# Meteorological influences on malaria transmission in Limpopo Province, South Africa.

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# DECLARATION

I Sandile B. Ngwenya, declare that the dissertation, which I hereby submit for Masters in Environmental Sciences at the University of Venda, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution. Any work taken from other authors or organisations is duly acknowledged within the text and references chapter.

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Sandile B. Ngwenya Date

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# ABSTRACT

Semi-arid regions of Africa are prone to epidemics of malaria. Epidemic malaria occurs along the geographical margins of endemic regions, when the equilibrium between the human, parasite and mosquito vector populations are occasionally disturbed by changes in one or more meteorological factors and a sharp but temporary increase in disease incidence results. Monthly rainfall and temperature data from the South African Weather Service and malaria incidence data from Department of Health were used to determine the influence of meteorological variables on malaria transmission in Limpopo from 1998-2014. Meteorological influences on malaria transmission were analyzed using time series analysis techniques. Climate suitability for malaria transmission was determined using MARA distribution model. There are three distinct modes of rainfall variability over Limpopo which can be associated with land falling tropical cyclones, cloud bands and intensity of the Botswana upper high. ENSO and ENSO-Modoki explains about 58% of this variability. Malaria epidemics were identified using a standardized index, where cases greater than two standard deviations from the mean are identified as epidemics. Significant positive correlations between meteorological variables and monthly malaria incidence is observed at least one month lag time, except for rainfall which shows positive correlation at three months lag time. Malaria transmission appears to be strongly influenced by minimum temperature and relative humidity ($R = 0.52$, $p<0.001$). A SARIMA (2, 1, 2) $(1, 0, 0)_{12}$ model fitted with only malaria cases has prediction performance of about 53%. Warm SSTs of the SWIO and Benguela Niño region west of Angola are the dominant predictors of malaria epidemics in Limpopo in the absence of La Niña. Warm SSTs over the equatorial Atlantic and Benguela Niño region results in the relaxation of the St. Helena high thus shifting the rainy weather to south-east Africa. La Niña have been linked with increased malaria cases in south-east Africa. During El Niño when rain bearing systems have migrated east of Madagascar ridging of the St. Helena high may produce conducive conditions for malaria transmission. Anomalously warmer and moist winters preceding the malaria transmission season are likely to allow for high mosquito survival and the availability of the breeding sites thus high population in the beginning of the transmission season hence resulting in increased epidemics.

Key words: Benguela Niño, Botswana Upper High, ENSO, malaria and malaria epidemics.

To my parents- Ben and Khanyisile Ngwenya; and my sons- Asiphile, Bayanda and Bandile.

"Everything about malaria is so moulded and altered by local conditions that it becomes a thousand different diseases and epidemiological puzzles. Like chess, it is played with a few pieces, but is capable of an infinite variety of situations".

Lewis W *Hackett 1937: 266.*

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| | |
|---|---|
| ACF | AutoCorrelation Function |
| ACT | Artemisinin-based Combination Therapy |
| ADF | Augmented Dickey-Fuller |
| AIC | Akaike Information Criterion |
| AIDS | Acquired Immunodeficiency Syndrome |
| *An*. | *Anopheles* |
| AOI | Antarctic Oscillation Index |
| AR | Autoregressive |
| ASO | August-September-October |
| BUH | Botswan Upper High |
| CFS-R | Climate Forecast System Reanalysis |
| COLA | Center for Ocean-Land-Atmosphere Studies |
| CSIR | Council for Scientific and Industrial Research |
| DDT | Dichloro-diphenyl-trichloroethane |
| DJF | December-January-February |
| DoH | Department of Health |
| ECWMF Forecasts | European Centre for Medium-Range Weather Forecasts |
| EMI | ENSO Modoki Index |
| ENSO | El Niño-Southern Oscillation |
| EOF | Empirical Orthogonal Function |
| GCMs | Global Circulation Models |
| GFS | Global Forecast System |
| GPCP | Global Precipitation Climatology Project |

| | |
|---|---|
| GrADS | Grid Analysis and Display System |
| HIV | Human immunodeficiency virus |
| hPa | HectoPascal |
| IOD | Indian Ocean Dipole |
| IOSD | Indian ocean subtropical dipole |
| IPCC | Intergovernmental Panel on Climate Change |
| IRI | International Research Institute |
| IRS | Indoor Residual Spraying |
| ITCZ | Inter-Tropical Convergence Zone |
| JAMSTEC | Japan Agency for Marine-Earth Science and Technology |
| JFM | January-February-March |
| JJA | June-July-August |
| KNMI | Royal Netherland Meteorological Institute |
| MA | Moving Average |
| MARA | Mapping Malaria Risk in Africa |
| MH | Mascarene High |
| NCBI | National Center for Biotechnology Information |
| NCEP | National Centers for Environmental Prediction |
| NCID | National Institute for Communicable Diseases |
| NDJ | November-December-January |
| NOAA | National Oceanic and Atmospheric Administration |
| OLR | Outgoing Longwave Radiation |
| OND | October-November-December |
| *P.* | *Plasmodium* |
| PACF | Partion Autocorrelation Function |
| PC | Principal Component |

| | |
|---|---|
| PR | Parasite Ratio |
| QBO | Quasi Biennal Oscillation |
| RH | Relative Humidity |
| SARIMA | Seasonal Auto-Regressive Moving Average |
| SIT | Sterile Insect Technique |
| SLP | Sea Level Pressure |
| SOI | Southern Oscillation Index |
| SP | Sulphadoxine-Pyrimethamine |
| SST | Sea Surface Temperature |
| SWIO | Southwest Indian Ocean |
| Tmax | Maximum Temperature |
| Tmin | Minimum Temperature |
| VBDs | Vector-Borne Diseases |
| WHO | World Health Organisation |

# CHAPTER 1

# INTRODUCTION AND BACKGROUND

## 1.1 General introduction

Southern Africa is predominantly semi-arid with substantial rainfall variability at intra-seasonal, interannual and longer scales, characterised by frequent droughts and floods (Lindesay and Jury 1991; Matarira and Jury 1992; Levey and Jury 1996; Mason and Jury 1997; Landman and Mason 1999; Reason and Mulenga 1999; Cook *et al.* 2004; Davis 2011). Its location in the subtropics ensures that it is affected by circulation systems prevailing in both the tropics to the north and temperate latitudes to the south (Tyson and Preston-Whyte 2000; Dyson and Van Heerden 2002). The region is vulnerable to climate change due to high levels of poverty especially among rural communities and dependence on rain-fed agriculture (IPCC 2007; Solomon *et al.* 2007).

Some of the inter-annual variability of rainfall over this region is determined by the El Niño-Southern Oscillation (ENSO) phenomenon. During warm (cool) ENSO events, dry (wet) conditions generally occur over much of the summer rainfall region of southern Africa (Mulenga 1999; Trenberth 2013). The influence of El Niño is strongest in the south-eastern region of southern Africa in late austral summer (Lindesay and Vogel 1990). The adjacent ocean also influence the rainfall variability through amongst others, the Indian Ocean Dipole, sub-tropical Indian Ocean Dipole and Benguela Niño (Zheng and Eltahir 1998; Behera and Yamagata 2001; Douville *et al*. 2001; Rouault *et al.* 2003).

The Inter-Tropical Convergence Zone (ITCZ) and Botswana Upper High (BUH) are also responsible for rainfall variability in southern Africa. During austral summer the ITCZ migrates southwards bringing rainfall over the tropical and sub-tropical regions due to high convective activities. The influence of ITCZ is sometimes suppressed by the BUH (Figure 1.1) which occurs from time to time and contributes to the aridity of Botswana and Namibia (Davis 2011). Landfalling tropical systems from the South West Indian Ocean (SWIO) are common in southern Africa during La Niña, sometimes resulting in devastating floods and record rainfall totals (Mavume *et al.* 2009; Malherbe *et al.* 2012).

Floods are a common occurrence in the region, together with droughts which are the most frequently occurring natural hazards (Lukamba, 2010). Floods account for the second largest damage to assets second to storms, of all weather-related disasters. Floods can also be associated with water-borne diseases. Flooding washes away mosquito breeding sites, however standing water that results can create new breeding sites, resulting in an increased vector population and potential for malaria transmission within a few weeks, depending on the local vector species and preferred habitat (Hunter 2003; Watson *et al*. 2007).

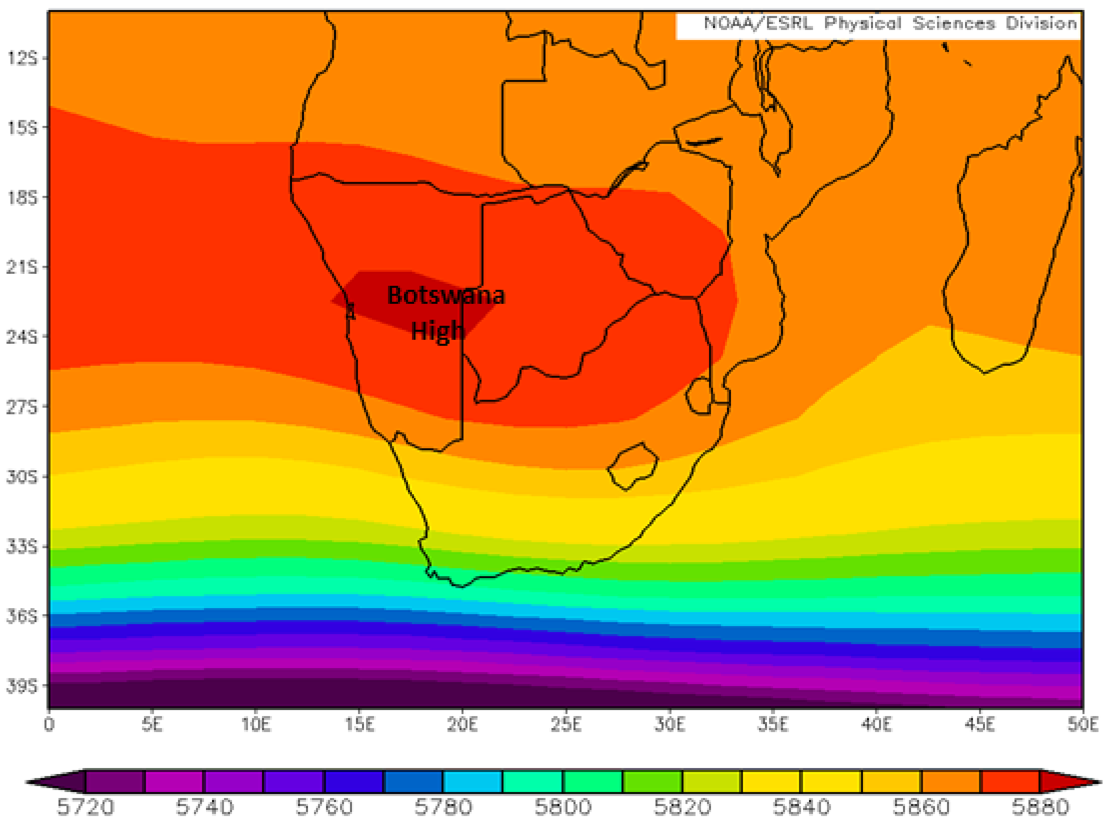



Figure 1.1 Geopotential height at 500 hPa showing the Botswana Upper High

Malaria is considered as the most detrimental mosquito-borne disease in tropical and subtropical regions of the world (Ohta and Kaga 2012). It is the fifth leading cause of death from infectious diseases in developing countries, after respiratory infections, Human Immunodeficiency Virus and Acquired Immune Deficiency Syndrome (HIV/AIDS), diarrheal diseases and tuberculosis (NCBI 2016). Most incidents of malaria transmission are reported in sub-Saharan Africa, especially amongst pregnant women and children under the age of five years (Martens and Thomas 2005; WHO 2009; Amek *et al*. 2012). Children under five are particularly susceptible to infection, illness and death; more than two thirds (70%) of all malaria deaths occur in this age group. The number of malaria deaths of children under the age of five years has declined from 440 000 in 2010 to 285 000 in 2016. However, malaria remains a major killer of children under five years old, taking the life of a child every two minutes (WHO 2016). Malaria is an acute febrile illness with an incubation period of seven days or longer. A fever illness that develops less than seven days after the first possible exposure is not malaria. In semi-arid and highland regions, the risk of mortality and morbidity associated with malaria vary spatially and temporally (WHO/UNICEF 2003).

In South Africa, malaria is endemic in north-east reaches of Limpopo, Mpumalanga and Kwa-Zulu Natal with the highest risk of transmission between September and May. *Anopheles funestus* and *Anopheles arabiensis* are the primary vectors of malaria in this region (Morris *et al*. 2013). All the dangerous malaria vector species bite at night. *Anopheles* mosquitoes breed in water and each species has its own breeding preference, some species (*i.e*. *Anopheles arabiensis)* prefer shallow collections of fresh water and other (i.e. *Anopheles funestus)* prefers permanent water bodies (Kikankie 2009).

Meteorological variables play an important role in the geographic distribution and seasonal occurrence of these vector species (Hopp and Foley 2001). This is because meteorological factors influence mosquito ecology, survival, behaviour, development and transmission rate, which makes malaria climate sensitivity (Reiter 2001; Martens and Thomas 2005). The epidemiology and life cycle of malaria, the *Anopheles* mosquito and human behaviour are of utmost importance in linking climate and malaria (Appawu 2004; Kearney *et al*. 2009). The most dangerous malaria vectors feeds on humans. Species which feed on animals are less harmful than those which feed on humans (WHO 1997).

## 1.2 Problem statement

Sustained malaria control has been successful in reducing transmission over many decades in most parts of South Africa, except for the north-eastern border regions adjacent to Mozambique, Swaziland and Zimbabwe. Passive and active detection of slide-confirmed malaria cases give a comprehensive, long-term picture of the effect of changing control strategies, climatic factors and other variables that have influenced the incidence of malaria over time (Maharaj *et al.* 2005).

Large parts of Africa are prone to malaria epidemics, where malaria transmission is largely limited by climate. Effects of temperature and precipitation variations on vector borne diseases and agriculture have long been a focus of research. Recent studies have indicated that the temperature and rainfall patterns are changing under global warming which may have an effect on vector borne diseases (e.g. Wu *et al*. 2016). Early warning systems are essential to help the health sector to be better prepared for future outbreaks and to help with adaptation to climate change in general.

Good long term climate and malaria data are needed to develop and test such early warning systems. Epidemics warning provided in advance will help give health services enough time to prepare (Craig *et al.* 2004b). However, in south-east Africa, the role of meteorological variables in driving changes in malaria patterns, reflecting changes in mosquito vector dynamics, still remains elusive (Zhou *et al.* 2004; Pascual *et al.* 2006; Pascual *et al.* 2008).

## 1.3 Motivation

In South Africa, approximately 10% of the total population resides in malaria risk areas which are currently restricted to low altitude border regions (below 1,000 m above sea level) of Limpopo, Mpumalanga and KwaZulu-Natal, with limited transmission (DoH 2011; Maharaj *et al.* 2012). The dominant parasite is *P.* falciparum. *P.* falciparum is transmitted by *Anopheles arabiensis* mosquito vector. Malaria transmission is meso-endemic, occurring between September and May with the peak in March (Maharaj 2002).

Malaria transmission is a complex interaction of many factors, including not only the behavior and density of parasites and vectors (MacDonald 1957), but also land use change, drug resistance public health control (Alonso *et al.* 1991; Snow *et al.* 1994; Binka *et al*. 1996). The influence of climate change on malaria transmission is still a subject of considerable debate. Temperature has a great influence on the feeding intervals, population density and longevity of Anopheles mosquitoes and the reproductive potential of the plasmodium parasite (Lindsay and Birley 1996) Most suitable climate conditions may facilitate malaria transmission , however, the evidence for increased incidence has not been clearly linked to climate (Shanks et *al*. 2000)

Weather and climate play an important role in the seasonal abundance and spatial distribution of malaria vector species (Breman *et al*. 2005; Thomson *et al.* 2006). Changes in weather and climate is likely to influence greatly on the development, longevity and reproduction of mosquito species (Martens *et al*. 1999). Each vector species has different preferred habitats, distribution, vectorial capacities biting and resting behaviors (Githeko and Shiff 2005), therefore meteorological influences on the transmission of malaria may vary largely across regions.

## 1.4 Aim and Objectives

The aim of this study is to determine the influence of meteorological parameters on malaria transmission in Limpopo, South Africa for the period 1998-2014.

The specific objectives of the research project are:

a) To analyse the mean climate of malaria-prone regions of Limpopo.
b) To investigate spatial and temporal characteristics of malaria epidemics.
c) To investigate the influence of the oceans on malaria transmission.
d) To investigate the influence of the pre-cursor meteorological conditions on the occurrence of malaria epidemics.
e) To investigate the predictability of malaria epidemics at seasonal time scale.

## 1.5 Research Questions

a) How do ocean-atmosphere interaction influence malaria transmission?
b) How is the transmission of malaria disease related to non-climatic factors in Limpopo?

## 1.6 Description of the study area

This study focuses on Limpopo Province which is the most northerly province of South Africa (approximately 22-25ºS, 27-32ºE). In this study, Limpopo refers to the Limpopo Province of South Africa not the whole Limpopo basin. The malaria prone regions of Limpopo are shown in figure 1.2. Limpopo Province covers a surface area of approximately 125 754km$^2$. This province was named after the Limpopo River that flows along its northern border and it comprises of several provincial and private game reserves. The largest section of the Kruger National Park is situated along the eastern boundary of this province with Mozambique (Pocket Guide to South Africa 2012).

This region is prone to significant drought and flood events and by significant intra-seasonal rainfall variability during the core rainy season (Dec-Feb) (Levey and Jury 1996; Cook *et al.* 2004). The main sources of rainfall in this region are cloud bands and associated thunderstorms; easterly waves and lows (Van Heerden and Taljaard 1998; Tyson and Preston-Whyte 2000). It is an important agricultural region with a relatively large rural subsistence population (Mulenga *et al*. 2003). Warm summer days are usually interrupted by short-lived thunderstorms (Limpopo Department of Agriculture 2008). During summer (October-March), the mean temperature is about 27ºC in summer. The rainfall totals over the region ranges from 400-600 (Anon 2007; Tshiala *et al.* 2011).

The geographic location of this region is unique as it incorporates climate characteristics of both tropics and subtropics. It is a gateway to the rest of Africa as it shares international borders with three countries: Botswana, Zimbabwe and Mozambique. It lies on the great curve of the Limpopo River characterized by bushveld, patchwork of farmland, gallery forests and majestic mountains (Thompson 2012).

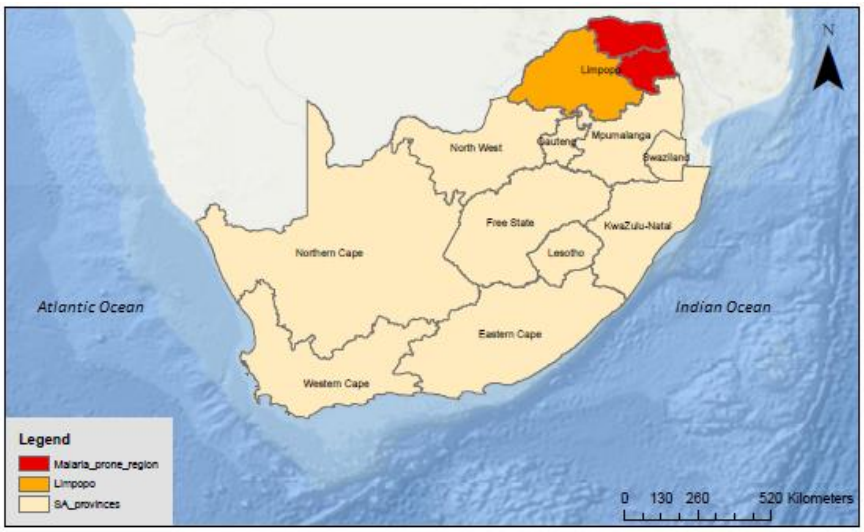
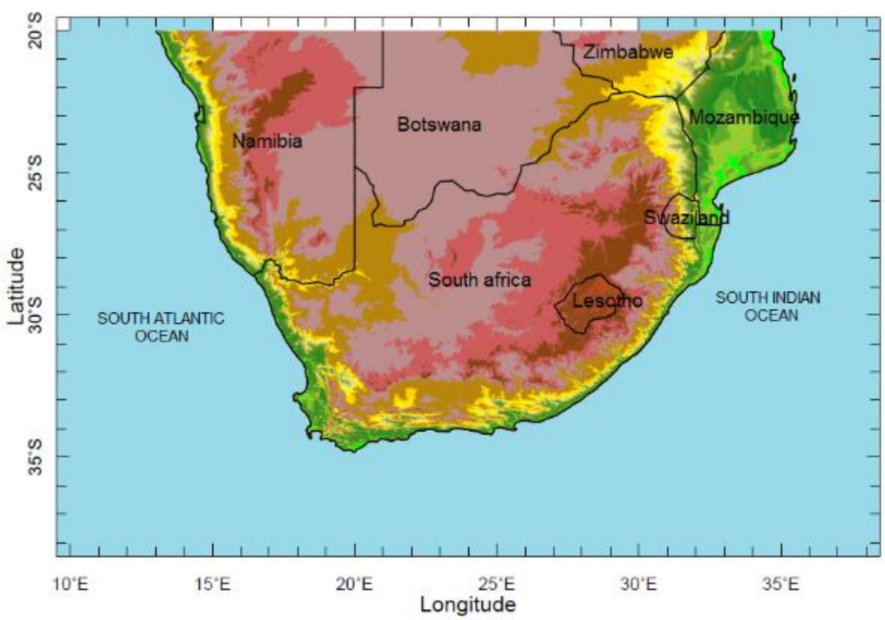



Figure 1.2 South Africa with focus on Limpopo



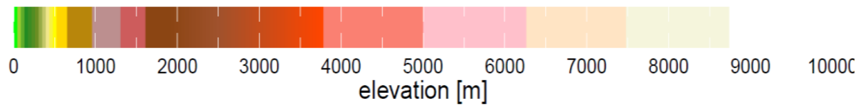



Figure 1.3 Elevation of South Africa, showing most of this region lies well above 1000 m with an exception of the Lowveld and coastal areas.

This province consists of several mountain ranges including the Drakensberg escarpment which starts at the vicinity of Tzaneen and includes the Wolkburg. This escarpment forms the eastern border of the Bushvelds. The Strydpoort Mountains form a western spur of the Drakensberg stretching towards Mokopane. The Lebombo Mountains border the Kruger National Park and Mozambique. The most northern mountain is the Soutpansberg which is situated north of Louis Trichardt. Most of the Limpopo province lies well above 1000 m with an exception of the eastern low veld which is where malaria is endemic (Figure 1.3).

## 1.7 Definition of terms

1. Benguela Niño- a weakening in the trade winds in the equatorial western Atlantic during the early monsoon, generation of down-welling equatorial Kelvin waves that transport a warming signal toward equatorial Africa, and then a coastally trapped signal propagating toward Angola (Florenchie *et al*. 2003; Florenchie *et al*. 2004).
2. Botswana Upper High- it is upper level anticyclonic circulation in late austral summer over Botswana which contributes to aridity of this region (Unganai and Mason 2002; Unganai and Bandason 2005).
3. ENSO- refers to the exceptionally warm sea temperatures in the tropical Pacific, linked to major changes in the atmosphere through the phenomenon known as the Southern Oscillation (SO) (Trenberth 2008).
4. Malaria- is a common and life threatening disease in many tropical and subtropical regions of the world. It is caused by protozoan parasite *Plasmodium.* It is an acute febrile illness with an incubation period of seven days or longer (Prasad 2010).
5. Malaria epidemics - an acute increase in the severity of malaria out of proportion to the normal to which the community is subject. Malaria epidemics normally occur in the regions of seasonal and unstable malaria, where very little changes in any of the transmission factors may completely influence the equilibrium, and where the restraining influence of immunity may be negligible or absent, and they therefore show a very marked geographic distribution (Hay *et al.* 2002; Maharaj *et al.* 2012).

## 1.8 Dissertation structure

The study consists of 7 chapters.

Chapter 1 introduced the general background of climate and malaria in southern Africa.The chapter outlined the aspects to be dealt with in the dissertation through sections on background and motivation, research aims and objectives. The selection of study area was justified.

Chapter 2 provides an in-depth review of literature of previous studies and is divided into sub-sections. The first section focuses on malaria transmission, the life cycle of malaria parasite and vector. The second subsection outline the vector control strategies and intervention programmes to combat malaria. The state of *plasmodium falciparum* resistance to drugs in South Africa is outlined in the third subsection. The climate influence on malaria transmission is outlined in subsection 5, while the remote influences such as ENSO and IOSD on malaria are provided on fifth subsection.

In Chapter 3, the datasets employed in this work are described in detail, alongside the methods used to analyze them. In Chapter 4, the mean climate of malaria prone regions of Limpopo is presented. Seasonal cycles, trends and variability of meteorological variability are analysed here.

The spatial and temporal characteristics of malaria epidemics, the influence of meteorological variables and ocean-atmosphere interaction on the occurrence of the epidemics of malaria in Limpopo is presented in Chapter 5.

Chapter 6 presents the precursor meteorological condition prior the occurrence of the epidemics, predictability of these conditions and thus the predictability of malaria epidemics. Synthesis of key findings of the study and recommendations for future work are presented in Chapter 7.

