confidence intervals. Thus, regression, multiple regression and correlation statistics were selected as a means to test the external factors that influence the delay in arrival times.

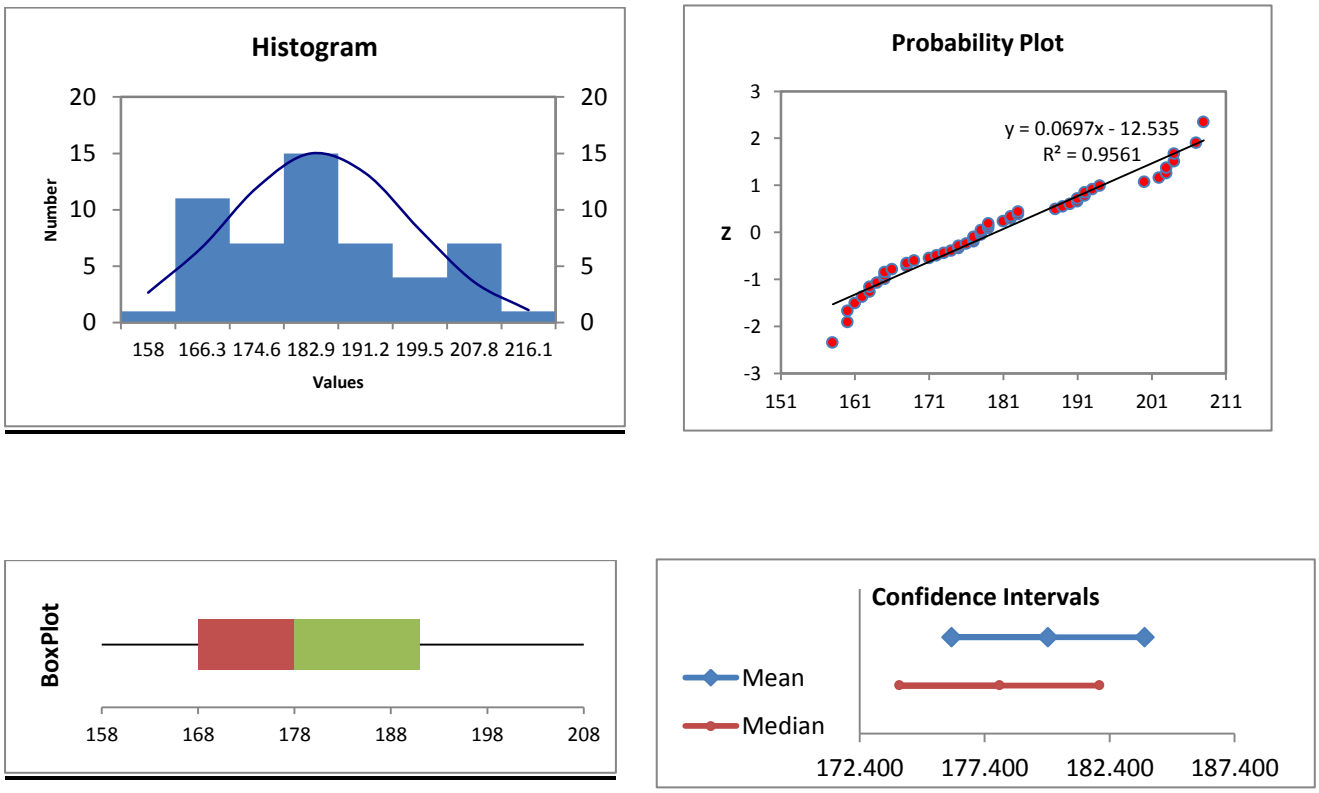


Figure23: Anderson Darling statistical result plots, the histogram suggests that the sardine run arrival times are normally distributed within 955 confidence intervals.

4.6.1 Temperature and Arrival Times

		Summer	Autumn	Winter
PSJ	Average	0.314	-0.056	0.167
PSH		0.223	0.042	0.155
PSJ	Minimum	0.272	0.042	0.203
PSH		0.202	0.107	0.19
PSJ	Maximum	0.062	-0.133	0.072
PSH		0.09	-0.105	0.072

Table 5: Correlation matrix of sardine arrival times and seasonal maximum, minimum and winter averages.

Table 2 presents results of a correlation analysis that determined which seasonal air temperatures at PSH and PSJ were more correlated to the arrival times of the sardine run. It is evident that summer average and minimum temperatures exhibit the strongest relationship. On the contrary, autumn exhibits the weakest relationship on a seasonal basis, which is to be expected, as the sardines have already arrived.

		December	January	February	March	April	May	June	July
PSH	Average	-0.148	0.287	0.157	-0.086	-0.064	0.026	0.079	0.195
PSJ		-0.098	0.338	0.197	0.095	0.057	-0.05	0.133	0.167
PSH	Minimum	-0.108	0.4	0.219	-0.047	-0.013	0.146	0.125	0.257
PSJ		-0.143	0.402	0.169	0.098	0.138	-0.008	0.168	0.164
PSH	Maximum	-0.113	0.173	0.073	-0.1	-0.144	-0.085	-0.003	0.094
PSJ		-0.11	0.231	0.166	0.054	-0.153	-0.100	0.036	0.125

Table6: Correlation matrix of sardine arrival times and seasonal maximum, minimum and winter averages.

