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# Variability and characterizations of wind events over the Cape Columbine region along the west coast of South Africa

**by**

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## Ephesians 1

[3] Blessed is the God and Father of our Lord Jesus Christ, who has blessed us with every spiritual blessing in the heavenly realms in Christ. [4] For he chose us in Christ before the foundation of the world that we may be holy and unblemished in his sight in love. [5] He did this by predestining us to adoption as his sons through Jesus Christ, according to the pleasure of his will – [6] to the praise of the glory of his grace that he has freely bestowed on us in his dearly loved Son. [7] In him we have redemption through his blood, the forgiveness of our trespasses, according to the riches of his grace [8] that he lavished on us in all wisdom and insight. [9] He did this when he revealed to us the secret of his will, according to his good pleasure that he set forth in Christ, [10] toward the administration of the fullness of the times, to head up all things in Christ – the things in heaven and the things on earth. [11] In Christ we too have been claimed as God's own possession, since we were predestined according to the one purpose of him who accomplishes all things according to the counsel of his will [12] so that we, who were the first to set our hope on Christ, would be to the praise of his glory.

# ABSTRACT

Wind data over Cape Columbine is investigated over a 38 year long time series to determine whether there are noticeable changes or variability through time. The long period dataset is collected using an Automatic Weather Station. Diurnal and seasonal to annual characterizations of wind together with occurrences of related events are established. Other linkages with synoptic to near-global (e.g., ENSO) scale circulations are investigated by examining relationships with other meteorological variables. This is achieved by complimenting long term data series with data from the new technologically advanced Automatic Weather Station (AWS).

From the new AWS, several relationships and connections between different atmospheric variables were developed. These include the relationship between Air Temperature and Humidity, Wind Speed and Atmospheric Pressure, and Wind Direction and Rainfall. The AWS is able to monitor the passage of synoptic (e.g., cold fronts) and mesoscale (e.g., coastal low) weather systems. Passages of cold fronts over time could easily be detected by utilizing all the different variables as recorded by the AWS (Air Temperature, Wind Speed and Direction, Relative Humidity, Atmospheric Pressure and Rainfall). The most significant atmospheric system that passed over Cape Columbine over the 2009/10 summer was a deep low pressure system, where a significant amount of rainfall, atmospheric pressure depression and drop in temperature were witnessed. There were 17 upwelling events during this six months study period. Several of them were short-lived at 4 to 6 day durations, and the longest upwelling event occurred on the 24th December 2009 and lasted until January 14th 2010.

An investigation into the variability in characteristics and behavior of wind signals at Cape Columbine was conducted. The study investigated wind behavior for the period 1957 to 1995 with data collected from a point source Automatic Weather Station. Apart

from the characteristics of wind over time period, linkages with large scale circulations, frequency and duration of these wind events occurrences were studied. These were achieved by partitioning the study period into different time scales; namely, the diurnal, seasonal, inter-annual and the decadal.

On the diurnal time scale, a strong variability in wind strength over the course of each day due to the land/sea breeze existed. Seasonally, the wind regime in Cape Columbine was found to be driven by the latitudinal shifting of the semi-permanent South Atlantic Anticyclone. However, there are pre-dominant southerly winds throughout the year. The long record showed the possible influence of ENSO and the Benguela Niño on interannual and decadal variations in the winds at Cape Columbine.

# Chapter One: Background of the research

In this chapter, background material about the greater Benguela Current and its upwelling cells is documented together with linkages to the south coast dynamics. A lot of research has been conducted over this area; however there is still some uncertainty about the influence of atmospheric circulation on ocean features. Historical ways of collecting meteorological and oceanographic data, with more emphasis on wind data from Cape Columbine are discussed.

## 1.1. The Benguela Current and upwelling cells

The Benguela Current system is an eastern boundary current resulting mostly from strong local wind and offshore oceanic flow (Hardman-Mountford *et al*, 2003). It is the only current enclosed by warm waters of tropical origin both to its north (Angola Current) and to its south (Agulhas Current) as highlighted by Shannon and Nelson (1996). This current possesses the strongest sustained wind-driven coastal upwelling in the global oceans (Bakun, 1993). Lutjeharms (1997) also discovered that an offshore divergence along the continental slope dividing the coastal and offshore flow of this current is very important. The coastal flow is influenced by the prevailing south-east Atlantic trade winds that enhance strong Ekman transport and upwelling of cool water (Shannon, 1985a). There is a clear contrast in wind speeds during winter and summer seasons. Highest speeds occur in the south (west coast of South Africa) in summer and in the north (Namibian coast) during winter due to the seasonal migration of the South Atlantic Anticyclone over the south-east Atlantic Ocean (Hardman-Mountford *et al*, 2003). This long shore variability in the strength of the wind divides the Benguela Current system into a series of upwelling cells associated with the cold upwelled water along the coast.

The strongest and most persistent upwelling cell is in the vicinity of Luderitz (27° S), where wind stress is greatest and sea temperature is coldest (Shannon, 1985a; Lutjeharms and Meeuwis, 1987). There is also a distinct contrast in characteristics to the north and south of this upwelling cell. Hence, it divides the Benguela Current into two parts with distinct physical and the biological features (Shannon, 1985a; Pitcher *et al*, 1992). Shannon (1985a) indicated that there is a marked change in the wind field south of 30° S. In the southern Benguela, south of Luderitz, a number of upwelling cells exist. In Hondeklip Bay (30° S), an upwelling cell referred to as the Namaqua Cell exists with two others at Cape Columbine (32° S) and Cape Point (34° S) (Shannon, 1985a; Lutjeharms and Meeuwis, 1987). These cells have a quasi-permanent nature and they are prominent on event scale (Shannon and Nelson, 1996). Analysis of Quickscat data has indicated that the longest upwelling episode was approximately 28 days over the southern Benguela in December 2000 (Blancke *et al,* 2005). The dynamics of these upwelling cells and their existence depend on long-shore wind stress, coastal orientation and topography of the continental shelf. Bakun (1993) also found that the intensity of wind mixing stabilizing the water column is important.

Along the south coast of South Africa, periods of strong persistent easterly winds are needed to generate classical Ekman upwelling (Schumann *et al,* 1982). The vertical stratification of the water column persists almost year-long due to the advection of near surface warm Indian Ocean waters by the Agulhas Current (Bakun, 1993; Largier and Swart, 1987). The fluctuation in the existence, periodicity and severity of these upwelling cells is modified by the El Niño Southern Oscillation (ENSO) events which occur every 2 to 7 years (Hardman-Mountford *et al,* 2003). Colberg *et al* (2004) highlighted the importance of ENSO impacts over the South Atlantic Ocean. During the onset of El- Niño (La- Niña), the Pacific South America tele-connection pattern leads to positive (negative) SLP anomalies in the Benguela region and warm (cool) SST anomalies. This warming (cooling) in the South East Atlantic peaks during the austral spring. However, by the mature phase (the austral summer), the extent of these anomalies has contracted to roughly the 25-30 ˚S zone and weak opposite signed anomalies have appeared both in the northern and far southern Benguela waters. These SST changes largely result from regional changes in the subtropical jet and hence in the surface winds (Colberg *et al,* 2004).

Rayner *et al (*2009) observed that historical SST, SLP and marine wind data were extracted from ship logbooks. In recent decades, buoys and satellites have provided significant source of marine data. Data collection was spatially poor prior to about 1950. Although climate centres such as NCEP and ECMWF have derived atmospheric re-analysis products that extend back prior to the satellite era, it is only with the incorporation of these data into the re-analysis scheme for dates after 1979 that more confidence is achieved in the reliability of these products. Much climate research has made use of these re-analysis products as well as other historical data measured during the instrumental period. Such historical records require caution in interpretation as they often depend on statistical techniques to fill in spatial and / or temporal gaps in the observations in order for a gridded dataset to be produced (Rayner *et al,* 2009). These techniques may lead to various biases, especially for periods when the original data collection methods were changed.

Different shipboard or in-situ methods (such as bucket and then engine intake sampling) of collecting data were used in the early 1900s. In the recent past, ship board observations have been supplemented by automatic measurements made by drifting and moored buoys. Drifting buoy measurements were standardized in 1993 and their collective data has been fairly stable since then. However, Rayner *et al* (2009) argues that relative to shipboard observations, drifting buoy SST measurements tend to be cooler. Since then, there has been an increase in the reliance on drifting buoy measurements and satellite data, leading as expected to a decline in the contribution to the database of ship-borne observations. This change has also led to further temporal and spatial biases in the data (Rayner *et al,* 2009).

Satellites started to collect ocean data in the early 1980s and they have since then been significantly used for research studies. Like any other point source data collector, observations from satellites suffered spatial biases. Thus, in most cases they are used to compliment in-situ observations. Data collected from drifting buoys are also used to calibrate or validate satellite measurements in an effort to reduce biases (Reynolds *et al,* 2001). The smoothing or validation of these data helps in climate variability research (Rayner *et al,* 2009). SST is one of the most measured ocean parameters as a result of these many observational platforms. However, this diversity alters the quality as the data recorded might not be homogeneous (comes from different sources). This situation then calls for improved dataset description methods so as to reconcile and understand oceanic features at event scale.

## 1.2. Linkages with SST and other large scale modes.

Many of the coastal mixed layer and upwelling investigations have been conducted in regions that are important for fisheries (Schumann, 1999) and this is also the case here where the focus is on the west coast of South Africa. Schumann (1999) noted that there is a close association of temperatures with wind. Significant changes in the temperature profile during the onset of south-easterly winds occur. A pulse in the pressure field followed by subsequent south-easterly wind of 5 to 10 days duration induces an upwelling event on the west coast (Roy *et al,* 2001). The area of Cape Columbine located on the west coast to the northwest of Cape Town is suitable for investigating upwelling events since atmospheric perturbations there often signal variability in the periodicity and frequency of features in the coastal ocean. Roy *et al* (2001) examined a time series of long-shore wind and cumulative upper ocean divergence at Cape Columbine. The results indicated that there is succession of events which affected the perturbations in upwelling along the west coast of South Africa. During the period November 1999 to April 2000, there were a total of 12 major upwelling episodes along the west coast with the longest episode lasting for 20 uninterrupted days. It appeared that these upwelling events were influenced by the strong and protracted La Nina event which started during winter 1998 and lasted until 2001 (Roy *et al,* 2001).

As already mentioned, ENSO is one large scale climate mode that influences the variability in the Benguela region and, more broadly, the South East Atlantic (Colberg *et al*, 2004). Over the northern Benguela region and tropical South East Atlantic, the Benguela Niño (Shannon *et al*, 1986**;** Florenchie *et al*, 2003, 2004) strongly impacts on SST and mixed layer characteristics, particularly near the Angola Benguela Frontal Zone (ABFZ) which separates upwelled cool Benguela waters from warm, tropical Angola Curent waters to the north. Wainer and Venegas (2001) showed model evidence that there may be oscillations of around 25 to 30 years period in South Atlantic temperatures and circulation which they associated with changes in the large scale atmospheric circulation. Haarsma *et al*, (2005) and Colberg and Reason (2007) examined basin scale variations in the South Atlantic that are related to changes in the South Atlantic Anticyclone. When these changes occur more broadly as part of variations in the mid-latitude atmosphere wavenumber 3 or 4 pattern, a so-called subtropical South Atlantic and South Indian Ocean Dipole SST event may occur (Fauchereau *et al*, 2003; Hermes and Reason, 2005). In addition to their impacts on the ocean, these climate modes typically also affect the rainfall of neighbouring southern Africa (Rouault *et al*, 2003; Reason *et al*, 2006).

Regionally, there are changes and fluctuations in the SST around the South African coast and these have been analyzed at a monthly scale from 1982-2009. In the southern Benguela, a significant decreasing variation of 0.5°C in a decade from January to August and a 95% positive correlation with ENSO exists (Rouault *et al,* 2009). Rouault *et al (*2009) further indicated that El Niño and La Niña suppresses and increases upwelling respectively; however, there is no proven linear relation between the strength of the ENSO event and the magnitude of the coastal SST fluctuation. El Niño and La Niña have in the recent past appeared to be linked to major warm and cool coastal events at a seasonal scale in summer over the southern Benguela region (Rouault *et al,* 2009).

Although much research has been conducted on the impacts of ENSO on southern African summer rainfall (e.g., Lindesay, 1988; Reason *et al*, 2000), much less is known about the effect of ENSO on SST and rainfall along the west coast of South Africa. However, Rouault *et al* (2009) highlighted the potential influence of ENSO on SST along the south-west coast with the 1992 El Niño event being one case that resulted in abnormal warming around the Cape Peninsula.

## 1.3. Motivation of the research

A study of historical variability and change in climate conditions is needed to understand future variations in climate. It has become widely recognized that under a changing climate, the frequency and intensity of meteorological, oceanographic, hydrological extreme events and associated damage costs may likely increase (Desanker and Magadza, 2001). Thus, better understanding of regional climate and its variations may help in expanding adaptive capacity of society and in minimizing future climate risks. To develop these strategies, solid scientific information on future projections and historical variability analysis of the extreme events is essential. In this thesis, attention is focused on these variations in wind over the southern Benguela Current region.

A further motivation for studying this region is that upwelling along the southern Benguela Current zone contains one of the richest fisheries zone in the world which is supported by high marine productivity. Thus, better understanding of the variability in the southern Benguela and its sensitivity to large scale modes is a high priority (Colberg and Reason, 2007). On longer time scales, secular climate change may alter regional patterns of wind and ocean circulation and in turn, increases or decreases the frequency and intensity of upwelling episodes. Such changes in upwelling influence the production of fish and invertebrate species.

Blanke *et al* (2009) highlighted that to better understand the dynamics of the Benguela Current Upwelling System, it is important to study the wind forcing as its seasonal and inter-annual variations depend mostly on wind variability.

## 1.4. Objectives of the research

The main objective in this study is to investigate the behavior and variations in wind over time in the southern Benguela. In order to achieve this, the long term wind record from Cape Columbine is subjected to careful analysis. The study will help understand the climatology of wind over Cape Columbine and to confirm links between wind events and other large scale atmospheric and oceanic circulations. Variations in wind and patterns will be studied over different time scales (diurnal, seasonal, annual and decadal). Other derivatives will be calculated from wind data as these may serve as good indicators for upwelling; these include wind stress (anomalies) and wind mixing.

A detailed case study will be made of the summer wind at Cape Columbine from September 2009 to March 2010. Links to upwelling events and distinct synoptic atmospheric systems will be emphasized. A comparison will be made of upwelling conditions at Cape Columbine and in the southern Benguela between the 2009/10 summer and the 2000/1 summer.

# Chapter Two: Wind variability over different time periods

In this chapter, the longest available time series of wind observations at Cape Columbine will be studied. Analysis of diurnal, seasonal and longer term variability will be performed. The data were collected from an Automatic Weather Station (AWS) at Cape Columbine along the west coast, adjacent to the cold Benguela upwelling area.

## 2.1. Data and Observation

An AWS located at Cape Columbine was used to record meteorological data for further understanding of atmospheric dynamics and environmental monitoring. For the purpose of this study, hourly wind data from 1957 to 1995 (38 years) was collected from sources within the Department of Environmental Affairs (Oceans and Coasts) and placed into a long time series.

Figure 2.1: Figure showing an Automatic Weather Station installed along the foghorn with the Cape Columbine Lighthouse on the background as shown on the figure on the right.

The instrument used deflective wind vanes and a propeller for wind direction and speed respectively. This instrument was installed through funding from the then Sea Fisheries Research Institute of South Africa, recently known as Marine and Coastal Management (MCM). It used an internal data storage system and data was downloaded manually by visitation which was later replaced by a dial-up logging system. For this reason, there are few gaps in the data with the most significant gap being the whole of 1976 due to technical problems. This AWS was located approximately 200 meters from the sea shore and about 4 m above mean sea level at the Foghorn of the Cape Columbine lighthouse with the wind sensor located 10 m above the ground.

The instrument recorded wind speed in meters per second (m/s) but absolute values of the actual wind direction to the nearest 5 degrees. This AWS processes measurements made during each hour to record hourly averages. It is important to note that the data has been corrected to account for the 23° difference between the Magnetic and True North.

## 2.2. Methodology, Analysis and Results

From the measured data, wind speed and direction subsets were extracted to create plots for different specified time frames. These will highlight different patterns, characteristics, and behaviour of wind over time. Derived wind stress anomalies will be calculated over these different time periods. Wind stress and its anomalies have proved to be a good indicator for upwelling episodes. Another important derived variable to be looked into is the wind mixing (W) index which measures the amount of turbulent energy transferred into the ocean from wind (Boyd, 1987).

A proxy for coastal upwelling intensity at the Cape Columbine was calculated from wind stress component given by the following formula;

$T_{(x,\ y)} = rho_{(air)}\ Cd\ |U|\ U_{(x,\ y)}$;

where rho is the air density (1.22 $Kg.m^{-3}$),

Cd (0.0013) is the drag coefficient,

|U| is the wind speed at 10 m,

$U_x$ is the zonal component of the wind,

$U_y$ is the meridional component of the wind,

$T_x$ = the zonal component of the wind stress, and

$T_y$ = meridional component of the wind stress.

### 2.2.1. Diurnal variability

Wind is an important atmospheric variable which drives several oceanic processes and these include upwelling, waves, evaporation at sea, cloud formation, etc. For this reason, wind changes on a diurnal scale are investigated. Vinning and Allen (1993) indicated that wind can change randomly and linearly over time. Some of these diurnal changes may be due to an overnight pressure variation although Haltiner (1958) had earlier indicated this was not the case, especially in a frictionless boundary layer. Bonnardot *et al* (2002) highlighted other factors contributing to diurnal variation of wind strength. His study investigated alternating sea breezes, their vertical and horizontal extent, thermal inversion, and the temperature gradient at the coastal interface as factors affecting diurnal variation of wind. Diurnal variations in the heating of the land surface in regions with topography drive mountain valley winds upslope during the day but downslope at night and these may interact with sea/land breeze circulations over Cape Columbine (Tyson and Preston-Whyte, 2000).

At Cape Columbine, the geostrophic wind is maintained by the pressure gradient between the South Atlantic Anticyclone and the air mass over the adjacent land. Peard (2007) indicated that over Luderitz, wind is variable along the continental shelf at diurnal and seasonal time scales. Tyson and Preston-White (2000) highlighted that baroclinicity of the lower atmosphere creates a thermal discontinuity between cold water and semi-arid plains at a day to night scale, a process associated to land and sea breeze. Peard (2007) further mentioned that the horizontal pressure gradient difference between this water mass and the mainly arid or semi-arid land bordering the Benguela is large and varies substantially through the day and night, and as a result, the coastal wind field develops a diurnal pattern of variability.