## 1.9 Summary

This chapter provided a brief introduction and background of the study, the statement of the problem, motivation of the study, aim and objectives of the study, description of the study area and the organisation/structure of the dissertation. These are the most important aspects of the research. To provide more support and understanding of the study, the literature should be reviewed. The next chapter provides the literature review.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

Malaria has been a threat to human lives since ancient times. It was first documented by the early Egyptians on papyrus, and later Hippocrates the Greek famous physician described it in detail (Cox 2002). The name is derived from the Italian, "mal aria" meaning bad air. Malaria devastated invaders of the Roman Empire, it lurked in marshes and swamps. Humans blamed the sickness on rot and decay that wafted out on the foul air in these areas (Carter 2002). The causative agent of malaria was discovered by the individual work of the French scientist Alphonse Laveran in the late 1800. Laveran discovered that malaria is caused by *Anopheles* mosquito (Harrison 1978).

The malaria eradication campaign held by the World Health Organization (WHO) in mid-19$^{th}$ century was successful in eradicating malaria in developed countries and reduced disease prevalence in most parts of the world (WHO 1995). This campaign however did not benefit the sub Saharan Africa but at least the widespread availability of affordable antimalarial drugs helped to sustain malaria mortality and morbidity (Holt *et al.* 2002).

The aim of this chapter is to present a comprehensive review of the literature, with a focus on the epidemiology of malaria, the life cycle of malaria parasite, the state of malaria control in different regions, resistance of malaria parasites to drug and the influence of weather and climate on malaria transmission. The literature review was conducted to identify gaps in the literature that might need further research.

## 2.2 Malaria

The epidemiology of malaria is very complex and multi-focal. It is dependent on many factors including the ecology of the prevalent species, biology of plasmodium, climate factors, resistance and immunity of the host (Nabi and Qader 2009). Vector-borne diseases (VBD) have been linked with climate variability (Houghton *et al.* 2001). Malaria is a mosquito-borne tropical infectious disease caused by parasitic protozoans of the *genus plasmodium* (*malariae, falciparum, ovale and vivax*). It lives part of its life in humans and part in mosquitoes (Kirk 2001). It is transmitted by female mosquito vectors of *Anopheles* species; the *plasmodium* multiplies in red blood cells destroying them in the process. Malaria is endemic in warmer climate regions of the world *i.e.* Asia, Africa, central and South America and some Caribbean islands (Feachem *et al*. 2010; Caminade *et al.* 2014) (Figure. 2.1).

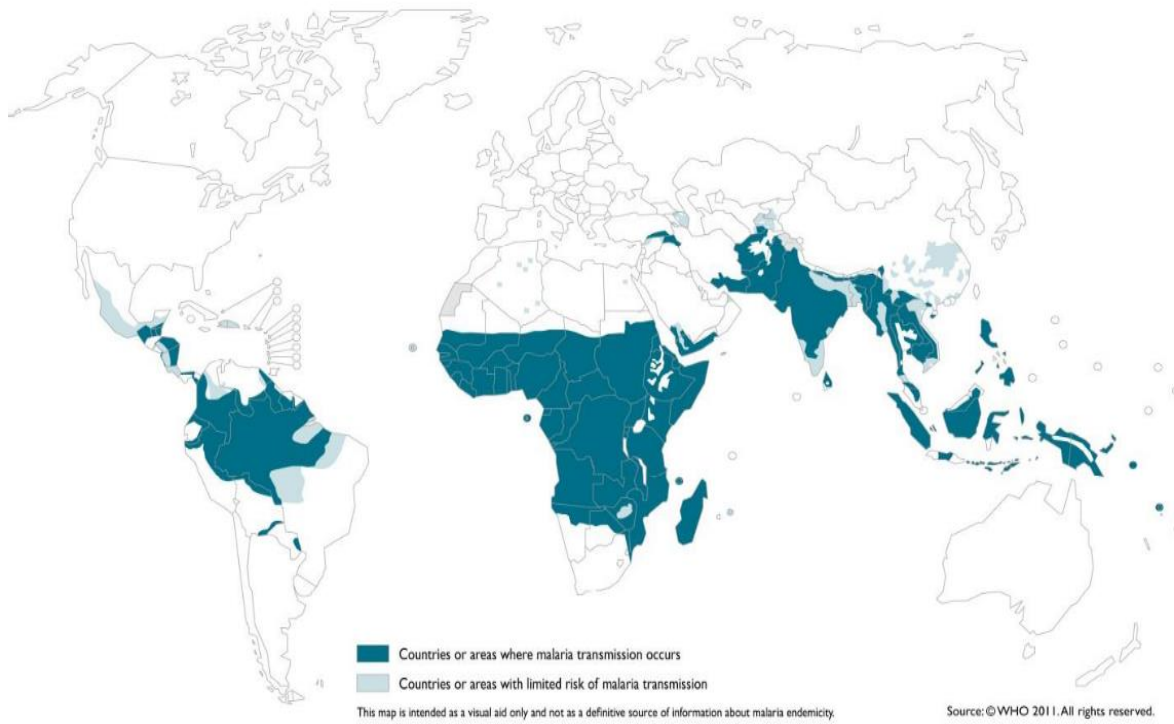



Figure 2.1. World malaria distribution (Source: WHO 2011)

Over one hundred *Plasmodium* species exist, each shows different features under the microscope and produces different symptoms. Out of more than one hundred species of *plasmodium* only four commonly infect human (Carter 2002). The malaria infection can produce several life-threatening complications resulting in the infected person being susceptible to other diseases. However, it is almost always curable when identified in time. An individual's likelihood to be affected by malaria is strongly governed by the type and degree of antimalarial immunity that they have attained (Machado 2013).

Two or more species can live in the same area and infect a single person at the same time. *P. falciparum* is responsible for most malaria deaths, especially in Africa. *P. falciparum* malaria is the most life threatening. When it remains untreated, cachexia takes place and results in the enlargement of the spleen. This can cause important organs like the lungs, kidneys and liver to stop functioning (Solomon *et al*. 2014). In the case of cerebral malaria, the brain is affected and may result in severe anaemia. These conditions are associated with most acute malaria mortality in Sub-Saharan Africa. *P. vivax*, is the most geographically widespread of the species in Africa but less life threatening than *P. falciparum*. P. *malariae* can persist in the human blood for decades without any symptoms. *P. ovale* is rare, generally found in West Africa and can cause relapses (Carter and Mendis 2002).

### 2.2.1 Malaria transmission

Environmental changes therefore affect the transmission of the parasites that causes malaria (Craig *et al*. 1999; Guerra *et al.* 2006). Mosquitoes are the first insects to be associated disease transmission, this includes malaria (Gillies 1967). Malaria is transmitted by infectious female *Anopheles* mosquitoes through blood feeding (Capanna 2006; Eckhoff 2011).

In rare cases one can contract malaria through contact with contaminated blood or mother to child transmission during pregnancy and this known as congenital malaria. Since the malaria parasite is found in red blood cells, malaria can also be transmitted through blood transfusion, organ transplant, or the shared use of intravenous needles or syringes contaminated with blood (Martin-Davila *et al.* 2008). Out of 100 *Anopheles* genus species, approximately 50-60 are capable of transmitting malaria but only 30 are considered important vectors. The most important vectors are *An. stephensi* and *An. Gambiae* (Clements 2000; WHO and CDC 2005).

a) Acquisition and loss of immunity

There are many biological processes that influence the transmission of the malaria parasite and the malaria prevalence. Humans in malaria endemic areas go through different state of immunity. Mother to child transfer of antibodies at birth partially protect infants from infection. The immunity is lost few months after birth (Wernsdorfer and McGregor 1988; Gupta *et al.* 1999). An immune status that prevents disease outbreak is usually acquired at age 12 years (Kun *et al*. 2002).

Malaria immunity is usually found in malaria endemic areas with stable transmission rate, where humans are exposed to repeated exposure to infections of malaria (Sutherst 2004; Uneke 2007; Doolan *et al.* 2009). Epidemic prone regions lack immunity and are prone to acute malaria outbreak (Kiszewski and Teklehaimanot 2004). During dry season and drought period when there is a lack of repeated exposure to different parasite clones, immunity malaria decreases (Connor *et al*. 1998). The effective protective immunity against malaria increases during the rainy season (Boudin *et al*. 1991; Boudin *et al.* 2005).

### 2.2.2 Life cycle of malaria vector

The life cycle of *Anopheles* mosquito and its interaction with malaria transmission need different phases and characteristics to be probable. All mosquitoes require standing water to complete their cycle. The *Anopheles* mosquito lays eggs preferably stagnant surface of water at night (Rios and Connelly 2009). In tropical regions, the eggs hatch after two to three days (Coluzzi 1988). Larvae go through four growth stages below the surface of water (rests parallel to water surface) before becoming pupa. This process happens for five minutes after seven to fourteen days. The pupa is in a shape of a comma (Figure 2.2) and is the least active stage (transition stage) of the *Anopheles* life cycle. Within 24-48 hours the pupa will metamorphose into an adult, this happens late in the evening (Muir 1988). In warmer months, it may only take a week for mosquitoes to develop from eggs (Rios and Connelly 2009).

Male mosquitoes emerge prior to female mosquitoes and will mate usually during flight. Female *Anopheles* mosquitoes generally need to feed on blood from human and mammals to provide proteins to assist with the development of her eggs (Koutsos *et al*. 2007). Male mosquitoes do not bite, but only feed on nectar and damaged fruits. An adult mosquito generally survives for between one week and one month (Johnsen and Renchie 2007). *Anopheles* mosquitoes rest with their abdomens sticking up in the air rather (both males and females) than parallel to the surface (Figure 2.2).

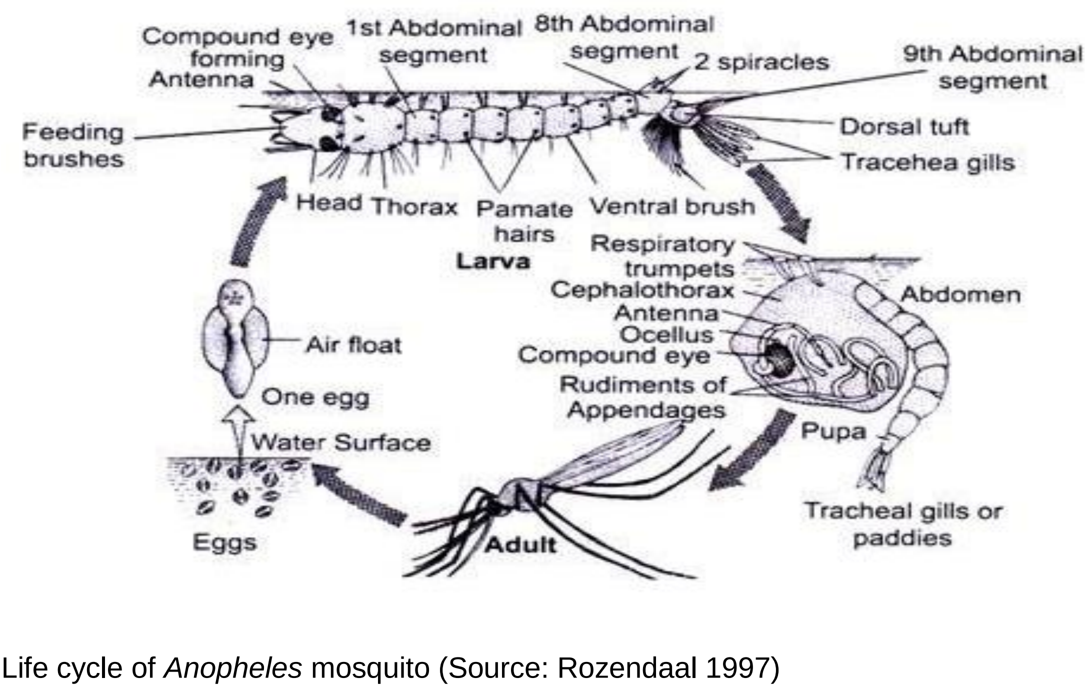



Figure 2.2. Life cycle of *Anopheles* mosquito (Source: Rozendaal 1997)

### 2.2.3 Life cycle of malaria parasites

All types of malaria parasites have a similar but complex life cycle. The cycle involves *Anopheles* mosquito and a human host as shown in figure 2.3. They have a sexual cycle, in which spores are formed, and an asexual cycle (Richard 2007; Solomon *et al.* 2014). A malaria infected female *Anopheles* mosquito injects sporozoites into the human during blood meal. The sporozoites infects the liver cells and develops to schizonts. The schizonts rupture and release sporozoites (for *P. falciparum*) or can persist in the liver causes relapses as hypnozoites (in *P. vivax* and *P. ovale)* this is known as dormant stage (Soulard *et al.* 2015). After exoerythroctic schizogony which is the initial replication in the liver, repeated cycles of parasitic development occur with precise periodicity, and at the end of each cycle, hundreds of daughter parasites are released and invade more red cells (Fujioka and Akaiwa 2002).

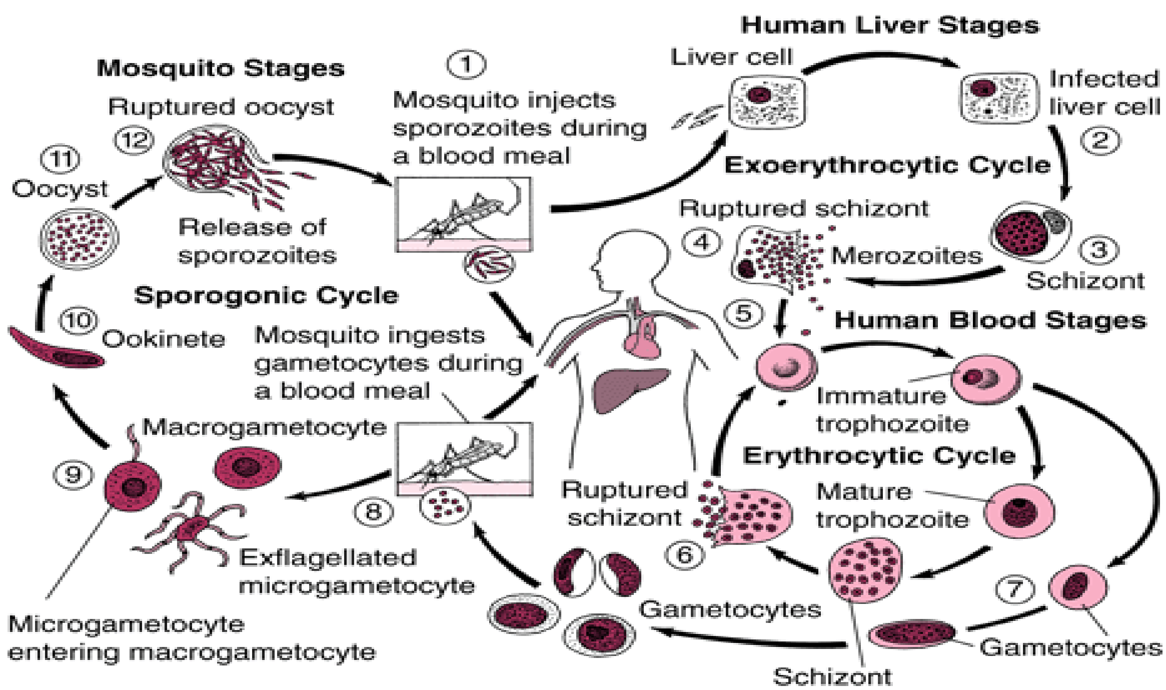



Figure 2.3. Schematic drawing of the life cycle of malaria parasite (Source: Fujioka and Akaiwa 2002).

The ring stage merozoites are released when schizonts rupture. Some parasites differentiate into gametocytes. In the mosquito stage (seven to ten days), the gametocytes are ingested by an *Anopheles* mosquito during a blood meal. A clinical manifestation of the disease is caused by blood stage parasites. The parasites multiply inside the mosquito abdomen, this stage is known as the sporogonic cycle. At this stage exflagellated microgametocyte penetrate the macrogametocyte to form zygotes. The zygotes develop into ookinetes which invade the midgut wall of the mosquito where they develop into oocysts. When the oocysts rupture, sporozoites are released and make their way to the mosquito's salivary glands (Figure. 2.3). A new malaria parasite life cycle begins during a blood meal (Weekley and Smith 2013).

## 2.3 Historical and current evidence of malaria in South Africa

The first devastating effects of malaria in South Africa to be documented were that of 1937/38 when 20 of Louis Trichardt trek got infected and died, including Louis Trichardt and his wife (Fuller 1932). During this time diagnosis for malaria was still purely clinical with high mortality rates (Gear 1989). There was than an increase in the rate of mortality from malaria and other fevers. From then on malaria was ranked amongst most dangerous disease in the Limpopo, Mpumalanga and Kwa-Zulu Natal (Then known as Transvaal and Natal) (Laidler and Gelfand 1971; Malan 1988).

The regions in South Africa which were known to be at risk of malaria in the late 1930s were the eastern Transvaal and Natal extending as far as Port St. Johns in Transkei, Orange River in North-West and Pretoria (Le Sueur *et al*. 1993) (Figure 2.4). Following the discovery of suitable vectors, the malaria risk map was then revised in year 2000, and malaria was found to be confined largely to the north-east of South Africa bounded by Richards Bay in the south and Louis Trichardt and Swartwater (Figure 2.5) (Morris *et al*. 2013).

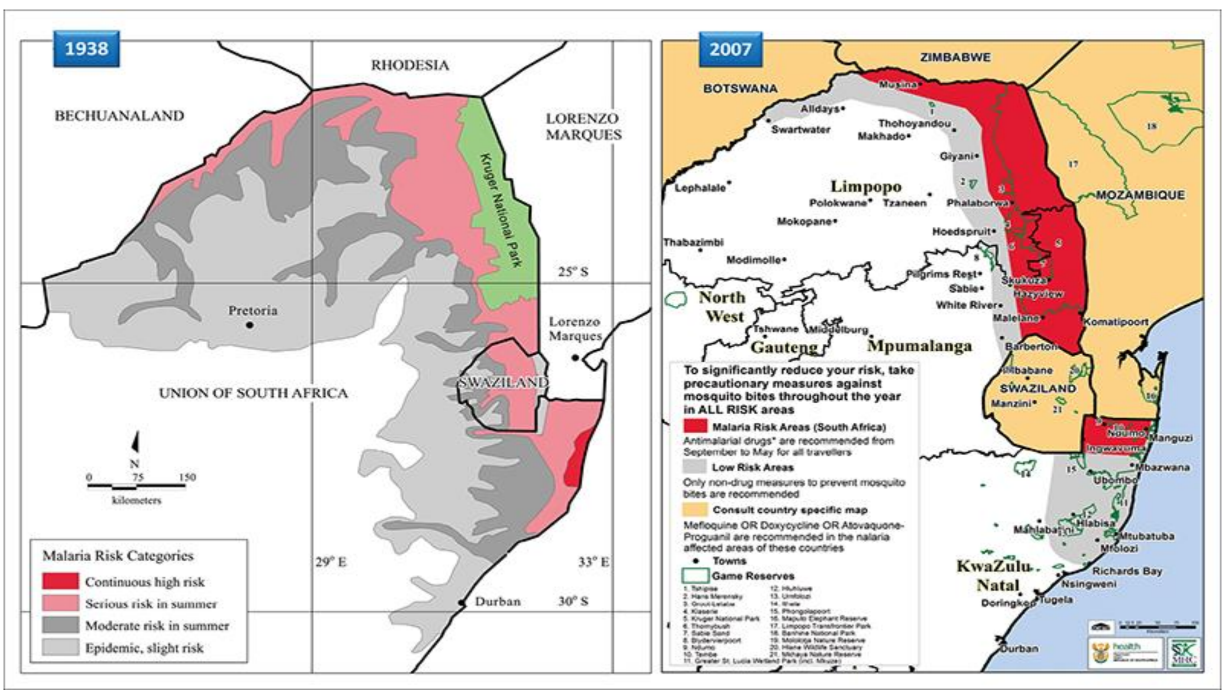



Figure 2.4. Malaria risk map for 1938 (left) and malaria risk map 2007 of South Africa following the implementation of regional cross-border control (right). (Source: Morris *et al*. 2013).

Malaria transmission in South Africa occurs in summer between September and May. Malaria is endemic to Mpumalanga and Limpopo low velds bordering Mozambique and Swaziland to the east and Zimbabwe to the north, and also UMkhanyakude district in Kwa-Zulu Natal (Figure 2.5). Negligible number of malaria cases are reported in areas adjacent Orange River and Molopo River in the Northern Cape and North-west respectively (DoH 2015).

Due to relevant malaria control interventions, the malaria risk map of 2007 was updated in 2013. The malaria low risk areas to the south which were extending as far as Richards Bay now ends in the northern reaches of Kwa-Zulu Natal in UMkhanyakude district. In Limpopo, malaria low risk areas extended from Swartwater to the west but they now end as far as All-days and Musina to the east. However, a fair number of cases reported are imported from neighboring country (e.g. Zimbabwe), which is in the proximity. A decrease in number of imported cases of malaria has resulted in a decrease in a total number of cases report in Limpopo (Morris *et al.* 2013).

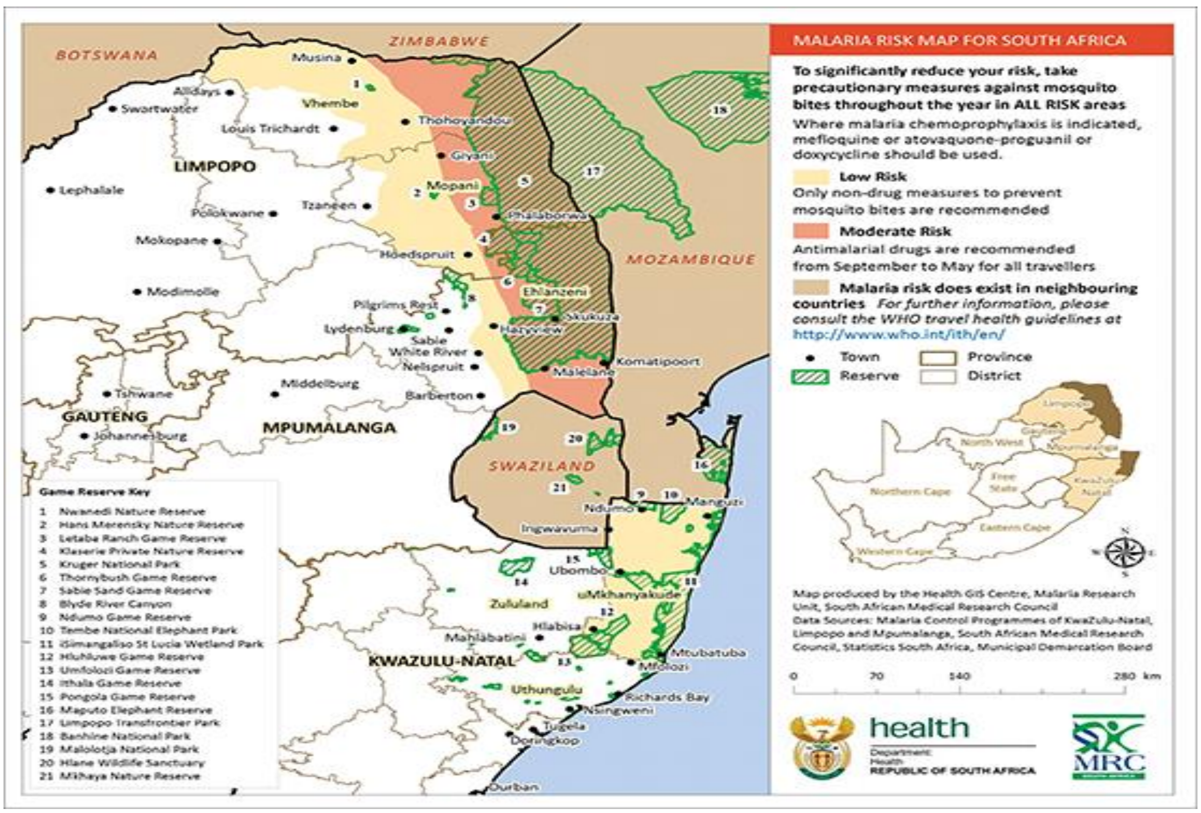



Figure 2.5. Malaria risk map of South Africa 2013 (Source: Morris *et al*. 2013).

In 1995 a new policy was introduced, resulting in moving away from the use of DDT to IRS. Many humans from Mozambique flocked to South Africa in search for malaria treatment. This was a wet period, which resulted in an increase in the number of malaria cases from 8750 in 1995 to 27 035 in 1996. However, the number of malaria cases doubled to 51444 in 1999 and 2000 saw a peak of malaria case (64 622) (Figure 2.6), the highest recorded since the replacement of DDT with IRS (Coetzee 2013).