Table 3 presents similar correlation results to that in Table 2, apart from the fact that in Table 3, individual months are correlated against sardine arrival dates for both PSH and PSJ. Correlation results show in finer detail which individual months that have air temperatures strongly correlated and those that are not. It is evident that minimum and average air temperatures in January for both PSH and PSJ are best correlated, and thereafter February, June and July, December and November are negatively correlated, while the months of August, September and October are weakly correlated. It was therefore decided to include both the minimum and average temperatures of January for both PSH and PSJ in the statistical analysis.

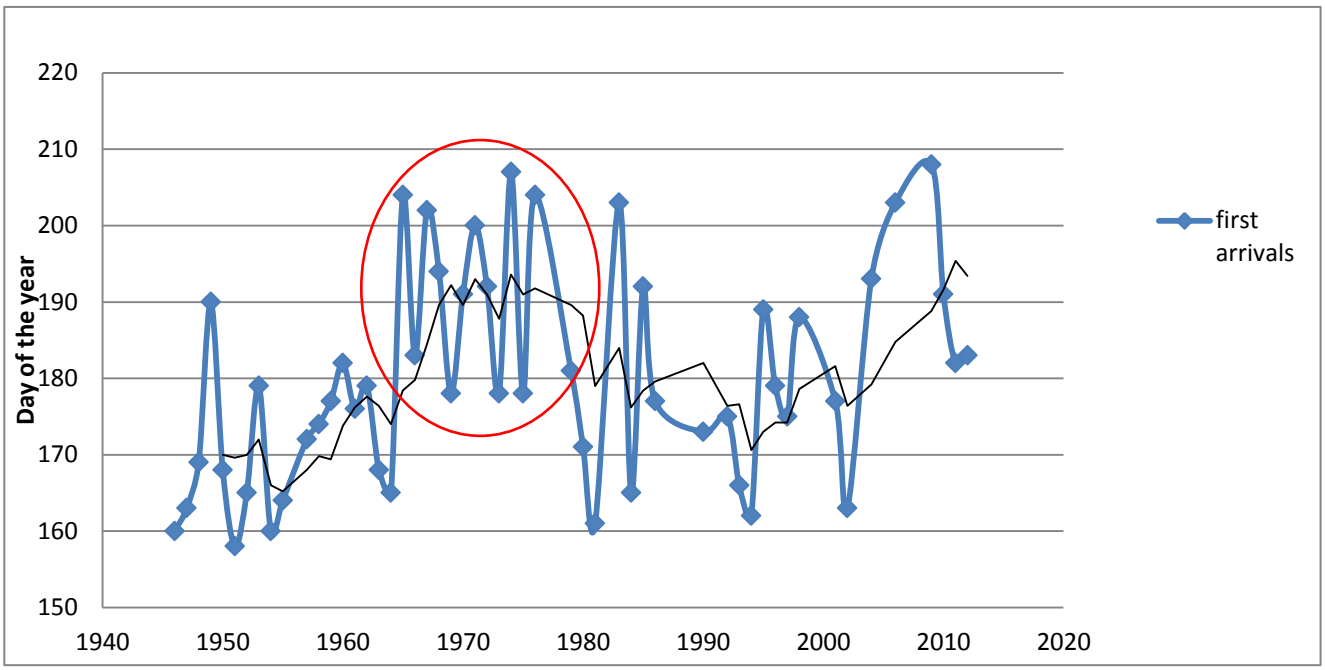


Figure24: Arrival times of the main shoal illustrating an important period between 1965-1979.

As mentioned before in the temperature analysis, a particular period occurring over the 1960's to late 1970's showed a rapid increase in temperature variability in the KZN region as seen for the DBN and PSH climatic stations. Thereafter, an ever increasing trend is observed, however, not as rapid as in the aforementioned period. Highlighted in Figure 24 is a particular response exhibited by the sardine run arrival times. It can be assumed that, due to a general increase in temperatures noted in both SST and air temperatures, the sardines adjusted their arrival times in accordance to this change. For the duration of 14 years between 1965-1979, the arrival times on average increased with 21.7 days than that prior to 1965, thereafter the arrival times had shifted on average by 10 days in comparison to those prior to 1965. Subsequently, the period after 1980 experienced on average, a 14.8 day delay in arrival times which is consistent with the general trend observed.

4.6.2 Mid Latitude Cyclones

Since distinctive mention was made in news reports that, more often than not sardines would follow a preceding frontal depression, as a result of favourable conditions arising, which enable them to move northwards, this frequently implicates a decrease in ambient atmospheric and ocean temperatures. Therefore, the correlation between cold fronts and associated air temperature was tested against the timing of sardine runs.

	April	May	June	July	August	Winter mean	Total
Correlation	-0.075	-0.037	0.303	0.054	0.032	0.161	0.087

Table 7: correlation results of sardine arrival times and the occurrence of cold fronts for each respective year the sardine run occurred between 1950 and 2011.