For the purpose of this study, diurnal fluctuations in the wind at Cape Columbine are analysed and studied to effectively determine if they influence changes in the ocean.

#### 2.2.1.1. Methodology

A full analysis of hourly wind strength was made at times (00:00 AM, 06:00 AM, 12:00 PM and 18:00 PM) during each day to coarsely resolve diurnal changes. These are then averaged into monthly timescales to eliminate noise on the data before considering seasonal variations.  Here we define day-time as 12:00 PM and night-time as 00:00 AM. Studies conducted in other areas along the west coast showed evidence of peaks in wind events over a 24 hour period (Peard, 2007). To confirm this hypothesis, wind over Cape Columbine was investigated to see if its behavioural pattern is similar and if it varies over time between night and day. Plots of the extracted dataset were created for each month over the full 38 year period. This will enable us to examine the diurnal, seasonal and inter-annual behaviour of the wind.

### 2.2.1.2. Analysis and results

The figure (Fig 2.1) below illustrates a complete hourly dataset for the full time series where daily variability in the wind is included. Typically, the wind varies in speed from a few $ms^{-1}$ and reaches over 16 $ms^{-1}$ in a few instances. A significant change in character or outlook of the wind signal was observed from 1983 until 1990. Prior this period, the average wind strength difference between day and night was 7 $ms^{-1}$. During 1983 to 1990, the average wind speed at Cape Columbine decreased to approximately 4 $ms^{-1}$.

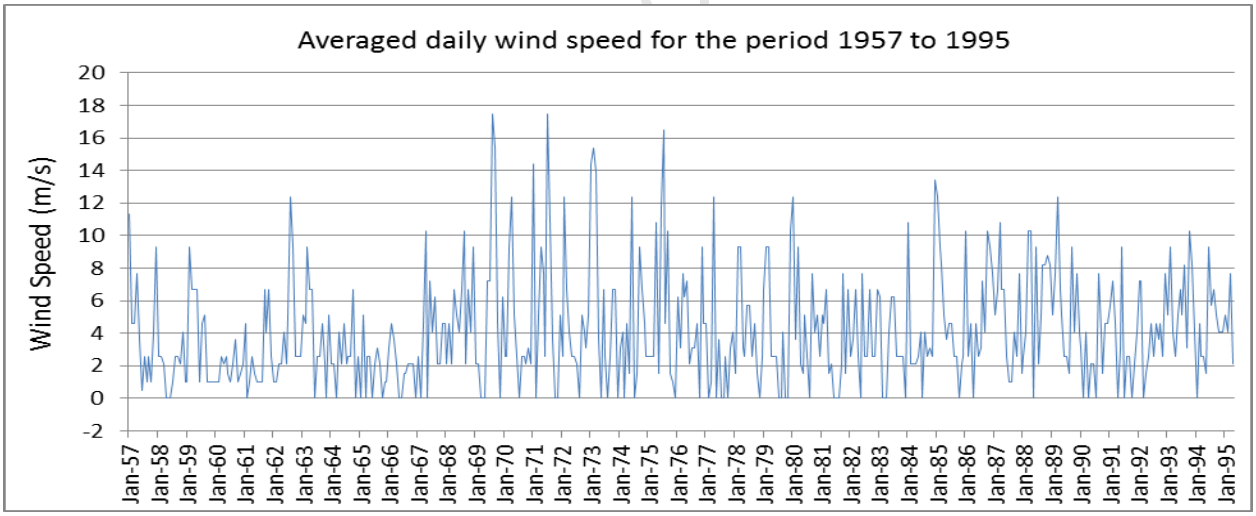

Figure 2.2: A plot of the averaged daily wind speed for full time series between 1957 and 1995 as measured from an Automatic Weather Station in Cape Columbine.

Plots of wind speed for different times (00:00, 06:00, 12:00 and 18:00 SAST) were made. These plots give a clear indication on how the wind behaves with time during the day. Although individually they seem to follow a similar behavioral pattern, the magnitude in variations between wind minima and maxima is not the same. For midnight (00:00 AM) run, the wind strength averaged 5.61 $ms^{-1}$ throughout the period. The wind varied from strength of 2.07 m/s to 10.24 $ms^{-1}$ for the whole time series. The least strong month for this time was April 1957 (2.07 $ms^{-1}$) with the strongest in December 1962 (10.24 $ms^{-1}$). However, during 1983 to 1990, the wind strength ranged between 3.24 $ms^{-1}$ (July 1988) and 8.96 $ms^{-1}$ (January 1983). Interannual and decadal variability will be discussed later in the sections to follow.

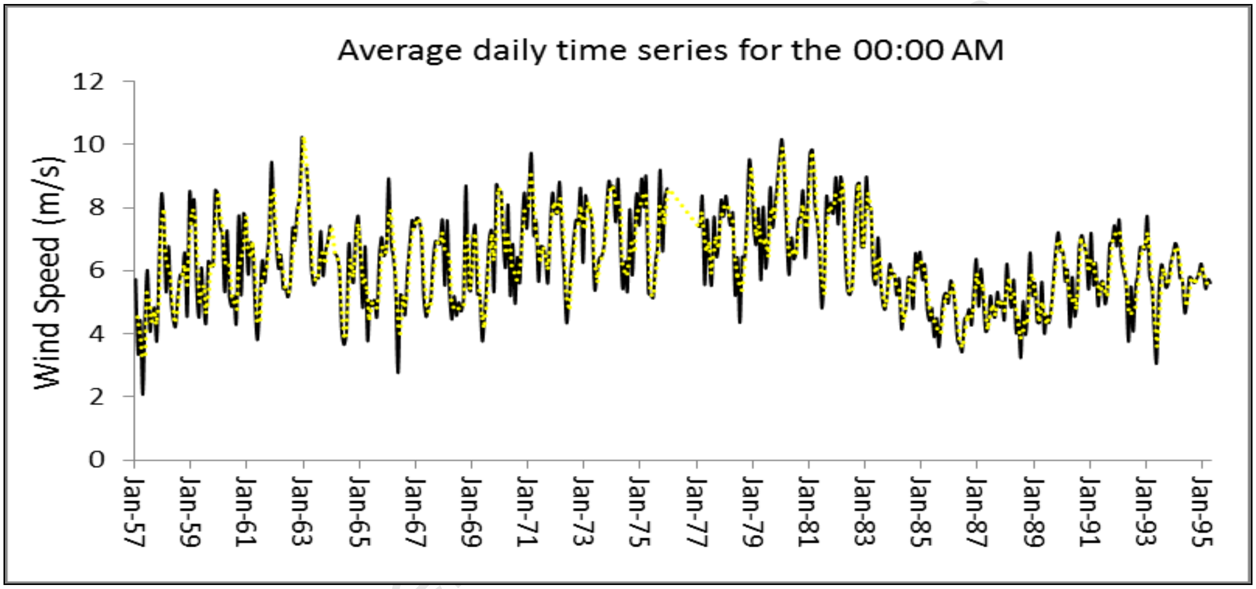

Figure 2.3: Time series for averaged hourly data for every 00:00 AM over the period 1957 to 1995.

The morning data (06:00 AM) produced similar variations but with weaker amplitudes. The minimum wind strength for this time was found to be 1.96 $ms^{-1}$ (April 1957) with a maximum of 8.02 $ms^{-1}$ (August 1981). Therefore, for the whole time series, the wind variance between wind minima and maxima was 6.06 m/s with an overall average of 5.16 $ms^{-1}$. The period 1983 to 1990 again showed weaker winds that ranged in speed between 3.08 $ms^{-1}$ and 6.91 $ms^{-1}$.

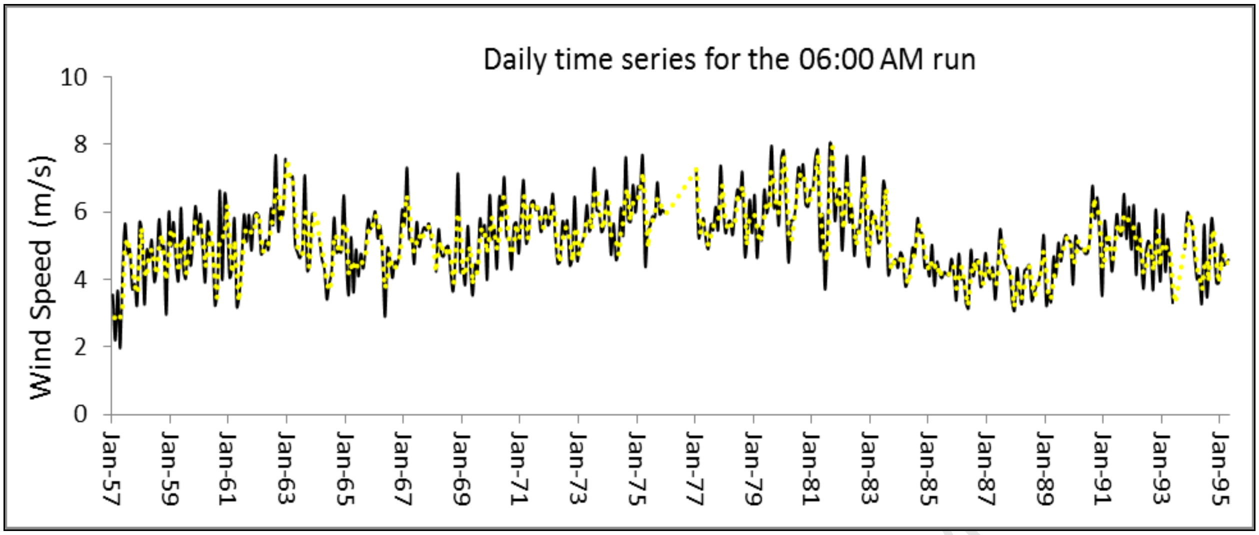

Figure 2.4: Time series for averaged hourly data for every 06:00 AM over the period 1957 to 1995.

The day time (12:00) showed stronger winds compared to the 06:00 am time series. The average 12:00 speed was 6.20 ms$^{-1}$ and can be associated with the general sea breeze circulation where wind speed get stronger during the day but weakens over-night. From the time-series plot below (Fig 2.4), the 1983-1990 period was again one of weaker wind speeds. Prior to this period, the monthly variations appear stronger whereas there is a more obvious decadal variation after about 1980. The strongest month was December 1962 where wind speed reached an average of 9.91 ms$^{-1}$. April 1957 was the month of weakest wind with an average of 2.83 ms$^{-1}$.

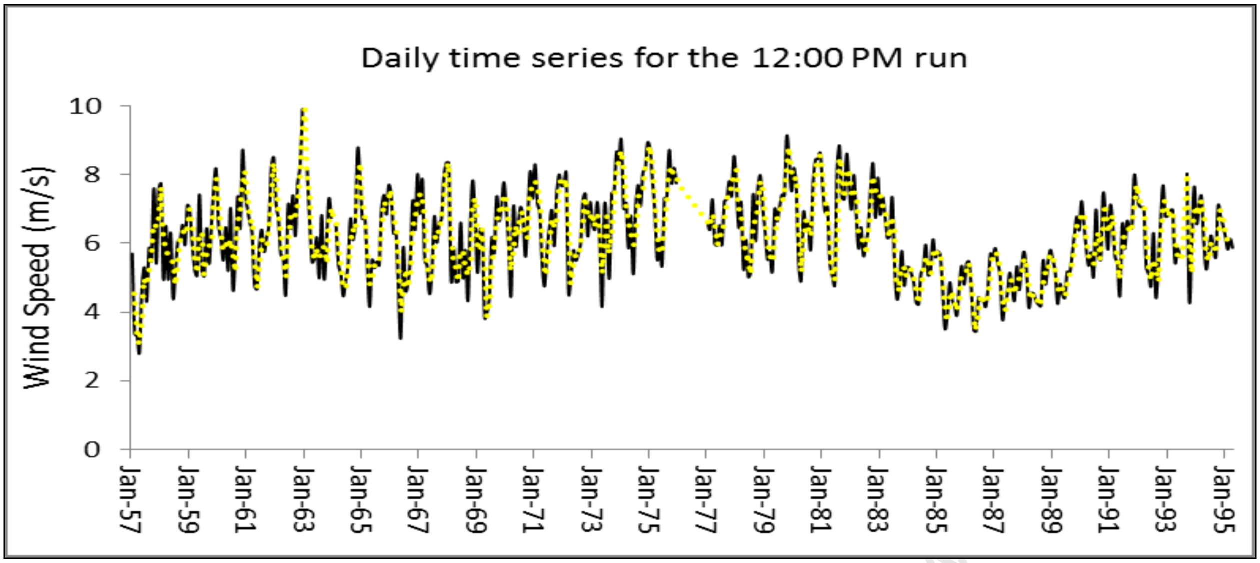

Figure 2.5: Time series for averaged hourly data for every 06:00 AM over the period 1957 to 1995.

In the evening (18:00 PM) data, the seasonal variability was more obvious while the 1983-1990 period of weaker winds was less apparent. Stronger winds were observed mainly over the summer months (December, January and February). Winter months were associated with weak (minima) wind events throughout the study period and this is true for most of the time series. Figure 2.5 generally shows stronger winds than at the other times. Overall, the wind speed at 18:00 averaged at 7.10 ms$^{-1}$ compared to 5.61, 5.16 and 6.20 ms$^{-1}$ for midnight, morning and midday respectively. The time series has amplitudes representing at-least 3 ms$^{-1}$ difference between the minima and the maxima. The strongest month was December 1962 with an average wind speed of 12.37 ms$^{-1}$ and the weakest wind minima occurred during 1964 winter with wind speed of 3.58 ms$^{-1}$. As for the other times, the amplitudes of the monthly variations tend to decrease with time through the record.

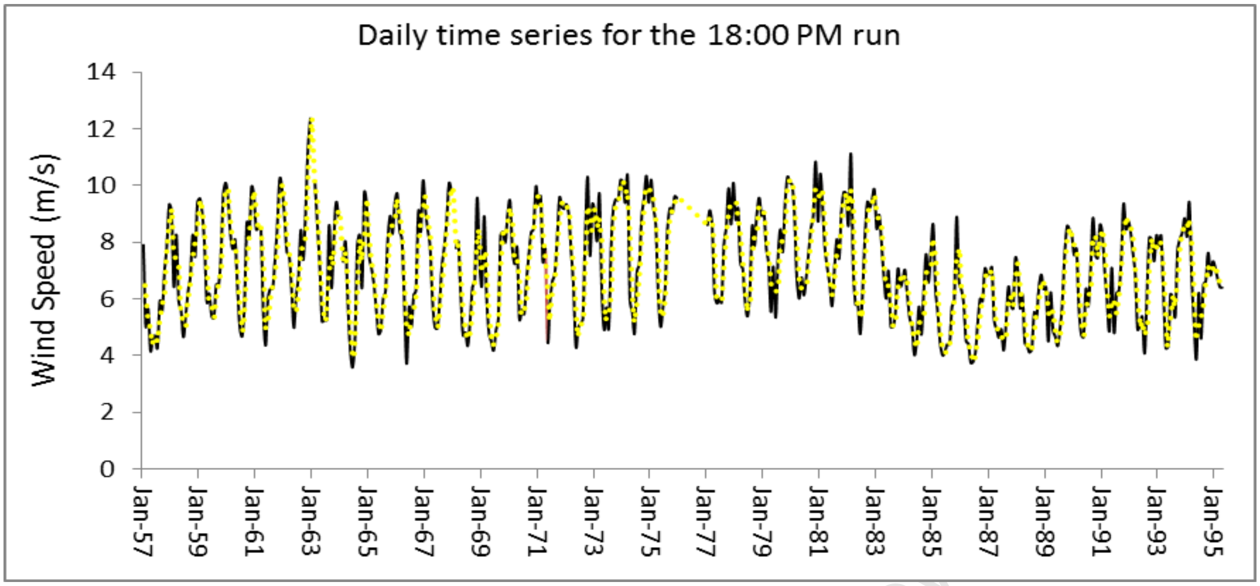

Figure 2.6: Time series for averaged hourly data for every 06:00 AM over the period 1957 to 1995.

### 2.2.2. Seasonal Variabilty

Winds along the western coast of southern Africa tend to be related to the variability in position and strength of the South Atlantic Anticyclone. This anticyclone responds to pressure and temperature gradients between interior South Africa and the South Atlantic Ocean, and between the tropics and the pole. Seasonal shifts in the South Atlantic Anticyclone (SAA) occur such that the SAA is about 3-6$^{o}$ further north and 4-13$^{o}$ further east in summer than it is in winter (Tyson and Preston-Whyte, 2000). It should be noted that there are two to three relative peaks/troughs in the latitude/longitude of the SAA during the annual cycle, thus the transition between the months of its extreme positions is complex. Along the coast near Cape Columbine, upwelling favourable winds are dominant throughout the year (Shannon *et al*, 1986) although the pressure gradient between the SAA and the adjacent continental Low varies throughout the year.

Blanke *et al* (2009) indicated in his model study that strong wind variability showing southerly components in summer existed over Cape Columbine and surrounding areas.These result in maximum alongshore wind stress there in summer. Chang (2009) also highlighted this seasonality in that region. Her study indicated the occurrence of an upwelling jet in spring and summer decreasing over autumn but not apparent in winter. Blanke *et al* (2009) further indicated that monthly to interannual variability in the winds there is important.

### 2.2.3. Analysis and Results

To further investigate wind variability over seasonal scales, monthly averages were calculated and plotted. Figure 2.7 below, shows seasonal variations over years. Peaks in wind strength were observed between seasons throughout the time series. A general variability in wind strength was observed.

The strongest wind event for this category was recorded in the summer (December) of 1962 with an average speed of 9.97 ms$^{-1}$. This event occurred prior to the onset of the suggested 1963/64 ENSO event. An average wind strength shift of approximately 4 ms$^{-1}$ was observed from December 1963 to January 1964.