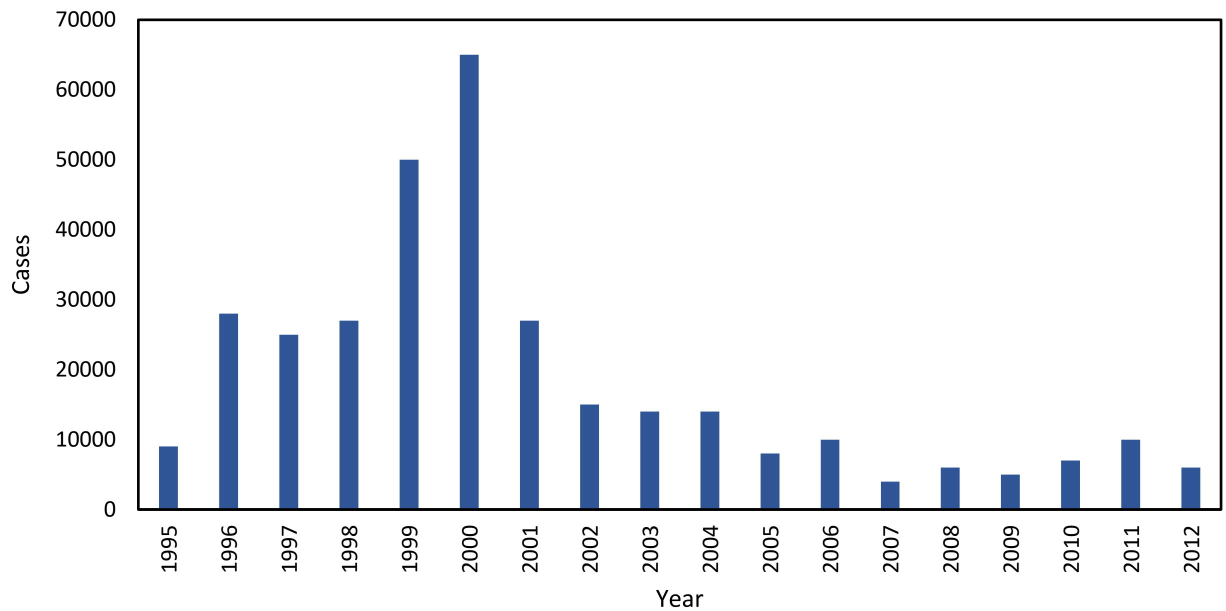



Figure 2.6. Malaria cases in South Africa from 1995-2012 (Source: Coetzee 2013).

## 2.4 Climate and Malaria

Through out much Sub-Saharan Africa malaria is endemic and the transmission occurs almost every year. The characteristics of transmission in the malaria endemic regions differ from place to place. There are some regions of stable malaria where the transmission occurs all year, where meteorological variables are sufficient for transmission and other regions where malaria transmission occurs in a form of epidemics from time to time or does not occur at all (Grover-Kopec *et al.* 2006). In the regions of epidemics of malaria, at least one meteorological variable is not sufficient for transmission. Strong interannual climate variability over this region results in strong seasonal outbreaks and epidemic of malaria (Carter and Mendis 2002).

Weather and climate play vital role in the transmission and distribution of malaria (Craig *et al*. 1999). Global temperature rise could result in an increase in malaria breeding grounds in Brazil, southern Africa, and the Horn of Africa by 2100 (Houghton *et al.* 2001; Ali *et al*. 2008). It is expected that malaria risk may fall in areas such as Namibia and the West African Sahel due to excessive heat, whilst areas which are at the high altitude may be at risk of malaria if the range in which the mosquito can live and breed increases (Shukla 2014).

Tropical regions have conditions which are conducive for mosquitoes and plasmodium parasite's development and survival. High humidity, availability of food, stagnant pools of water and a temperature of around 20°C-30°C are important for development of *Anopheles* mosquitoes (Khasnis 2005; Abiodun *et al.* 2016). However, mosquitoes tend to flourish in areas with high humidity and ample rainfall (Nabi and Qader 2009).

### 2.4.1 Temperature effects on malaria transmission

Temperature plays a vital role in the environmental suitability for malaria transmission as it modulates the endemicity (Gething *et al*. 2011). Temperature determines the mosquito survival rate and the sporogonic duration (Onori and Grab 1980). The number of mosquitoes surviving the incubation period determines the lower limit of temperature suitability. There are lower chances of transmission below 18°C because very few mosquitoes can survive the period required for sporogony at that temperature, and long larval duration limits the mosquito abundance (Molineaux 1988).

Table 2.1 Favorable temperature range for malaria parasite development and transmission (Source: Nath and Mwchahary 2012).

| Parasites | Class | Transmission window (°C) |
|---|---|---|
| P. Vivax | Class I | 15-20 |
| | Class II | 20-25 |
| | Class III | 25-30 |
| P. Falciparum | Class I | 20-25 |
| | Class II | 25-30 |
| | Class III | 30-35 |

Temperature rise shortens the malaria parasite life cycle thus increasing the malaria risk. Temperature above 40°C are associated with low malaria transmission as mosquitoes cannot withstand such temperatures (Martens 1997). On average malaria parasite carrying mosquito live for up to 21 days. At 30°C it takes about eight days for malaria inside the mosquito to mature. The time decreases with temperature increase, e.g. it takes about sixteen more days for malaria parasite to complete its cycle at 20°C, therefore there are greater chances of malaria vector surviving long and completing the transmission cycle at temperature greater than 20°C (Hay *et al.* 2000).

The mean temperature of sub-Saharan region of Africa is suitable for malaria transmission (Githeko 2008). For P. *falciparum,* temperatures below 20°C are considered not to be suitable for transmission of malaria. When the temperatures are greater than 32°C there is a high mosquito survival rate resulting in increased transmission of malaria (Craig 1999). There is a possibility in malaria transmission in a future warming climate (IPCC 2007).

### 2.4.2 Rainfall effects on malaria transmission

The relationship between mosquito abundance and rainfall is complex and best studied when temperature is not limiting. Studies to identify the relationship between *Anopheles* mosquitoes and rainfall have been carried out in many parts of the world but a direct and predictable relationship was not found. Temporal patterns of the rainfall influences persistence of standing water and thus rainfall patterns can affect mosquito population dynamics in water limited environments (Molineaux 1988; Charlwood 1995).

Surplus rainfall is known to destroy the mosquito breeding sites and interrupt the development of mosquito eggs and larvae. This does not necessarily eliminate the vector but temporarily reduces the vector. Therefore, high rainfall is still considered optimal for transmission because pools of water resulting from this high rainfall will be mosquito breeding sites. The required rainfall amounts for the transmission of malaria can be explained by extracting the climate patterns in regions where the status of malaria was known. The combination of rainfall and humidity influences the survival of mosquitoes (Ayanlade 2010).

In semi -arid areas malaria epidemics are associated anomalously high rainfall which results in increased mosquito population. In arid regions, such as Botswana variations in December-February rainfall explains more than two thirds of January-May malaria incidences observed over the years (Thomson *et al.* 2005). A major malaria epidemic that affected semi-arid regions of northeastern Kenya in January-May 1998 was reportedly associated with anomalous rainfall and floods during November-December 1997 (Brown *et al.* 1998). Therefore, monitoring rainfall alone provides fairly accurate malaria transmission risk forecast (Grover-Kopec *et al*. 2005; Thomson *et al*. 2006).

### 2.4.3 Humidity effect on malaria transmission

The amount of moisture in the atmosphere may be expressed in percentage. 100% humidity would mean that the air is completely saturated with moisture, whilst 0% humidity would mean the air is dry and. *Anopheles* mosquitoes are highly sensitive to humidity.  The sensitivity of *Anopheles* mosquitoes to humidity arise from their high surface area to volume ratio and they become active when the humidity rise to up to at least 60%. *Anopheles* mosquitoes prefer to bite at night because relative humidity is higher at that time. Mosquitoes needs to live at least 8-10 days to be able transmit malaria, depends on the vector species.  When the monthly average relative humidity is below 60%, the life cycle of *Anopheles* mosquitoes is reduced such that they are unable to survive long enough to transmit malaria. Relative humidity of <10% is fatal, usually within hours (Yamana and Eltahir 2013).

## 2.5 Ocean-atmosphere interactions and malaria

The oceans contain a vast amount of heat energy which is released into the atmosphere by boundary layer exchange processes operating at the surface. The heat flux to the atmosphere is by the sensible and latent heat exchange. Sensible and latent heat are transferred upward in the atmosphere by turbulent mixing of air, both these are dependent on sea surface temperature (SST). Air flowing over a relatively warm ocean will acquire additional heat energy and moisture from the underlying surface thus enhancing the capacity of that air to precipitate moisture. In this way ocean and atmospheric variability are linked (Tyson and Preston-Whyte 2000).

### 2.5.1 El Niño Southern Oscillation

The Walker circulation is responsive to SST variability between the east and west Pacific Ocean, these temperature changes results in atmospheric pressure oscillation between Indian and Pacific Ocean (Misra 2003). This phenomenon is known as the Southern Oscillation and it is observed by pressure difference between Tahiti and Darwin. When the SSTs are anomalously high (low) over eastern Pacific (Indonesian) region and pressure falls (rise) (Trenberth 2013). The Walker circulation than develops an ascending limb over eastern Pacific and descending limb over Indonesia. The circulation intensifies and near surface westerlies and upper easterlies completes the cell. Similar cells develop over Indian and Atlantic Oceans with descending limbs over South America and Southern Africa. This is the conditions prevailing during El Niño and is referred to as El Niño southern Oscillation (D'Abreton 1993).

This atmospheric perturbation is believed to be responsible for interannual climate variability in east and southern Africa. El Nino events tend to bring wet (dry) conditions in east Africa (southern Africa), while La Niña events is associated with dry (wet) conditions in east Africa (southern Africa) (Mwafulirwa 1999; Wang *et al.* 2014). The 1997-1998 El Niño event resulted in extreme wet conditions over east Africa while southern Africa experienced dry conditions, the most recent is 2015/16 El Nino event. The 1999-2000 La Niña was associated with devastating floods in Mozambique (Bellprat *et al.* 2015) (Figure 2.7).

La Niña conditions in the Pacific Ocean and positive SST anomalies over the Mozambique Channel favour the formation of tropical lows (Malherbe *et al.* 2012). During La Niña, the ascending limb of the walker cell is centered over central southern Africa resulting in widespread rainfall over southern Africa. Tropical lows form over central to western southern Africa and easterly wave comes into conjunction with tropical lows. Cloud band which are associated with major energy and momentum flux form over southern Africa (Tyson and Preston-Whyte 2000) (Figure 2.8).

During El Niño, the descending limb of the Walker cell falls over central southern Africa, forming the region of high pressure with reduced meridional flux of energy. Tropical easterly lows and waves form over east Africa or western Indian Ocean, and the convergence zone of the cloud bands which bring rainfall during summer is displaced eastwards to lie over the Indian Ocean east of Madagascar (Tyson and Preston-Whyte 2000) (Figure 2.9).

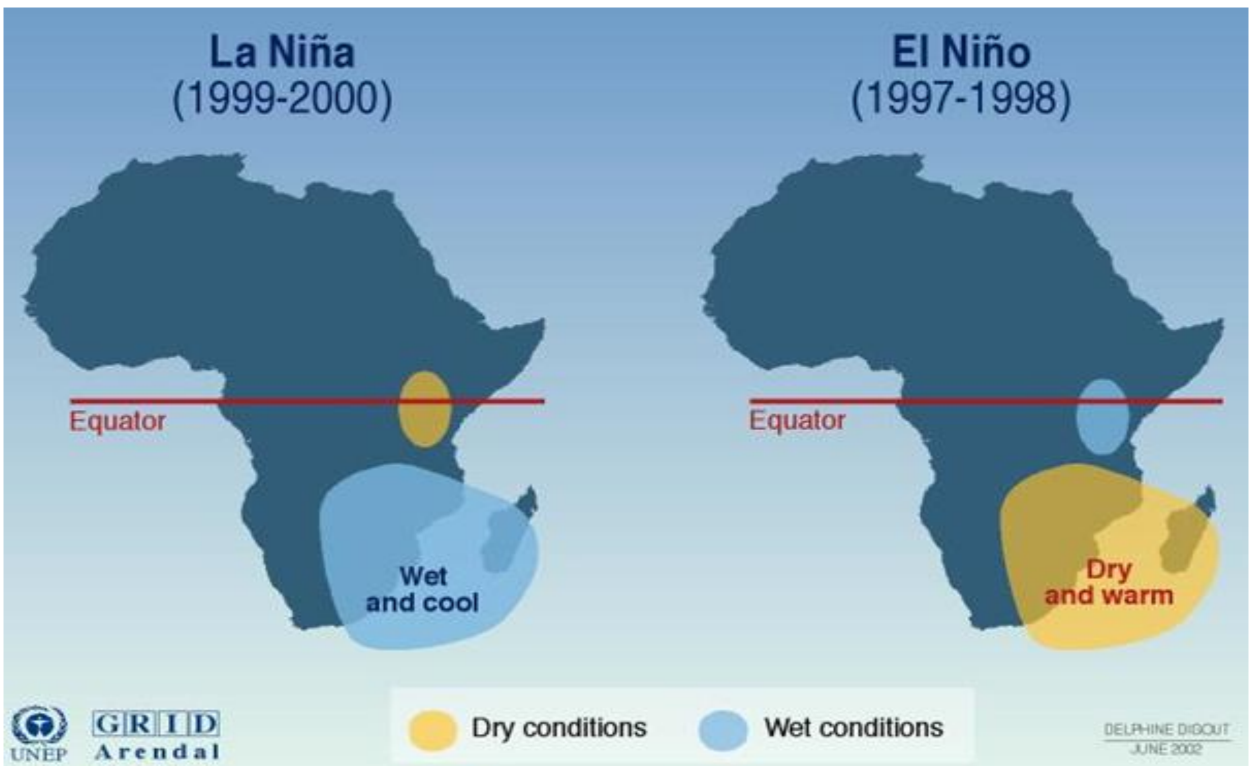



Figure 2.7. ENSO influence on east and southern Africa (Source: Digout 2005)

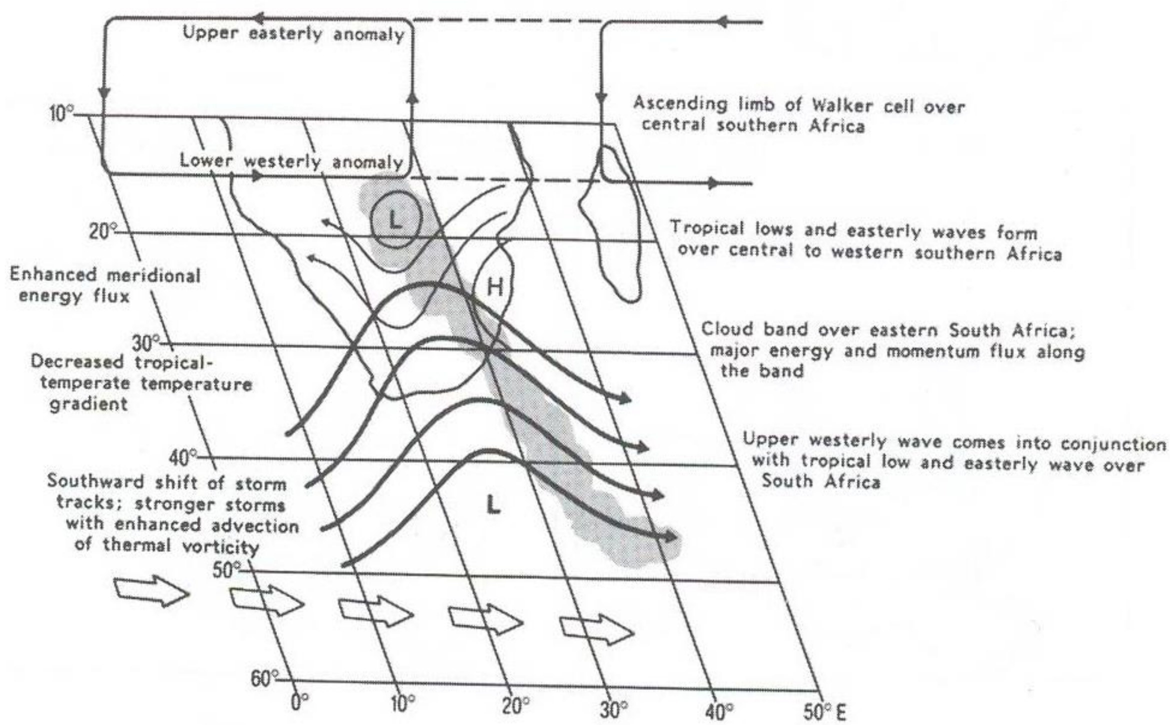



Figure 2.8. Schematic representation of anomalous Walker Circulation over southern Africa, showing La Niña conditions (Source: Tyson and Preston-Whyte 2000).

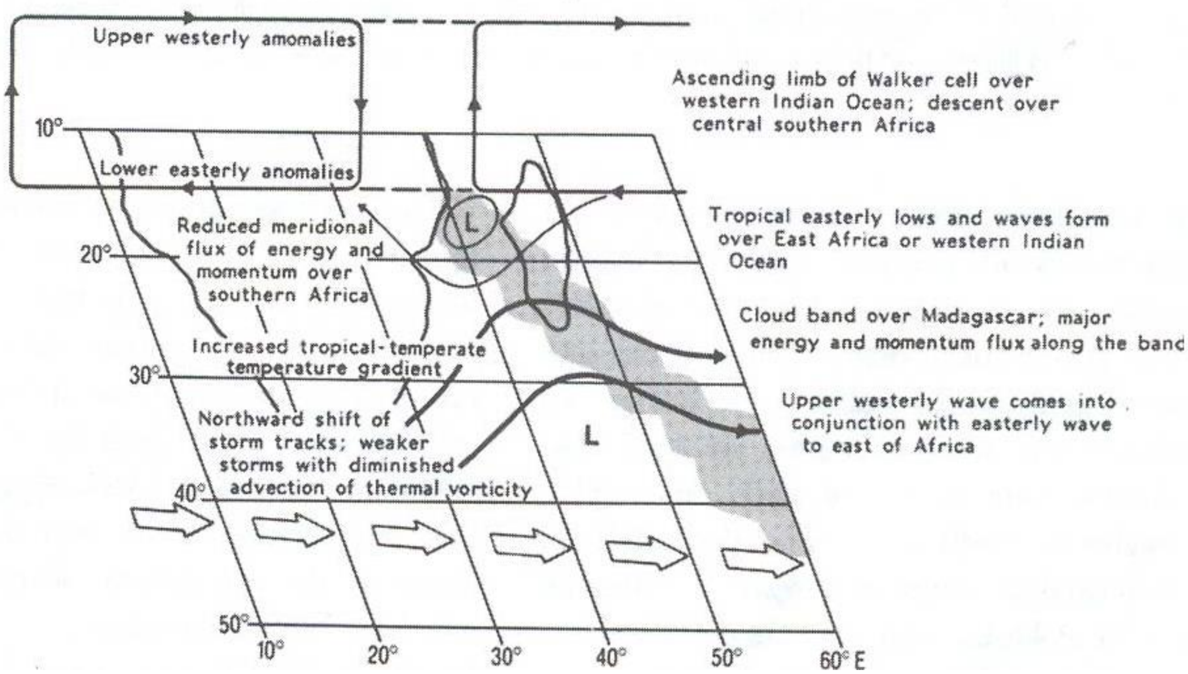



Figure 2.9. Schematic representation of anomalous Walker Circulation over southern Africa, showing El Niño conditions (Source: Tyson and Preston-Whyte 2000).

Several disease outbreaks such as malaria, dengue fever and cholera have been associated with ENSO in endemic regions. ENSO is the strongest inter-annual signal of climate variability and its positive and negative phases cause significant worldwide climatic anomalies (Kovats 2000; Kovats *et al.* 2003). It is for this reason ENSO has been linked with interannual variations of malaria incidence and epidemics (Gagnon *et al.* 2002). Several other vector-borne diseases (VBDs) have been linked with climate anomalies forced by ENSO events. In many parts of the world malaria outbreaks have been linked with malaria. VBDs may cluster over a region after flooding in association with the ENSO phenomenon. In Ecuador and Peru epidemics of malaria appear to be related to extreme wet events (Epstein *et al*. 1995).

During negative ENSO phase, the Pacific Walker circulation intensify, the east pacific cools and the east Atlantic warms. During this time of the year, north easterly winds around Madagascar transfer warm moist air towards the east coast of southern Africa, this often brings widespread rain over southern Africa resulting in an increase in cases of malaria (Jury and Kanemba 2007). Malaria incidences in southern Africa are significantly synchronized with the ENSO, with below average incidence during El Niño years and above average incidence during La Niña years (Mabaso *et al*. 2007).

### 2.5.2 Indian Ocean Dipole

The Indian Ocean was previously considered to be largely affected by the interannual forcing of ENSO until the late 1990's when numerous studies discovered a distinct mode of interannual variability known as IOD (e.g. Saji *et al.* 1999; Webster *et al*. 1999). This coupled ocean-atmosphere phenomenon is characterized by anomalous warming of SSTs in the western equatorial Indian Ocean and anomalous cooling of SSTs in the south eastern equatorial Indian Ocean. This mode impacts both local and remote region (Yamagata *et al.* 2004).

IOD events occurs concurrently with El Niño, in fact IOD events are usually triggered by El Niño events (Ashok *et al*. 2003; Currie *et.al*. 2013). However, IOD events sometimes occur independently and they can influence against El Niño, they are thus dimed an independent climate mode (Yamagata *et al.* 2004). During a Positive Dipole Mode (Figure 2.10) anomalously easterly winds in the central Indian Ocean and cold SST anomalies off the coast of Indonesia occurs, the anomalously easterly winds raise the thermocline in eastern tropical Indian Ocean. While during the negative dipole Mode the reverse is true (Feng and Meyers 2003).

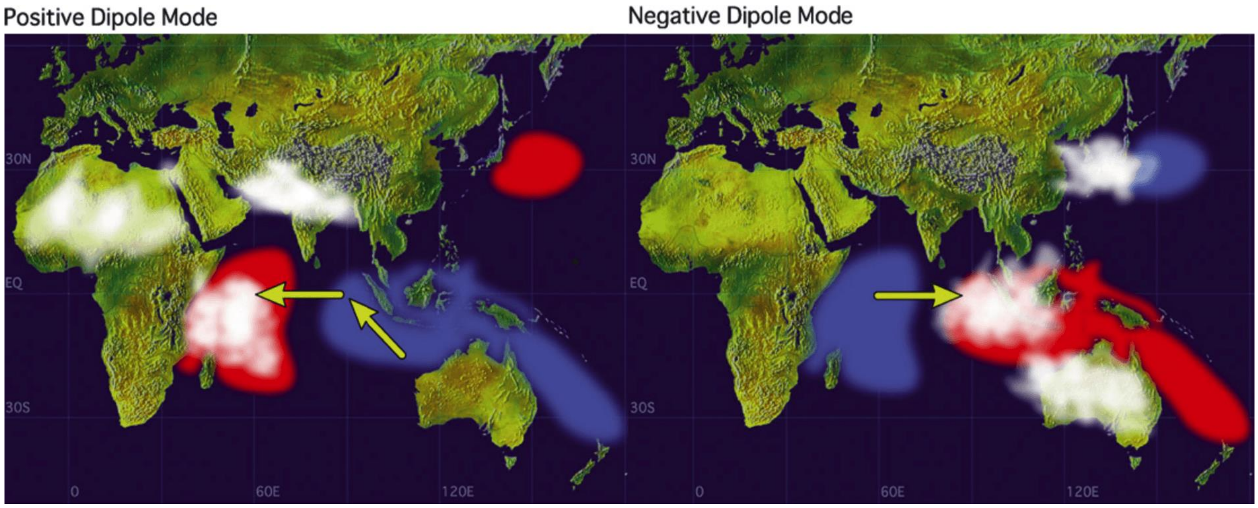



Figure 2.10. Positive mode of IOD (Left) and Negative mode of IOD (right) (SST anomalies are shaded where red color is for warm anomalies and blue is for cold. White patches indicate increased convective activities and arrows indicate anomalous wind direction (source: JAMSTEC 2016).

### 2.5.3 Indian Ocean Subtropical Dipole (IOSD)

IOSD is the oscillation of the sea surface temperatures (SSTs) of the Indian Ocean, where the South West Indian Ocean is warmer or colder than the South-east Indian Ocean (west of Australia). This dipole was identified through model simulations and observational studies while studying the relationship between rainfall anomalies of south central Africa and SST anomalies. (Reason 2001; Zinke *et al.* 2004).

During negative phase of IOSD in austral summer warm (cold) SST anomalies are observed over in the western (Southeastern) Indian Ocean. The timing and place of occurrence of vary among individual events. It usually occurs in December, peaks in February and cease in May. In some occasions the does not cease completely by revive to become a second consecutive event (Behera and Yamagata 2001).

Positive (negative) SST anomalies occurs in the southwestern (southeastern) subtropics in the austral spring to early summer of the La Niña years. While the reverse pattern is observed during El Niño years (Chiodi and Harrison 2007). However, both these conditions have also been observed in the non-La Nina and non-EL Niño years (Reason 1999; Behera and Yamagata 2001).