Table 5 required considerable analyses for a logical explanation of the results obtained. Firstly, the months of April and May both exhibit weak negative correlations and may be interpreted as follows. The months of April and May occur prior to when the sardines generally arrive, which is usually in June or July. These months have been deemed important because they may be influential in terms of climate. Cold fronts passing over the KZN coastline during April and May could possibly decrease the water temperature sufficiently to allow for earlier arrival times, therefore the negative relationship may be explained here. An increase in occurrence of frontal depressions may increase the negative correlation, however as Figure 13 implies, a decrease in the occurrence of frontal depressions has occurred for this region for the months of April and May, hence the likelihood of this occurring may be rejected. This theory is speculative because of the weak relationship observed based on the results obtained, therefore it may be assumed that no relationship exists.

The months of June and July are furthermore fundamental as these months are generally the periods when the sardine shoals arrive along the LSC. June has a moderate positive correlation with arrival times, however, the relationship is contrary to the former months, whereas July has a weak positive relationship. Upon investigating the results further, it was observed that an influx of frontal depressions, besides having a positive effect by creating favourable conditions, may also create unfavourable conditions. Increased incidents of frontal depressions passing over the LSC during the arrival months of the sardines may be detrimental to weather and oceanic conditions, which consequently disrupt the passage of the sardines or in some cases, prevent them from reaching the shore. It was evident, that in years with above normal incidence of frontal depressions the arrival times would be delayed

substantially more than during years with average or below average incidence of frontal depressions. Therefore, it is assumed that average incidence of mid latitude cyclones are more conducive to typical arrival times. July and August have weak positive relationships, and the frequency of cold fronts during these two particular months is less influential than other months because more often than not, the sardines have arrived in July or have arrived prior. It was theorised that months preceding and during the runs are more influential and the above correlations suggest that a weak to moderate relationship exists.

As the relationship between temperature variability and sardines is the focus of this paper the influence of mid latitude cyclones on ambient air temperature was further investigated.

		Maximum	Minimum	Average
PSH	Correlation	-0.16	-0.236	-0.227
	P value	0.221	0.07	0.08
PSJ	Correlation	-0.297	-0.295	-0.373
	P value	0.023	0.025	0.004

Table 8: Correlations of Cold front Occurrence and ambient winter air temperatures at PSH and PSJ 1950-2012

It is evident from Table 4 that cold front occurrence and frequency has a relationship with ambient air temperatures at both study sites PSJ and PSH. The correlations between cold front frequency and occurrence are negative for maximum, minimum and average temperatures for both PSH and PSJ. This implies that their occurrence along the LSC and the Eastern Cape Coast decrease ambient air temperature when they pass over the region in question and, is consistent with all the literature (Tyson and Preston-Whyte, 2000; Grab and Simpson, 2000) . It is observed that the strongest relationships are with minimum and average temperatures, PSJ has the stronger relationships and is statistically significant. Nonetheless, the relationship between mid-latitude cyclones and temperature are still significant with p values under 0.05 and therefore formed part of the statistical analysis.

4.6.3 Multivariate ENSO Index

The MEI data set was statistically analysed to observe any relationships existing between it and the sardine run data. Being an oceanic derived data set, it was theorised that ENSO cycles of positive and negative intensity might be influential with regards to the arrival of the sardines along the LSC.

Enso Cycles	Dec/ Jan	Jan/ Feb	Feb/ Mar	Mar/ Apr	Apr/ May	May/ Jun	Jun/ Jul	Jul/ Aug	Aug/ Sep	Sep/ Oct	Oct/ Nov	Nov/ Dec
Correlation	-0.064	-0.056	-0.104	-0.112	0.035	0.14	0.113	0.093	0.001	-0.023	0.02	0.024
P values	0.65	0.69	0.46	0.423	0.803	0.319	0.42	0.508	0.995	0.868	0.887	0.862

Table 9: Correlation values between MEI and sardine arrival times.

Table 5 contains correlation values from a statistical analysis between sardine arrival times and MEI indices. It is evident from Table 5 that ENSO is weakly correlated to sardine arrival times and are mostly statistically insignificant. However, although depicting weak relationships in relation to sardine arrival times, ENSO plays an important role in influencing oceanic mechanisms and drivers that are influential to sardine runs. Regrettably the coastal waters around South Africa are poorly surveyed and no historical data investigating this intricate relationship exists and could thus not form part of this study. Should such data become available, it should shed more light on other causes that impact the arrival times of the sardines not investigated in this study.

4.6.4 Statistical Analysis of Sardine Arrival Times and Environmental Factors

The null hypothesis in this study theorises that, if a delayed response of arrival times of the sardines exists, environmental factors believed to be influential in the arrival times in this study would not be able to explain any variance of a delayed response, therefore, there would be no statistically significant relationship between the variables (i.e. the environmental factors and the arrival times of the sardine shoals). The alternative hypothesis theorises that changes witnessed in environmental conditions are statistically significant and are influential with regards to the sardine arrival times.