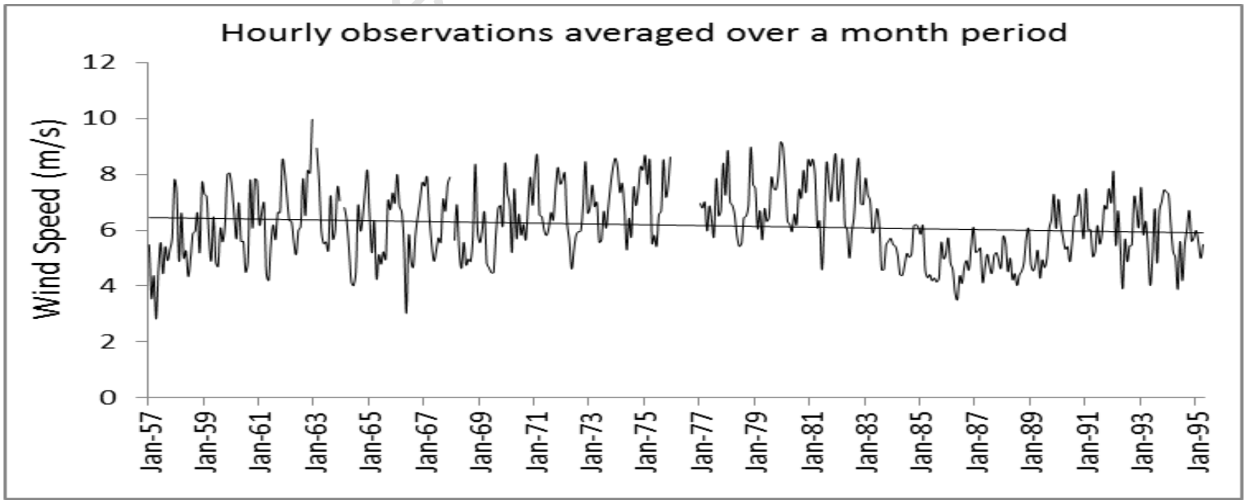

Figure 2.7: A time series plot for averaged monthly wind strength, derived from hourly data for the full dataset over the period 1957 to 1995.

Variability of wind strength over different months was then investigated to facilitate and filter any influence of diurnal representation of the wind. As a result, a seasonal representation of wind structure over Cape Columbine was constructed. Monthly wind averages for different times were calculated and plotted. From these plots, a general behavior where wind strength is at maximum (minimum) in summer (winter) was apparent.

Figure 2.8 shows that autumn had weakest day and night winds, especially in the month of April. However, the month of May recorded the weakest average winds. In the morning, the general average wind for April was 4.64 $ms^{-1}$ with August having the strongest winds. The overall winter average wind for the morning period was 5. 54 $ms^{-1}$. At midday, winds followed a general behavior with strong events being persistent in summer and weaker through autumn to winter. The wind was strongest (7.28 $ms^{-1}$) in December but weakest (5.12 $ms^{-1}$) in April. The general overall wind speed averages for the day time (06:00 and 12:00) were 5. 54 $ms^{-1}$ and 6. 19 $ms^{-1}$ respectively.

From the night time runs (18:00 and 00:00), a general characterization of wind pattern with strong (weak) winds in summer (winter) season was also apparent. The 18:00 run proved to be the strongest where wind speed averaged at 7.10 $ms^{-1}$ followed by the midnight run at 6.27 $ms^{-1}$ respectively. May proved to be a calmer month at night time than April.

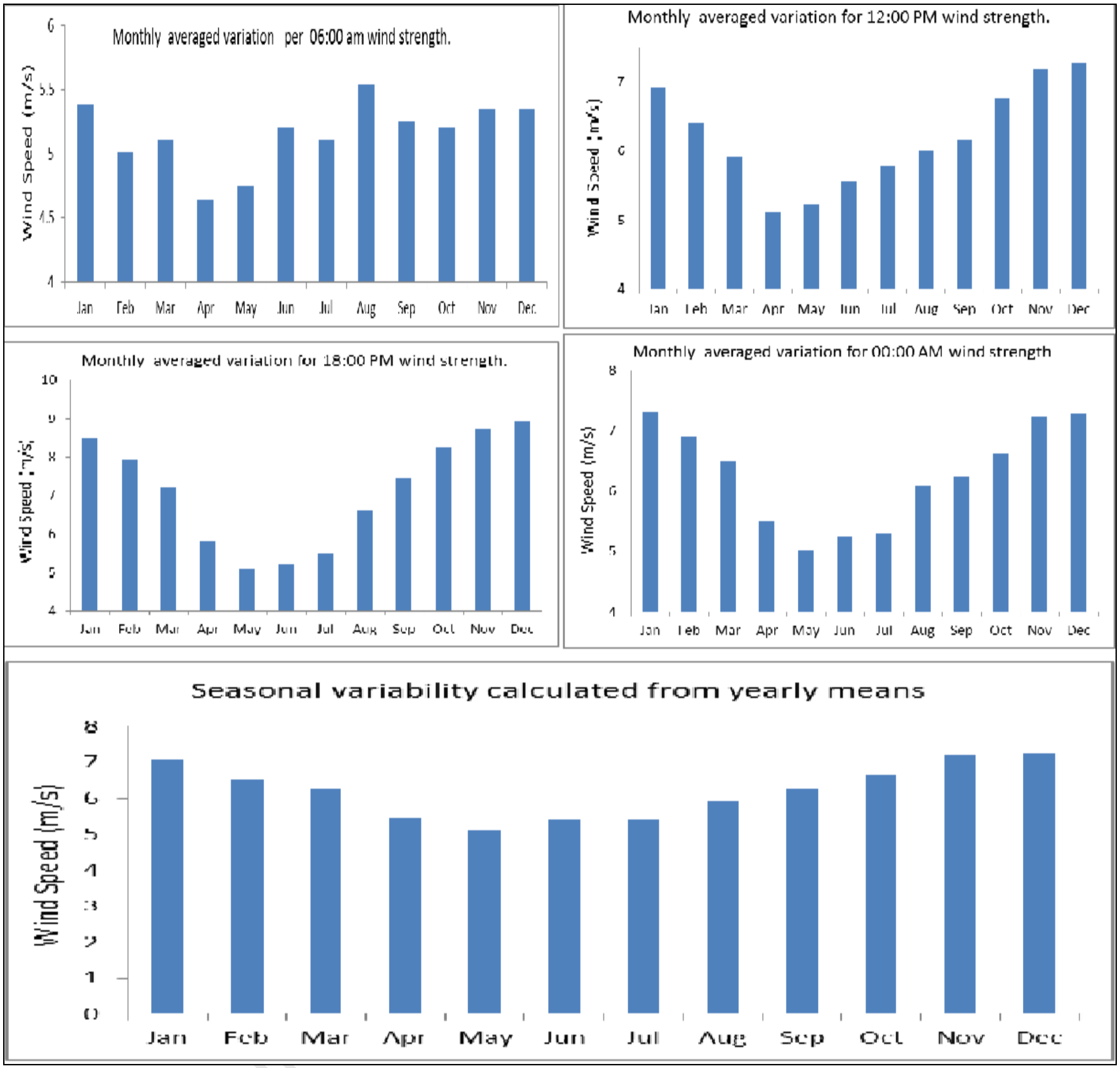

Figure 2.8: Monthly variations in wind at different times of day at Cape Columbine.

The summer of 1962 recorded changes in amplitude of 4.17 $ms^{-1}$ between a midnight peak (6.06 $ms^{-1}$) and evening peak (10.23 $ms^{-1}$), whilst the winter preceding that recorded a minimal change in amplitude between measured times. The 18:00 wind run was generally the strongest but the weakest winds were recorded in the morning (06:00).

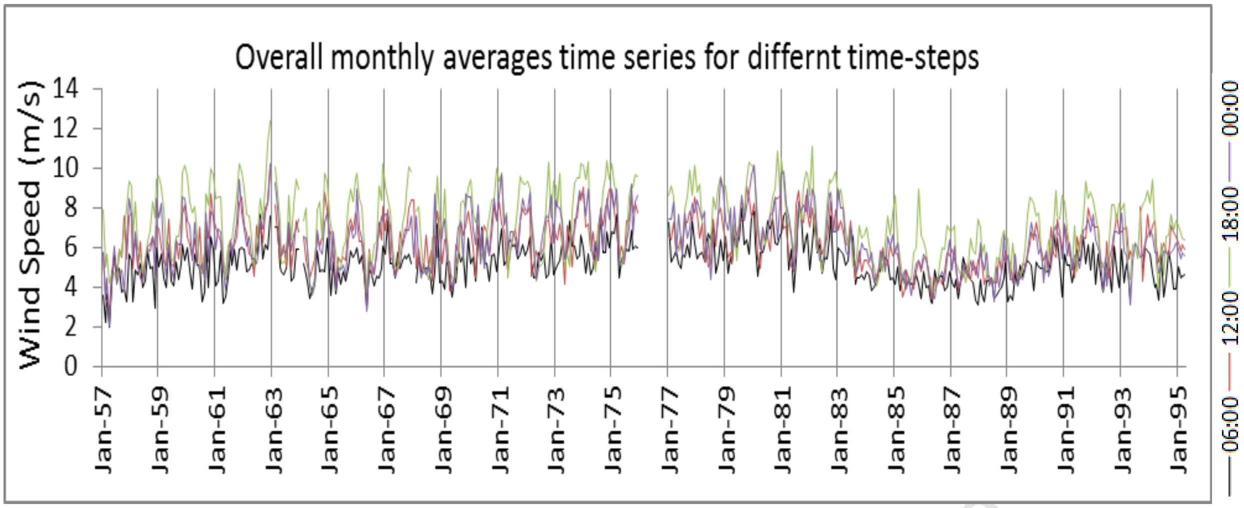

Figure 2.9: A time series for different time-steps over the period 1957 to 1995. This is derived from monthly averages of wind strength for Cape Columbine which also clear indicate the data window in 1976 due to lack of data for that year. Major vertical gridlines are inserted for better indication of peaks in wind strength during summer seasons.

### 2.2.4. Inter-annual variability

In the earlier section, analyses of monthly wind events and their frequency of occurrence were discussed. These gave a platform to detect variations within different months to seasons over the full study period. From this monthly climatology, yearly variations or behaviour of wind were established. Singleton and Reason (2007) in their studies for cut-off lows indicated that there exists characteristic variability in their occurrence over variable time periods. They further concluded that Cut off lows are related to La Nina occurrence and to variability in the semi-annual oscillation and wavenumber 3 pattern in the atmosphere. This was brought about by the difference in position of the Atlantic high pressure cell at seasonal level.

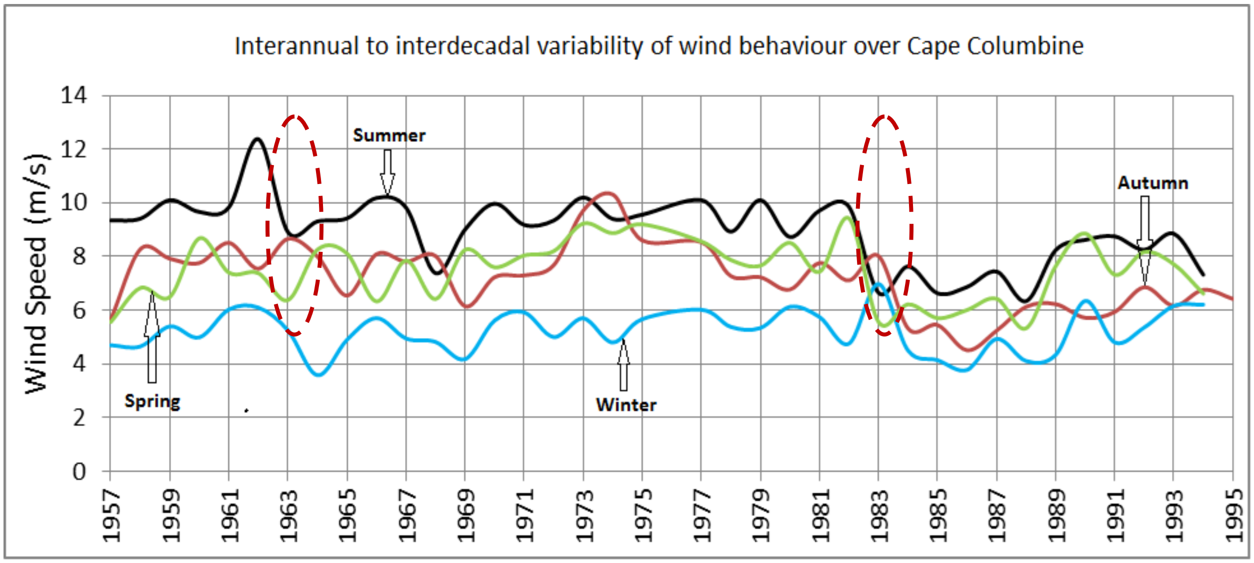

Figure 2.10: A plot indicating variations in seasonally averaged winds for Cape Columbine over the years 1957 to 1995.

In order to determine how the seasonal signals might vary with time, seasonal averages of wind strength for the whole study period were plotted (Figure 2.9 above). In this case Summer is defined as December, January and February (DJF), Autumn is March, April and May (MAM), Winter is June, July and August (JJA) and Spring is September, October and November (SON). The plot was created by averaging all the hourly data into monthly averages. These monthly averages were then averaged according to their seasons of the year. Means of these seasonal representations were then plotted to facilitate and visualize annual variability.

Some significant events are highlighted in Fig. 2.10. These are suggested to be associated with large scale global annual anomalies such as the 1963/4 and 1983/4 Benguela Niño events. It was apparent that winter had the weakest winds at Cape Columbine with summer dominated by strong winds. However, contrasting oscillations in wind signals between spring and autumn were observed overs annual cycles. Overall averages for the full time series are 8.95 $ms^{-1}$ in summer, 5.21 $ms^{-1}$ over winter, 7.18 $ms^{-1}$ and 7.46 $ms^{-1}$ for autumn and spring respectively. There was a significant strengthening of wind observed in the 1962 summer, and was associated with the possible linkage to the suggested ENSO event onset where wind speed reached an average of 12.37 $ms^{-1}$.

A biennial oscillation between peaks for both autumn and spring seasons was observed to exist for most parts of the annual time series. These oscillations took two years to complete one full cycle (shifting between peaks and troughs) for most of the events; but some had a timescale more characteristic of ENSO (large scale circulations) characterisation, in taking 3 to 4 years to complete. A significant change in wind behavioural patterns occurred in the 70s (1971 to 1978). These changes were only apparent over the spring and autumn seasons. During this period, the 1974 autumn was the windiest season reaching an average of 10.31 $ms^{-1}$. In general, the summer and winter averages showed smaller variations through the record than spring and autumn.

Following the 1983/4 Benguela Niño event, the spring and summer winds were similar in strength for a period of almost a year. The summer winds were decreased to match those of winter signal during the 1983 summer season. Autumn recorded the strongest wind event with spring experiencing the lowest wind strength. These highlighted a shift in wind behaviour associated with the Benguela Niño occurrence that year resulting in a possible year-long delay in terms of signals with winter lagging behind summer.

# Chapter Three: The analysis and inter-connectedness of atmospheric variables at the Cape Columbine weather station during the period September 2009 to March 2010

In this chapter, a distinct case study over Cape Columbine was examined with a newly advanced Automatic Weather Station (AWS) used to collect data. The time period for this study was six months, starting from September 2009 ending in March 2010.

## 3.1. Synoptic systems of influence

The area around Cape Columbine is dominated by the semi-permanent South Atlantic Anticyclone in the general atmospheric circulations. This anticyclone gives rise at most to the southerly wind stress along the entire west coast (Shillington *et al*, 2006). Due to seasonal migrations of this anticyclone in both the zonal and meridional directions and heating/cooling over the land and ocean regions, an enhanced zonal pressure gradient exists in summer leading to intensified southerly wind stress. Wind strength is also highest in summer along the west coast and adjacent areas (Kruger *et al*, 2010).

The onset of these persistent strong wind periods in spring and their continuance in summer is interrupted on time scales of a few days by the passage of different synoptic and meso-scale weather systems. Seasonal variations in response to these atmospheric circulations in the Cape Columbine areas and the surrounding oceans exist. Although, the anticyclone dominates, there are disturbances due to passages of cold fronts and continental troughs (Taljaard, 1995). Cold fronts cause changes in air-mass as cold dense air from the south is advected into the area. Kruger *et al* (2010) indicated that cloud formation and later rainfall may result due to this advection of moist marine air into the subcontinent and the resulting instability as this air interacts with dry continental air. At times this air can be uplifted through topography or convection and thunderstorms activity might occur.

Another rain producing weather system over Cape Columbine is the Cut-Off Low (COL). COL can be defined as a closed circulation in the upper troposphere extending down to the surface with cold core upper tropospheric temperatures which is cut off or isolated from the main mid-latitude westerly flow and is accompanied by heavy falls (Dyson, 2000). COL system is responsible for most floods and flash-floods events in the country especially in the areas that are not prone to heavy rainfalls. One highlighted example is the Laingsburg floods of January 1981 in the Little Karoo region. During this event, hundreds of people lost their lives as the town was flooded. Laingsburg received 6 times the annual mean January rain during that event (Singleton and Reason, 2007).

A coastal low is another type of meso-scale atmospheric weather system that influences conditions over and around Cape Columbine. This generally develops along the west coast and affects the adjacent interior as developments of Berg wind conditions can be associated with its propagation (Reason and Jury, 1990). Kruger *et al* (2010) associated it to systems that develop ahead of an approaching cold front. However, Reason (1993) defined it as a relatively small scale weather system of limited vertical extent and an example of orographically trapped disturbances. Their existence is characterized by a general pattern of relatively hot and dry conditions followed by abrupt cooler and moist weather. Coastal Lows are also responsible for extreme wind conditions and heavy gusts as they circulate over a small spatial area at a very short temporal scale (at most, two to three days). These lows may also be accompanied by low clouds, fog or drizzle (Carter, 2005). Carter (2005) further indicated that these lows may owe their existence to cyclonic vorticity, lee troughing and offshore flow (Reason and Jury, 1990) steered by upward and downward motion over escarpments or high interior plateau adjacent to the coast. Over Cape Columbine, these dynamics may result in upwelling events as southerlies blow parallel to the coast after the coastal low has passed. The Coriolis force acts to deflect the surface waters away from the coastline (Olivier, 2002). The results of which is the upwelling process as cold, deep water is pushed upwards to replace the advection of surface waters offshore through Ekman transport

Cape Columbine is known for fog conditions throughout the year but most frequently during the March, April and May months.  September is the least foggy month (Olivier, 2002). All these seasonal variations are related to the position and migration of the South Atlantic Anticyclone. Inter-annually, Cape Columbine has the least variability of fog occurrence and this is associated to the semi-permanent upwelling cell in that region (Olivier, 2002; Shannon, 1985). This means that there is less variability in terms of fog type and formation over the area in response to this semi-permanent upwelling cell.  The most dominant fog type over Cape Columbine is the advection fog. Its formation is due to warm moist air being advected over cool upwelled waters (SST), getting cold and condensation takes place in the first few 100 metres of the marine boundary layers (Oke, 1988). Kloesel and Albrecht (1989) defined the marine boundary layer (MBL) as that part of the troposphere which is directly influenced by the presence of the ocean's surface and reacts with little variation to diurnal changes. The MBL is usually capped by a strong temperature inversion that typically exists a few hundred metres above the sea surface on the west coast (Burls and Reason, 2008).