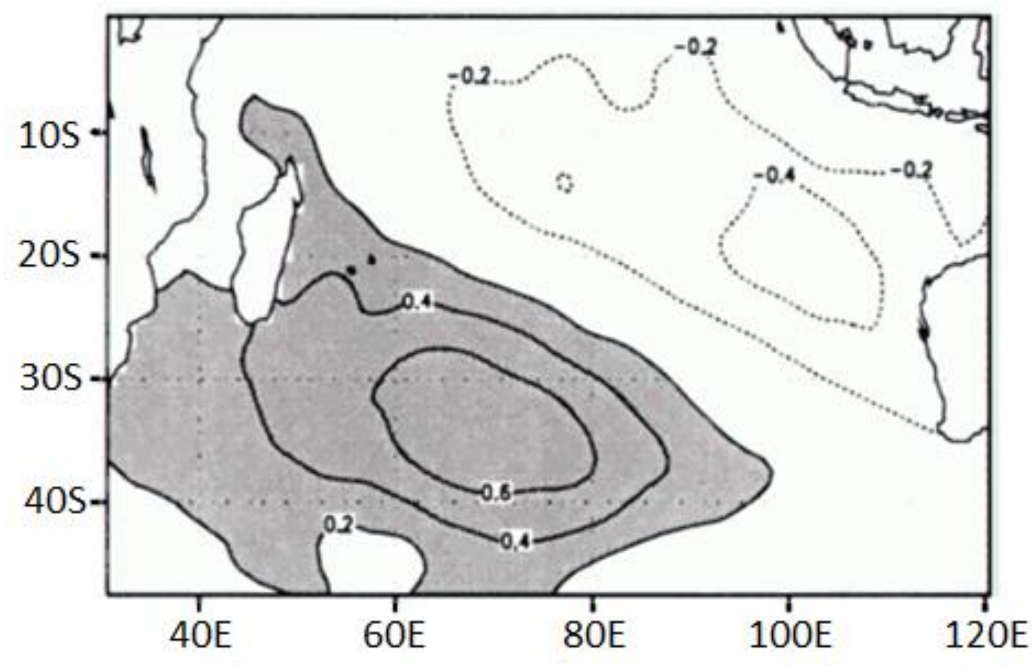



Figure 2.11. Positive Indian Ocean Subtropical Dipole. Above normal SSTs are shaded in grey (Source: Behera and Yamagata 2001).

Behera and Yamagata (2001) found that the evolution of anomalous SST during IOSD events are associated with the strengthening and weakening of the Mascarene High (MH) over the SWIO. The interannual intensity and movement of the MH is important for the IOSD formation (Suzuki *et al.* 2004). The wind on the eastern side of the MH is stronger between 20°S-30°S, which is consistent with cooler SST there (Figure 2.11). The warm pole to the west results from a decrease in the advection of cold air to the equator, increased poleward Ekman transport of warm waters from tropical latitudes and decreased ocean surface evaporation. While the cold pole in the east results from southeasterly trade winds and enhanced ocean surface evaporation and mixing (Ash 2012; Sovara 2014). During a negative event, warm air advection is located more frequently over the southeastern part of the basin. The cold SST and equatorward Ekman pumping occurs over the southwestern Indian in correspondence with frequent passage of cold fronts (Venzke *et al.* 2000; Behera and Yamagata 2001).

## 2.6 Non-climatic factors

There are other factors that play a role in the transmission of malaria which are non-climatic. Type of vector and parasite, level of human immunity, parasites drug resistance, human movement and migration, urbanisation and environmental change and development all play a significant role in severity and the occurrence of malaria.

### 2.6.1 Water development projects

Water development projects near house-holds increases chances of malaria transmission, since they provide more breeding sites for *Anopheles* mosquitoes. Irrigation schemes have been blamed for creating breeding sites for *Anopheles* mosquitoes leading to increased malaria transmission (Mwadime 1996; Gujja and Perrin 1999). The development of water resources through proper water management can bring opportunities of cost-effective vector control creating conditions which are less favourable for mosquito vector breeding (Mutero *et al.* 2000).

### 2.6.2 Urbanization

Malaria transmission is lower in the urban areas than the outskirts and rural areas. This may be because of the availability of sufficient space for vector breeding vector breeding sites in urban outskirts and rural areas whereas there are insufficient breeding sites in urban areas since much of its surface are is covered by buildings and roads. Water collection found in urban areas are normally polluted making it almost impossible for main African malaria vectors to breed since they prefer clean water for breeding (Robert *et al.* 2003; Donnelly *et al.* 2005; Hay *et al.* 2005; Tatem *et al*. 2008).

Other explanations could include the fact that there are better malaria prevention strategies, increased ratio of humans to malaria and better access to health care services (Robert *et al.* 2003). Whereas less developed regions on the outskirts of urban centers usually have poor quality housing and in adequate provision of health care and sanitation (Keiser *et al.* 2004). It is predicted that there will be a significant reduction of up to about 54% in malaria transmission by 2030, largely due to expected demographic changes (Klinkenberg *et al.* 2008; Saugeon *et al.* 2009).

### 2.6.3 Population movement and migration

Population movement has long been linked to the spread of malaria. It is believed that failure in the 1950's and 1960's malaria interventions resulted from population movement (Bruce-Chwatt 1968; Prothero 1977). The movement of humans from malaria endemic areas to areas where malaria has been eradicated might result in the resurgence of the disease, this could also result in the spread of drug resistance in malaria parasites.

Population movement involve humans moving from the malaria free area with little or no immunity against the disease to the malaria-endemic areas for different reasons. Humans can also carry infectious mosquitoes to malaria free areas, reintroducing the disease (Rajagopalan *et al.*1986). Movement of humans can also increase the risk of acquiring malaria through the introduction of new technologies (e.g. deforestation and irrigation) as these activities may create favorable conditions for malaria vectors (Service 1991).

### 2.6.4 Vector control and intervention

Malaria is still endemic throughout tropical Africa and is responsible for an alarming number of morbidity and mortality due to climate suitability and a lack of effective malaria control strategies. A key challenge is to achieve the sure sustainability of antimalarial efforts; however, they may be formulated. There are many ways of controlling the malaria carrying vectors (Carter and Mendis 2002).

There is a variety of methods used to control the transmission of malaria, one of which is through controlling malaria vector by introducing the use of insecticides to reduce the vector population and protect communities from mosquito bites. However, the disadvantage of using insecticides is that mosquitoes develop insecticide resistance after repeated application. Therefore, there will be an increase in the mosquito population, and thus the risk of malaria infections rises and many humans can be affected. But there is an inverse relationship between mosquito bites and risk of malaria (Lindblade *et al.* 2015).

a) Biological control methods

Biological methods of controlling vectors of malaria is a process of introducing a predator in a mosquito habitat to reduce the population. This method is essential and effective means for controlling transmission of several VBD such as malaria (Ghosh *et al*. 2005). The use of larvivorous fish as a predator has been there since the 19$^{th}$ century and has since been a preferred method in many countries all over the world and is well documented (Hoy *et al.* 1971; Wu *et al*. 1991; Gubler 2008).

One example of Larvivorous fish which is tolerant to different ranges of climatic conditions is *Gambusia affinis*. They can withstand temperature as low as 0.5°C to temperatures as high as 42°C and water bodies with a pH of 5-9 (Knight *et al.* 2003). They are a good biological control agent of mosquitoes in wetlands and waste water ponds. After they have been introduced in the new habitat they reproduce rapidly in early summer, however the rapid growth of the population results in food scarcity in the habitat (Gamradt and Kats 1996; Rupp 1996). They eat the food on surface water, where mosquitos' larvae are mostly found. The strength of larvivorous fishes decrease in areas of thick vegetation (Coykendall 1980; Knight *et al*. 2003).

b) Genetically modified (GM) mosquitos

One of the vector control methods is the sterile insect technique (SIT). This method is environmental friendly and species-specific (Phuc *et al*. 2007; Wilke and Marrelli 2012). This technique consists of mass rearing, radiation mediated sterilization, and many male mosquitoes are released into the target area (Reiter 2007). These genetically modified male mosquitoes must mate with the female mosquitoes, if the mating is successful no progeny will be produced (Pates and Curtis 2005).

This therefore reduce or even eliminate *Anopheles* mosquitoes and therefore reducing malaria transmission (Wilke *et al*. 2009). This method has an advantage over the other methods such as biological control, insecticide use and breeding sites removal since male mosquitoes seek female mosquitoes of the same species therefore reducing the population of the targeted species (Alphey 2002).

The cost and operational difficulties of irradiation are amongst a few other disadvantages of this method (Alphey 2007). Many sterile mosquitoes are needed since the procedure is repeated frequently because of a damage that sterile mosquitoes may suffer during transit and release (Thomas 2000). Bisexual releases of *Anopheles* mosquitoes have proved ineffective in decreasing the population (Fu *et al*. 2010).

### 2.6.5 Drug resistance in malaria parasites

*P. falciparum* is said to be extremely lethal and has contributed for over 90% of malaria infections in South Africa (Maharaj 2013). *P. falciparum* malaria infection rates were suppressed until the early 1980s due to effective control measures. Monitoring system had to be implemented to regularly review the effectiveness of first line treatment and the relationship between drug resistance and trends in the occurrence of malaria (Craig *et al*. 2004).

Different drug treatments have been introduced over the past 50 years. Chloroquine and sulphadoxine-pyrimethamine are no longer used most tropical countries due to resistance. Chloroquine and sulphadoxine-pyrimethamine had to be replaced with effective drugs since most endemic countries could barely afford the failing medicines (Nostine and White 2007).

The period 1980 to 1987 saw a sharp increase in malaria case numbers due to chloroquine treatment failures which arose from the emergence of chloroquine resistant parasites. This resulted in major drug policy changes. In 1998 sulphadoxine-pyrimethamine (SP) was introduced as first-line treatment to replace chloroquine treatment, this resulted in a decline in case numbers (Freese *et al.* 1988).

The number of malaria cases increased and peaked during 1999/2000 malaria season and it is believed to be due to the development of SP resistant parasites (Bredenkamp *et al*. 2001; Roper *et al*. 2003; Maharaj *et al.* 2012). Artemisinin-based combination therapy (ACT) using artemether-lumefantrine replaced SP in 2001 resulting in a dramatic decline in malaria (Barnes *et al*. 2009).

## 2.7 Summary

This chapter presented the review of history and background of malaria, and the different types of malaria parasites. The chapter also provided an in-depth over view of the role that climatic and non-climatic factors play on malaria transmission. It also covered the intervention and control strategies that have been introduced over the years to combat this scourge of malaria. Small changes in rainfall and temperature are expected to support malaria epidemics in malaria fringe regions. Positive rainfall, temperature and relative humidity combined can result in an increased risk of malaria epidemics following the disappearance of suitable breeding habitats.

The malaria control programme in South Africa has been active since 1945, the programme included:

a) Indoor residual spraying (IRS)
b) P falciparum-specific HRP-2 rapid test
c) Artemisinin combination therapy (ACT)
d) Disease surveillance
e) Epidemics preparedness and response
f) Health promotion

# CHAPTER 3

# RESEARCH METHODOLOGY

## 3.1 Introduction

Before the early 1980s, knowledge of synoptic scale phenomena was based on meteorological observations from isolated ground and upper-air stations (Wallace 1971; Yanai 1975), with great limitations on global scales where the data was sometimes ambiguous and confusing (Dunkerton and Baldwin 1995). However, in recent years climate data is widely available because of the use of satellite data in combination with models, and is made accessible through numerous internet data sources and climate observational institutes.

Our understanding of meteorological influences on malaria transmission in Limpopo can be facilitated using station data, satellite remote sensed estimates data, malaria incidence data, and climate-malaria model interpreted using sound methods of analysis. For malaria transmission to occur the climate conditions of the region need to be suitable for the survival the malaria vectors and therefore malaria transmission.

Reanalysis data takes its name from the analysis phase of weather forecasting, merging and contouring of weather observations that are used to initialise a forecast. In the first-time steps taken by numerical weather model, these observations are interpolated onto a three-dimensional grid and the values of derived variables are calculated (Kalnay *et al.* 1996; Schulze 2007).These values are physically constrained to varying degrees by the observations and after a few times step can be regarded as good approximation to an actual observation. A data set collected from these derived values can subsequently be used to describe the behaviour of several variables that are difficult to observe.

To achieve the objectives of this study, station, reanalysis and malaria incidence data sets are used and analysed using sound methods of analysis which include time series analysis, correlation analysis and Empirical Orthogonal Function analysis. The aim of this chapter is to provide data sets and techniques that are used in this study. Rainfall, temperature and relative humidity data are the key meteorological observations analyzed in this work.

## 3.2 Description of data sets

### 3.2.1 Rainfall

Both station and Global Precipitation Climatology Project (GPCP) reanalysis rainfall datasets are used in this work. Monthly data for the stations with at least 90% data within the malaria prone regions of Limpopo was provided by the South African Weather Service. Gaps within the data were filled using neighboring interpolation method. Stations that were used are shown in table 3.1.

GPCP v2.3 combined monthly precipitation dataset from 1979-present which is a combination of observations and satellite precipitation data into 2.5°x2.5° global grids (Adler *et al*. 2003) is correlated with climate indices (Niño 3.4 index and SOI) to analyse the influence of the oceans on rainfall variability in Limpopo. GPCP data was also used to perform empirical orthogonal function analysis and wavelet analysis.

Table 3.1 Weather Stations used.

| **Station names** | **Climate Number** | **Latitude** | **Longitude** | **Altitude (m)** |
|---|---|---|---|---|
| Alldays | 0764161A7 | -22.68 | 29.10 | 762 |
| Hoedspruit | 0638081 1 | -24.35 | 31.05 | 524 |
| Krugerwildtuin shangoni ars | 0724790 5 | -23.17 | 30.94 | 444 |
| Letaba | 0682141A2 | -23.85 | 31.57 | 235 |
| Levubu | 0723485A0 | -23.09 | 30.28 | 706 |
| Louis Trichardt | 0722693A4 | -23.05 | 29.90 | 961 |
| MARA | 0722099 1 | -23.14 | 29.55 | 894 |
| Messina | 0810081 3 | -22.35 | 30.05 | 538 |
| Messina macuville | 0809706 X | -22.27 | 29.90 | 525 |
| Mopani | 0681722 8 | -23.53 | 31.42 | 335 |
| Pafuri | 0812567 3 | -22.45 | 31.32 | 202 |
| Phalaborwa | 0681266 3 | -23.93 | 31.15 | 407 |
| Punda Maria | 0768011A8 | -22.69 | 31.01 | 457 |
| Shingwedzi | 0725756A8 | -23.11 | 31.44 | 275 |
| Thohoyandou | 0723664 6 | -23.08 | 30.38 | 614 |
| Tshipise | 0766277 1 | -22.62 | 30.17 | 527 |
| Waterpoort | 0765234A5 | -22.90 | 29.63 | 742 |

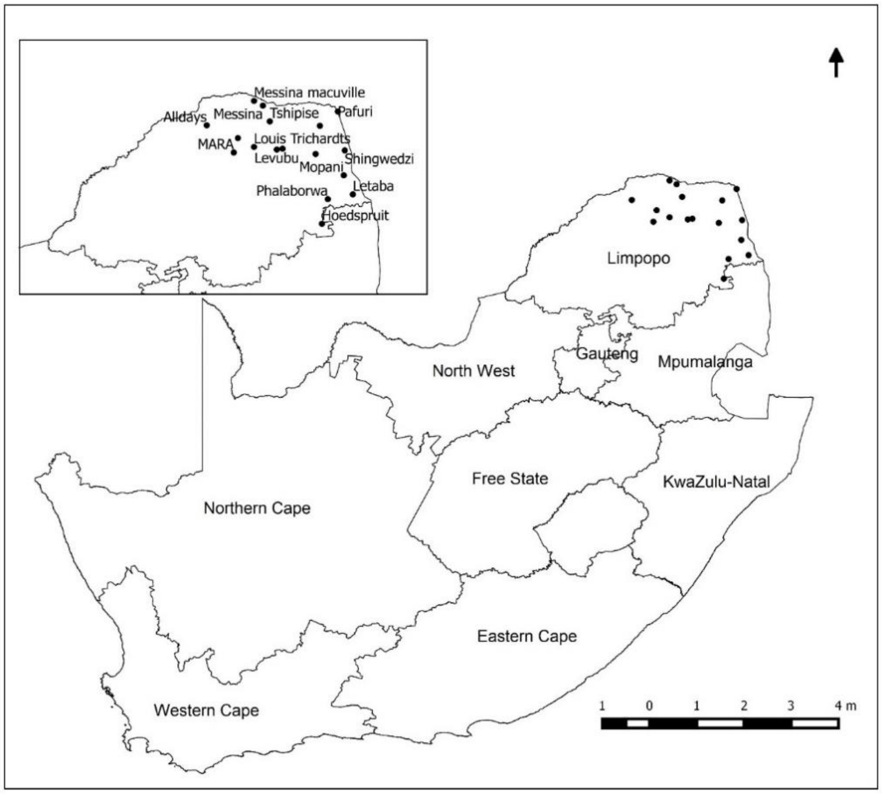



Figure 3.1 SAWS weather stations

### 3.2.2 Temperature

Monthly station maximum temperature (Tmax) and minimum temperature (Tmin) for 12 weather stations with at least 90% data availability within the malaria prone region of Limpopo (Mopane and Vhembe district municipality) was provided by South Africa Weather Service. The data spans the period 1985-2014, it was used in to analyze temperature variability at different time scales and it was also correlated with malaria data. NCEP reanalysis temperature data was used to analyze the spatial variability using empirical orthogonal function.

### 3.2.3 Relative humidity

Relative humidity (RH) is a ratio of the partial pressure of water vapor in the air-water mixture to the saturated vapor pressure of water at the prescribed temperature. Relative humidity is highly variable and is influenced by both temperature and pressure. RH is directly proportional to the total pressure and inversely proportional to temperature. However, the value of RH is limited to 100% as actual partial pressure (p) cannot be greater than saturation pressure (ps). Any comparison of relative humidity must be made at similar times of day to eliminate the effect of diurnal inverse variation of temperature (Tyson and Preston-Whyte 2000; Lawrence 2005; Jyothis and Ratheesh 2013).

RH equation is given by:

$$RH = \frac{p}{Ps}\ x\ 100\% \text{.......................................} (1)$$

Both station and NCEP reanalysis RH datasets were used in this study.

### 3.2.4 Outgoing Longwave Radiation (OLR)

Outgoing Longwave Radiation (OLR) at 200 hPa is the emission to space of terrestrial radiation from the top of the earth's atmosphere (Salby 1996). In physical terms it is strongly controlled by the presence of water vapour in the atmosphere, atmospheric and terrestrial temperature and the presence of clouds, which block most outgoing infra-red radiation from the surface (Pluss and Ohmura 1997). OLR has been used in several studies as a proxy for convective activity (e.g. Jury *et al.* 1996; Liebmann *et al*. 1999). Low OLR values in the tropics and summer sub-tropics indicate convective weather systems, in contrast to cloud free regions where warm surface emits high OLR. OLR is measured at the top of the atmosphere (200 hPa). The OLR data that is used in this study is from National Oceanic and Atmospheric Administration (NOAA).

### 3.2.5 Sea Level Pressure (SLP)

SLP is the atmospheric pressure at sea level or when measured at a given altitude, the station pressure is adjusted to sea level if the temperature falls at a lapse rate of 6.5 °C per km in the fictive layer of air between the station and sea level (Liu *et al.* 2014). Different weather types are associated with high and low pressure. Usually high pressure systems (anticyclones) are associated with settled weather whilst low pressure systems (cyclones or depressions) bring unsettled weather (ECWMF 2016).

### 3.2.6 Geopotential height

The geopotential ($\Phi$) is the work done to raise a unit mass against earth's gravitational field. High geopotential heights indicate ridges and anticyclones whilst low geopotential heights indicate troughs and cyclones. Geopotential height in this study is mapped at 500 hPa (steering levels) since a flow at this level is assumed to be approximately parallel to the height contours and weather systems beneath, near to the Earth's surface move roughly in the same direction as the winds at the 500 hPa (Holton 1992).

Therefore:

$$d\Phi = g\, dz = -\alpha\, dp \text{.......................................} (2)$$

The geopotential $\Phi$ (z) at height z is thus given by:

$$\Phi(z) = \int_0^z g\,dz \ldots\ldots(3)$$

Whereas, geopotential height (Z) approximates the actual height above mean sea level, and it is given by:

$$Zg(h) = \frac{\Phi(h)}{g} \ldots\ldots(4)$$

### 3.2.7 Vertical velocity

Wind flow in the vertical is of relatively lower speed than horizontal wind. Vertical motion is two times smaller in magnitude than horizontal motion (Dobrovolski 2016). Changes in vertical velocity are linked to changes in surface pressure. Vertical velocity indicates areas of large-scale rising and sinking motion. Negative values indicate regions of low pressure and enhanced uplift, often leading to precipitation. Whereas, positive values indicate regions of high pressure, descending air, and often dry weather (Finley and Raphael 2007). NCEP reanalysis vertical velocity dataset was used in this study.

Vertical velocity (ω) is given by:

$$\omega = \frac{dp}{dt} \ldots\ldots(5)$$

Since pressure decreases monotonically with height ω is positive for subsidence and negative for uplift. Therefore, vertical velocity can also be approximated by the following equation

$$\omega = -g\rho w \ldots\ldots(6)$$

Where: *p* represents pressure, *t* represents time, *g* represents acceleration due to gravity, *ρ* represents density and *w* represents vertical velocity components (x, y, z).

### 3.2.8 Wind vector

The wind vector is described by wind speed and direction; the vectors point in the direction to which the wind is blowing. Wind vector at 500 hPa from NCEP was used to represent the circulation in the middle levels prior the occurrence of malaria out breaks. It is generally used to determine areas of advection and divergence.

### 3.2.9 Sea Surface Temperatures (SSTs)

NOAA's Optimum Interpolation Sea Surface temperature (OISST) also known a Reynold's SST provides global fields that are based on a combination of ocean temperature observations from satellite and in situ platforms. Statistical methods (optimum interpolation, OI) are applied to fill in where there are missing values. The methodology includes a bias adjustment step of the satellite data to in situ data prior to interpolation. SST analyses are used in a range of applications including weather forecasting, climate studies, oceanography, modelling and as a reference field for other satellite algorithms (Reynolds *et al.* 2002). In this study NOAA OI SST is used to analyse the surface temperatures of the Indian Ocean and Atlantic Ocean prior the occurrence of malaria epidemics.

### 3.2.10 Niño 3.4 index

Niño 3.4 index is an anomaly of central equatorial Pacific Ocean's sea surface temperatures 5°N-5°S and 170°W-120°W (Figure 3.2). These anomalies are strongly correlated to the ENSO phenomenon, with respect to its association with world-wide climate variability (Barnston *et al.* 1997). Niño 3.4 index was used in this study to investigate the influence of ENSO on rainfall variability in Limpopo and therefore malaria incidences.

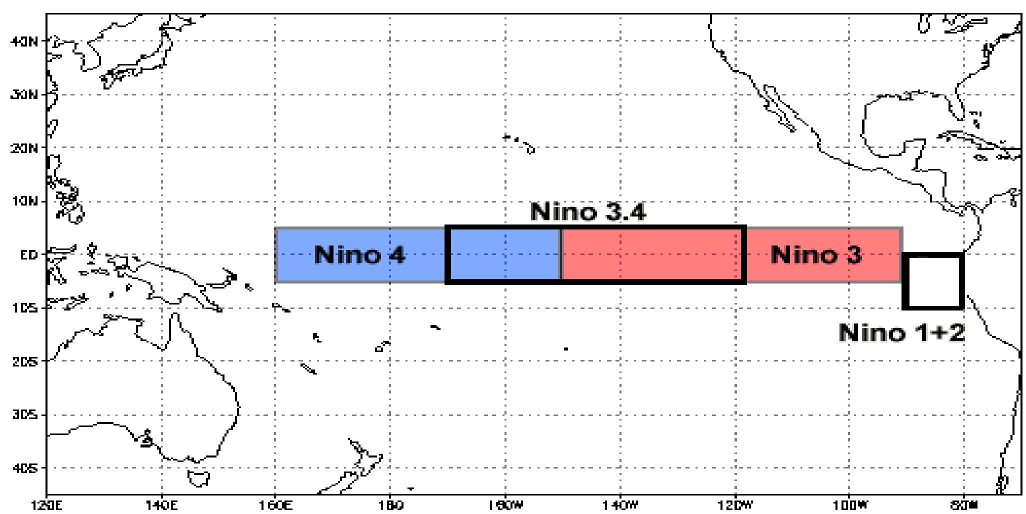



Figure 3.2. Niño regions of the Pacific Ocean (Source: NOAA 2016)

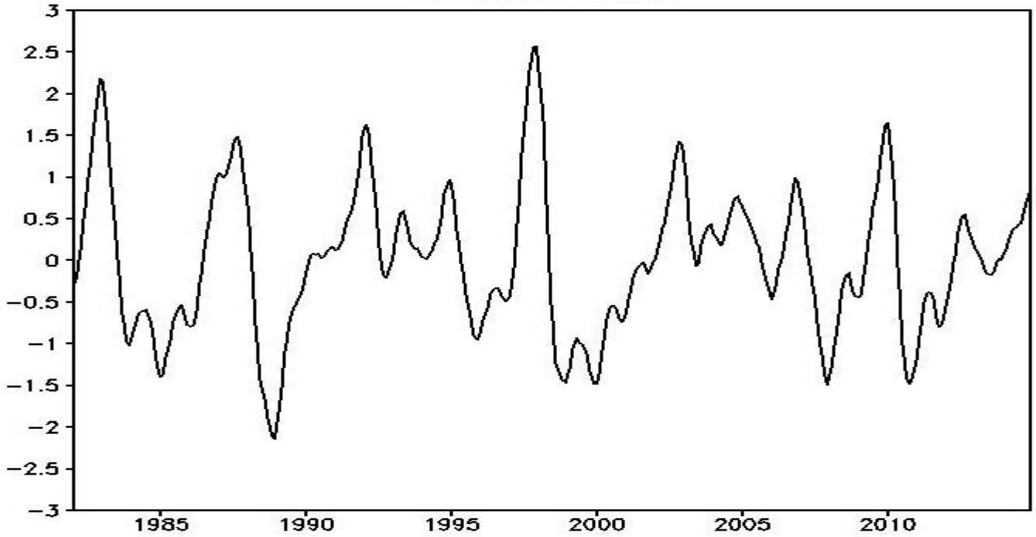



Figure 3.3. Nino 3.4 index from 1985-2014

### 3.2.11 Normalized Difference Vegetation Index (NDVI)

Normalized Difference Vegetation Index (NDVI) quantifies vegetation by measuring the difference between near-infrared (which vegetation strongly reflects) and red light (which vegetation absorbs). NDVI always ranges from -1 to +1. But there isn't a distinct boundary for each type of land cover. The notion behind NDVI is that plants' chlorophyll absorbs sunlight, which is captured by the red light region of the electromagnetic spectrum, whereas a plant's spongy mesophyll leaf structure creates considerable reflectance in the near-infrared region of the spectrum (NDVI) uses the NIR and red channels in its formula (Govaerts and Verhulst 2010). NDVI is calculated using the following equation.