As previously determined, data on the sardine arrival times are normally distributed, therefore a multiple regression analysis can be used to determine the statistical significance between arrival times and the environmental elements already discussed in this chapter. The multiple

regression analysis incorporated the environmental factors that had the most statistical significance in relation to the arrival times of the sardine shoals. The temperatures deemed to be most significant were the January minimums, the frontal depression frequency in June and ENSO cycles in June. The multiple regression analysis was completed for both PSJ and PSH. PSJ is of importance because the main shoals would often be held up in this area before they migrate northwards or not at all, the oceanic gyre in the area that is responsible for the Waterfall Bluff hypothesis, is believed to be responsible for them being held in the area or allows them to migrate northwards (Oosterbaan et al., 2013). PSH is in the vicinity where the sardines would be sighted first along the south coast and temperatures here need to cool down sufficiently to allow the northward movement of sardines.

Port St Johns	
Regression Statistics	
Multiple R	0.50410833
R Square	0.25412521
Adjusted R Square	0.20084844
Standard Error	12.644493
Observations	46
P value	0.006

	Coefficients
Intercept	14.3828476
January min	7.81630087
Frontal Depressions	3.6200019
ENSO	-0.8876369

Port Shepstone	
Regression Statistics	
Multiple R	0.4373553
R Square	0.19127966
Adjusted R Square	0.13485731
Standard Error	13.0131579
Observations	46
P value	0.026

	Coefficients
Intercept	44.858733
January Min	6.09459777
Frontal Depressions	3.13135414
ENSO	0.07916243

Table 10: Multiple regression analysis results of January minimum temperatures, frontal depression occurrence and ENSO intensity of Port St Johns and Port Shepstone.

Table 8 represents the results of the two different multiple regression analyses that were completed for PSJ and PSH. The arrival times are 50% correlated with the environmental factors used in the regression analysis for PSJ, whereas they are only 43% correlated with PSH. About a third of the variance in the delay of arrival times of the sardines can be explained by the environmental factors of PSJ, whereas only 20% thereof can be explained by the environmental factors of PSH. Therefore, about two thirds to three quarters of the

variance in arrival times of the sardines can be attributed to other factors, of which, oceanic drivers and mechanisms should be the main factor and other factors such as a decline of sardine population as a result of overfishing. However, overfishing may not have an influence on the sardine run. Both Baird (1971) and Heydron (1978) theorized the that the sardine are a breakaway shoal from the main population of sardines found at the Agulhas Banks where they are commercially caught (van der Lingen et al., 2010). However, Freon et al. (2010) explain that the sardines that migrate annually are a genetically distinct sub population, hence not affected by overfishing the resident Agulhas population of sardines. Both regression analyses are statistically significant and reject the null hypothesis, considering that environmental factors have no significance in the variance observed in arrival times of the sardines.

It is believed that PSJ is more statistically significant in terms of the arrival times of the sardines because of the oceanic gyre present at this location. Migratory fish species are influenced more by daily changes in temperature than longer temporal changes in temperature that affect other migratory animal species (Tseng et al., 2011; O'Donoghue et al., 2010). Fish species, such as in the case of the Pacific Saury, can change their habitual range in a shorter period of time (Tseng et al., 2011). Therefore, in the case of the sardines, once oceanic temperatures and oceanic mechanisms are favourable enough for them to migrate northwards, they will. However, changes in these systems as well as environmental factors presented in this study could have a negative outcome on sardine run frequency and timing.

To further test the significance of environmental factors influencing the arrival times of sardines, the SST of PSJ were utilized because of their significance and because of the importance the area has with regard to their migration patterns.

	Amax	Amin	Aavg	Wmax	Wmin	Wavg
Multiple R	0.322	0.315	0.320	0.225	0.248	0.239
R Square	0.104	0.099	0.103	0.051	0.061	0.057
Adjusted R Square	0.086	0.081	0.085	0.032	0.043	0.038
Standard Error	13.245	13.279	13.256	13.634	13.556	13.588
Observations	52.000	52.000	52.000	52.000	52.000	52.000
Significance F	0.020	0.023	0.021	0.109	0.077	0.088

Table 11: Statistical regression observations for annual (Amax, Amin, Aavg) and winter (June, July, August) (Wmax, Wmin, Wavg) maximum, minimum and average SST from 1946-2012.

Table 5 displays the statistical results from a regression analysis of SST in PSJ and the arrival times of the sardine runs. From these results it can be observed that annual temperatures are more statistically significant than winter temperatures, representing p values between 0.020 and 0.023. The SST are weakly correlated to the arrival times and can only explain about 10% of the variance observed in the arrival times of the sardine runs. Although significant, the other environmental factors analysed in this study explain more of the variance than only SST. Smit et al., (2013) explain that it has been noted that large biases exist between satellite derived SST and *in situ* recorded data. Therefore, with the lack of historical oceanic instrumental recorded data, and large biases found between satellite derived data and *in situ* recordings, historical records of air temperatures are more suited for this study and is possibly why more variance in the sardine runs could be explained by them.