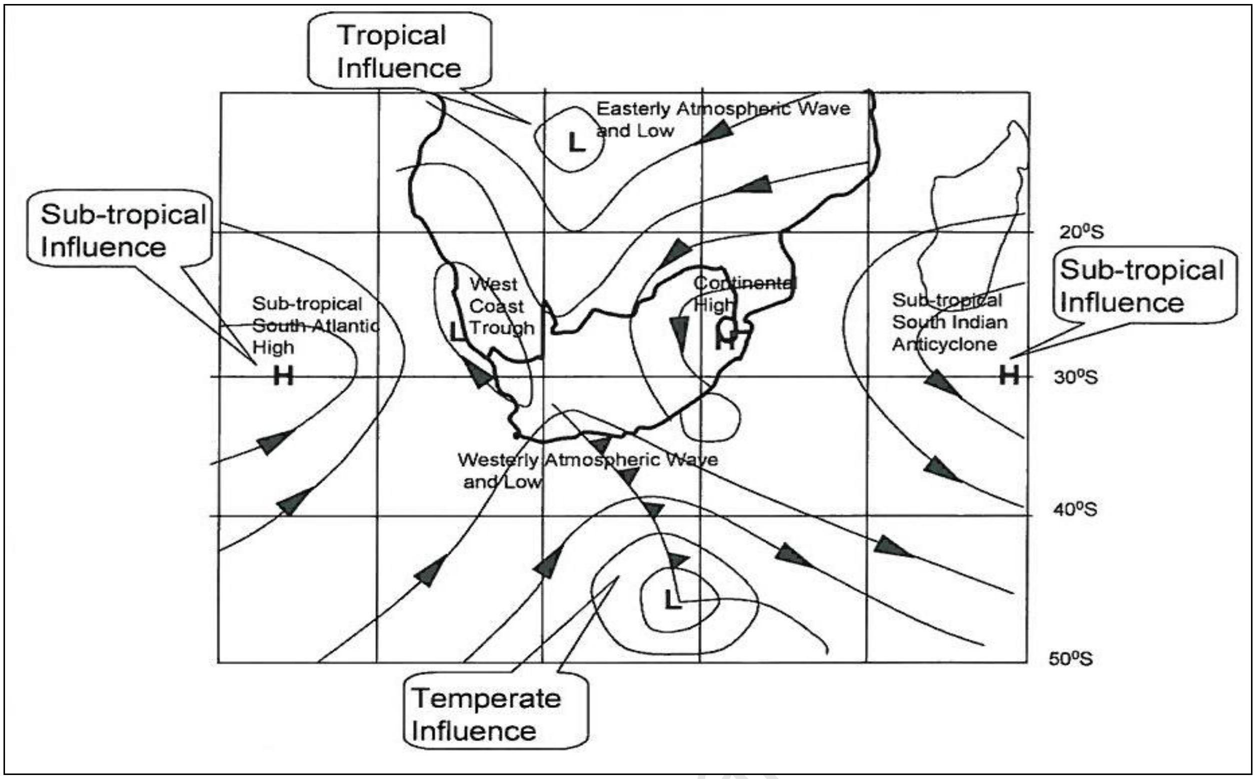

Figure 3.1: Map illustrating the general synoptic atmospheric systems over South Africa as discussed in the section above. For this study, more emphasis will be given to the South Atlantic High Pressure cell west of the country, Coastal Low along the south coast, the Cold Front passage over and along the southern parts. The influence of Indian Ocean High, Tropical Lows and Heat Low is negligible for the purpose of this study (MacHutchon, 2006)

Oceanographically, these synoptic systems influence changes in the ocean as Shannon (1985a) indicated that marked variations in the wind field at Cape Columbine are important for the development of upwelling in that area. Historically, results showed that the longest upwelling event lasted for 28 days in December 2000 (Blancke *et al*, 2005). Bakun (1993) also indicated that stabilization of water column due to wind mixing intensifies upwelling. Schumann *et al* (1982), however; postulated that periods of persistent easterly (southerly) winds are needed to generate a classical Ekman upwelling along the south (west) coast.

## 3.1. Objectives

The main objective of this case study is to provide a detailed analysis of atmospheric variables at Cape Columbine in the period from September 2009 to March 2010. Another intention is to address questions on the interconnectedness of meteorological parameters and their effects on climatic variability in the region. The importance of studying these parameters is to help in identifying and understanding atmospheric systems passing over Cape Columbine. Understanding these small scales features leads to better prognosis and diagnosis of their large scale counterparts, together with impacts of climate change variability at large.

Further subsequent studies on how these atmospheric features link-up and interact with oceanographic features (upwelling) and circulations also follow. This will lead to improved prediction of onsets of extreme coastal oceanographic and meteorological events.

## 3.2. Data collection and methods.

A Vaisala Automatic Weather Transmitter, WXT520 is a small probe which measures wind speed and direction, precipitation, atmospheric pressure, temperature and relative humidity. It is very accurate, stable and it is ultrasonic (no moving objects) with an all-in-one sensor. It consumes less power and promotes green and renewable energy as it works on solar power.

### 3.2.1. Technical specifications

The wind sensor has three arrays of equally spaced transducers on a horizontal plane. Wind speed is determined by measuring the time it takes the ultrasound to travel between the transducers. It measures the transit time in both directions and this depends on the wind speed along the ultrasonic path. For zero wind speed, the forward and reverse transit times are the same. It uses the following equation to perform wind speed calculation:

$$V_w = 0.5 \times L \times (1/t_f - 1/t_r)$$

Where $V_w$ = Wind speed

$L$ = Distance between two transducers

$t_f$ = Transit time in forward direction

$t_r$ = Transit time in reverse direction.

Its measurement ranges between 0 to 60 $ms^{-1}$ with an accuracy of +/- 0.3 $ms^{-1}$ in the 0 to 35 $ms^{-1}$ range and +/-0.5 $ms^{-1}$ in the 36 to 60 $ms^{-1}$ range. These transducers also record wind direction ranging between 0 to 360° with +/- 3° accuracy.

The sensor also uses Raincap Sensor Technology for precipitation measurements. It detects the impact of individual raindrops and the signal from the impact is proportional to the volume of the accumulated rain in millimeters. It also filters out signals from other sources than raindrops. It ranges between 0 and 200 mm/h of rain accumulation. It also uses the PTU (Pressure, Temperature and Humidity) measurement module which contains separate sensors. Barometric Pressure ranges from 600 to 1100 hPa and it is accurate to +/- 0.5 hPa at 0 to 30 °C. Temperature ranges from -52 to 60 °C with accuracy of +/- 0.3 °C. Relative Humidity ranges between 0 and 100 %RH with an accuracy +/- 3% within 0 to 90 %RH and +/- 5 % between 90 to 100 %RH.

## 3.3. Methodology

In this study, an analysis of parameters recorded through the AWS at Cape Columbine over six months was made. Hourly averages for atmospheric variables (wind speed, wind direction, atmospheric pressure, relative humidity, temperature and rainfall) were assembled. Each dataset was then analyzed using specialized statistical software.

A time series plot was constructed for 4706 hourly averages from each dataset. To depict variability over small scale variations in the datasets, box plots were constructed. A box plot is a convenient way of graphically showing groups of numerical data within each time series. This helps in picking behavior and other characteristics of the dataset. For each variable, the data in the time series was classified into 10 consecutive groups, each of 20 days. A box plot was constructed for each group of 480 hourly averages and shows the median, interquartile range (IQR), the spread of the data and any outliers in the group.

In each box plot, the median is indicated by a small square inside a rectangular box which shows the IQR between the lower quartile at the bottom and the upper quartile on top which encloses 50 per cent of the data distribution in that group. From non-parametric statistics, the acceptable spread of data points outside the central box should lie within 1.5*IQR of the upper and lower quartiles, which are shown by the whiskers. Observations that are numerically distant from the rest are then shown as outliers beyond the whiskers of the box plot. These outliers can also be classified as indicators of extreme events occurring in each group.

## 3.4. Data and Analysis

### 3.4.1. Wind Speed and Direction

The west coast of South Africa is renowned for its significant upwelling cells that, according to Bakun and Nelson (1991); are driven and sustained by wind forcing. In the Cape Columbine region, the prevailing southerly winds enhance strong Ekman transport throughout the year. This in turn enforces upwelling of cold bottom water into the surface (Shannon, 1985a). A clear variation in wind strength between winter and summer seasons exists in the area due to the migration and position of the South Atlantic Anticyclone. Our time series however is too short to fully confirm this hypothesis.

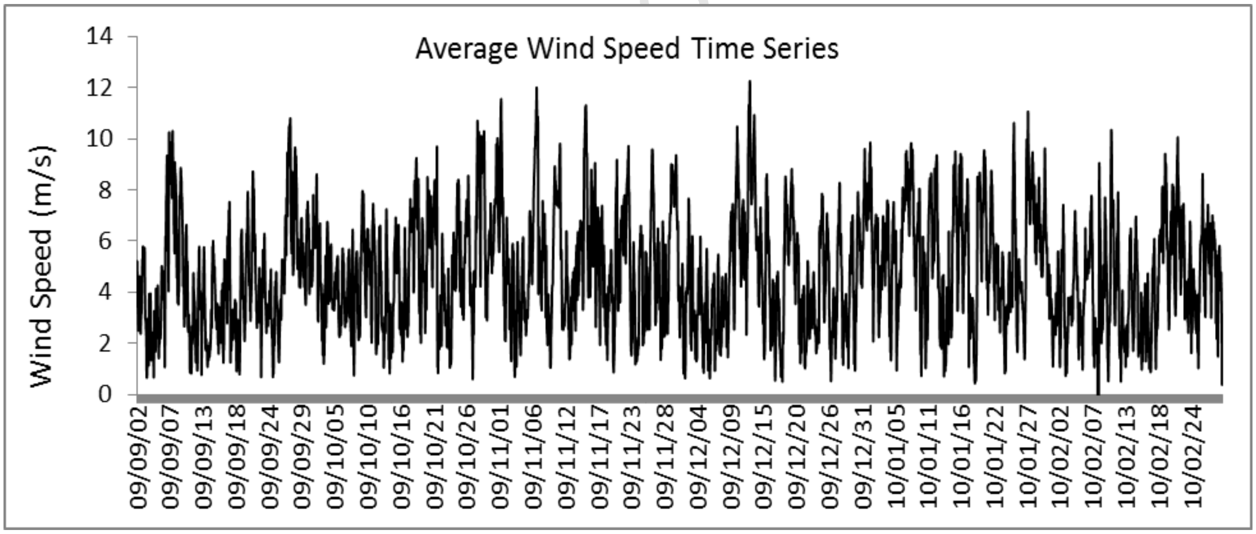

Figure 3.2: This plot shows the hourly averaged wind speed for Cape Columbine during the period September 2, 2009 to March 1, 2010. There are periods of relatively strong and persistent wind events at the station as winds (≥ 8 m/s) are observed.

Figure 3.2 shows a complete time series of hourly average winds recorded at the Cape Columbine for the period September 2009 to March 2010. Significant weekly variability between light and moderate winds over the area was observed during most parts of the time series. In the first 3 months, the wind showed an increase in strength (Fig 3.3). It then weakened over the mid to late November but picked its strength until mid-January before dropping its strength again towards the end of the series. In December, the wind gradually weakened over the first two weeks but picked up and reached over 12 m/s on the 12th day. This general decrease in value continued with periods of relatively strong wind events dominating but with few weak wind events occurring at minimal frequency. The overall average wind strength at Cape Columbine was 4.8 m/s. The weakest wind event was recorded on the 05th February 2010.

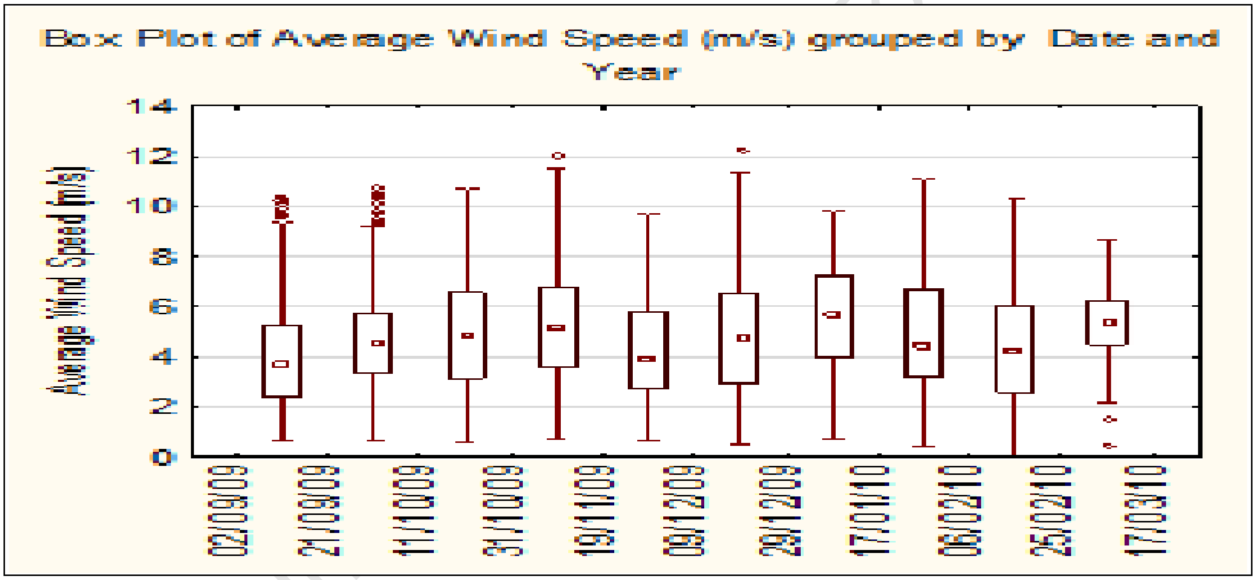

Figure 3.3: Statistical evaluation indicating the box plot of Average Wind Speed at the Cape Columbine Weather Station.

After processing the data, an alternative representation of the wind data in the form of box plot shown in Figure 3.3 indicating medians and the IQR was plotted. There were several outliers observed in the dataset and these were concentrated within the month of September. These outliers may indicate extreme wind events, where wind strengths were either too strong or weak. They can also be indicative of highly unstable wind variability over a time period. In the beginning, calm and variable wind events were observed; but wind also gusted to speeds of over 10 ms$^{-1}$ over a short temporal scale resulting in those outliers. There were several events where wind strength peaked above normal expected range and these occurred during the period, 07th to 08th September, the wind averaged at 10.2 ms$^{-1}$ but reached a maximum (gust) of 17.8 ms$^{-1}$ which is not shown in the analysis. Another period of interest was during the first two weeks of November, at the wake and during the deep continental low that passed over Cape Columbine resulting in above average rainfall. Wind strengths averaged at 11.8 ms$^{-1}$ but reached a maximum of 15.2 ms$^{-1}$ throughout the period of the existence of that event. Plots of maximum wind speed are not shown in this chapter.

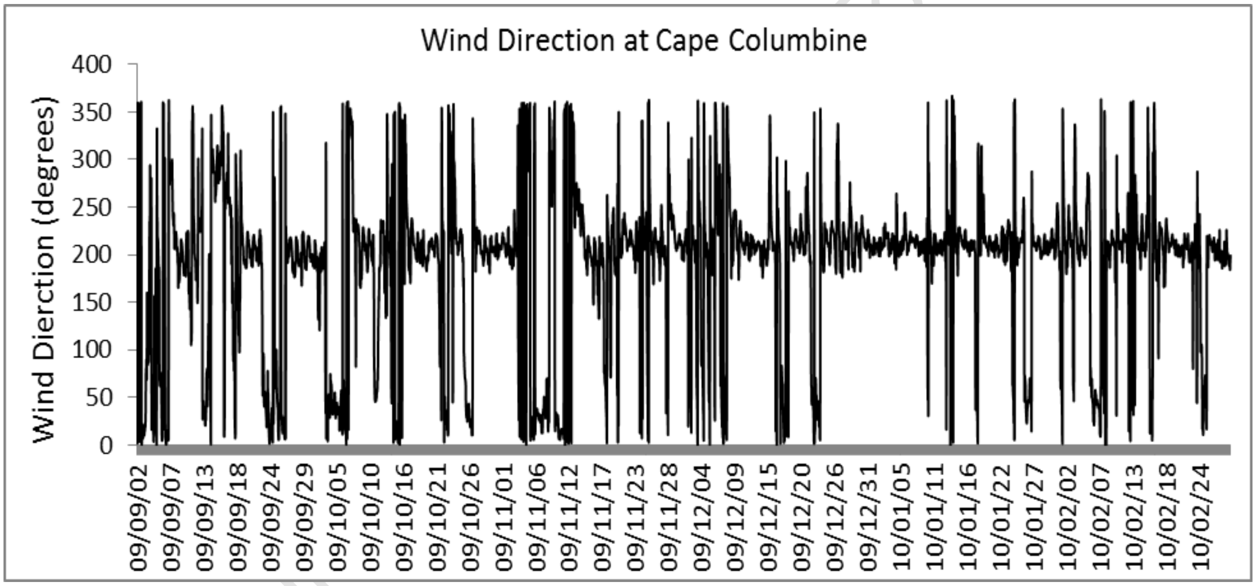

Figure 3.4: Wind direction (degrees) recorded at the Cape Columbine from the 2nd September 2009 until the 01st March 2010.

From Figure 3.4, it was apparent that during the six months period, southerlies were the dominant and persistent winds. Diurnal variation in wind direction was observed frequently; and these can be associated or related to a common land-sea breeze circulation and topographical effects over the Cape Columbine area. North-westerlies were also observed frequently during the study period. These are associated with series of cold fronts that passed over Cape Columbine. Most of these passing frontal storms were not intense. As cold fronts approach, the leading winds are relatively strong depending on the intensity of the storm. These winds then lose their strength and veers into relatively weaker north-westerlies behind the centre of the storm. As depicted in Figure 3.5 below, most of the activities in terms of wind direction were concentrated in the 150° to 200° range narrowing down and getting more direct towards the end of the period. The non-outliers ranges were smaller and most of the data measurements were confined to a very small surface area. This indicates that there was minimal variability in wind direction as southerly winds dominated over the Cape Columbine weather station. The median range was more stable and well defined with minimal change in amplitude along the 200° band. In relation to Figure 3.2, it is observed that during periods of calm and light winds, the wind direction was not well defined. Figures 3.4 and 3.5 respectively confirm this, more especially during the first week of the time series. Over that period, the wind was blowing at an average of ≤ 4 m/s and the direction varied from 0 ° to 180 ° to 360 ° diurnally. However, as the wind speed strengthened; less variability in direction was observed. During the passage of a cold front, a sudden change in wind direction was apparent.

There was a clear and well defined resolution for wind direction variation as the wind strengthened. These evidently confirm the intensification of the fronts as they pass near Cape Columbine. During the passage of cold fronts, changes in wind direction occurring over a short time interval were observed (Fig 3.4). Temperature (Fig 3.8) also had a variation factor of 3 °C within an hour. All these are good indicators for the occurrence of frontal passage in that area.