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \quad \text{.................................................(7)}$$

### 3.2.12 Malaria incidence data

To demonstrate and quantify a relationship between meteorological variables and malaria incidence good malaria data sets are required. Sixteen years of malaria incidence data was obtained from the Malaria Institute of Department of Health – Tzaneen, Limpopo. Malaria incidences are reported to the Department of Health per 100 000 population (for the relevant year) by season, since malaria transmission in Limpopo is seasonal limited to the warm and rainy summer months (Craig *et al.* 2004b). Source of infection is determined for all cases. If a patient has recently travelled to a malaria-endemic area or if there are no evident malaria cases within

500 m radius of the place of residence the case is reported as imported (Martin *et al.* 2002; Gerritsen *et al.* 2008; Maharaj *et al*. 2012).

## 3.3 Ethical consideration

This study is an analysis of secondary data. Ethical approval for use of the malaria data was obtained from the University of Venda Research Ethics Committee and the Malaria Institute of Department of Health - Tzaneen. Written consent was given by the patients for their information to be stored in the hospital database and used for research.

## 3.4 Research methods

### 3.4.1 Theoretical framework

The theoretical framework of this study is presented in Figure 3.4. Malaria cases and meteorological variables datasets are analysed in this work. It has been noted from the literature that malaria transmission, weather and climate of southern Africa (south of 10°S) is strongly seasonal. Therefore, time series analysis is being employed to analyse seasonal cycles (of both malaria and meteorological variables) at different percentiles and analyse trends and how cycles of ENSO affects the occurrence and distribution of malaria. Precursor meteorological conditions prior the occurrence of the epidemics of malaria are analysed both at event scale and as a composite to get an insight on the drivers of the occurrence of the epidemics. Meteorological conditions are correlated with the malaria case (with a lag of 0 to 3 months).

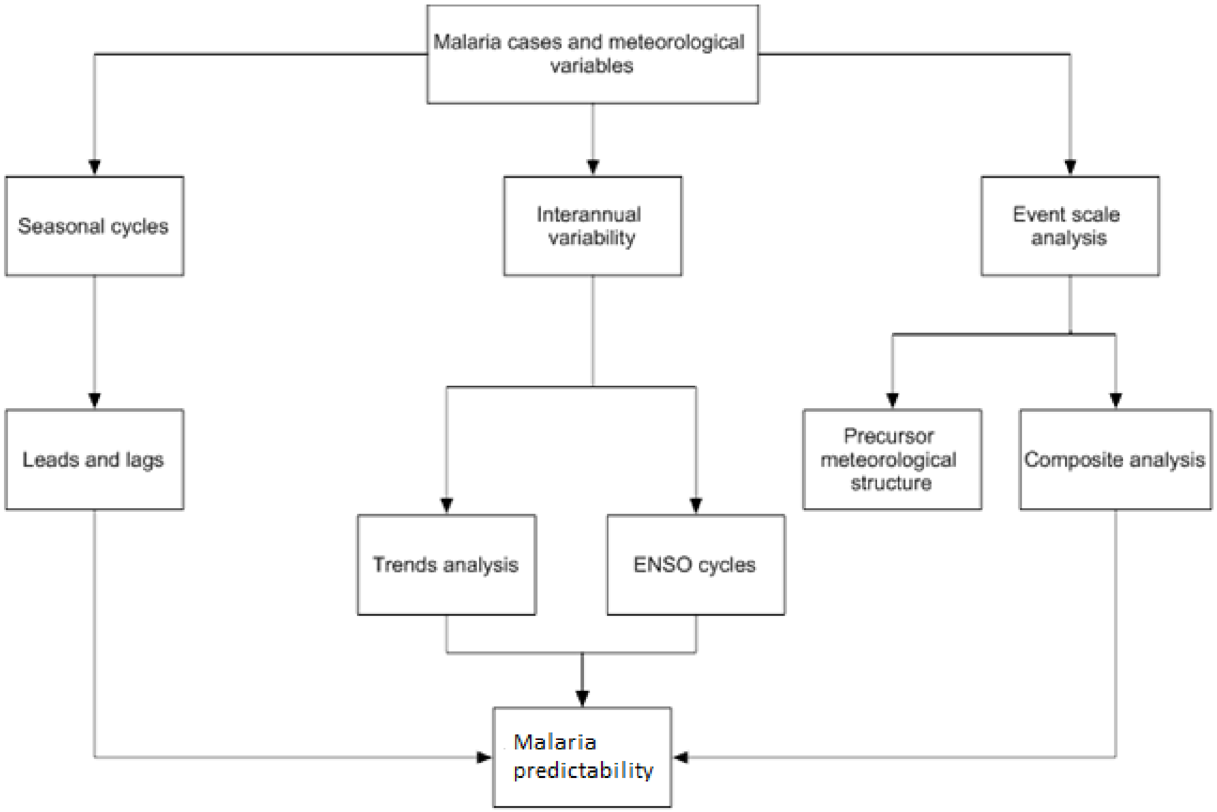



Figure 3.4. Schematic representation of the theoretical framework

### 3.4.2 Time Series Analysis

A time series is a collection of quantitative observations that are evenly spaced in time and measured successively, it can be used to identify trends and seasonal variation, understanding and modeling the data to predict the short-term trends for previous patterns and in investigation how single events affect time series and how it can be decomposed into its components e.g. cycles and Irregular components. It is given by the equation:

$$Xt = T_t + S_t + C_t + R_t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Where: $X_t$ represents value of series at time t, $T_t$ represents trend component of the time series, $S_t$ represents cyclical or seasonal component with a period S, $C_t$ represents other cycles in the data and $R_t$ represents random effect for which we have no explanation. In this study, random effects are neglected since they cannot be explained. Therefore, time series analysis was then subdivided in three techniques of analysis. In this study malaria epidemics were identified from the time series, the precursor meteorological events 6 months prior to the epidemic.

a). Seasonal cycles

The seasonal cycles of meteorological variables (rainfall, temperature and relative humidity) and malaria incidences were determined.

b). Trend analysis

A trend analysis is process of analyzing a significant change over time exhibited by a random variable, detectable by statistical parametric and non-parametric procedures. Simple linear regression technique was employed to establish trends in the meteorological variables [rainfall (wet spells) and temperature] and malaria cases. This technique involves regression equation with coefficient of determination. Coefficient of determination represents the fraction of variability between two variables. It explains how close the points are to the line. A decreasing trend is indicated by negative regression equation whereas an increasing trend is indicated by a positive regression equation. Malaria cases were also correlated to remote influences such as cycles of ENSO and the Indian Ocean Subtropical Dipole.

c). Wavelet analysis

Wavelet analysis is a time series analysis method used to determine variance spectra when amplitudes of dominant oscillation are time dependent. This technique allows the decomposition of the signal $x(t)$ in terms of wavelets from a single function $\varphi$ by scale and position (Najmi and Sadowsky 1997).

$$\varphi_{b,a}(t) = \frac{1}{a}\varphi\left(\frac{t-b}{a}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

The wavelet is transformed and defined as continuous since $a$ and $b$ may be varied continuously. The choice of wavelet depends on the signal to be analysed.

The wavelet is defined by

$$\varphi(t) = \pi^{-1/4}\, e^{-t\,z/2} e^{i\omega ot} \ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

Where $i = \sqrt{-1}$ and $\omega = 5.4$ is chosen large enough to ensure that $\varphi$ satisfies the admissibility condition.

$$\int_{-\infty}^{\infty} \varphi(t)dt = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

In morlet wavelet the inverse of the scale to frequency is identified by:

$$f = \frac{\omega}{\partial\pi}\left(\frac{\omega_0}{a} + \frac{\sqrt{2+\omega^2}}{\omega_0}\right) \ldots\ldots (12)$$

The morlet wavelet is interpreted as a band pass linear filter of weight $1/_a$ centered around $\omega = \omega_0 \,/\, a$.

$$\frac{\partial\phi_{b,a}}{\partial b} = \frac{\omega_0}{a} \ldots\ldots (13)$$

$$f(t) = C_g^{-1}\int_0^{+\infty}\int_{-\infty}^{\infty} a^{-2} w_x(b,a)\phi_{ab}(t)\, db\, da \ldots\ldots (14)$$

Where Cg is the integral of $\|\hat{\varphi}\|^2\omega^{-1}$

Wavelet analysis technique was developed to overcome the short comings of Fourier decomposition and spectral analysis. It determines dominant timescales of variability and their evolution in time through transforming time series data into time-frequency data. In this work wavelet analysis was used to look for possible cycles in meteorological parameters and malaria incidences.

### 3.4.3 Pearson correlation

Pearson correlation analysis was then used to investigate relationships between meteorological variables and malaria epidemics. If the variables are highly correlated, then the association is further investigated to determine if there is any causal mechanism operating. The Pearson's coefficient (r) is a measure of intensity between variables and ranges from -1 to +1, it is given by:

$$r = \frac{\Sigma xy}{\sqrt{\Sigma x^2 \Sigma y^2}} \ldots\ldots (15)$$

### 3.4.4 Empirical Orthogonal Function (EOF) analysis

EOF is a powerful tool for data compression and dimensionality reduction and it is widely used in meteorology, climatology and oceanography to study possible spatial modes of variability and how they change with time (Monahan *et al.* 2009). EOF analysis is not based on physical principles. Rather, a field is partitioned into mathematically independent modes which sometimes may be interpreted as atmospheric and oceanographic modes. These modes consist of eigenvalue which quantifies the variance and eigenvectors that describe the spatial distribution and a set of time scores that define the evolution, and they vary with in the data (Venegas 1997).

### 3.4.5 MARA distribution model

The distribution model of climatic suitability for malaria transmission is a web based fuzzy logic model which is based on long-term climate averages rather than actual malaria data. This model was first developed by Craig *et al*. (1991) and it is also included in the Climate and Malaria Resource Room. MARA distribution model provides insight into potential for transmission of malaria, it was used to map climate suitability and the length of the transmission season of malaria in Limpopo. Values between 0 and 1 defines the conditions suitable for the transmission of malaria by *P. falciparum* in an average year.  Where zero represents completely unsuitable and one represents completely suitable conditions for the transmission of malaria.

### 3.4.6 Event scale analysis and composite analysis

Malaria epidemics were identified from the malaria incidence time series. Pre-cursor synoptic and meso-scale meteorological structure were then determined going up to 3 months before the epidemic first occurred. These pre-cursor events were then studied via Composite Analysis.

Composite analysis is a sampling technique based on the conditional probability of a certain event occurring. When studying the influence of meteorological variables on malaria, the character and intensity of an individual event may vary considerably. However, when studied as a composite, key patterns often emerge. Composite analysis has an advantage of being able to reduce the number of maps produced thus making the analysis easier to handle and interpret. It also enhances the density of the observed data and reflect patterns and trends better than individual cases (Jury 1997). The NCEP GFS model (Saha *et al*. 2010) was used for composite analysis. This procedure forms the core of this work.

### 3.4.7 COLA Grid analysis and display system (GrADS)

GrADS is an interactive desktop tool used for easy access, manipulation, and visualization of earth science data. It uses a 4-Dimensional data environment: longitude, latitude, vertical level, and time. Data sets are placed within the 4-D space by use of a data descriptor file (Doty 1995). The format of the data may be either binary, GRIB, NetCDF, or HDF-SDS (Scientific Data Sets). Once the data have been accessed and manipulated, they may be displayed using variety of graphical output techniques, including line, bar and scatter plots, as well as contour, streamline, wind vector, shaded grid box and station model plots (Kinter 1994). In this work, GrADS was used to map and analyse the precursor meteorological structure of the atmosphere.

### 3.4.8 Royal Netherlands Meteorological Institute (KNMI) Climate Explorer

KNMI Climate Explorer is a wed based climate research tool that includes an integrated library of climate data available. This tool provides a wide range of climate data, including daily and monthly station data (e.g. Nino 3.4), 6-hourly to monthly gridded observations and reanalysis data and monthly seasonal forecasts based on Global Circulation Models (GCMs) and historical reconstruction.

The tool includes an option to enter user-defined time series or field data. Once the time series has been selected there are many options to investigate the data, correlating it to other data and generating derived data from it. While the tool itself is not intended to create forecast, it offers easy access to climate information and supports exploratory analysis that can help identity appropriate climate predictors.

The data is available for download and analysis in a variety of formats (eps, pdf, raw data and netCDF). KNMI provided access to numerous data sets (GPCP v 2.3 monthly rainfall data, monthly relative humidity etc.). Some important analysis such as spatial correlation of rainfall of southern Africa and Seas Surface Temperatures of the central Pacific Ocean (Niño 3.4) and wavelet analysis was performed in KNMI climate explorer web site.

### 3.4.9 Seasonal Autoregressive Integrated Moving Average (SARIMA) model

The SARIMA model incorporates both seasonal and non-seasonal factors in a multiplicative model. One shorthand notation for the model is:

$$ARIMA\ (p, d, q) * (P, D, Q)S \qquad (16)$$

With p = non-seasonal AR order, d = non-seasonal differencing, q = non-seasonal MA order, P = seasonal AR order, D = seasonal differencing, Q = seasonal MA order, and S = time span of repeating seasonal pattern.

Without differencing operations, the model could be written more formally as

$$\Phi(BS)\varphi(B)(xt - \mu) = \Theta(BS)\theta(B)_{wt} \qquad (17)$$

The non-seasonal components are:

$$AR:\ \varphi(B) = 1 - \varphi 1B - \ldots - \varphi pB^{p} \qquad (18)$$

$$MA:\ \theta(B) = 1 + \theta 1B + \ldots + \theta_q B^{q} \qquad (19)$$

The seasonal components are:

$$\text{Seasonal AR: } \Phi(B^S) = 1 - \Phi_1 B^S - \ldots - \Phi_P B^{PS} \quad \ldots\ldots(20)$$

$$\text{Seasonal MA: } \Theta(B^S) = 1 + \Theta_1 B^S + \ldots + \Theta_Q B^{QS} \quad \ldots\ldots(21)$$

The left side of equation (17) the seasonal and non-seasonal AR components multiply each other. On the right side of equation (17) the seasonal and non-seasonal MA components multiply each other.

### 3.4.10 R

R is a tool for statistical computing and graphics. R has an effective data storage and handling facility, a suite of operators for calculations on arrays for data analysis sing S programming language (Venables *et al.* 2008). In this work, R was used for correlation analysis of climate variables and malaria. R was also used to produce high quality plots of annual cycles and interannual variability of meteorological variables and malaria.

## 3.5 Summary

This chapter presented and described the datasets used in this work alongside the methods of analysis employed to achieve the aim and objective of this work. The data sets used include station data (Rainfall and temperature) from South Africa Weather Service, malaria incidence data from malaria institute of Department of Health-Tzaneen, satellite data (OLR), reanalysis data (SLP, geopotential heights, relative humidity, velocity potential and wind vector) and ENSO indices data.

The next chapter provides the analysis of the mean climate (spatial patterns, seasonal cycle and Interannual variability) of the malaria prone regions of Limpopo.

# CHAPTER 4

# CLIMATE CHARACTERISTICS OF THE MALARIA PRONE REGION OF LIMPOPO

## 4.1 Introduction

The climate of a region is described by the total of all statistical weather information that helps to describe the variation of weather at a given place averaged for at least 30 years (Kabanda 2004). The frequency of occurrence of events such as floods, droughts and land falling tropical systems are also vital to describe the climate of a region (Peterson *et al.* 2013). The climate of southern Africa is strongly determined by the position of the subcontinent in relation to the major circulation patterns of the southern hemisphere, the complex regional topography and the surrounding ocean currents (Davis 2011).

The weather and climate of southern Africa varies spatially and temporally on several time scales, with extreme weather events most common being floods, droughts, fires and large storms (Bruwer 1993; Forsyth *et al.* 2010; Theron 2011). Extreme weather events have been responsible for many socio-economic impacts, including loss of properties and lives in recent years (Morss *et al.* 2011; Kabanda 2004). Interannual climate variability is an important determinant of epidemics in Sub-Saharan Africa where climate drives both mosquito vector dynamics and parasite development rates. Hence, skilful seasonal climate forecasts may provide early warning of changes of risk in epidemic-prone regions (Thomson *et al.* 2006).

The aim of this chapter is to describe and analyze the mean climate of the malaria prone regions of Limpopo using sound methods of analysis discussed in Chapter 3.

## 4.2 Rainfall

### 4.2.1 Spatial patterns

Rainfall over Limpopo exhibits a strong gradient from west to east, with more rainfall occurring in the eastern region due to orographic effect forced by the Soutpansberg mountain ranges and from the land falling tropical systems from the Indian Ocean that affect this region from time to time. A west-east rainfall gradient is however distorted by mountainous regions as increased rainfall is received due to orographic effect. A north-south rainfall gradient is also observed in

Figure 4.1. The spatial patterns are visible on satellite-derived Normalized Difference Vegetation Image (NDVI) shown in Figure 4.2. The mean low level circulation over the region is strongly anticyclonic, this wind circulation tends to draw moisture from the Indian Ocean (Figure 4.1).

The mean circulation of the atmosphere over South Africa is predominantly anticyclonic, except for lower atmosphere pressure levels during summer when heat troughs develop over the subcontinent (Taljaard, 1996). During winter months, the moisture source from the tropics is reduced by the northward migration of the ITCZ and intensification of the BUH (Tyson and Preston-Whyte 2000). The combination of Agulhas, Benguela and this continuous Mozambique currents and subtropical highs enhance the spatial west to east rainfall gradient over South Africa (Figure 4.3)

The Empirical Orthogonal Function (EOF) analysis (Figure 4.4) shows 3 distinct modes of rainfall variability over Limpopo. The first three EOFs describe about 55.04% of the variance of rainfall over Limpopo. EOF 1 exhibit a positive loading over the Limpopo valley, which can be associated with the landfalling tropical cyclones and it explains about 32.18% of the variance of rainfall. EOF 2 explains about 13.16% of the variability, showing a NW-SE pattern of positive loading which can be associated with cloud bands. The third EOF explains about 9.7% variability, which shows a negative loading over the region between 20°S-25°S. This region was identified by Usman and Reason (2004) as “drought corridor”, and it frequently experiences dry spells during half or more of the wet season.

There are a number of synoptic situations that can result in wet spells over the region. During austral summer wet spells are pulsed at frequencies that are consistent with the passage of tropical waves over the southeast African and South West Indian Ocean region (Hayashi and Golder 1992; Malherbe *et al*. 2012) while anomalous easterly flow in the 5°S-20°S band in the region of Madagascar also leads to increased rainfall over this region (Mulenga *et al*. 2003). The blocking effect associated with the ridging of the Mascarene high over south eastern regions of southern Africa results in slower propagation of cloud bands and also the influx of moisture from South West Indian Ocean (SWIO) resulting in high rainfall over most regions of the South Africa (Figure 4.5)

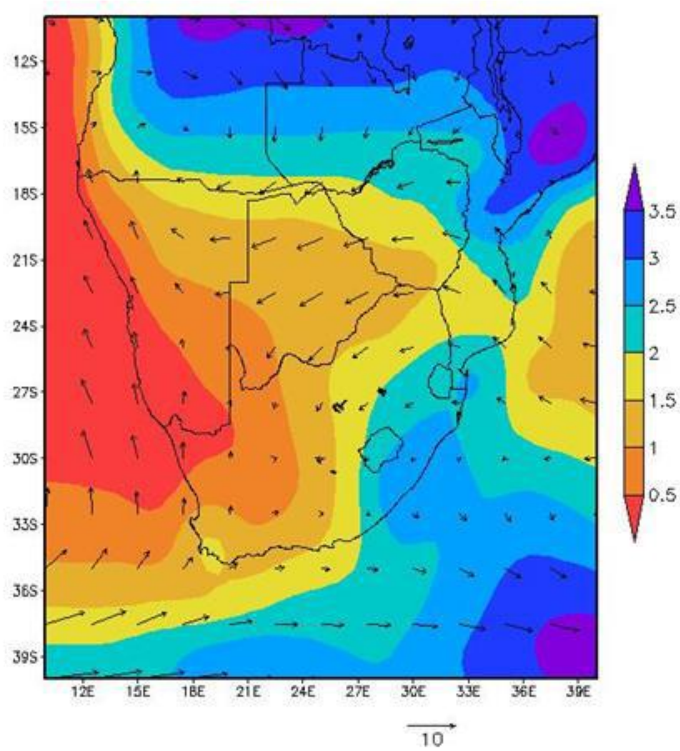



Figure 4.1. Mean spatial pattern of GPCP precipitation (mm/day) and wind vector (m/s) over southern Africa from 1985-2014.

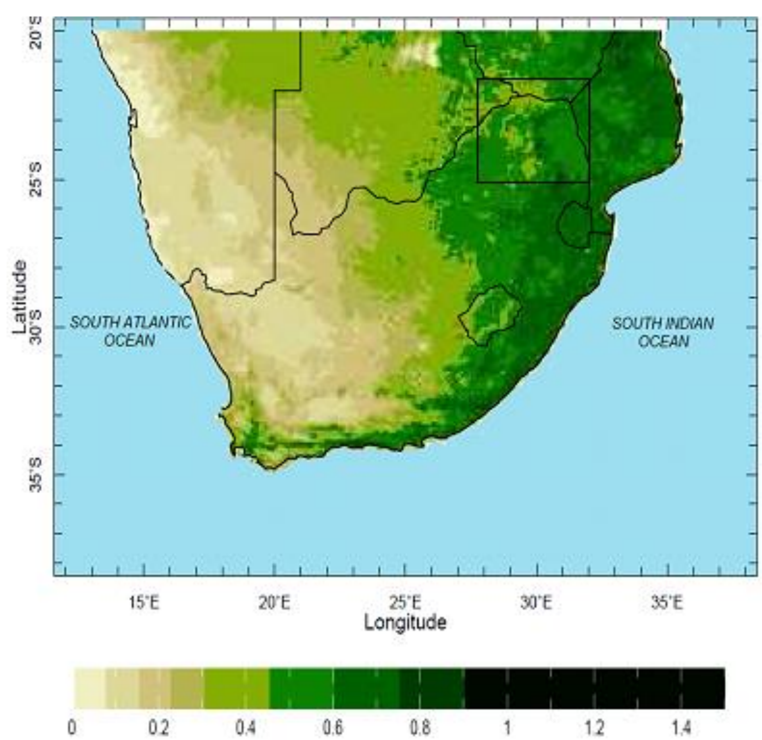



Figure 4.2. Mean Normalized Difference Vegetation Index over southern Africa from 1985-2014.