Chapter 5: Conclusion

The purpose of this study was to determine if there were any observed changes in the phenology of historical sardine runs. With the use of documentary evidence, a chronology of past sardine run events was created to establish the timing and first arrivals of sardine shoals along the lower south coast of KwaZulu-Natal over a period of 66 years. Coupled with climatic data such as: SST; surface air temperature; mid-latitude cyclones and ENSO cycles, the aim was to determine whether or not the sardine runs displayed any delays in their annual arrival times and if so, to what extent has climate change played a role in delaying their arrival and/or affected the events frequency.

5.1 Observations of Temperature Increase

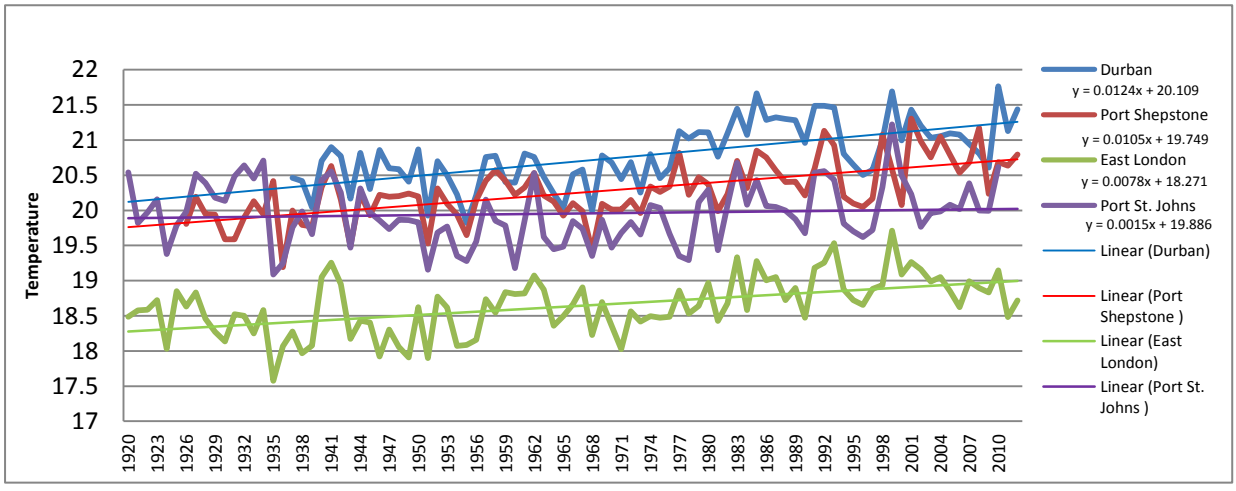


Figure 4: Annual average long term temperatures trends for the four climatic zones with a running mean of 11 years

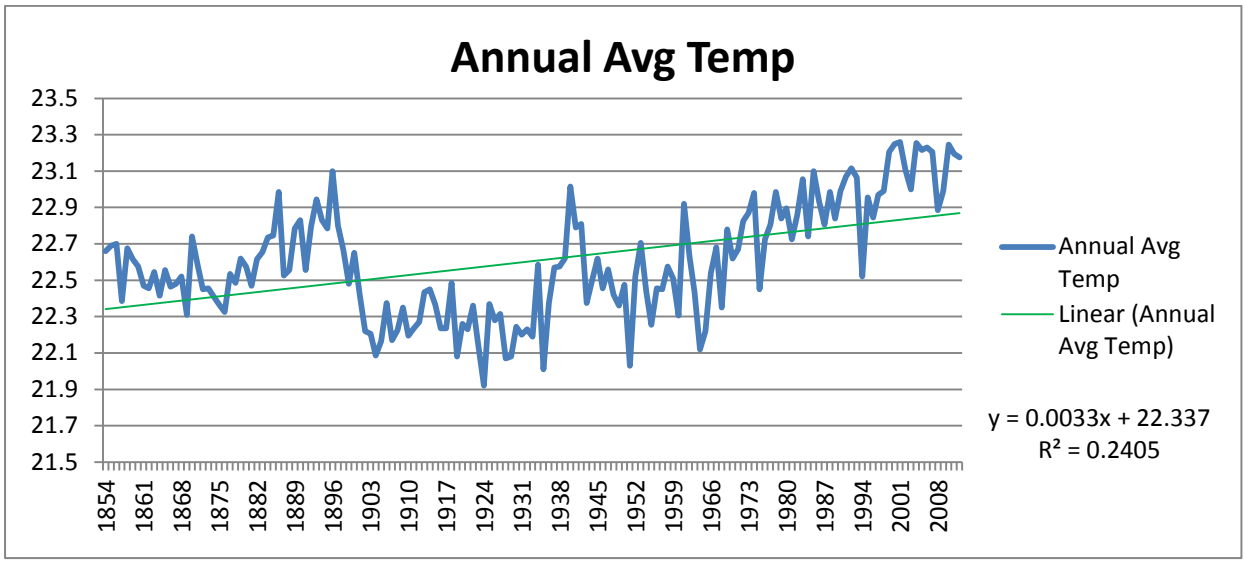


Figure 7: SST annual average decadal trends for the southern African East Coast 1912-2012

Figure 1 and Figure 7 display the general trend that was observed in the study area; both surface air temperatures and SST warming has taken place. Based on air and ocean interactions, it was hypothesised that the oceanic and surface air temperatures would display a similar increase in temperature, as a result of the exchange between the two systems (Alexander et al., 2002).