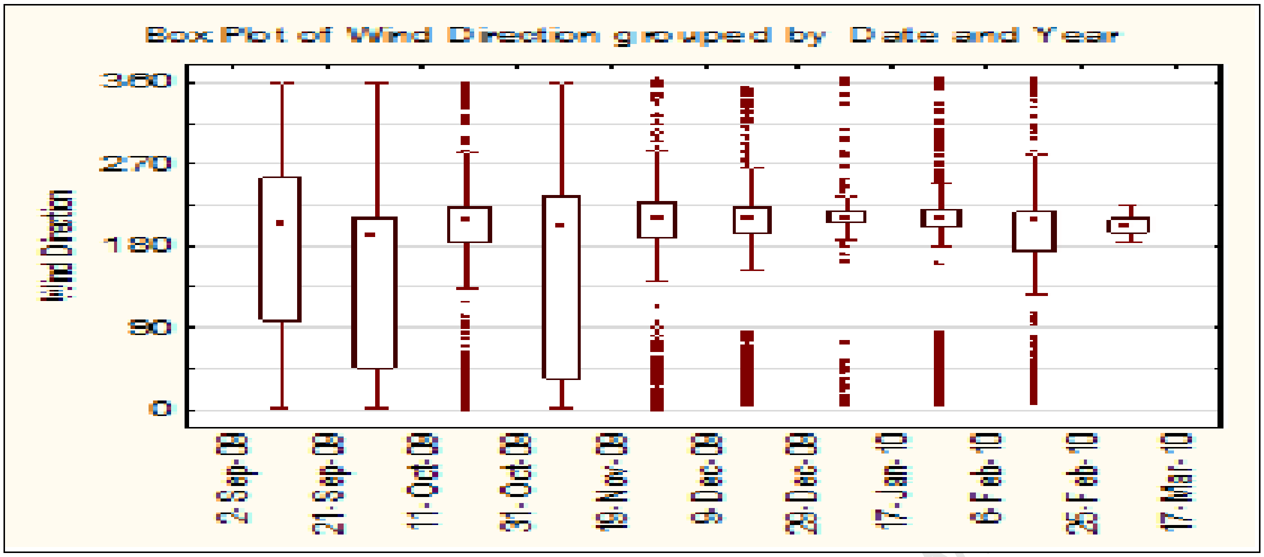

Figure 3.5: The box plot for wind direction in degrees and time. The measured data in the beginning varied from 0 to 360 indicating uncertainty in wind propagation and diurnal effects, however this improved and the expansion range of data distribution diminished.

### 3.4.2. Rainfall

Rainfall is an important indicator for air-sea interaction, especially in high rain areas of the tropics and mid-latitude storm tracks. It may reflect wind and atmospheric pressure changes. In coastal areas, rainfall is associated with the direction of the air flow relative to the coast and the presence of uplift in the atmosphere. In some cases, coastal precipitation may be related to deep convective systems such as Cut-Off Lows (COL), Tropical Temperate Troughs (TTT), and Thunderstorms.

In this study, there were few rainy events recorded as expected since the data are mainly for the summer half of the year and Cape Columbine is a winter rainfall region. It rained only on 18 days (445 hours) of the 196 days (4708 hours) of the study period. In 6 months, the average daily rainfall reported amounted to 0.03 mm. However, during the first week of the study; a sum of 14.41 mm of rainfall was recorded. It then stopped raining due to a shift in wind direction and change in wind strength. Rainfall events continued at variable intervals but with less significance. November received the highest amount of rainfall (42.44 mm) with December receiving the least rainfall at 3.80 mm (Table 1, below). During the month of November, a very strong depression which extended from mid to lower troposphere passed over the area. This weather system resulted in significant rainfall in the area which persisted for more than 24 hours non-stop. It started to rain on the 7th November at approximately 05:00 in the late afternoon until the morning of the 09th. Over the same period, the total rainfall accumulated equals 31.63 mm at an average of 0.83 mm an hour. The highest amount of rainfall accumulated in an hour was 6.12 mm on the 09th November at 01:00 AM. This weather system contributed 25 % of the overall rainfall during the six months study period. Overall, the total amount of rainfall in Cape Columbine recorded between September 2009 and March 2010 is 127.57 mm.

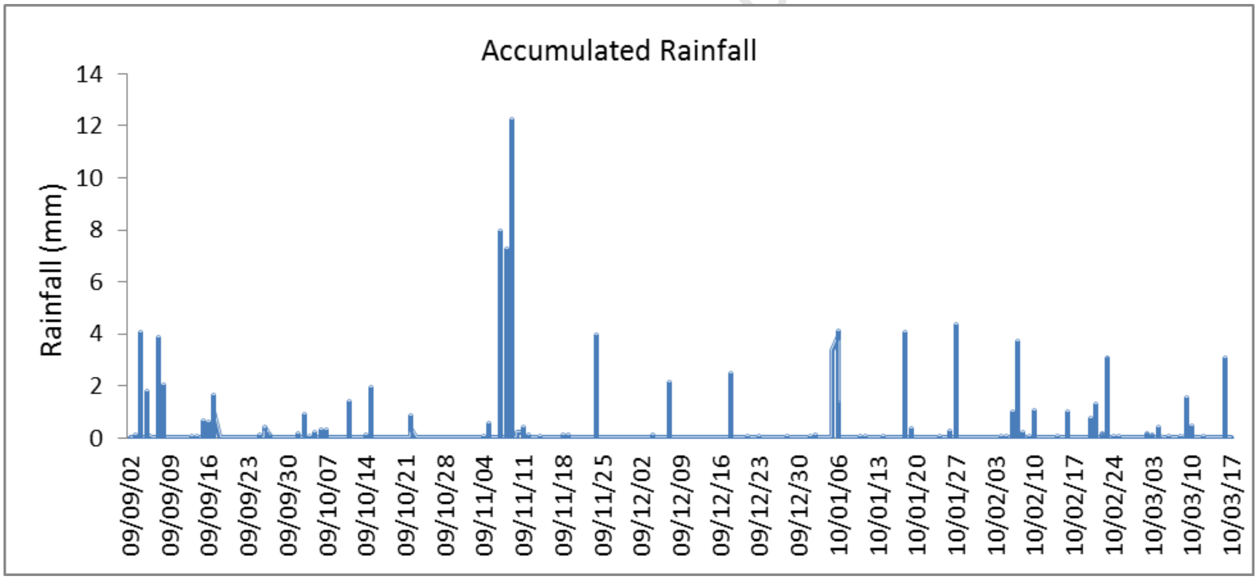

Figure 3.6: A plot of Total Hourly Rainfall (mm) accumulated at the Cape Columbine weather station during the period 2 September 2009 to 17 March 2010.

### 3.4.3. Atmospheric Pressure

The position of the South Atlantic Anticyclone is very important for oceanic, meteorological and climate variability studies in South Africa. There is a clear influence of this anticyclone on wind, air temperature, SST, rainfall and moisture flux. In this study, the interconnections between all these variables and the influence of the South Atlantic Anticyclone are highlighted. Although, our time series is very short temporally and very localized, it is clear that there are clear interconnections amongst these variables.

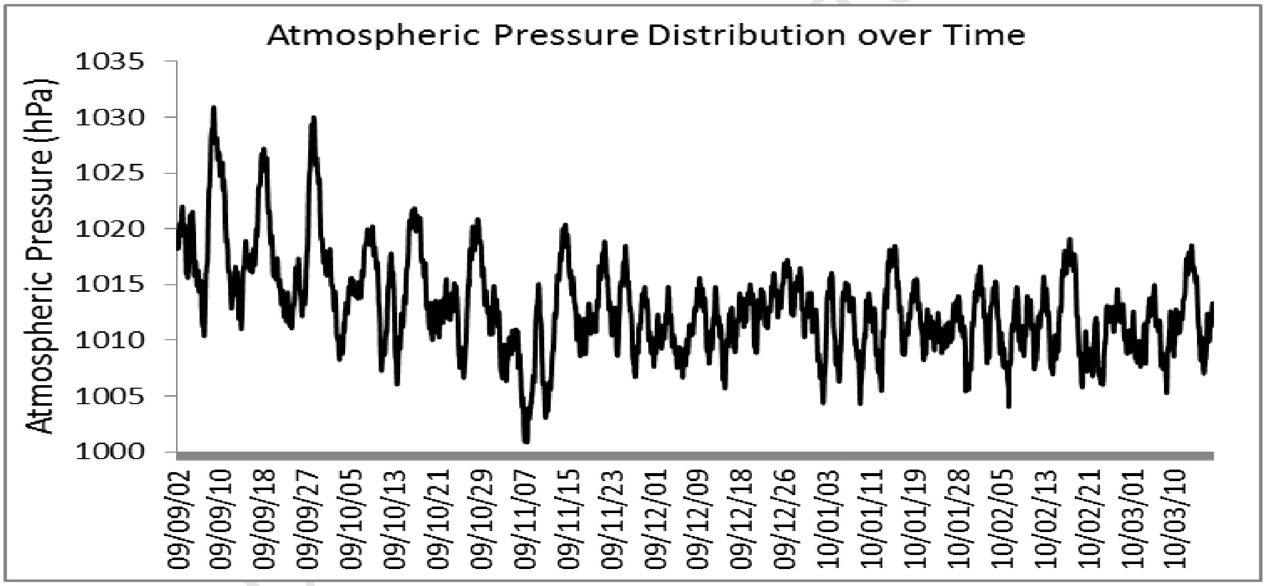

Figure 3.7: Atmospheric Pressure (hPa) at the Cape Columbine showing a general decrease in value over time. It also highlights the depression that is caused by the passage of the deep Low pressure system.

The atmospheric pressure distribution time series is smoother than that for wind (Figure 3.2). On the large scale, alongshore wind strength is related geostrophically to the pressure gradient in the across-shore direction. As the pressure gradient weakens following the trailing edge of an anticyclone, relaxation in the geostrophic wind field and hence light and variable winds are reported. Post-frontal conditions and the onset of ridging of migratory anticyclones south of the country typically are associated with strong across-shore pressure gradients and strong alongshore winds on the west coast. During the first two months, the changes in pressure over time were bigger indicating more variability in atmospheric forcing over Cape Columbine. In September, atmospheric pressure reached peaks of 1030, 1026 and 1029 hPa in intervals of 8 days respectively. These events resulted in weak wind period as shown in Figure 3.2. Conversely, in between these events relatively stronger winds and rainfall were recorded.

A significant depression in pressure from the 02nd to 12th November was observed and is evident as shown in Figure 3.7. During this period, atmospheric pressure reached 1002 hPa on the 07th November. However, a consistent atmospheric pressure less than 1010 hPa was recorded throughout this period. This was the same system which resulted in a significant amount of rainfall. This high amount of rainfall was associated with the passage of the deep low over the area. To further confirm this, it was recorded that the lowest pressure occurred on the 07th November at 01:52 AM and was 1000.8 hPa. This is exactly the same time when the highest amount of rainfall accumulation was recorded. On contrary, the highest pressure of 1031.1 hPa was recorded on the 09th September at 09:48 AM.

### 3.4.4. Temperature

In this study, air temperature was also investigated to establish any interconnectedness with other different atmospheric variables at Cape Columbine.

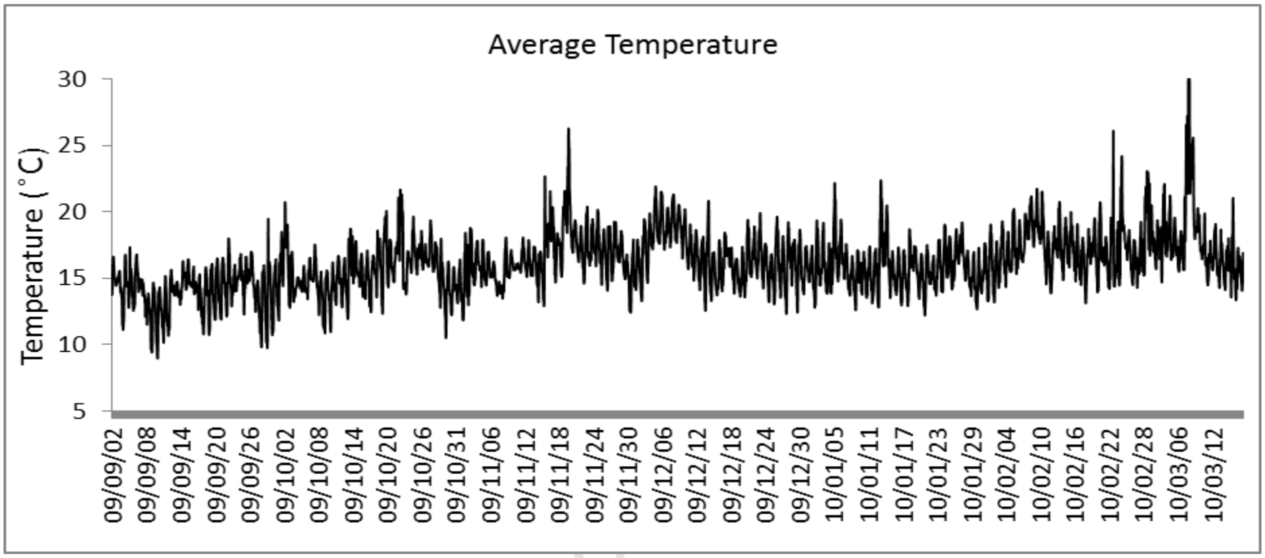

Figure 3.8: Temperature plot for the period September 2009 to March 2010 at the Cape Columbine. It shows a generally increasing variation as the seasons change from winter towards summer. There is no bigger variation diurnally over time since the overall average night and day temperature difference is 2.1 °C.

From the dataset, the daily averaged observed temperature at the Cape Columbine was 16.26 °C. In the first week, a more stable variability in temperature was observed and was followed by a significant drop over the second week. Figure 3.7 showed a drop in atmospheric pressure, whilst rainfall, relatively strong wind and shift in wind direction were evidently observed during the same period. Clearly, the atmosphere was close to saturation and cloudy with rain were apparent as witnessed in Figure 3.7. All these support the arguments that a frontal system passed over Cape Columbine in that period. Temperature dropped tremendously and resulted in the coldest temperature of 8.96 °C being recorded. This was recorded on September 09th at 07:00 AM. The coldest event occurred exactly at the same time where the atmospheric pressure reached its peak. The presence of a high pressure cleared the atmosphere allowing for deep tropospheric mixing; hence low level warming escaping into high levels of the atmosphere resulting in a very cold morning.

Figure 3.9 also confirms the reduced variation in diurnal temperatures in the first phases of the series. Temperature shows an increasing tendency from the beginning until December. This was expected given that our time period starts from arguably the end of winter towards summer. A day time high of 24.75 °C on November 11th at exactly 03:00 PM was observed. This happened over the same period where less humid conditions were observed over Cape Columbine (Figure 3.10 below).

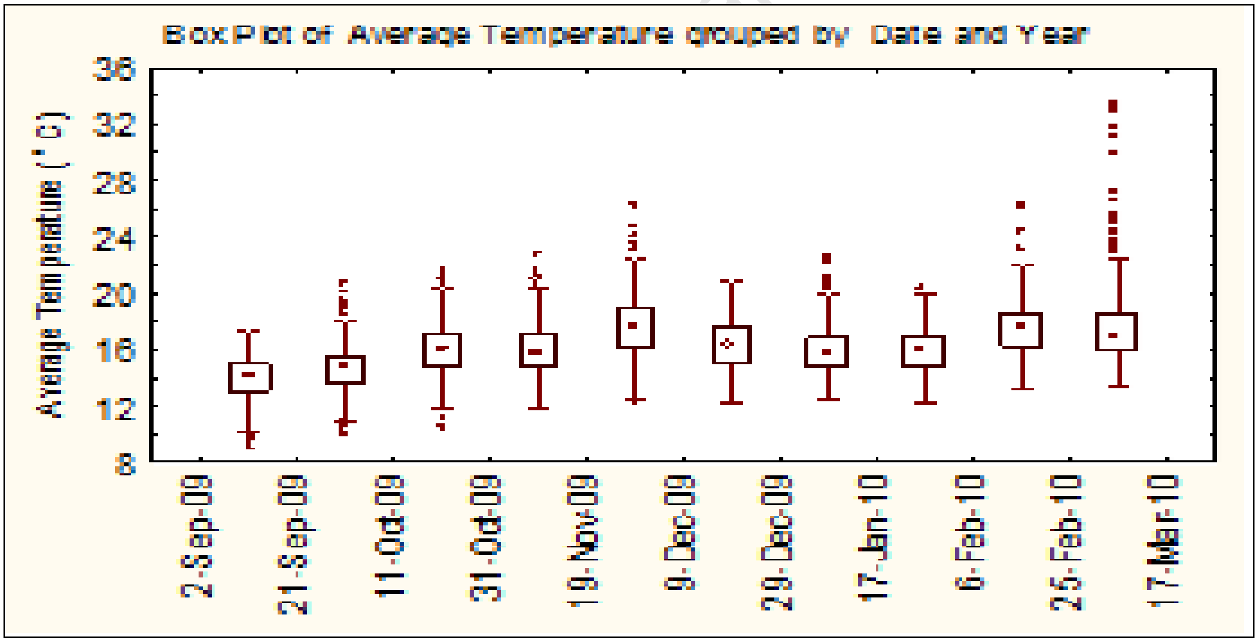

Figure 3.9: A plot showing the data distribution for Average Temperature at the Cape Columbine.

The temperature distribution in the summer months (between December and February) was fairly stable, however January was colder. The warmest event (record temperature of 33.31 °C) was recorded on the 08th March which was one of the least humid days as shown in Figure 3.11 below in the next section.

Table 1: Results for the average monthly temperature and overall rainfall analysis at Cape Columbine

| Month | Ave Temp (° C) | Lowest (° C) | Highest (° C) | Rainfall (mm) |
|---|---|---|---|---|
| Sep | 14.07 | 9.06 | 19.41 | 25.24 |
| Oct | 15.53 | 10.50 | 21.67 | 5.79 |
| Nov | 16.64 | 11.83 | 26.25 | 42.44 |
| Dec | 16.71 | 12.29 | 21.91 | 3.80 |
| Jan | 15.83 | 12.19 | 22.37 | 30.25 |
| Feb | 17.27 | 13.08 | 26.05 | 13.54 |
| Mar | 17.81 | 13.22 | 33.31 | 6.51 |

Further investigations need to be made as to how temperature dropped during January. Generally, January has hottest temperatures in Cape Columbine being in the mid-summer season. However, Figure 3.4 implies that persistent southerly winds were dominant leading to the decreased January temperature. This resulted in highly intense upwelling episode over Cape Columbine as discussed below and plotted in Figure 3.14.