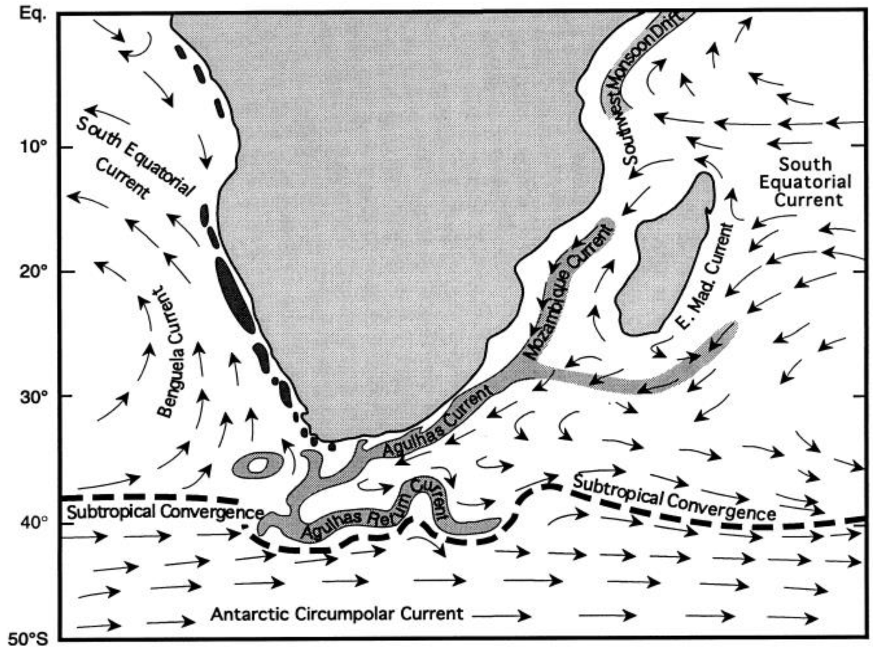



Figure 4.3. Ocean currents adjacent to southern Africa (source: Lutjeharms *et al*. 2001)

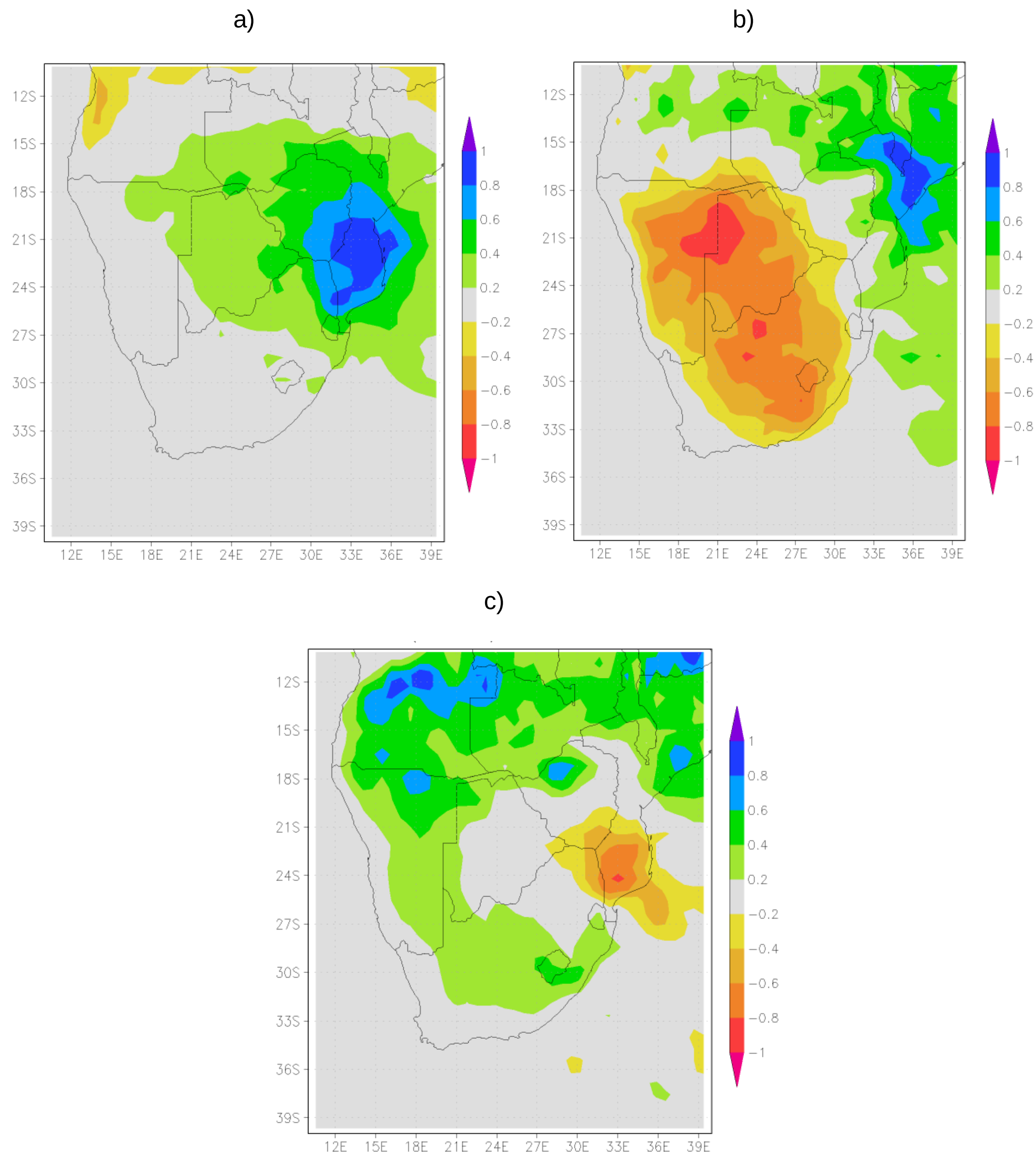



Figure 4.4. a) PC1, b) PC2 and c) PC3 of summer GPCP rainfall over southern Africa. PC1, PC2 and PC3 explains about 32.18%, 13.16% and 9.7% of rainfall variability respectively.

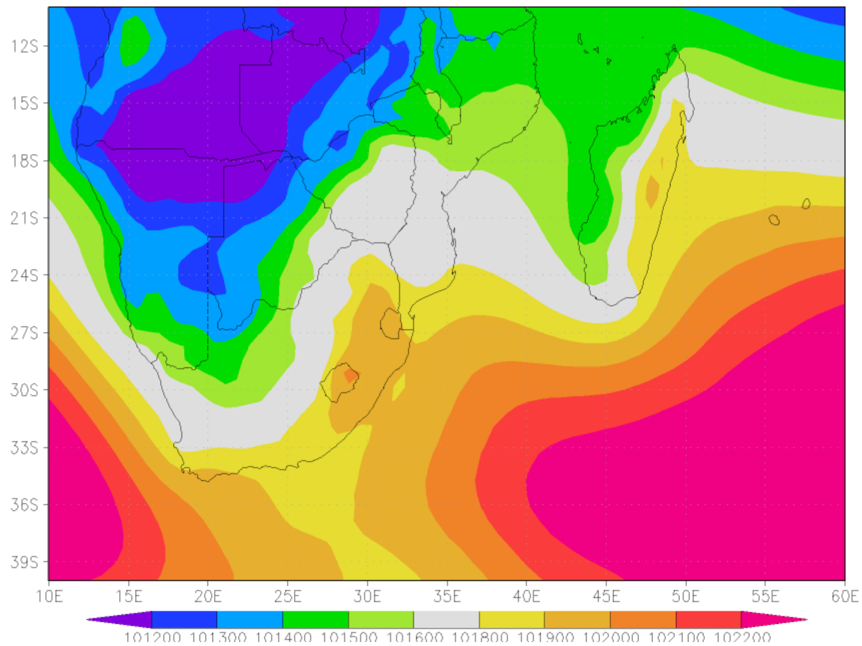



Figure 4.5. Mean sea level pressure associated with the blocking effect of the subtropical highs.

### 4.2.2 Seasonal cycles

Rainfall over Limpopo is strongly seasonal, with vast amount of rainfall received between October and March, nearly half a year (approximately 182 days) (Kabanda 2004). Rainfall amounts peak in core austral summer months from December to February (Figure 4.6). However, this region sometimes experiences early onset of the rainy season (September), and the cessation of the rainy season is sometimes delayed. The onset, duration and cessation of a rainy season is determined by occurrence of alternating wet and dry spells, and also the frequency of occurrence of tropical systems which are the main rain bearing system over southern Africa. The dominant rain-bearing systems over this region are Tropical Temperate Troughs (Harangozo and Harrison 1983), contributing about 40%-60% (Hart *et al.* 2010).

The region is characterized by sequence of alternating of wet and dry spells (Rouault and Richard 2003; Reason *et al.* 2005), which have critical implications on agriculture, since a wet spell can mark the onset of the rainy season, while extended mid-summer dry spells may accumulate into a drought (Mupangwa *et al.* 2011). Usually during dry spells an intense mid-tropospheric anticyclone is established with a centre over Botswana causing subsidence and restricting rainfall over most of the subcontinent (Chikoore and Jury 2010). Rainfall over this region shows a distinct seasonality with a wet season in austral summer (DJF) (Figure 4.3 a) and a dry season in austral winter (JJA) (Figure 4.3b). The west to east rainfall gradient is strongest during austral summer months.

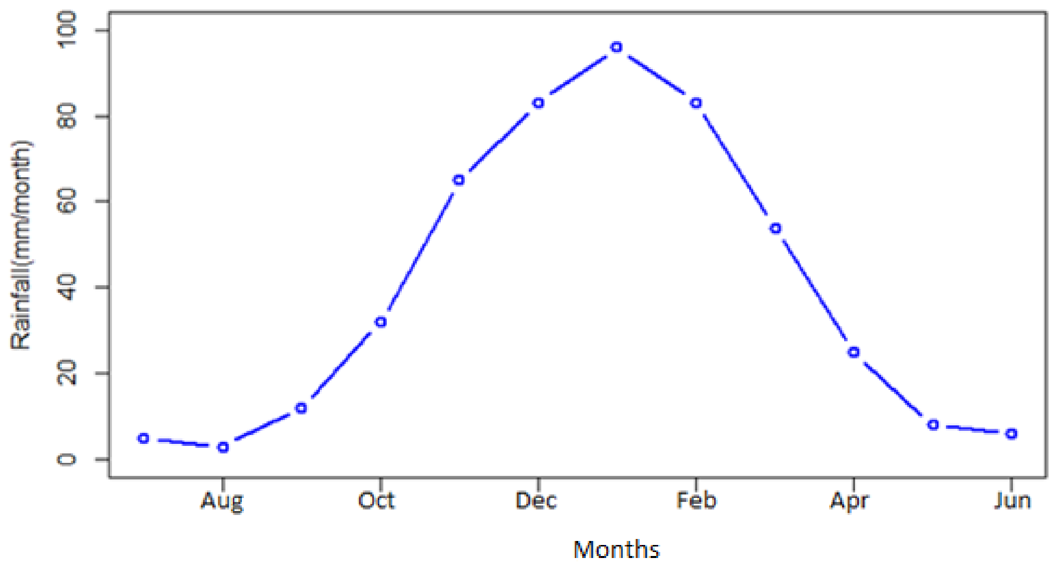



Figure 4.6. Seasonal cycle of SAWS station rainfall over the malaria prone region of Limpopo from 1985-2014.

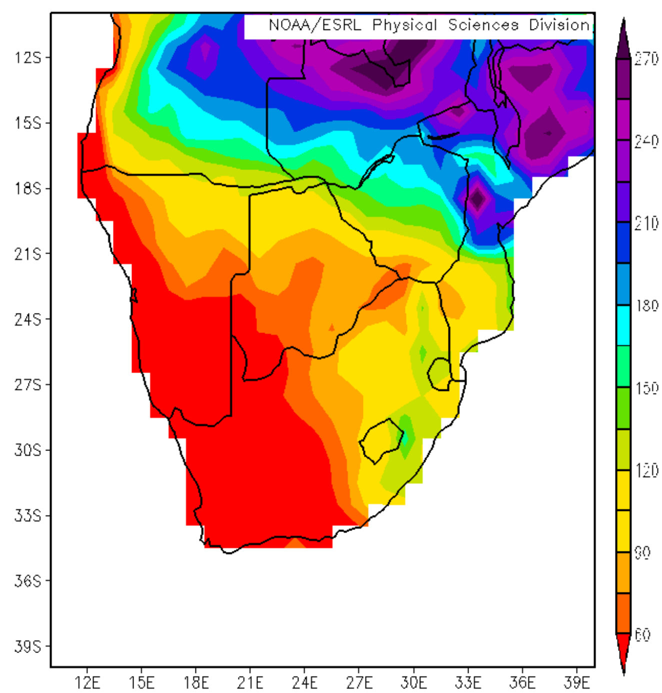



Figure 4.7a December-January-February mean GPCP (mm/month) over southern Africa from 1985-2014.

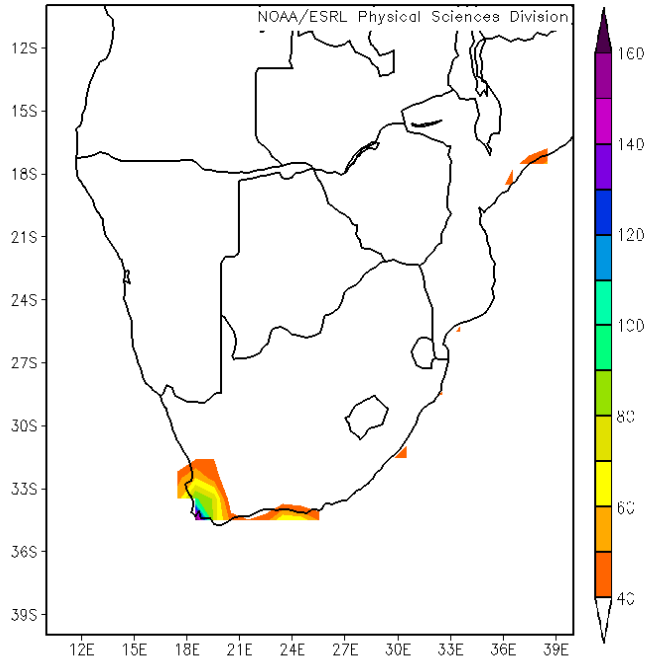



Figure 4.7b June-July-August mean GPCP (mm/months) over southern Africa from 1985-2014.

### 4.2.3 Interannual variability

A distinct feature of the climate southern Africa is its high Interannual variability and notably the gradual increase in the incidence of extreme events (Figure 4.8). Figure 4.9 shows a slight increase in rainfall, notably from 2000 with more positive rainfall anomalies observed. The eastern sector of the sub region exhibits high interannual variability. The effects of tropical systems and teleconnections with remote forcings maximize there. Negative correlation between rainfall and Niño 3.4 index are shown on Figure 4.10.

Figure 4.11 shows a positive relationship between SOI and rainfall. Simultaneous variations of SOI and rainfall accounts for about 20% of rainfall variance over South Africa. Such that high rainfall tends to coincide with high phase of the southern oscillation, and vice versa (Dube 2002). The close relationships between summer rainfall area and SOI spectra at both quasi-biennial and southern Oscillation periods support the physical mechanism linking phase changes of the oscillation with zonal and meridional circulation adjustment over southern Africa, and hence with rainfall variations over South Africa (Lindesay 1988).

Wavelet analysis of 1985-2014 GPCP v 2.3 monthly precipitation shows significant cycles of rainfall variability at 2.3 years which may be related to cycles of quasi biennial oscillation (QBO) (Figure 4.12). The QBO is an upper air wind reversal system occurring at about 30 hPa. QBO has been found to be responsible for seasonal rainfall variability in southern Africa (Tyson and Preston-Whyte 2000). The easterly phase of QBO has been linked with dry conditions, while the westerly phase has been linked with wet conditions over the subcontinent. The movement of the ITCZ with apparent movement of the overhead sun to the north and south of the equator also contributes to the determination of the seasonal characteristics of rainfall of this region.

A strong signal of significant cycle of rainfall variability at 3-7 year which may be linked to equatorial pacific SSTs and cycles of ENSO (Figure 4.12). The signal of ENSO is transmitted via a zonal cellular circulation over the Pacific Ocean extending from Indonesia to the Peruvian coast known as the Walker circulation. Warm ENSO events usually result in warm and dry conditions over the subcontinent. During this time of the year rain bearing systems migrate eastward towards Madagascar. Low rainfall is usually projected over southern Africa with above normal rainfall over east Africa. Most notable warm ENSO events of 1982/83, 1991/92 and the most recent 2015/16 resulted in severe drought over the most parts of southern Africa. However not all droughts over this region are ENSO induced (Table 4.1, Figure 4.9). Within this climatic context, this region supports a large rural population dependent on rain-fed agriculture. The region is therefore largely vulnerable with regards to the impact of rainfall variability (O'Brien and Vogel 2003).

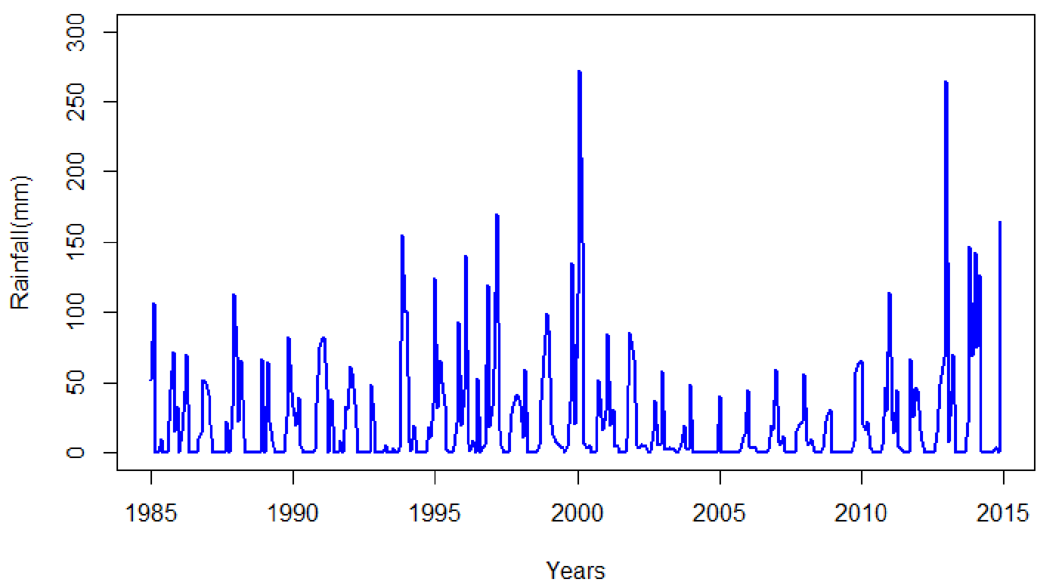



Figure 4.8. Interannual variability of SAWS station rainfall over the malaria prone region of Limpopo from 1985-2014.

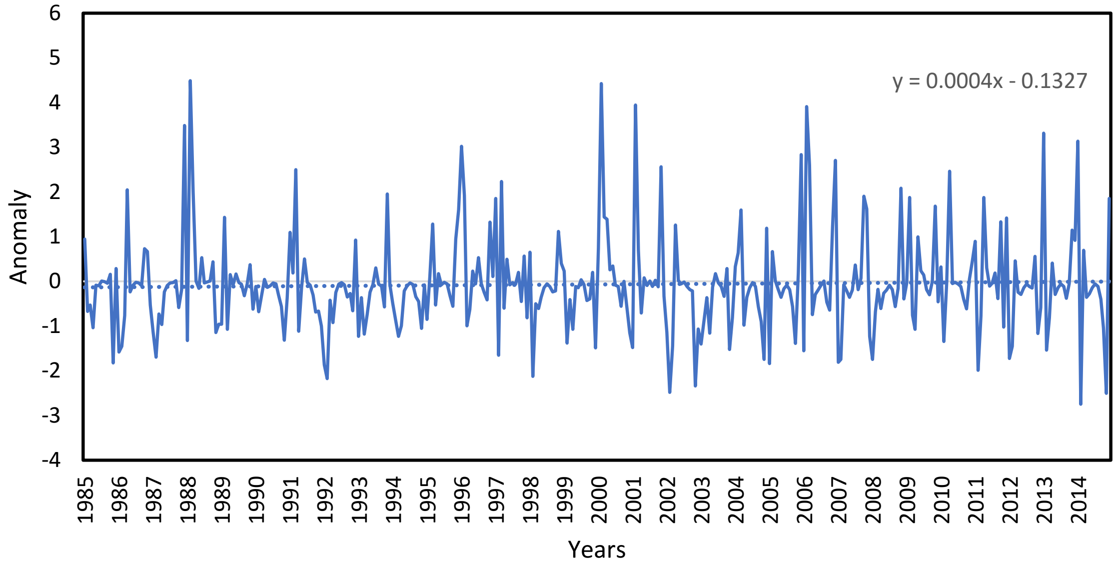



Figure 4.9. Departure from mean of SAWS station rainfall in malaria prone region of Limpopo from 1985-2014.

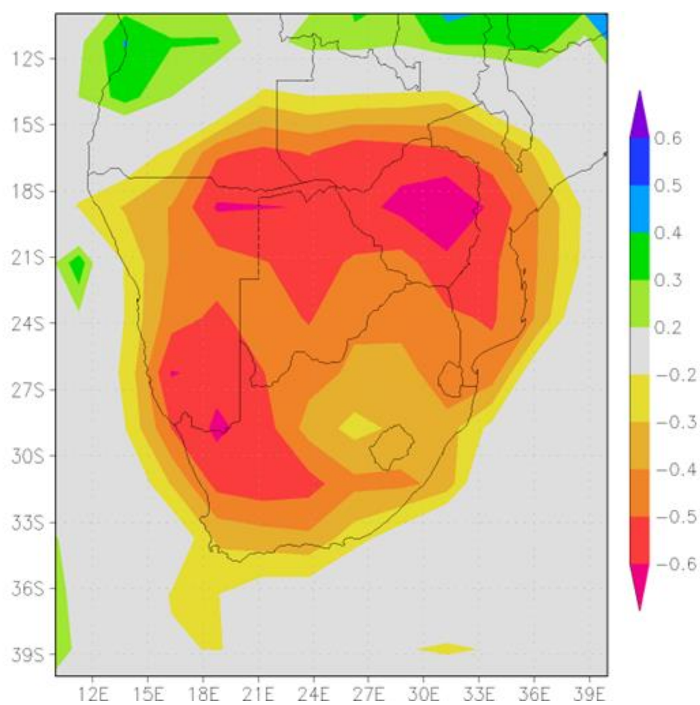



Figure 4.10. Correlation of DJF Niño3.4 index with GPCP precipitation 1985-2014, $p<0.05$

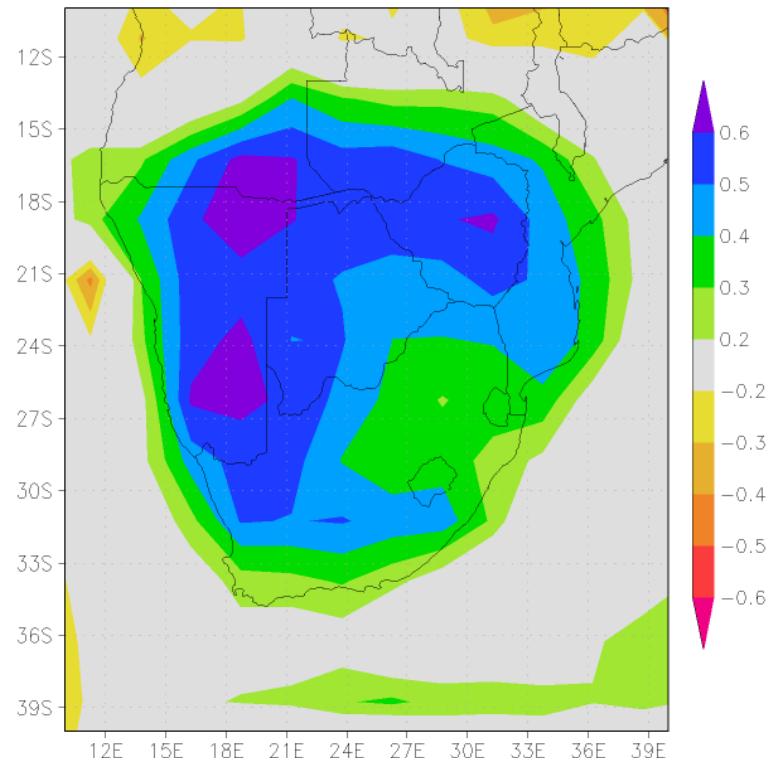



Figure 4.11. Correlation of DJF SOI with GPCP precipitation 1985-2014, p<0.05

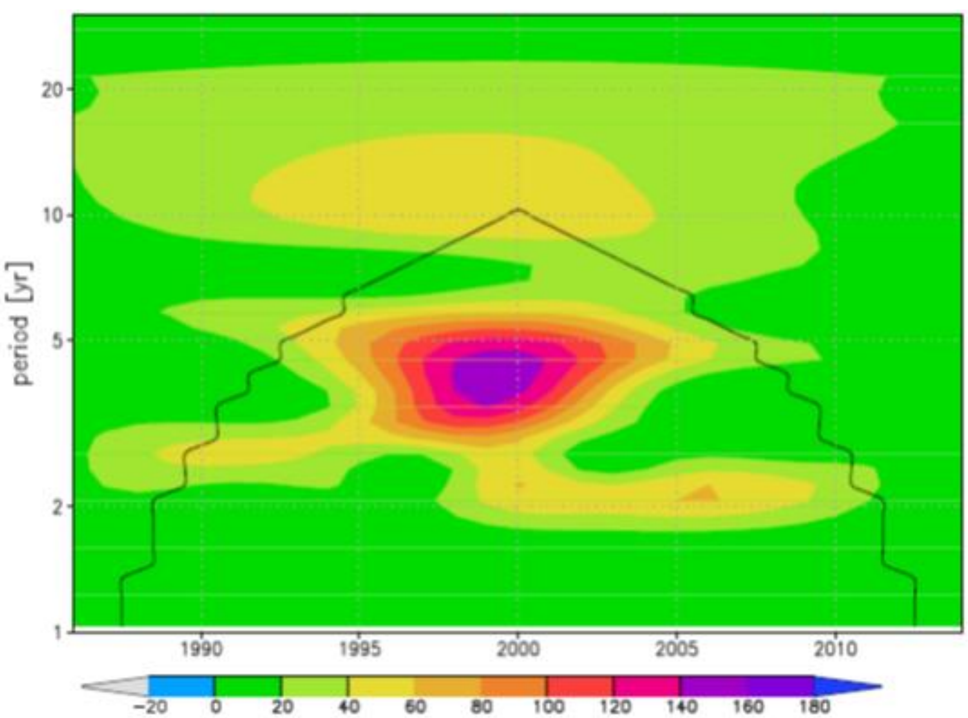



Figure 4.12. Wavelet transform showing rainfall cycles over Limpopo (27-32°E- 22-25°S) from 1985-2014.