The change in SST observed is conclusive with other SST studies (Misihima et al., 2010; IPCC, 2013), and is an accurate representation of how the coastal waters have changed over time. However, as Smit et al., (2013) explain, caution should be taken when drawing conclusions with SST because of the biases that exist. Due to a lack of *in-situ* oceanic temperature records for where the sardine runs occur, surface air temperatures were substituted as a more forthcoming record. Another issue that exists with sardine runs and SST records is the coastal bleed in the satellite images. Because the sardines are forced inshore by the Agulhas current on the continental shelf, more often the sardines are found in this coastal bleed where no temperature readings are present. Nevertheless, it is evident from both records that climate change and variability was evident in the region, and hence the

importance to test whether climate change influenced the timing and frequency of sardine run events.

5.2 Mid –latitude Cyclones and the Sardine Run

Although the frequency of mid latitude cyclones over KZN has not changed dramatically over the study period it never the less has importance with regards to the sardine run events. Between periods of cold fronts passing the region the presence of sardines is considerably higher than when a cold front is present in the area, in other words, favourable conditions exist between the passage of cold fronts and unfavourable conditions exit when a cold front is present. For instance cold fronts bring along with it high winds and rain which is detrimental to oceanic conditions which the sardines prefer. Winds create large swells and turbulent seas whereas the rains cloud the water with silt (O'Donoghue et al., 2010). Between the passage of cold fronts a cold snap is present immediately after the cold front has passed (Tyson and Preston-Whyte, 2000). If warmer ocean temperatures were prevalent before the passage of the cold front the cold snap would have cooled down the water sufficiently allowing the sardines to move northwards. This instance was reported numerous times in the newspaper articles such as: "In my opinion they should arrive after the present or next cold front passes over" – Barry Smith *South Coast Herald* 4 July 1986. Therefore, in concluding about mid-latitude cyclones, the frequency over the study period seemed to have no immediate effect on the overall timing of the sardine runs, however, they are instrumental in creating favourable or unfavourable conditions in the region.

5.3 Sardine Run Timing and Frequency

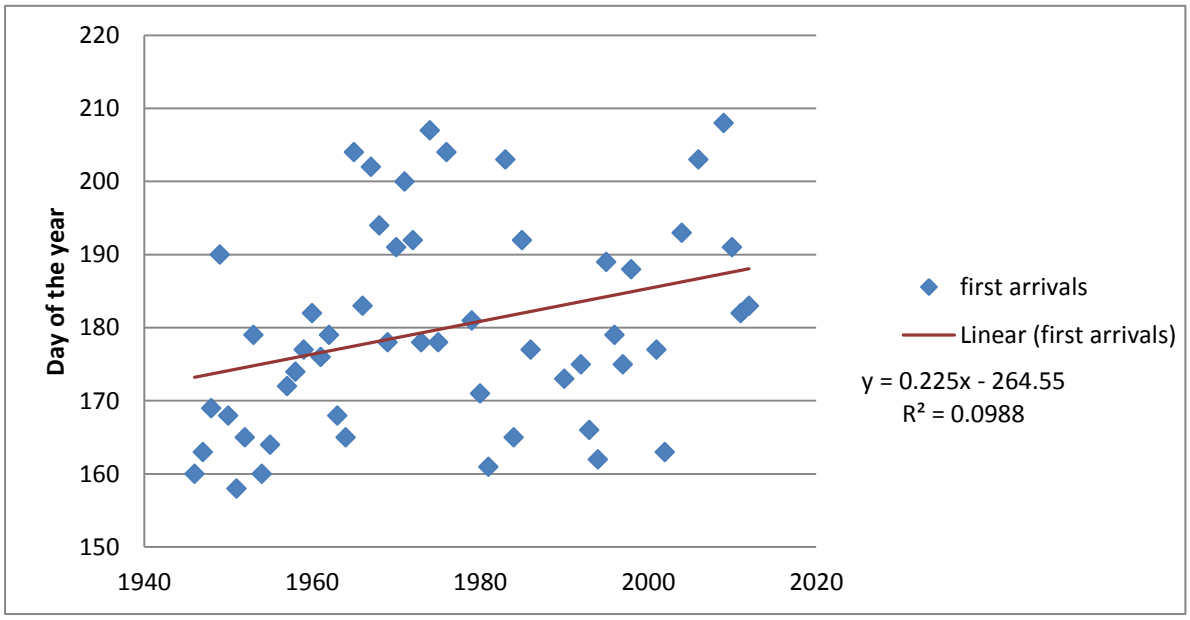


Figure 5: Graphical representation of the first arrival times of the main shoal on the lower south coast of KZN, the period observed was between 1946 and 2012. Similarly to figure 17 in some years the main shoal failed to appear along the lower south coast and therefore were classified as a non-run, therefore there are fewer listed points as in figure 16.