### 3.4.5. Relative Humidity

There is a severe shortage of water throughout the year in most parts of the South African west coast. Cape Columbine is an example with its meager rainfall throughout the year. It receives on average 250 mm of rainfall a year (Olivier, 2002). However, the region is subjected to high water vapour content which in most cases results in foggy conditions. Due to the strong subsidence inversion that exists most of the year, this low level moist air is often unable to rise and form rain-bearing clouds unless a strong synoptic weather system is passing nearby. Olivier (2002) observed that in Cape Columbine, about 2.5 $lm^{-2}$ (liters per square meter) of water can be accumulated per day of which 90% is from fog deposition alone due to high volumes of humidity in the area.

Water Vapour content is a Green House Gas (GHG), thus it is very important in climate change studies. It affects the atmospheric heat budget and its exchange with the ocean. This GHG scatters and reflects incoming solar radiation back into the atmosphere whilst reflecting outgoing long wave terrestrial radiation.

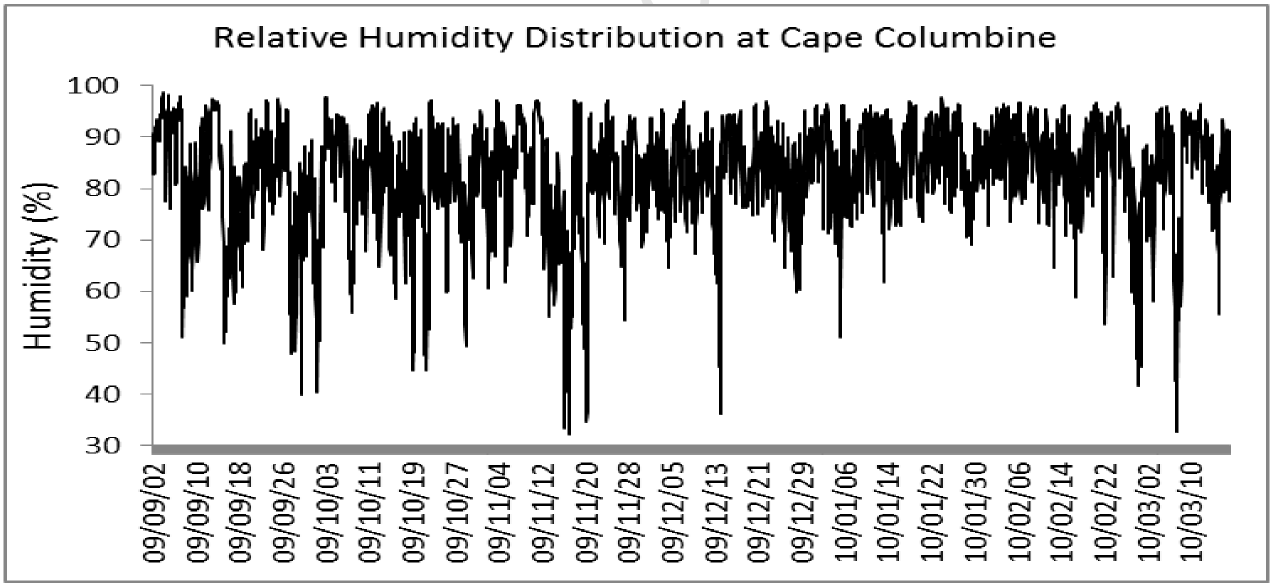

Figure 3.10: A plot of daily Relative Humidity over time at the Cape Columbine.

From Figure 3.10, it is apparent that Cape Columbine is a very humid area and as a result very prone to fog formation with an overall average relative humidity of 82.88 %.

Week one of the time series was rainy as discussed above and shown in Figure 3.6. The average Relative Humidity for Week 1 was 91.45 % but the atmosphere dried up to 71.98 % in the following week. Figure 3.11 shows the distribution of data over time. The most humid event occurred in the first week of the study where water vapour content reached 98.76 %. However, there were several dry events. On the 17th November, the driest air-mass over Cape Columbine was recorded with only 32.1 % of Relative Humidity.

There are a few factors driving this variability in moisture content in the lower atmosphere. South-easterlies winds were observed during this less humid period. Meteorologists refer to such wind as an offshore flow. This refers to winds blowing from the land off into the adjacent ocean. These winds are associated with hot conditions and fine (clear) weather along coastal regions. Figure 3.8 shows hot conditions were observed over Cape Columbine during the dry November period.

These wind conditions together with dryness may also indicate the passage of a Coastal Low ahead of an approaching frontal system. Coastal Lows are short-lived meso-scale atmospheric systems. In few hours, the wind changed direction into south-easterlies and a small amount of precipitation was recorded for three hours on the 18th November (0.01, 0.05 and 0.04 mm) as shown in Figure 3.6.

Another dry airmass event occurred on the 07th March, where the moisture content was at 32.6 %RH as indicated in the earlier section (Figure 3.10). This was also the hottest day of the time series where temperature reached 33 ˚C at one instant. The wind sensor at this stage was broken and data for wind speed and direction was not recorded.

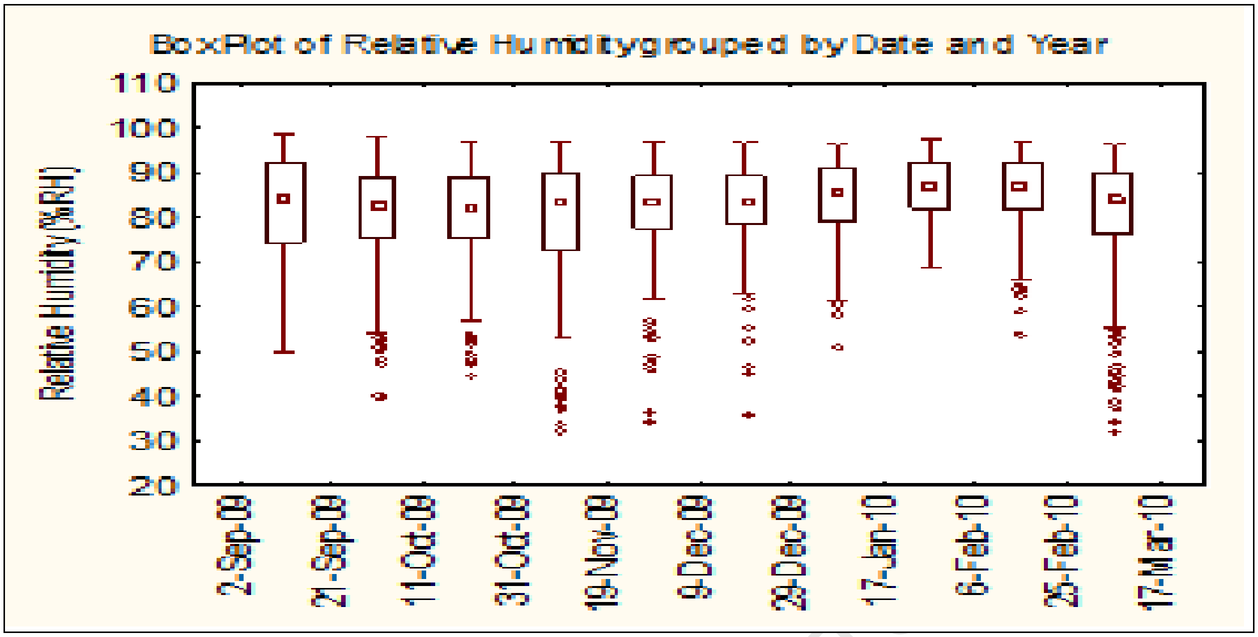

Figure 3.11: Relative Humidity distribution over the Cape Columbine over time. Its average of 82.88 %RH can be visibly followed. Mostly humidity can be categorised into diurnal event and that can be deduced to the large range of distribution over time with several outliers and few extreme values.

## 3.5. Discussion

A clear relation was found between Air Temperature, Wind (Speed and Direction), Atmospheric Pressure and Humidity. All of these parameters influence moisture content in the atmosphere and rainfall seasonality. At Cape Columbine, rainfall occurred on days where winds were favorable, mostly south-westerlies to north-westerlies. However, during the relatively heaviest precipitation event of the study, the winds were north-easterlies due to the position of the deep low pressure system located to the north of Cape Columbine causing a clockwise flow around its vicinity.

Another conclusive observation from this study was the relation between moisture content and temperature. The hottest day was also the least humid day of the study period. Temperatures were observed to be soaring at 33.3 °C whilst the humidity factor was at 32.6 %. We also witnessed through our study that the wind strength and atmospheric pressure are related. Periods of relatively strong winds were observed around a cyclonic pressure system and weak winds occurred during the passage of high pressure anticyclone. It was observed that, as the atmospheric pressure tendency rose, the wind strength was falling. A proven interconnection between atmospheric variables as shown in the results and analysis of this dataset was established. All these variables cohesively make an atmospheric system and cannot be studied in isolation. The same can be said between ocean and atmosphere interaction, however, the extent at which one influences the other will be investigated in subsequent studies.

The study also affirmed the use of these variables in identifying atmospheric features or systems which passed over Cape Columbine. Thus, monitoring of these atmospheric variables through the use of an automatic weather station is very important. It will help in understanding these systems better and for future predictive and early warning models. One of those systems that we identified was a deep low pressure system (Fig: 3.12) which, according to Singleton and Reason (2006), is visible as a trough of cold, high latitude air extending into the middle and upper troposphere (700 hPa to 500 hPa). These systems are associated with very deep moisture convection, instability and a lot of mixing as observed in the case study which resulted in heavy rainfall.

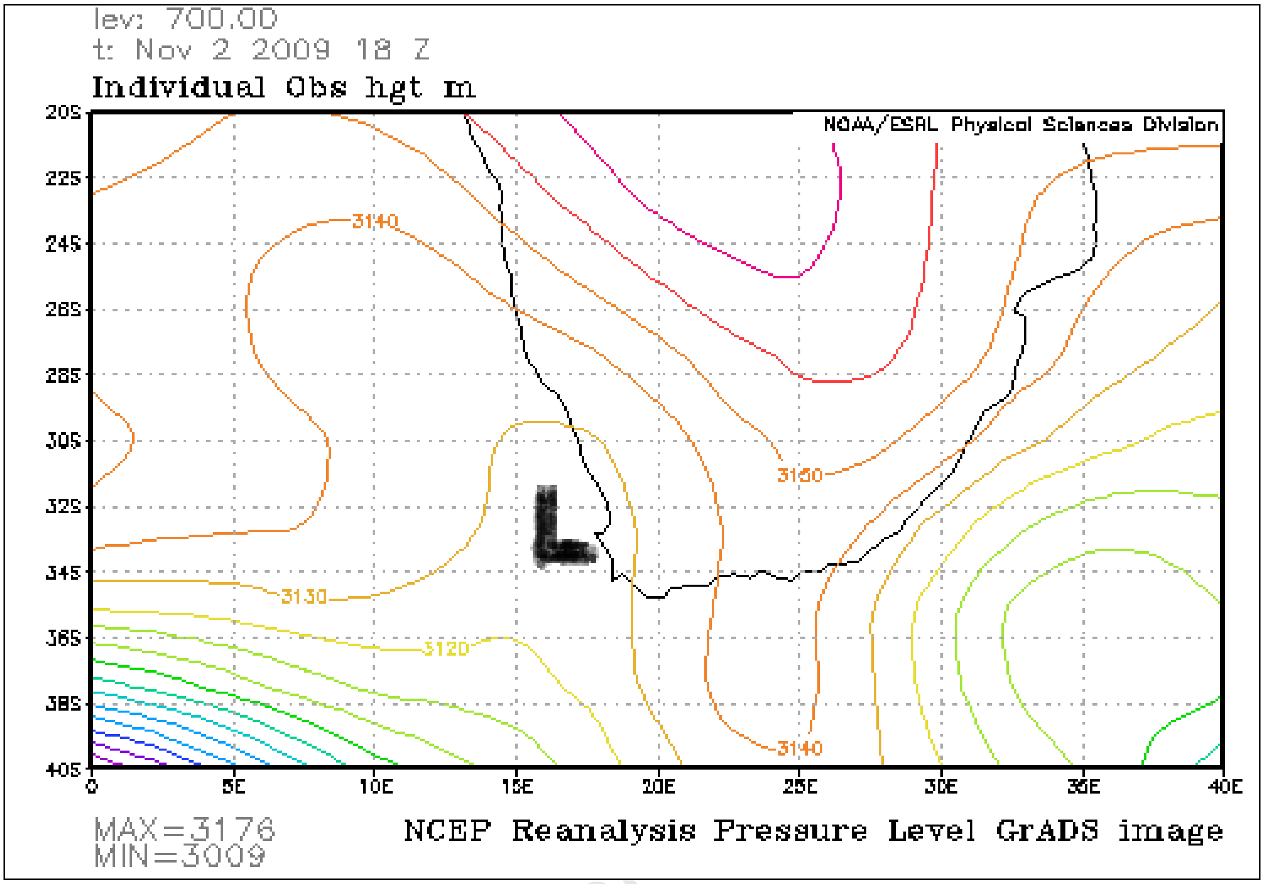

Figure 3.12: A plot indicating the position of the deep Low pressure system on the 2nd November 2009. This figure is generated from the NCEP Reanalysis dataset using GraDS and shows the 700 hPa level at time 18Z. It was a quasi-static system that drifted eastwards with time before it existed the country into the Indian Ocean as a deep mid-level trough.

It has been discovered that there are changes and fluctuations in temperature around South African coasts in general (Rouault *et al*, 2009). However, in the southern Benguela, there is a significant decreasing variation of 0.5 °C in a decade from January to August and a 95% positive correlation with ENSO (Rouault *et al*, 2009). Rouault *et al* (2009) further indicated that El Niño and La Niña suppress and increase upwelling respectively, but there is no proven linear relation between the strength of the ENSO and magnitude of coastal temperature fluctuation. El Niño (La Niña) has in the recent past, appeared to be associated with major warm (cool) events at a seasonal scale in the region (Rouault *et al*, 2009). It was also shown by Colberg *et al* (2004) that ENSO influences temperature in the South Atlantic. However, its relationship with rainfall is not linear; Fauchereau *et al* (2003) showed that there is a statistical significance between rainfall anomalies, SST and winds.

We now look into the two case studies where upwelling episodes and their intensity were investigated over Cape Columbine area during two different summer seasons. These different cases were compared in this study and were between the 1999/00 and 2009/10.

Both summers were dominated by a significant high pressure system over the South Atlantic Ocean. This resulted in weak pressure gradient and hence weakened winds. However, passages of cold fronts and coastal lows in both summers subsequently resulted in variation in wind strength and direction, and variable atmospheric pressure. There were 12 major observed upwelling episodes from November 1999 to April 2000 and these were triggered by the eastwards movement of the South Atlantic Anticyclone. The longest of these events according to Roy *et al* (2001) persisted for 20 uninterrupted days and this upwelled and injected about 1306 $x10^6$ $kg.m^{-1}$ of water along the coast. Roy *et al* (2001) indicated that an eastward shift of the South Atlantic Anticyclone occurred during February and March 2000. This shift induced strong gradient between the anticyclone and the continental low pressure, resulting in strengthened southerly winds in the area. However, this strengthening of wind was also driven by pronounced modes of ENSO passage over the Pacific Ocean. It was also observed that all these events followed a very hot period in the early stages of the season.

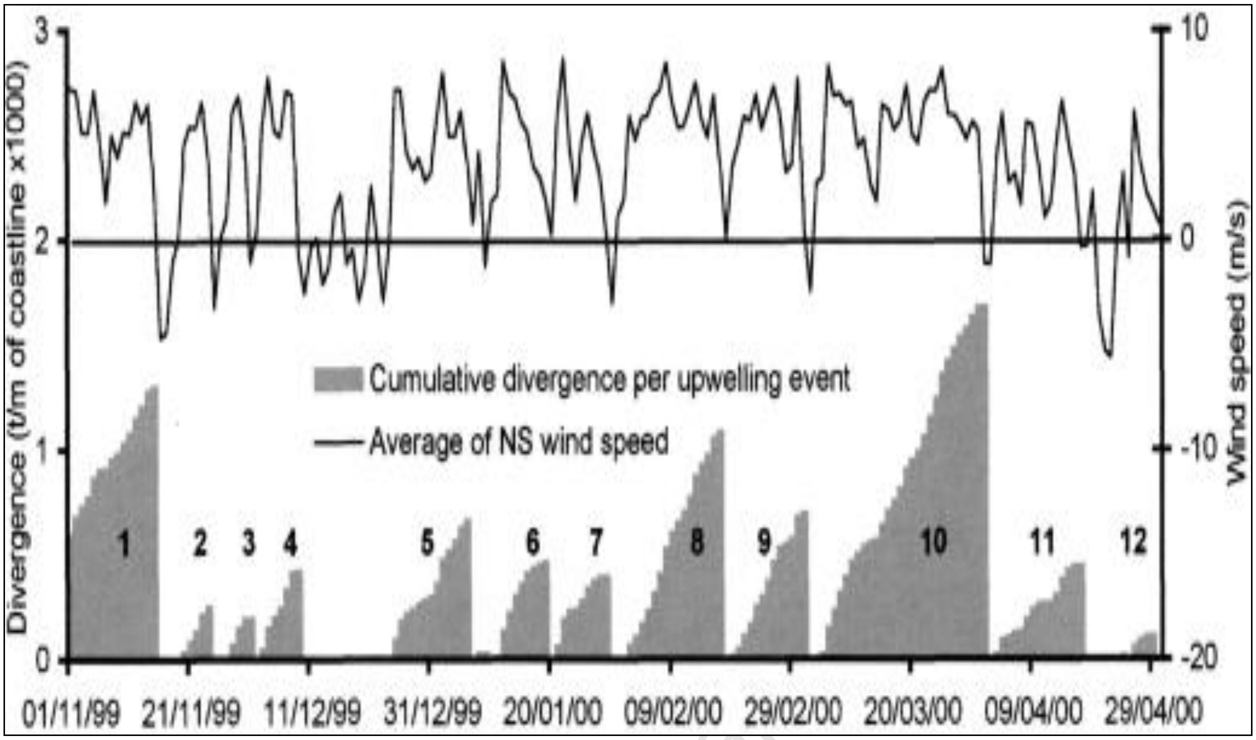

Figure 3.13: Plot of the cumulative proxy for upwelling embedded with the average speed for the North/South winds. All the 12 upwelling events are shown in the plot (Adopted from Roy *et al,* (2001)).