Table 4.1. Historical El Niño and La Niña seasons

| El Niño seasons | | | La Niña seasons | | |
|---|---|---|---|---|---|
| Weak | Moderate | Strong | Weak | Moderate | Strong |
| 1994-95 | 1986-87 | 1982-83 | 1983-84 | 1998-99 | 1988-89 |
| 2004-05 | 1987-88 | 1997-98 | 1984-85 | 1999-00 | |
| 2006-07 | 1991-92 | | 1995-96 | 2007-08 | |
| | 2002-03 | | 2000-01 | 2010-11 | |
| | 2009-10 | | 2011-12 | | |

## 4.3 Temperature

The mean spatial patterns of temperature vary across the region with lowest temperatures recorded in the interior of the province along the escarpment. Whereas the highest temperatures are recorded at the eastern low veldts, Limpopo valley and far west region bordering Botswana. Altitude plays a significant role in the temperature variations of this region (Figure 4.13).

The malaria prone regions of Limpopo Province are found in the eastern low veld and they tend to experience relatively higher temperature than the rest of the province. The mean annual temperature of this region is 23°C (Figure 4.13).

The highest temperatures are usually experienced during austral summer (October-March), with a peak in December. Low temperatures are experienced during austral winter months between May and August, with the lowest temperatures 15°C in July (Figure 4.14).

During core winter months (June-July-August) temperature of the region falls well below the suitable temperature ranges for the survival of *Anopheles* mosquitos thus making the transmission of malaria almost impossible (Figure 4.15). While during core summer months temperature falls within a suitable range for the transmission of malaria thus increasing *Anopheles* mosquito population by the increased chances of mosquito survival, biting rate and shorten the life cycle of the mosquito vector over the prone region of Limpopo.

Departure from mean temperature is shown in Figure 4.16. Higher than normal temperatures during the 1991/92, 1997/98 and the 2004/05 droughts seasons are notable from the time series. There is an increasing trend in temperature, with more observations of higher than normal temperatures since 2002. Both maximum temperature (Tmax) and minimum (Tmin) exhibit a similar trend. However, Tmax exhibits a much steeper trend (Figure 4.17 and Figure 4.18).

Figure 4.19 show the first two PCs which explain about 53.12% of the variability of temperature over Limpopo. PC1 explains 41.95% of variance in temperature. There is a positive loading (positive anomalies in temperature) over the malaria prone region of Limpopo. This signal might be linked with the intensification of the Botswana high pressure system to the north. PC2 which explains 11.21% of the variability, shows a negative loading of temperature (negative anomalies) over south eastern region of southern Africa (including the malaria prone regions of Limpopo) during core summer months (DJF). This loading could be linked to the land-falling tropical evolving systems over the Limpopo valley.

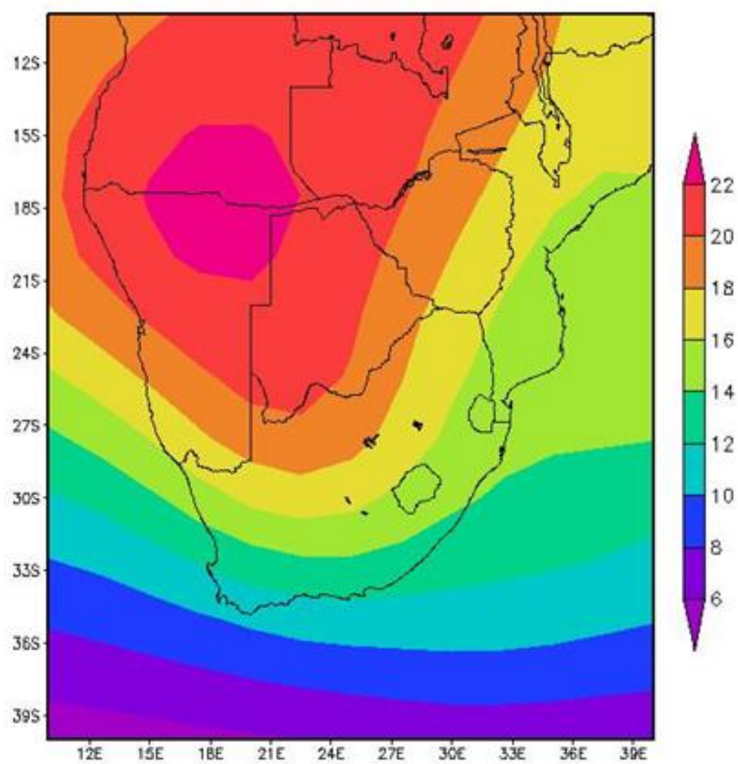



Figure 4.13. Mean spatial pattern of NCEP reanalysis temperature (°C) over southern Africa from 1985-2014.

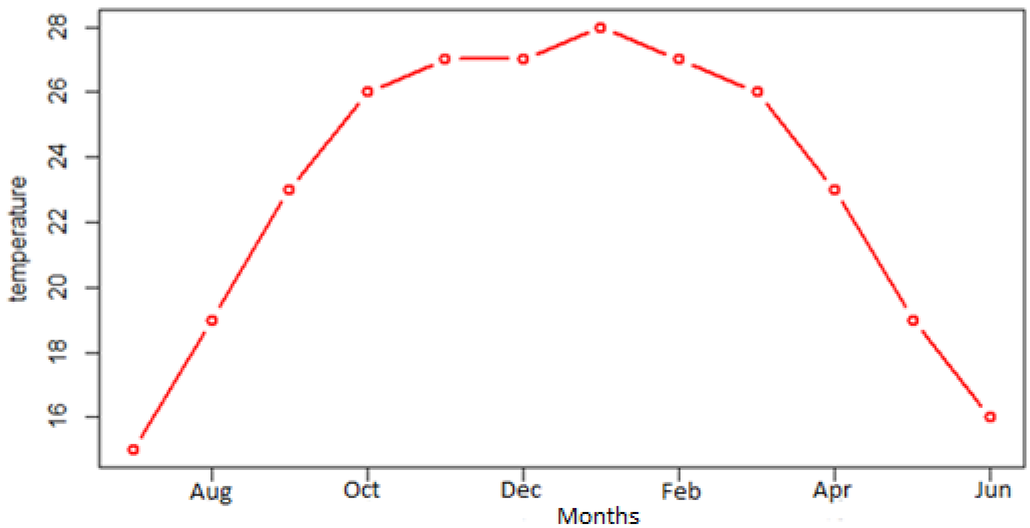
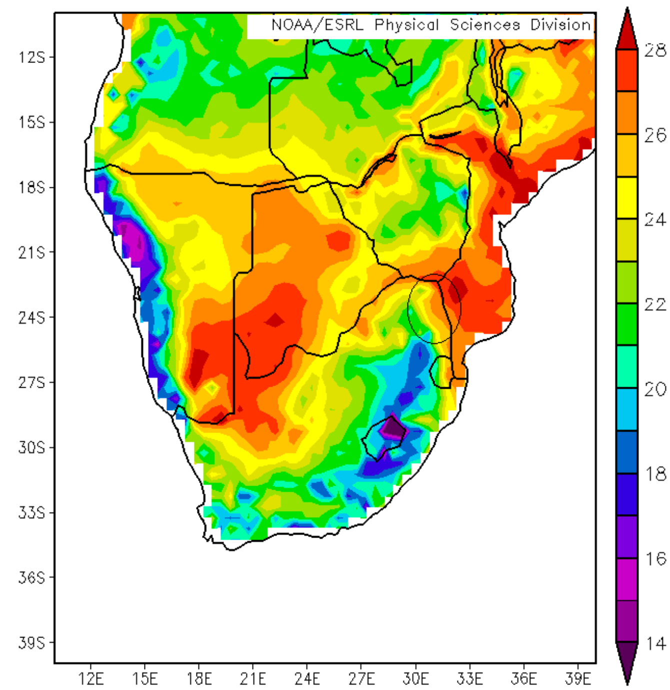



Figure 4.14. Seasonal cycle of temperature (°C) over the malaria prone region of Limpopo from 1985-2014

a)




b)

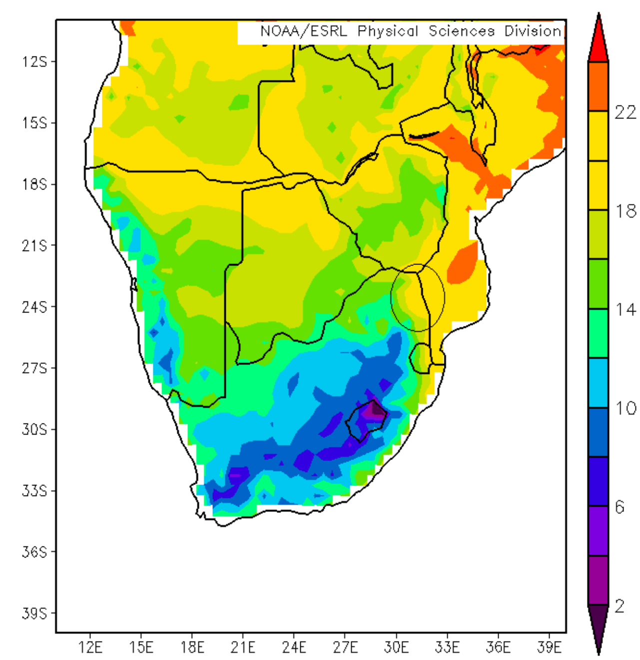



Figure 4.15. Surface air temperature composite mean (°C) for (a) December-January-February and b) June-July-August from 1985-2014.

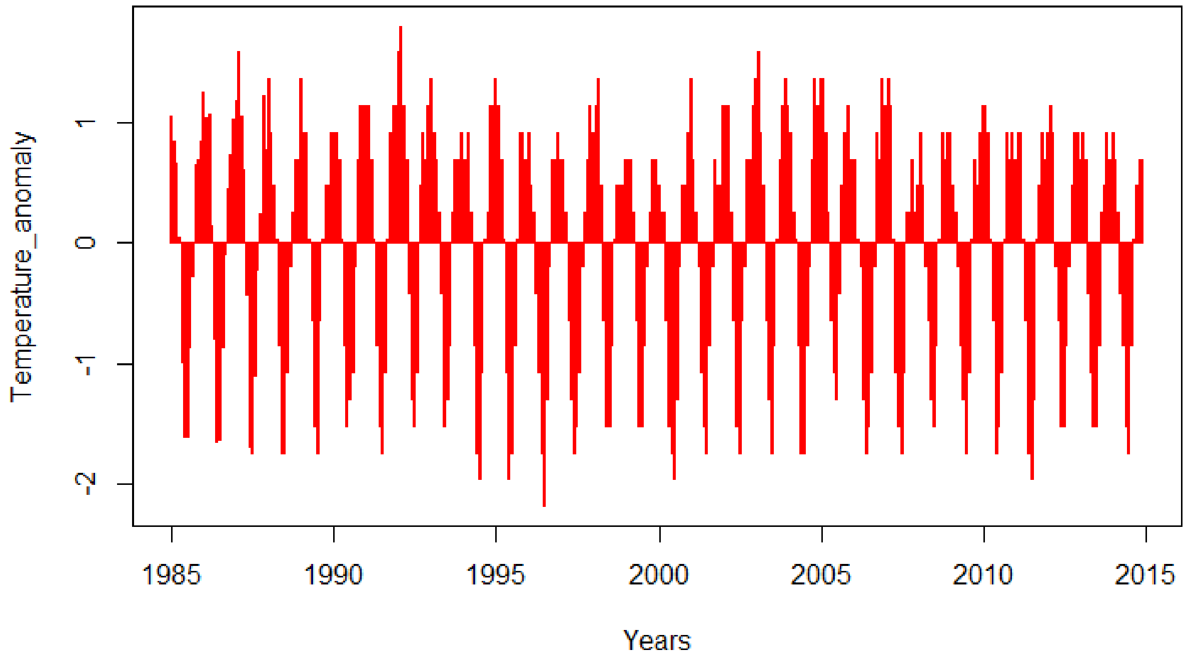



Figure 4.16. Departures from mean of SAWS station temperature over the malaria regions of Limpopo from 1985-2014.

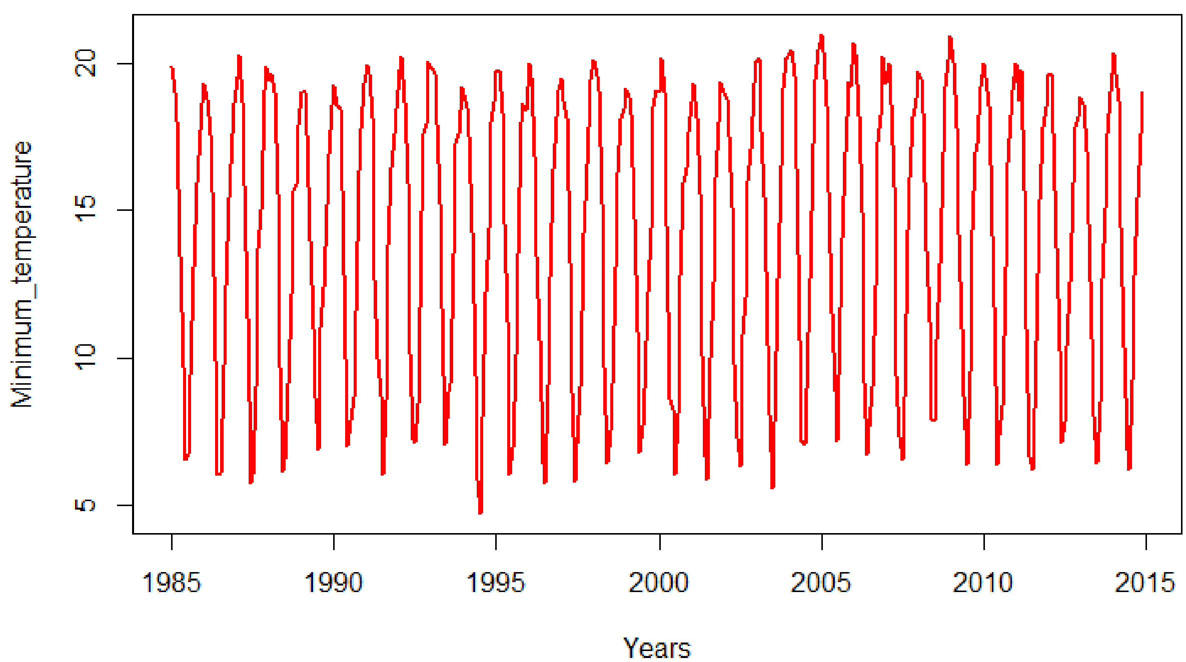



Figure 4.17. Interannual variability of SAWS station minimum temperature over the malaria regions of Limpopo from 1985-2014.

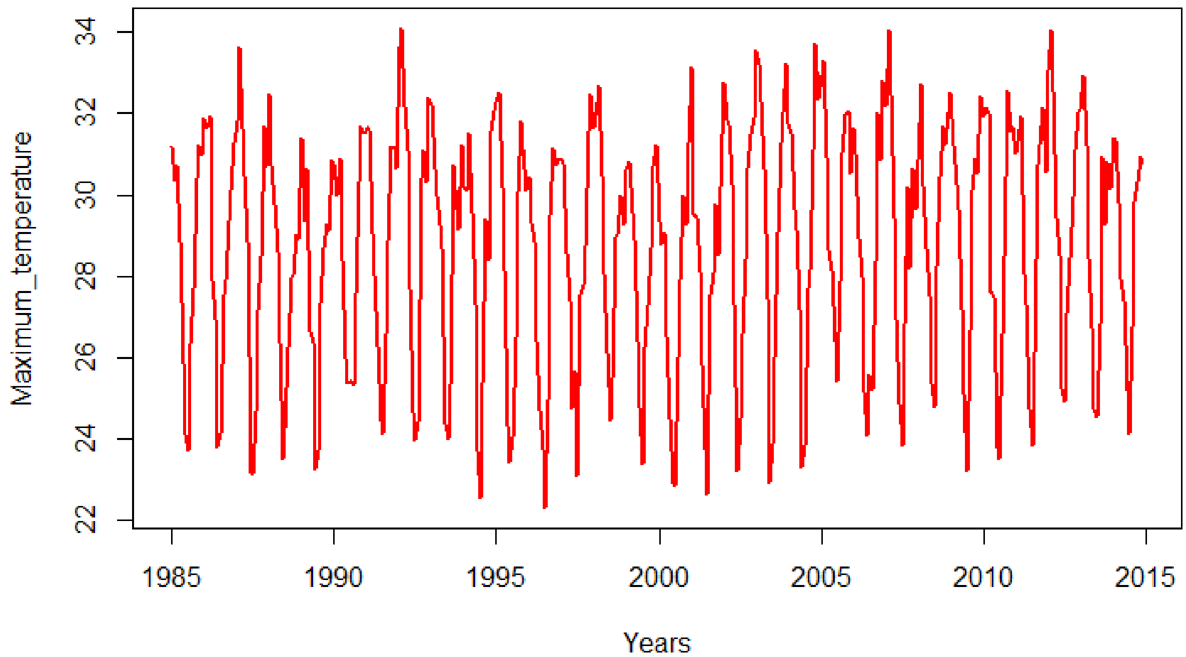



Figure 4.18. Interannual variability of maximum temperature of SAWS station minimum temperature over the malaria regions of Limpopo from 1985-2014.

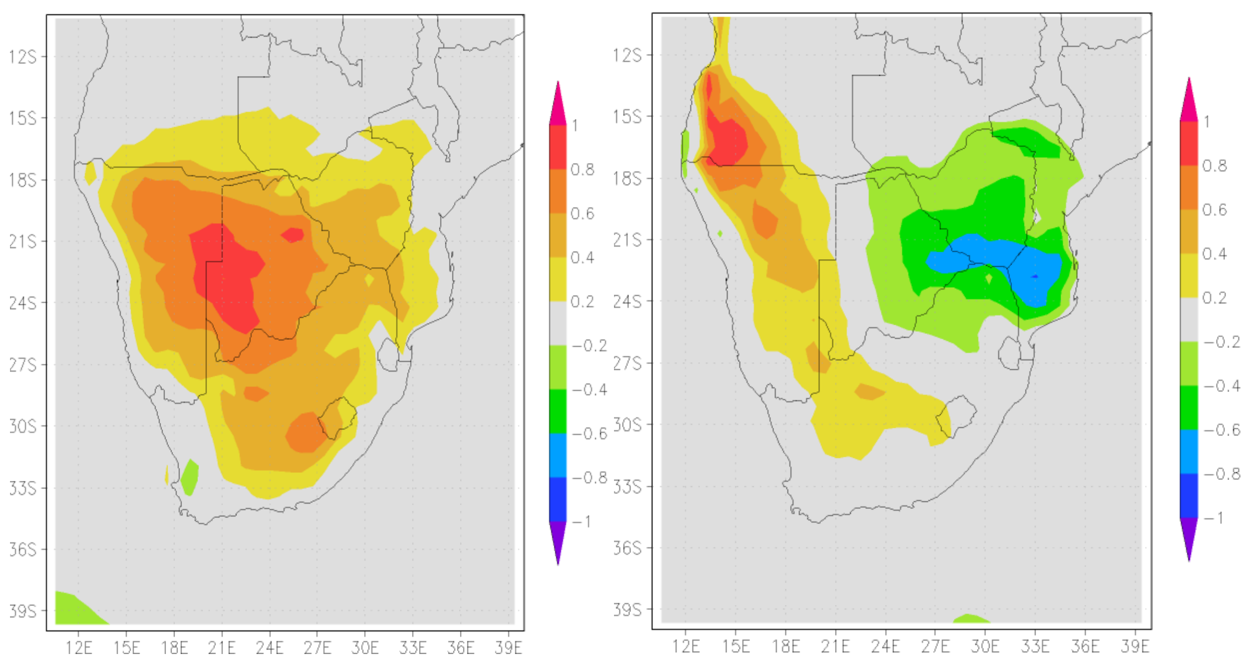



Figure 4.19. PC1 (left) and PC2 (right) of summer temperature over southern Africa. PC1 explains 41.95% and PC2 explains 11.21% of temperature variations.

## 4.4 Humidity

There is a strong west to east gradient in humidity over southern Africa (Figure 4.20). The mean relative humidity of the malaria prone region of Limpopo lies well above 60% (Figure 4.19). High values of relative humidity are observed during austral summer months and peaks in February, whereas low values of relative humidity are experience during austral winter months with the lowest in September (Figure 4.21).

Figure 4.22 shows a decreasing trend in relative humidity since 1985. Figure 4.23 shows that there is a strong Interannual variability of the atmospheric moisture content. More negative anomalies are observed from 2000 to 2014. There is a decreasing trend on the atmospheric moisture content. However, it remains well above 60% during core summer months (DJF). This is one of the conditions that are conducive for both the development of the falciparum parasite and the life cycle of the mosquito vector. During Late winter months (JJA) the atmospheric moisture content falls to well below 60% (Figure 4.24).

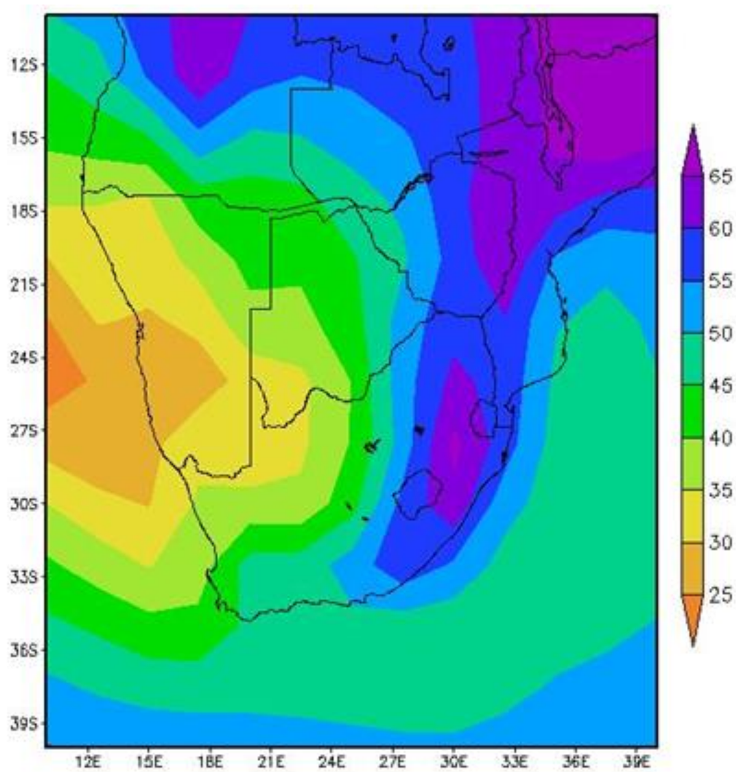



Figure 4.20. Mean annual spatial patterns of NCEP reanalysis relative humidity over southern Africa from 1985-2014.

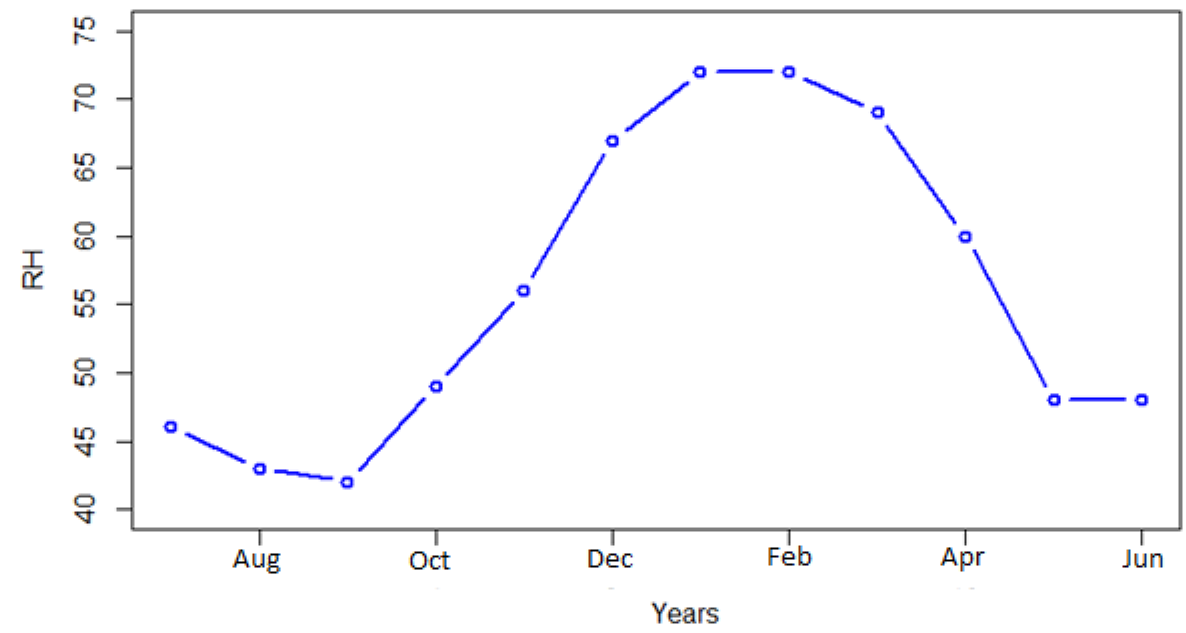



Figure 4.21. Seasonal cycle of SAWS station relative humidity (%/month) over the malaria prone region of Limpopo from 1985-2014.