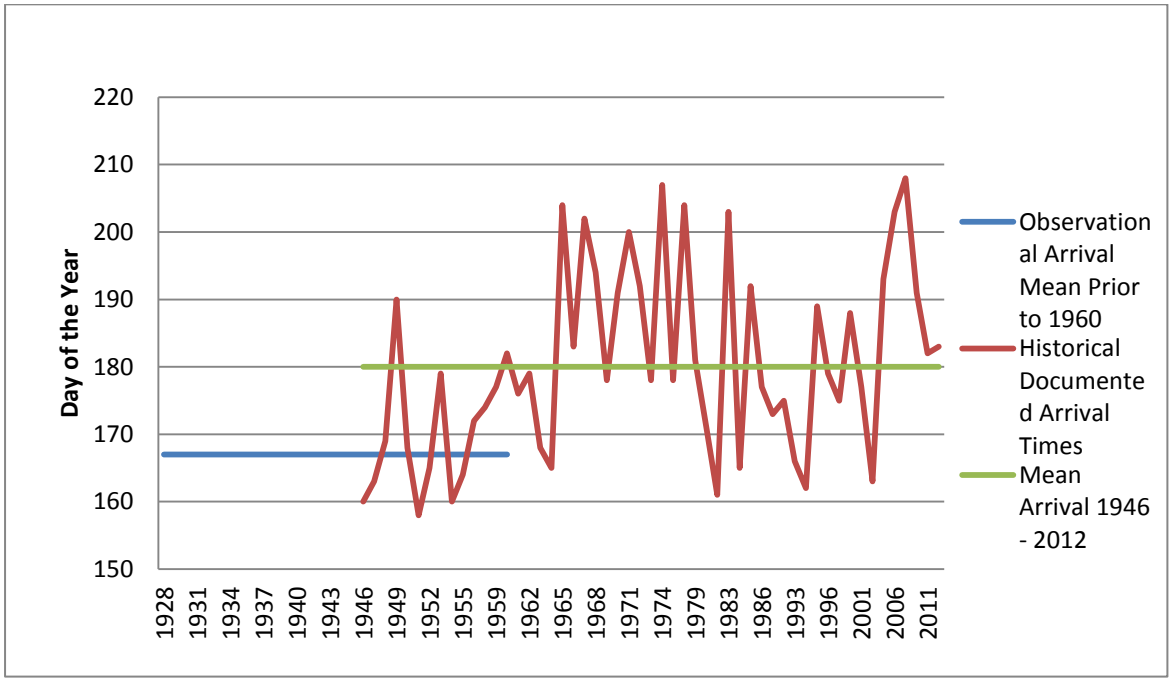


Figure 21: Documented and observed arrival times of sardine runs 1928-2012. Observational arrival time means calculated from arrival dates published by Ronnie Cooper

Based on Figures 20 and 21, it can be concluded that there has indeed been an apparent delay in the annual timings of the sardine runs over the study period, and thus to at least some extent, climate change has played a part in this delay. A general warming trend in both surface air temperatures and SST is evident with SST depicting warming from 1910 to present times. Along with the observational arrival dates captured by Ronnie Cooper, it can be seen that the arrival time graphics and temperature graphics emulate the same general increasing trend. Drawing from the statistical analysis that the results are statistically significant, although not strong, the rise in temperature in part is responsible for the delay observed in the graphic and statistical analysis.