From the 2009/10 case study, the data set was a month longer compared to the 1999/2000 case study above and as a result more upwelling events were observed during the 2009/10 season. 17 notable upwelling events occurred over the Cape Columbine area (Fig 3.14) during the 6 months study period. These events varied in terms of strength and periodicity. In the early stages of the study, it was evident that upwelling events persisted for a short period with relatively strong intensity. Many of these events were observed in the first half of the study, from event 1 to event 9. Overall, most of these events lasted for 4 to 6 days uninterrupted. There was one big event (12) that persisted for 21 days uninterrupted between the 24th December and 14th January. This explains the cooling temperatures observed over Cape Columbine during the December and January months. During this period, there were persistence southerly winds and significant wind stress magnitude observed over Cape Columbine.

Most of these events, although short-lived had a strong driving force (wind stress). This was evident through strong signals in wind stress during events 1, 3, 6, 7, 10, 14 and 16. Between events 6 and 7, there was a period of very strong wind stress forcing but the wind blew from a north-easterly direction making it an unfavourable condition for the development of upwelling. Therefore, we can conclude that the 2009/10 summer was an upwelling dominated season.

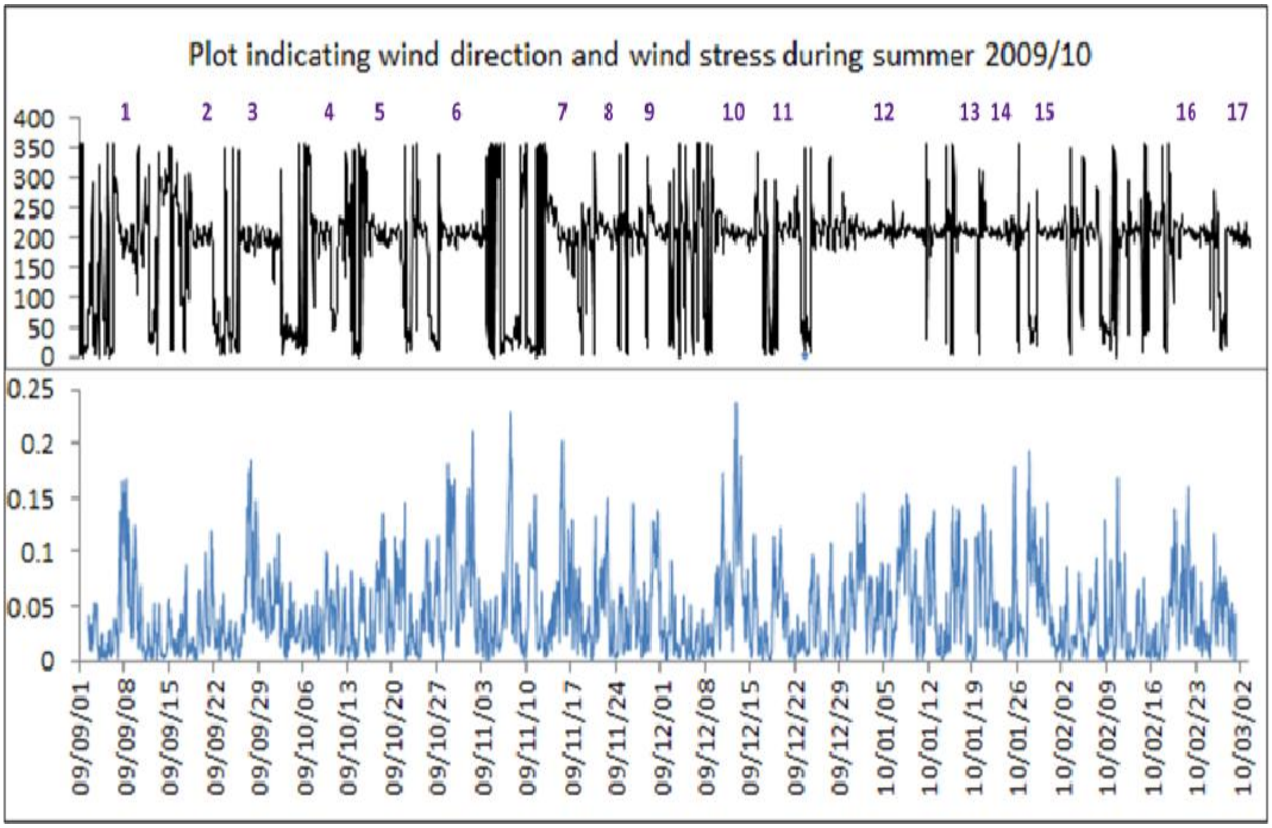

Figure 3.14: A plot showing upwelling events over the Cape Columbine region during the summer of 2009/10. Wind stress and direction are plotted in order to extract periods where there is an overlap between strong wind forcing and southerly wind component.

# Chapter Four: Discussion

In this study, variability in characteristics and behavior of wind signals were examined at Cape Columbine along the west coast of South Africa adjacent to the southern Benguela upwelling cell. The study investigated wind behavior for the period 1957 to 1995 with data collected from a point source Automatic Weather Station. It also investigated seasonal, interannual and decadal variability in these observations together with possible linkages to atmospheric patterns. Emphasis was given to the frequency and duration of these wind events. This was achieved by partitioning our study period into different time intervals, namely; diurnal, seasonal, annual and decadal.

Burls and Reason (2008) indicated that the Benguela upwelling system and its dynamics vary both temporally and spatially. Variability depends on the orientation of the coastline which channels and enhances alongshore wind stress. Temporal variability is also related to changes in the wind stress forcing which variably occurs at time scales ranging from hourly to decadal and longer. Diurnal variability occurs in response to contrasting heating over the land and sea at day and night. This also influences the pressure changes during daytime heating and nighttime cooling between these two masses (Peard, 2007). Such changes in pressure lead to fluctuations in the pressure gradient force (PGF) between the South Atlantic Anticyclone and the Continental Low inland. However, this pattern can at times be disturbed by passages of other synoptic to meso-scale circulations like cold fronts and coastal lows, as observed in the case study.

Passages of these features may intensify the PGF resulting in culmination of strong winds. These fluctuations are stronger during the day (Fig 2.2). There are also variations during the night. Peard (2007) mentioned that an intensification of the PGF in the evening results in strong coastal winds but this weakens in the morning, leading to an overall relaxation. This was confirmed by the results obtained in the study (as shown in Fig 2.10 above) where stronger winds are found in the evening (18:00) and weaker winds are in the morning (06: 00). These changes essentially reflect the land/sea breeze circulation although diurnal changes in heating associated with the regional topography near Cape Columbine also reflect local mountain-valley wind circulations.

Strong seasonality was apparent in the diurnal wind events. The morning time however showed the least variability in terms of wind strength throughout the year whereas there was greater variability through the record for the evening data. This was due to the normal relaxation of the synoptic systems in the morning hence relaxing the winds along the coast. Figures 2.3 to 2.6 indicate that wind was strongest in summer and in the evening but weakest in winter and in the morning. This was also confirmed by a composite diagram of wind strength at an annual time scale (Figure 4.1).

Different phases of wind characterization over the full time period were observed. In the earlier periods of the time series, wind behaved in an oscillating fashion with clear variability over years. In the middle part (1971 to 1978) of the record, the wind behavior changed to a more stable profile with less variability apparent. Towards the end of the record, there was little variation in the wind behavior from year to year.

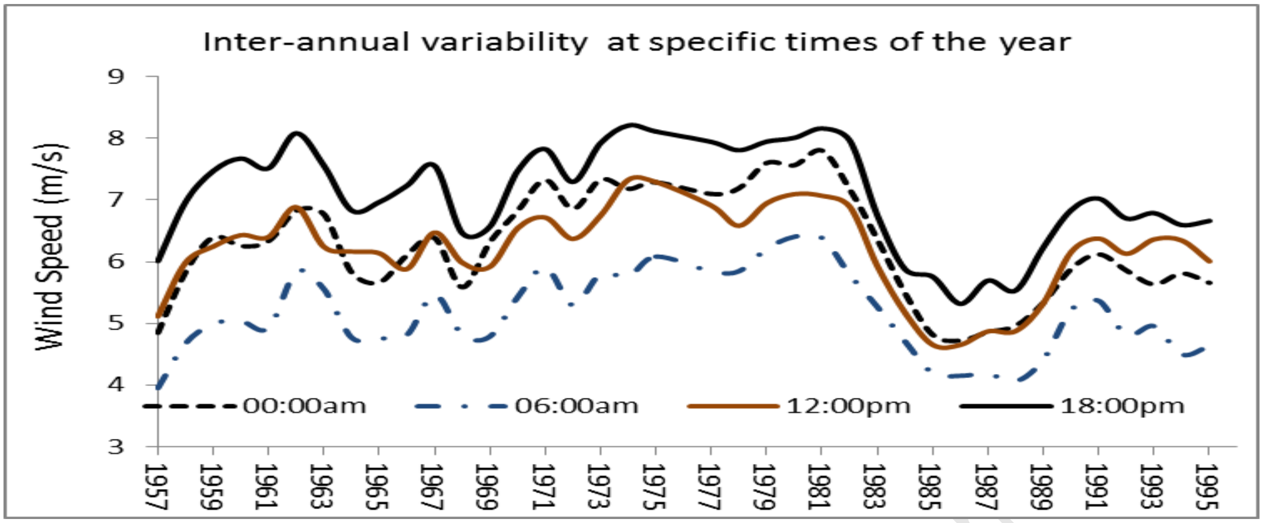

Figure 4.1: Variability of wind over years as depicted by measurements at different times during the day. There are different phases in behavioral characterization of wind structure with time which highlights different climatological cycle.

Seasonality of the wind regime in Cape Columbine is driven by the latitudinal shifting of the South Atlantic Anticyclone (Tyson and Preston-Whyte, 2000). However, there was a pre-dominant southerly wind regime throughout the year, consistent with Peard's (2007) findings. Winds were stronger (weaker) during summer (winter) and this was true for most of the times of the day. These findings are also consistent to those by Hardman-Mountford *et al* (2003) in that there are variable wind characterizations throughout the year with strong (weak) winds in summer (winter). They also mentioned that along the west coast, there is a dominant southerly wind component throughout the year, especially in areas around Cape Columbine as shown in Figure 4.2.

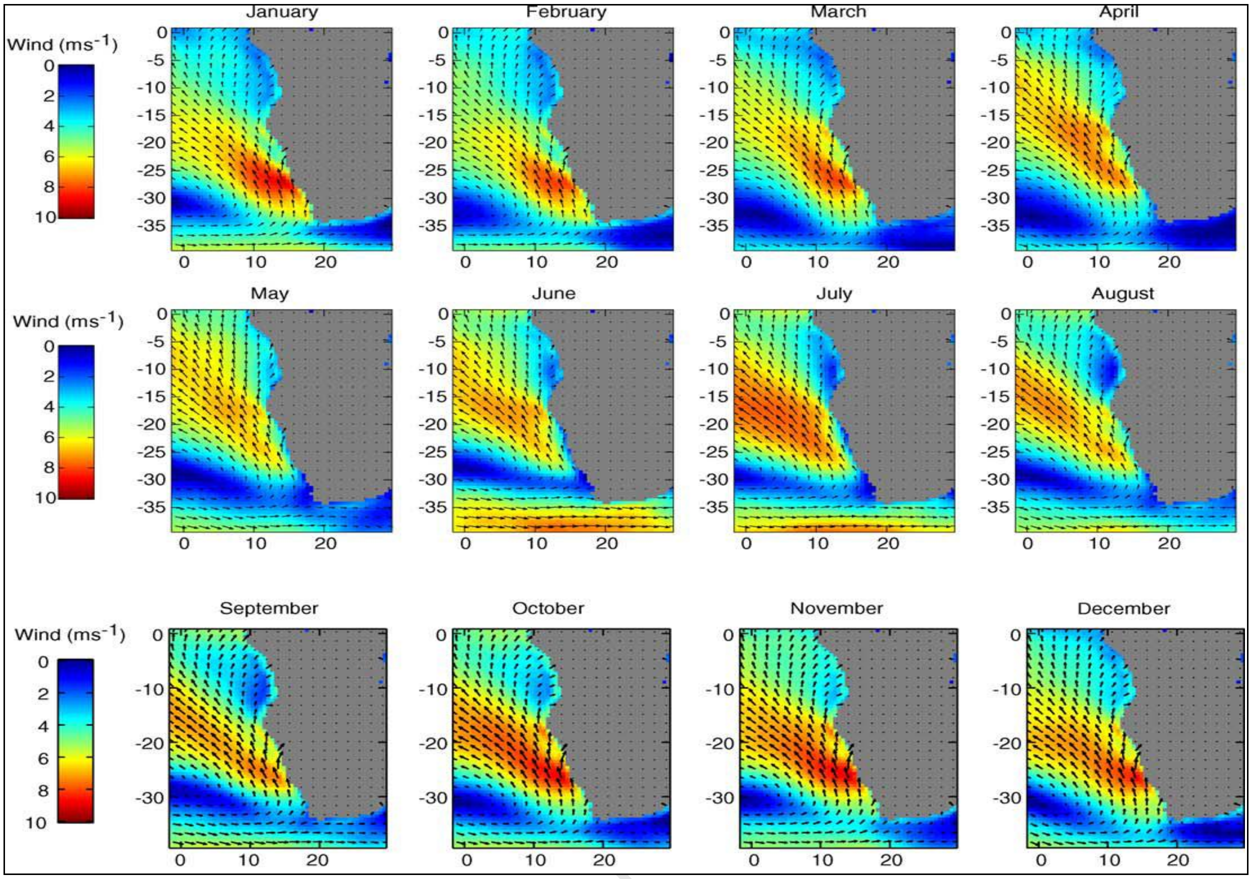

Figure 4.2: Monthly mean of ocean surface QuickScat winds along the Cape Columbine area and the Benguela Current region at large in the south-western Atlantic Ocean (Adapted from Hardman-Mountford *et al*, 2003).

Wind stress can be defined as a measure of wind induced force over a unit area and is proportional to the square of wind speed (Peard, 2007). It has since been used as a proxy or indicator for upwelling favorable conditions, with positive (negative) wind stress values considered more favorable for upwelling (downwelling). However, it was discovered that wind stress is not only an indicator for upwelling; but may also be linked to large scale global circulations. Peard (2007) in her study at Luderitz indicated that there is seasonality in the characterization of wind stress with maximum stress occurring in summer decreasing fourfold in winter. From our results (Fig 4.3), it appeared that there is seasonality about the occurrence and behavior of wind-stress events, but the difference in intensity at which these events occurred between summer and winter was far less than Peard (2007) observed at Luderitz. This seasonal relationship was also not linear as some events occurred for longer, uninterrupted periods. Therefore, periodicity of these events does not necessarily only depend on the seasonal migration of the South Atlantic Anticyclone but also on large scale modes such as ENSO. This was observed from our analysis, where periods of positive (negative) wind-stress are associated with onsets of large scale La-Nina (El- Niño) circulations like the 1962/3 and 1983/4 shifts between El- Niño and La- Niña together with the Benguela Niños and Niñas. Strong upwelling events coinciding with periods of strong wind stress (Fig 4.6) were also discovered from the analysis. There was a corresponding relationship between the wind field and upwelling events. High amplitudes of wind stress magnitudes were observed from the analysis at Cape Columbine and their occurrences were mostly during the summer seasons. This too was consistent with Hardman-Mountford *et al* (2003)'s findings that upwelling occurs in summer over the southern Benguela region.

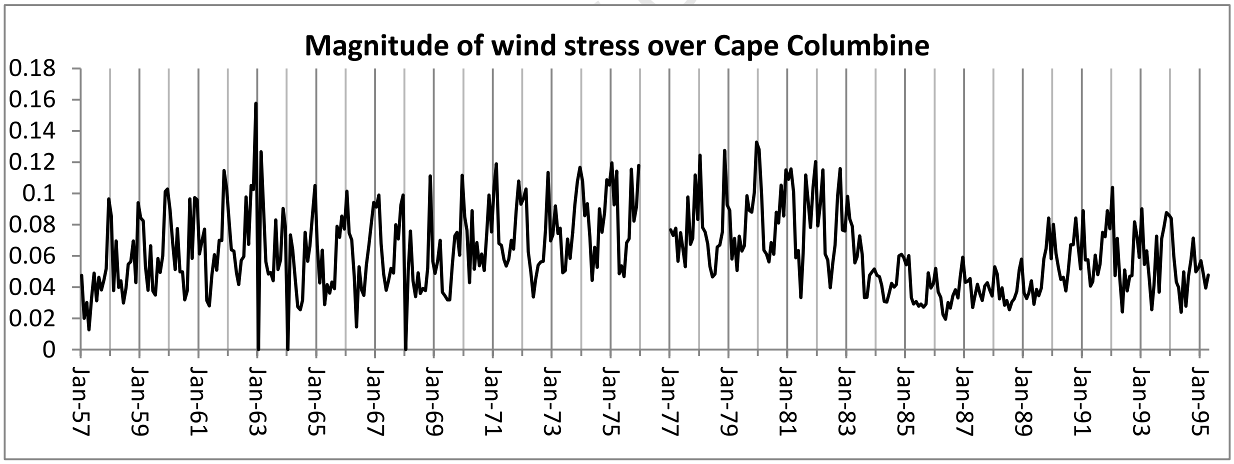

Figure 4.3: A plot indicating the seasonality of wind stress over Cape Columbine.

There was also a corresponding relationship between upwelling occurrence and thermal energy regulated by wind mixing in the upper layer of the ocean waters. Wind mixing was defined by Bakun (1996) as a measure of the rate of input of turbulent kinetic energy from wind to the ocean. Hardman-Mountford *et al* (2003) postulated that a weak wind mixing signal exists in winter, whilst Boyd (1987) associated this thermal mixing with the winter migration of fish stocks. Cury and Roy (1989) stated that a wind mixing value of $250m^3s^{-3}$ is preferred for pelagic spawning habitats. From this study, periods of strong wind mixing corresponded with those of favorable upwelling events. Similarly, this relationship between wind mixing and upwelling episodes was also noted by Shannon *et al* (1986). High (low) values indicate the occurrence of cold (warm) events over the Benguela upwelling regions. It was also apparent that strong and major signals (Fig 4.4) of wind mixing (cold events (upwelling)) coincided with anomalous high wind stress and preceded strong warming events in the form of the 1964 Pacific Niño and the 1984 Benguela Niño.

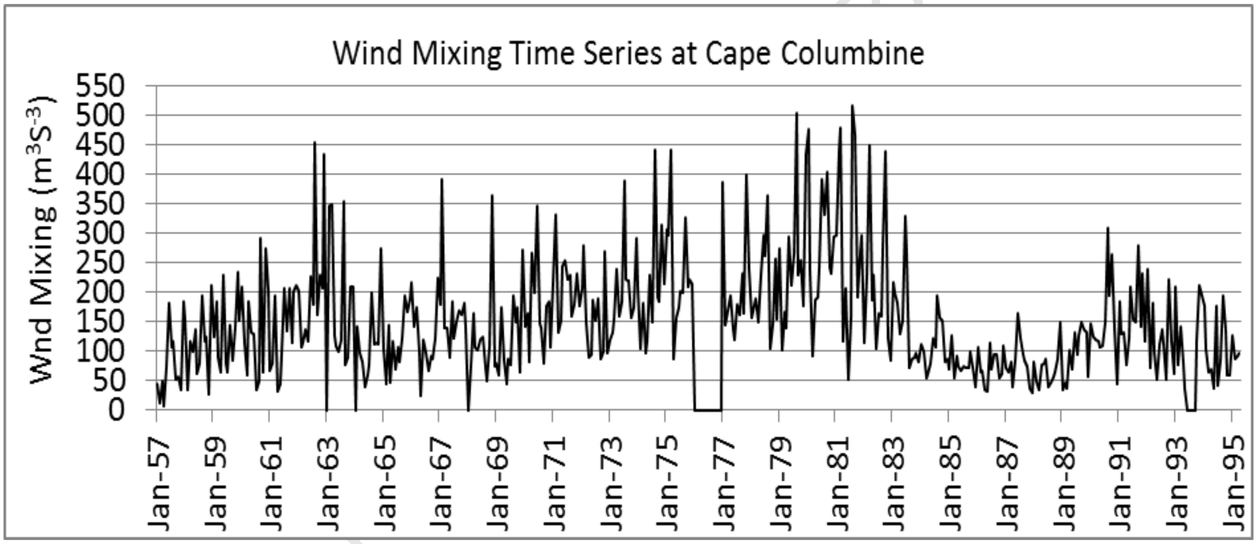

Figure 4.4: A plot indicating variation of thermal energy regulated by wind mixing at Cape Columbine from 1957 to 1995.

Large scale circulation patterns may influence the onset, duration and strength of different regional to local scale wind events. Miron and Tyson (1984) conducted studies on some of these regional events as manifest in wet and dry conditions over South Africa and adjacent oceans. Their studies looked at the period between 1963 and 1979 where a general distribution of above-average and below-average rainfall during that period occurred. Above average rainfall according to their studies was recorded between 1973 and 1979. This corresponds with a period of above average (positive) wind stress in our studies as depicted by the Figure 4.5. . Furthermore, their results showed that the period 1963 to 1972 was the driest and this period corresponds to one of mainly negative wind-stress anomaly at Cape Columbine (Fig 4.5). According to these authors, this period was characterized by relatively intense high pressure anomalies which extended into the mid-latitudes as far as the Gough Island regions. From our findings, there was an extended period of increased autumn and spring winds from 1971 to 1979 peaking in 1974. Therefore, there was an anomalous behavior in the wind field at Cape Columbine which can be associated with the onset of extended period of wet and cold events (Fig 2.9).

From the analysis of wind stress (Fig 2.10 and 4.3) at Cape Columbine, linkages with large scale circulations (Fig 4.3) are suggested. It was found that there are strong suggested linkages between the shift in wind behavior and the occurrence of major Benguela Niño events in the years 1963 and 1984. During periods of Benguela Niños (Niñas), weak (strong) and persistent winds were evident which in turn increased (decreased) temperatures profiles over the ocean and adjacent inland regions. There was also very low (high) amount of turbulent energy input to the ocean from coastal winds during Benguela Niños (Niñas) events (Fig 4.6).

During the 1963 Benguela Niño event, temperatures off Angola increased by 4 $^{o}$C in 1963 and up to 6 $^{o}$C during the 1984 event. This was due to the warm water intrusion from the north. Shannon *et al* (1986) indicated that this penetration of warm saline water resembled that of the 1963 event where higher than normal and the warm water intrusion extended about 5° of latitude farther south than normal.

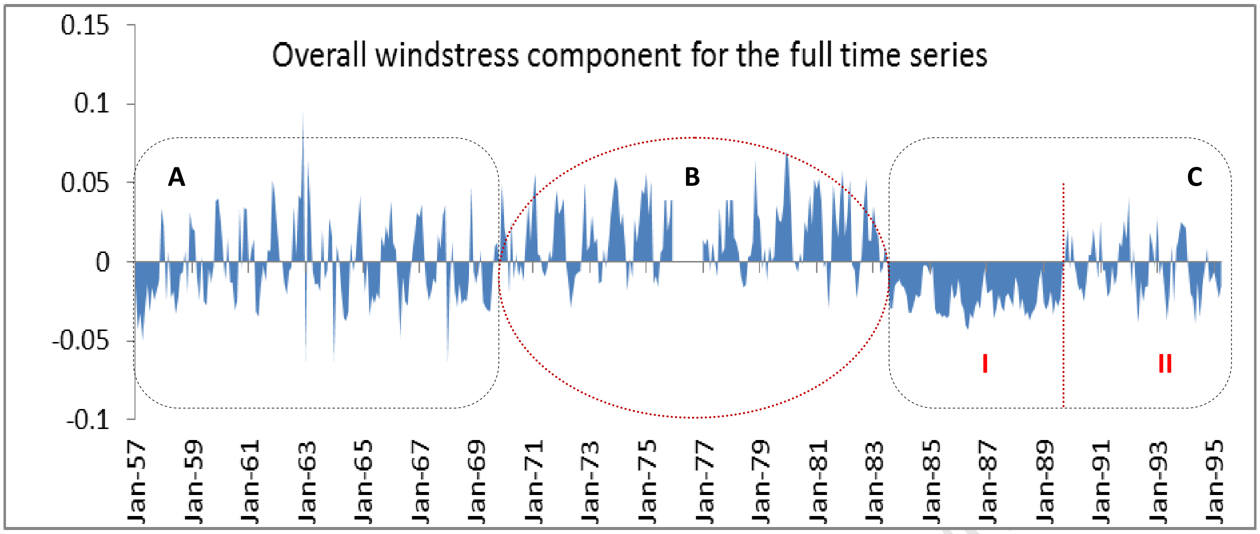

Figure 4.5: Wind stress anomaly for Cape Columbine during the period 1957 to 1995. This indicates the intensity, frequency and periodicity of upwelling favorable conditions along the West Coast of South Africa. Decadal cycle is also shown in the figure with different phases and their shift or decay.

Fig. 4.5 suggests that there may be some quasi-decadal variability to the wind stress anomalies at Cape Columbine with three somewhat different periods present. The composition of this wind pattern plot was derived from calculating wind stress anomalies from the overall dataset. The three phases were classified as Period A, B and C but Period C was subdivided into two phases I and II.

Period A comprised relatively regular shifts between positive and negative anomalies of roughly equal magnitude except for the much larger anomalies in 1963. Signals of upwelling favorable wind stress anomaly occurred interchangeable with those of less favorable upwelling conditions. These oscillations occurred every year with positive and negative wind stress anomaly setting in over the summer and winter seasons respectively. Period A phase existed from the start of the time series and ended in the year 1970, before an apparent shift in the behavior of the wind anomalies was observed.

Period B behaved differently from Period A. An overall tendency for mainly positive wind stress anomalies existed during Period B (1970 until the end of 1983). These positive upwelling favorable anomalies were interrupted relatively infrequently by mainly weak negative anomalies. Thus, the upwelling favorable events behaved differently in terms of intensity, frequency and period of occurrence from those in Period A. Most of these events existed for almost the whole year un-disturbed by any negative anomalies with the 1974 and 1975 events good examples for these. A magnified intensity of the wind stress anomaly was observed during this phase. Unlike those of Period A, Period B events had high magnitudes with many reaching a difference 0.04 from the normal. However, these events had less frequency of occurrence as their periods of existence were longer.

For Period C, the first 6 years showed a dominance of negative wind stress anomalies that were followed by about 6 years with more regular alternation between positive and negative anomalies of roughly similar magnitude. In the first 6 year period, hot conditions, persistent droughts and other hazardous conditions were recorded. Fish stocks also suffered a lot of stress due to this environmental forces with by-catches on small pelagic (sardine and anchovy) and hakes dropping to below average (Van der Lingen *et al*, 2006), The behavior of the wind stress was unusual in this period, with relative stable and sizeable negative anomalies almost the whole time. Phase II of Period C reverted to a pattern more similar to Period A with variations between spells of positive and negative wind stress events between 1990 and 1995.

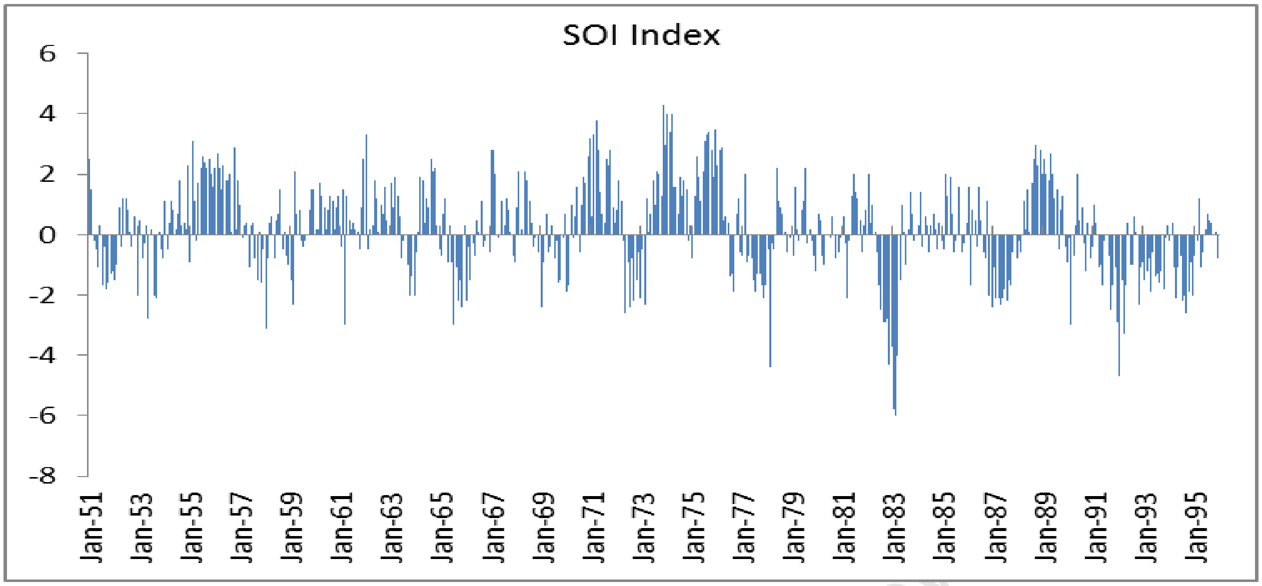

Figure 4.6: ENSO large scale events calculated from the SOI data downloaded from NCEP/NOAA re-analyses (http://www.cpc.ncep.noaa.gov/data/indices/soi).

Analysis of Southern Oscillation Index (SOI) data from NCEP (National Centre for Environmental Predictions) gave an indication of years where El- Niño and La- Niña events occurred. El- Niño (La- Niña) events typically coincided with reduced (increased) wind stress values at Cape Columbine. The major event of 1983/4 was classified as the Benguela Niño (Shannon *et al*, 1986; Hardman-Mountford *et al*, 2003) because it was due to the southward movement of tropical waters into the Benguela current region. However, the 1963/4 period also coincided with a Pacific El Niño event.

Chapter 3 examined the case study, and the main results are summarised here. Wind strength and atmospheric pressure are related in many ways and they can both help detect onsets or decay of various synoptic and mesoscale systems. In one of many events, atmospheric pressure dropped by approximately 10 hPa in few hours. Eventually, the wind strength peaked by almost 10 m/s. Such occurrences are associated with the passage of coastal lows and cold fronts along the west coast. Carter (2005) indicated that the occurrence of Coastal Lows are signalled by a rapid and dramatic increase in wind strength and direction. Offshore winds, known as berg winds, coincided with very dry conditions over a short temporal scale, these are characteristic of the approach of a coastal low. These dry, warm winds may result in conditions favourable for veldfires. This calls for good predictive capability of coastal lows which is critical for avoiding subsequent disasters that may impact on society. Following coastal low passage, the winds shift to cool, moist onshore flow.

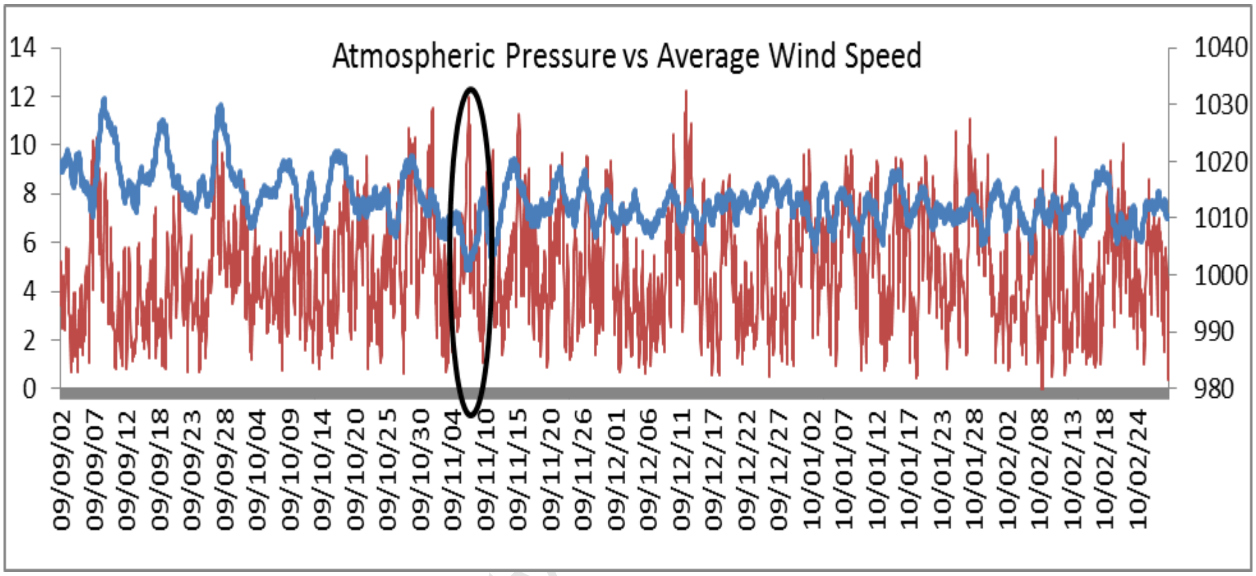

Figure 4.7: A plot showing the relationship between Atmospheric Pressure and Wind Speed. Onset of such occurrences is good in predicting the wake of Coastal Lows or cold fronts. The marked area reflects a deep low pressure system that passed over Cape Columbine bringing above average rainfall.

From the 6 months of the case study, it was observed that a clear relationship between Air Temperature, Wind (Speed and Direction), Atmospheric Pressure and Humidity exists. All these influence moisture content in the atmosphere and rainfall seasonality. Over Cape Columbine, rainfall occurred when there were favorable conditions (ie: mostly south-westerlies to north-westerlies). However, the highest rainfall event occurred due to the deep low pressure system that passed over Cape Columbine in early November 2009. Other findings are that relative humidity and air temperature are related. Very hot conditions were observed when the atmosphere was less humid or the moisture content (RH) was the lowest. Temperatures reached over 33 °C whilst the humidity factor was lowest at 32.6 %, the driest in the study period on the 07th March 2010. It was also found that wind strength and atmospheric pressure relates. It was observed that, as the atmospheric pressure tendency rose, the wind strength weakened.

## Conclusion

In this mini-thesis, an investigation into the nature of wind variability 37 years of hourly data at Cape Columbine was conducted. Variability of wind over diurnal, seasonal and annual to decadal time scales was discussed. In addition, a case study for the summer of 2009/10 at Cape Columbine was made. This was aimed at understanding the relationships between different atmospheric variables, the atmospheric forcing of upwelling events and the importance of using the AWS as a tool in identifying atmospheric systems passing over that area.

Diurnally, it was found that wind behavior varied over different times and this is associated with changes in daytime and nighttime heating. Wind strength was found to be higher during the night, especially in the evening. It was found that the wind is strongest throughout the time series (37 years) in the evening (18:00) and very weak in the morning (06:00). These differences in heating are brought about by diurnal changes in the pressure gradient force (PGF) between the semi-permanent South Atlantic Anticyclone and heat lows over the neighbouring land which are prominent during summer. The PGF is strongest in the late afternoon to evening where rising warm air through convection intensifies the continental heat low, thus increasing the wind strength along coastal regions.

On seasonal scales, the wind has a predominant southerly component throughout the year. This was due to the positioning of the South Atlantic Anticyclone relative to the landmass. At times, there are shifts to winds with a northerly component, typically associated with an approaching cold front and more common during the winter half of the year. In general, the wind at Cape Columbine tends to be stronger in summer than in winter due to the stronger PGF between the ocean and land in this season and the more southeastward location of the South Anticyclone. In addition, the diurnal wind characterization follows the seasonal patterns. These were apparent in that, at all times of day, the winds tend to be stronger in summer than in winter.

Other derived parameters such as wind stress and wind mixing also followed the same patterns as they depend on wind strength. Coastal upwelling in response to southerly wind stress by divergence of surface water also showed seasonal variations. Positive wind stress anomalies (upwelling favorable) were generally observed during summer seasons with negative anomalies during the winter seasons. These indicated that upwelling is a common and dominant feature along the west coast during summer especially in the Cape Columbine region. The occurrence of strong southerly winds is a characteristic of the summer whereas winter has winds weakest in magnitude. Autumn and spring seasons are characterized by more variable winds.

The winds at Cape Columbine show both interannual and quasi-decadal variability. In terms of the former, both ENSO and the Benguela Niño may impact on the west coast region. On the quasi-decadal scale, three somewhat different phases were identified through the 37 year record. In the first phase, there were shifts between spells of relatively large positive and negative anomalies that lasted several months. The second phase of around 14 years was characterized by similar sized anomalies but mainly positive (southerly) in direction. Only a few negative anomalies, weak in magnitude, occurred during this phase. The last phase showed two components; the first six years had relatively weak anomalies but almost always negative. This sub-phase was followed by a period that had similar behavior in terms of sign to the first phase but much weaker in magnitude.

The value of the new technologically advanced weather station has been demonstrated in the case study. It is effective in identifying significant atmospheric systems such as a deep low pressure system which brought relatively heavy rainfall over Cape Columbine.

Other advantages are its ability to monitor different variables which after analysis lead to a better understanding of atmospheric systems passing over Cape Columbine and their impacts on coastal upwelling.  A denser network of these instruments is needed along the west coast to better understand the weather and climate patterns of the Benguela Current region, their impacts on the upwelling system, and to help in forecasting.

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