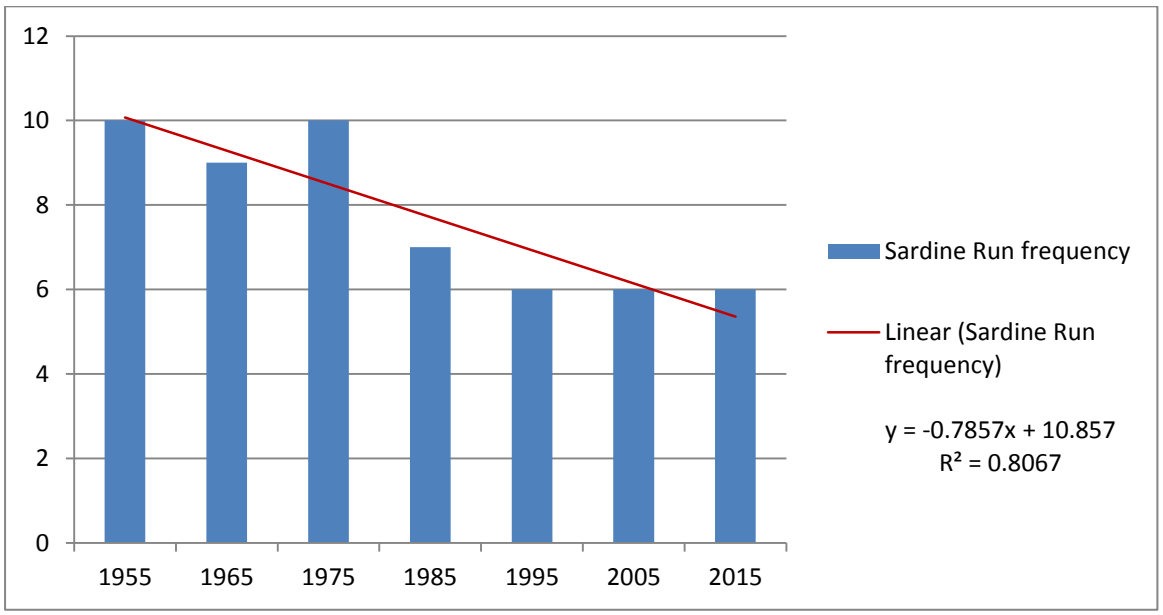


Figure 22: Decadal sardine run occurrence 1955-2015

There has been a notable decrease in the frequency of sardine run events from taking place as well as a prominent delay in the annual timing; this has been observed on both, decadal scales and over the entire study period. This can be attributed to the fact that the environment is changing as a result of climate change. The increase of the global energy budget and the impact it has on the atmosphere and atmospheric oceanic interaction has caused these environments to change, hence physiological intolerances of species arise and this forces shifts in phenological events, range and distribution (Doney et al., 2012). .

5.4 Environmental Factors and the Sardine Runs

As standalone environmental factors, the above mentioned had weak correlations and did not explain much of the variance of the observed in the timing of the annual sardine runs. However, when the environmental factors where combined in a multiple regression analysis, a stronger relationship was found and more of the variance, of the arrival times of the sardine runs could be explained by the environmental factors. It can therefore, be assumed that more than one environmental factor is influential, and which is why the sardine run phenomena is poorly understood and challenging to study (O'Donoghue et al., 2010).

Oceanic gyres play an important role in assisting the annual sardine run and should historical data sets have been available for these oceanic mechanisms, then more of the variance of the annual timing of sardines might be explained. Theses oceanic mechanisms, in the first instance, are key to the northward movement of the sardine runs. The Port Alfred upwelling cells introduce a cooler northward flowing current that counter acts the warm Agulhas current, which consequently increases the sardines favourable habitat range and eases their movement (van der Lingen et al., 2010; Roberts et al., 2010). The last important oceanic mechanism is the Durban break away eddy - once this moves southwards it opens the "gate" present at waterfall bluff i.e. the waterfall bluff gate hypothesis, which is the last mechanism needed for the sardines to continue northwards, as tested by Oosterbaan et al. (2013), who confirm that the sardines were indeed responsive to these mechanisms.

Because of ENSO's prominent role in affecting global weather and climatic patterns by teleconnections and the resulting impact it has with regards to oceanic and atmospheric interactions, it is thus hypothesised that oceanic factors influencing the sardine run may have changed over the same period of time. Historical oceanic temperature records along with ENSO cycles could further explain to what extent climate change is influencing the sardine runs. ENSO cycles could be used to determine how the oceanic mechanisms have been influenced over time, specifically by ENSO cycles. This then could potentially enable better predictions of the sardine arrival times.

The sardine run phenomena is very complex to explain, and it is equally as complex to determine how certain environmental factors have influenced it over time. This research initiative set out to determine how, and to what extent, climate change and certain measureable environmental factors have influenced the annual timing of sardine runs. The

results have shown that a portion of the variance could be explained by the environmental factors used in the research analysis.

However, the sardine run relies on a combination of factors to be favourable in order for them to "appear" ("run") along the lower south coast. The ocean conditions need to be calm and clear, the water temperature needs to be in their favourable range, they need to be present between the passage of cold fronts and the oceanic drivers need to be present creating the current reversal, and thus allowing them to move northwards along the coast. Once all these conditions are present, the sardines are most likely to migrate. If one or more of these factors is not present in unison or creates unfavourable conditions, this may ultimately result in a "miss". The sardine run can therefore be said to rely on 'The Goldilocks Effect' (Watson, 1999; Katz, 2012), the environmental conditions have to be just right in order for the run to occur.

5.5 Future Research Opportunities

Because only a third of the variance in arrival times could be explained by the environmental factors examined in this study, there are other factors to be examined for their measured influence. It is theorised that other environmental factors such as *in situ* recorded oceanic temperatures and the change in oceanic currents and drivers could explain more of the variance determined by this study as demonstrated by Oosterbaan et al., (2013). However, the lack of historical instrumental data sets makes future research challenging. The use of the historical chronology of past sardine runs created by this study could be used in a similar study conducted by Oosterbaan et al., (2013) and the influence of the oceanic gyres deemed important for the Waterfall Bluff Gateway Hypothesis (van der Lingen et al., 2010; O'Donoghue, et al., 2010; Oosterbaan et al., 2013) could be extended to the early 1980's which could potentially create a research project spanning 35 years. This could be sufficient to determine any change in these gyres, i.e. their frequency occurrence and timing. This research initiative could, therefore, explain the remainder of the variance discovered by this research project.

5.6 Final Thoughts

It therefore can be stated climate variability and change has impacted the annual timing of the sardine runs and the frequency of runs occurring on a decadal scale. It is stressed that should nearshore oceanic water temperatures increase to a threshold that is not accommodating to the favourable habitat range of the sardines, we could potentially see a cessation of the sardine run entirely which would have dire socio-economic and ecological implications. Therefore, it is important that, future sardine runs should be monitored to determine any changes in timing and frequency that may indicate negative trends.

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