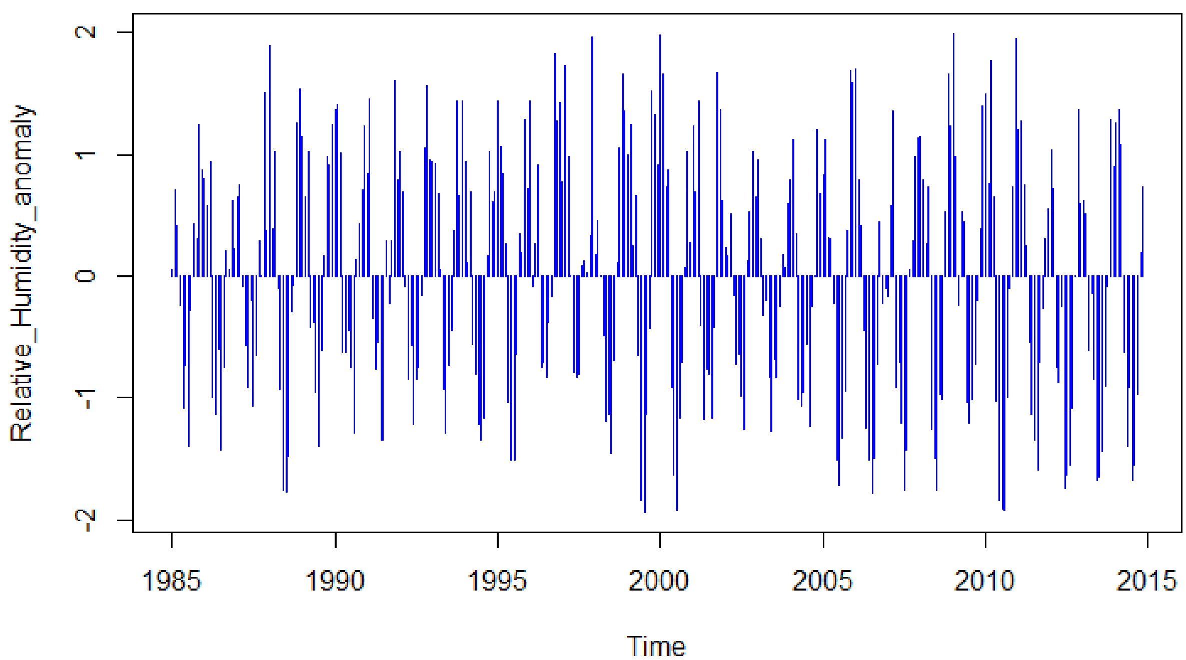



Figure 4.22. Departure from mean of SAWS station relative humidity over the malaria prone region of Limpopo.

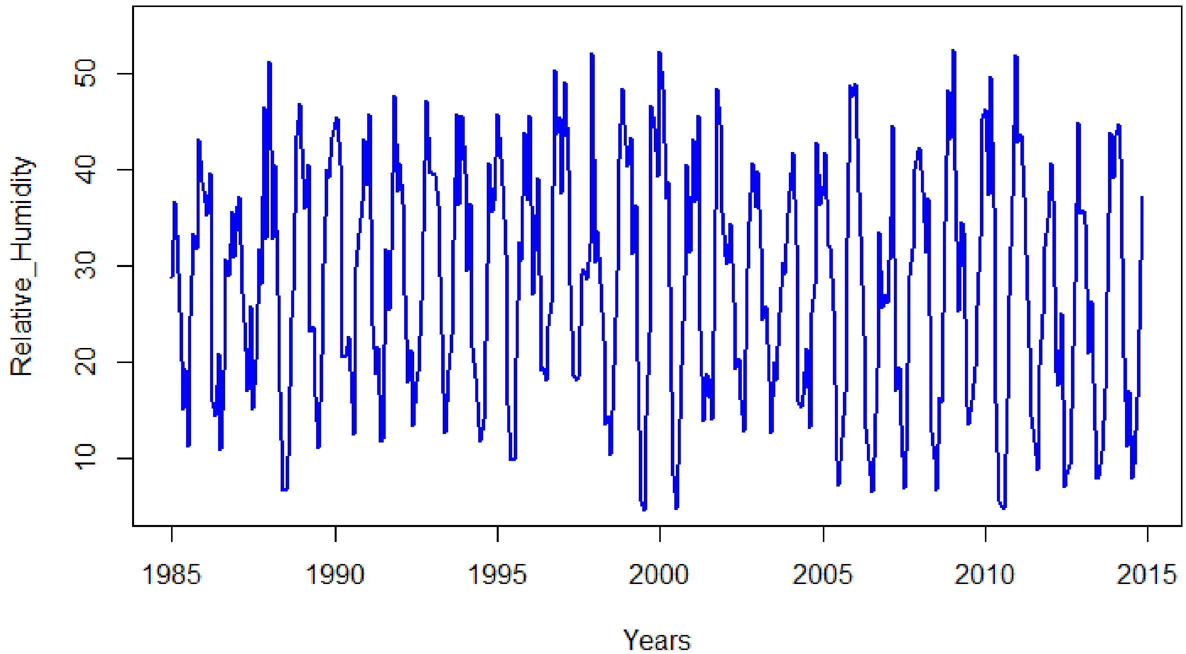
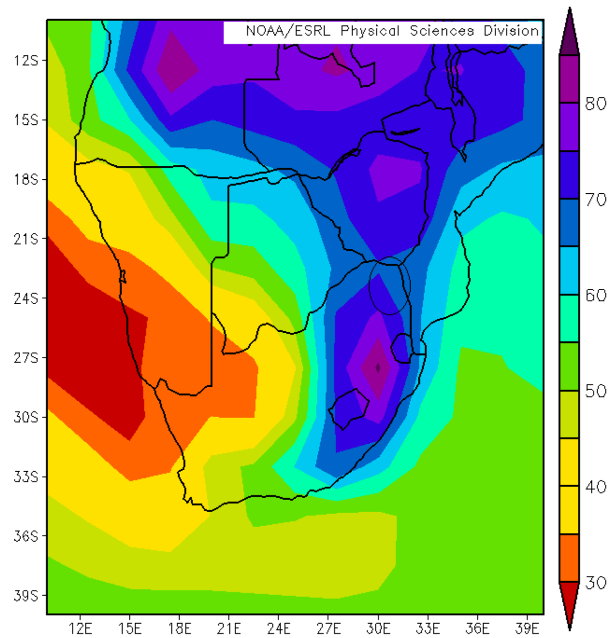



Figure 4.23 Interannual variability of SAWS station relative humidity (%/month) over the malaria prone region of Limpopo.

a)




b)

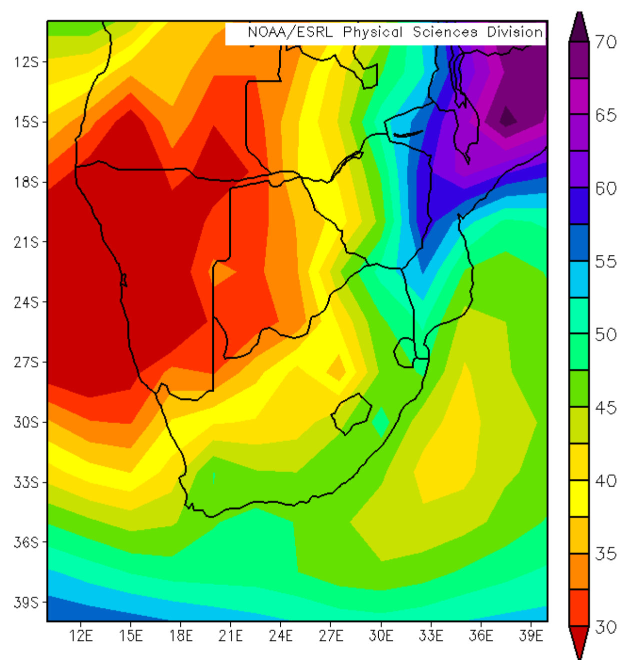



Figure 4.24. NCEP reanalysis relative humidity (%) for (a) December-January-February and (b) June-July-August 1985-2014.

## 4.5 Remote influences

The first two leading Empirical Orthogonal Function (EOF) modes of the monthly Sea Surface Temperatures (SSTs) over the tropical Pacific region are presented in figure 4.25 and 4.26. The EOF 1 shown in Figure 4.25 captures a tongue of positive loading stretching from eastern to central tropical pacific (El Niño pattern). This mode explains 47% variability of the tropical Pacific SST. This pattern has been associated with deficits in rainfall over most parts of southern Africa, with a strongest signal over south-eastern Africa.

EOF 2 shown in Figure 4.26 explains about 11% of the variability, captures a zonal tri-pole pattern in the tropical region. This pattern is known as El Niño Modoki (pseudo El Niño). During El Niño Modoki, both eastern and western tropical Pacific SSTAs show similar patterns, while the patterns of the central tropical Pacific are the opposite. This horse-shoe pattern straddles the tongue of negative loadings in the equatorial eastern Pacific. The magnitudes of the loadings in the central and eastern Pacific are comparable.

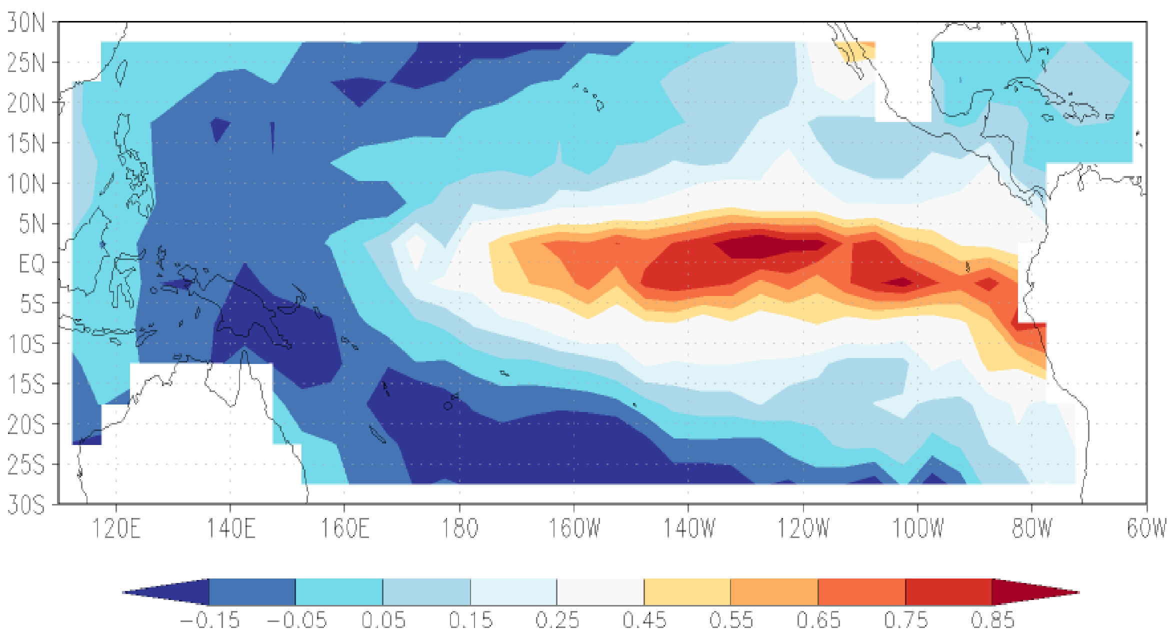



Figure 4.25.The first EOF mode of the tropical Pacific that describes about 47% variability.

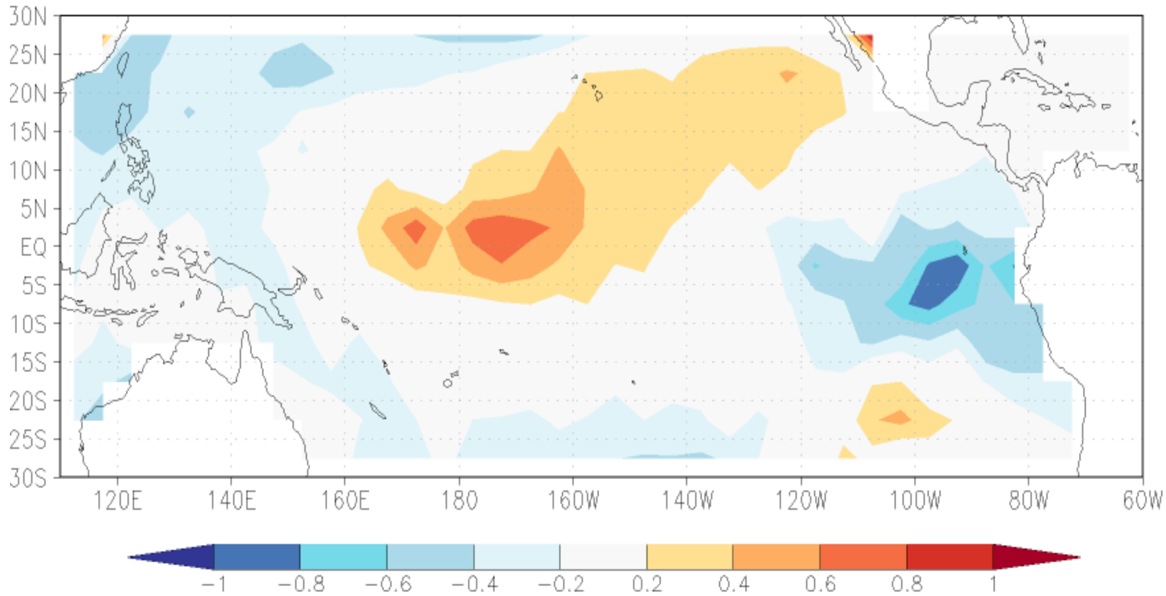



Figure 4.26.The second EOF mode of the tropical Pacific that describes about 11% variability.

## 4.6 Summary

This chapter presented the spatio-temporal climate characteristics of the malaria prone regions of Limpopo. The climate of the malaria prone regions of Limpopo is highly seasonal and varies from time to time, with vast amount of rainfall received during austral summer. There is a notable west to east rainfall gradient. Limpopo is frequent by alternating wet and dry spells. With the Limpopo valley spend most of the season under dry spell.

The summary of the findings of this chapter is as follows:

a) The strong west to east gradient of rainfall, humidity and temperature gradient.
b) Limpopo valley produces a conducive avenue for propagation of tropical evolving systems resulting in extensive floods in austral summer.
c) EOF analysis show 3 distinct modes of rainfall variability over Limpopo can be associated with land falling tropical cyclones, cloud bands and intensity of the Botswana upper high.
d) The blocking effect associated with the ridging anticyclone causes slower propagation of cloud bands and also promote the influx of moisture from the SWIO resulting in high rainfall.
e) The mean temperature of this region is 22.5°C, the highest (28°C) temperatures are experienced in December and the lowest in June (15°C).
f) An increasing trend in both Tmin and Tmax, notably after 2000.

g) Highest relative humidity is observed during late summer with a peak in February, while the lowest observed in September.
h) ENSO and pseudo-ENSO explains about 58% of the climate variability in the malaria prone regions of Limpopo.

# CHAPTER 5

# THE OCCURRENCE OF MALARIA AND ITS LINK TO CLIMATE IN LIMPOPO

## 5.1 Introduction

Approximately 110 million humans in Africa live in regions prone to explosive malaria epidemics. Humans in these regions are not always affected by malaria and therefore they lack immunity to malaria. It is for this reason that malaria remains a life-threatening disease. Epidemics occur after excessive rainfall, usually with a lag-time of several weeks during which mosquito population and malaria infection increases rapidly (Hii *et al.* 2012). The effect of the epidemics can be severe if there is an occurrence of a prolonged wet spell during a drought. However, the effect of malaria can be reduced by the use of early warning systems (Grover-Kopec *et al.* 2005).

South Africa is at the southern extreme of malaria distribution in Africa, where the transmission is strongly seasonal and occurs in out breaks and explosive epidemics. Until the advent of effective vector control methods and antimalarial drugs in the 1930s and 1940s seasonal malaria epidemics caused many deaths. Recently the country has managed to implement practically and evidence-based intervention recommended by World Health Organisation (WHO). Now the programme is on a trajectory for malaria elimination as it has moved beyond malaria control (WHO 2007; Blumberg *et al.* 2014; Raman *et al.* 2016).

Over most parts of southern Africa, the transmission of malaria is strongly seasonal and is characterised by epidemics. Malaria epidemics might result from several factors including human population movement and displacement, malaria control break down, environmental changes and meteorological factors. Meteorological factors are considered important since both *Anopheles* mosquitoes and plasmodium are strongly dependent on them (Na' jera *et al*. 1998). Rainfall, relative humidity and temperature are the main factors that drive the feeding cycle and abundance of *Anopheles* mosquitoes which transmit malaria. Temperature alone drives the rate of development of *Plasmodium* parasite within mosquito vectors. The combined value for climate suitability is an indication of the lower limit for potential malaria transmission.

Limpopo Province is the highest contributor of malaria in the country. Malaria is therefore a priority disease due to its potential to cause explosive epidemics during austral summer months which results in high morbidity and mortality. Historically, the entire Limpopo province was at risk of Malaria (Maharaj *et al.* 2012). Through targeted and sustainable malaria control interventions over the past decade, malaria is now restricted to the eastern Lowveld of Mopani and Vhembe districts. Areas in southern Sekhukhune and western Waterberg however are also prone to low-intensity focal outbreaks during austral summer (Khosa *et al.* 2013).

Climate conditions suitable for malaria fall within a certain specific threshold. The climate conditions are suitable for the transmission of malaria when relative humidity is greater than 60%, monthly accumulated rainfall is greater than 80 mm and temperature ranges between 18°C and 32°C. These thresholds determine both the development of the *falciparum* parasite and the life cycle of the mosquito vector (Grover-Kopec *et al*. 2005).

There are various causal factors (meteorological and non-meteorological factors) that play a role in the distribution and transmission of malaria over a region. This includes, population movement break down or interruption of effective surveillance and control activities, climate anomalies, land use or environmental change. These factors change ecological and transmission equilibrium between malaria parasites, mosquito vectors and human hosts leading to epidemics. This study focuses on the meteorological factor, particularly temperature, humidity and rainfall. The influence of the non-meteorological factor is discussed in the literature review section.

The aim of this chapter is to identify the malaria epidemics in Limpopo from 1998 to 2014, investigate their spatio-temporal characteristics and how meteorological variables and the oceans influence the occurrence of epidemics and the transmission of malaria. Malaria epidemics during the study period are identified in the following section.

## 5.2 Spatial characteristics of malaria

The intensity and endemicity of malaria varies from region to region. Malaria predominantly occurs in humid tropical regions, where temperatures are warm enough for the development of both parasite and vector. The spatial distribution of vectors of malaria is an important factor in malaria endemicity as well as the success of its control.

The potential distribution of stable malaria transmission in an average year is shown in Figure 5.1. Areas with unsuitable climate for the occurrence and transmission of malaria are represented by white color. In these areas, malaria can occur in a form of epidemics probably due to the presence of surface water in an area where there is little or no rain. In the marginally suitable areas between 0.1 and 0.9 malaria transmission is strongly seasonal with a strong interannual variability. Where climate is suitable (red = 1), malaria is likely endemic (hypo-, meso-, hyper- or holo-endemic). Malaria control activities can also dramatically alter the transmission situation.

Therefore, suitable areas may have little or no malaria because of malaria control (Craig *et al.* 1999).

Most parts of Limpopo are suitable for malaria transmission, but the eastern low veld, in Mopane and Vhembe Districts are the most suitable regions (Figure 5.1). The seasonal suitability for malaria transmission used in this study is based on empirically-derived thresholds of at least 80 mm accumulated rainfall, mean temperature ranging between 18°C and 32°C and at least 60% monthly relative humidity. The latter is applicable for plasmodium *falciparum* which is a dominant species in Limpopo (Grover-kopec *et al.* 2006; Olayemi *et al.* 2014). However, in practice, the optimal and limiting conditions for transmission are dependent on the species of the parasite and vector (Grover-Kopec *et al.* 2006). Due to strong malaria intervention strategies that have been put in place in recent years, malaria transmission tends to occur in a form of epidemics with strong seasonal cycles and varies greatly from year to year as shown in section 5.3 (Griffin *et al.* 2010) (Figure 5.2, 5.4 and 5.5).

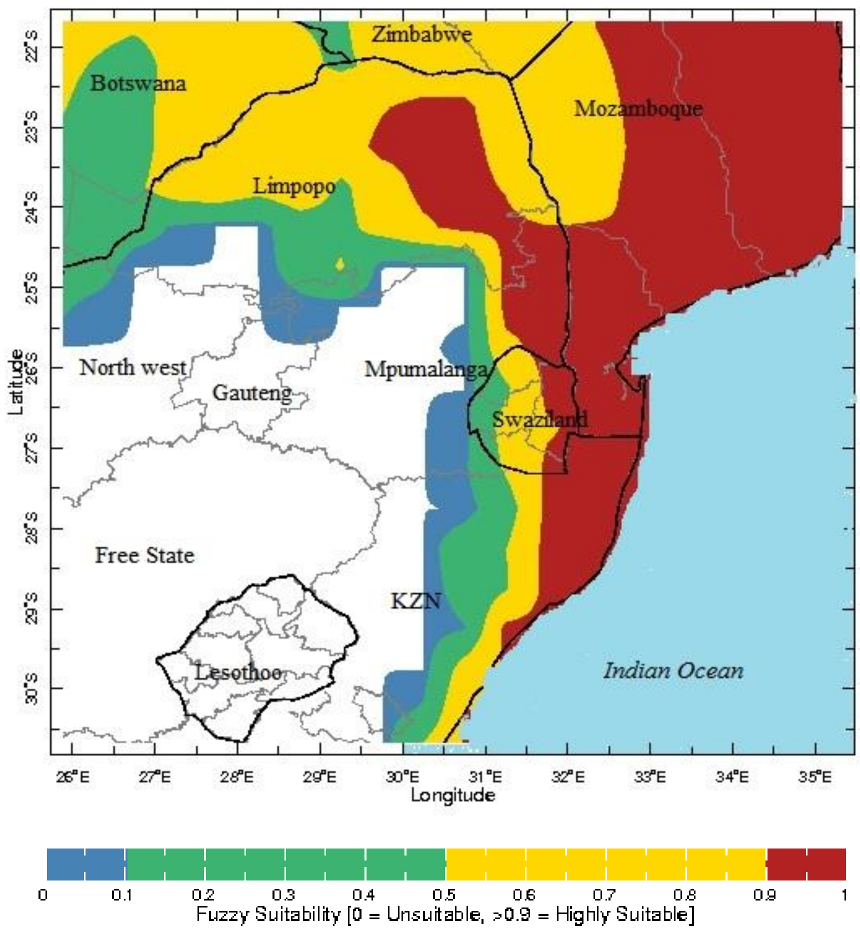



Figure 5.1. MARA-climatic suitability for malaria transmission over southeast Africa.

## 5.3 Temporal characteristics of malaria

Malaria transmission in the prone regions of Limpopo is strongly seasonal. The annual cycle was considered using monthly mean malaria cases averaged over the region. Malaria incidences rise from September to March with a peak in January, followed by a sharp decline. On average above 700 cases of malaria are reported during January. This coincides with a peak number of humans returning from Christmas holidays from the neighbouring malaria prone regions. It can then be argued that a considerable percentage of the reported cases are imported. A negligible number of cases being are during core winter months (JJA) (Figure 5.3).

The number of months suitable for malaria transmission vary from zero suitability in the western reaches of Limpopo province to about 7 months in the east coast of Kwa-Zulu Natal. Malaria transmission in the prone regions of Limpopo is suitable for about 5 months, with a pronounced west to east suitability gradient (Figure 5.4).

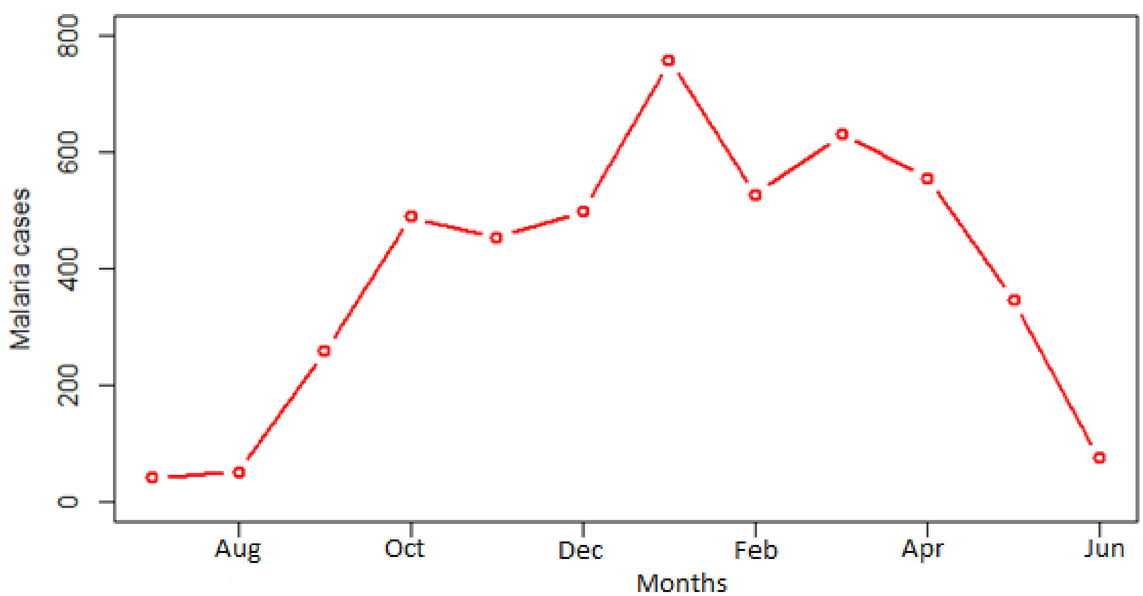



Figure 5.2. Seasonal cycle of malaria over Limpopo from 1998-2014.

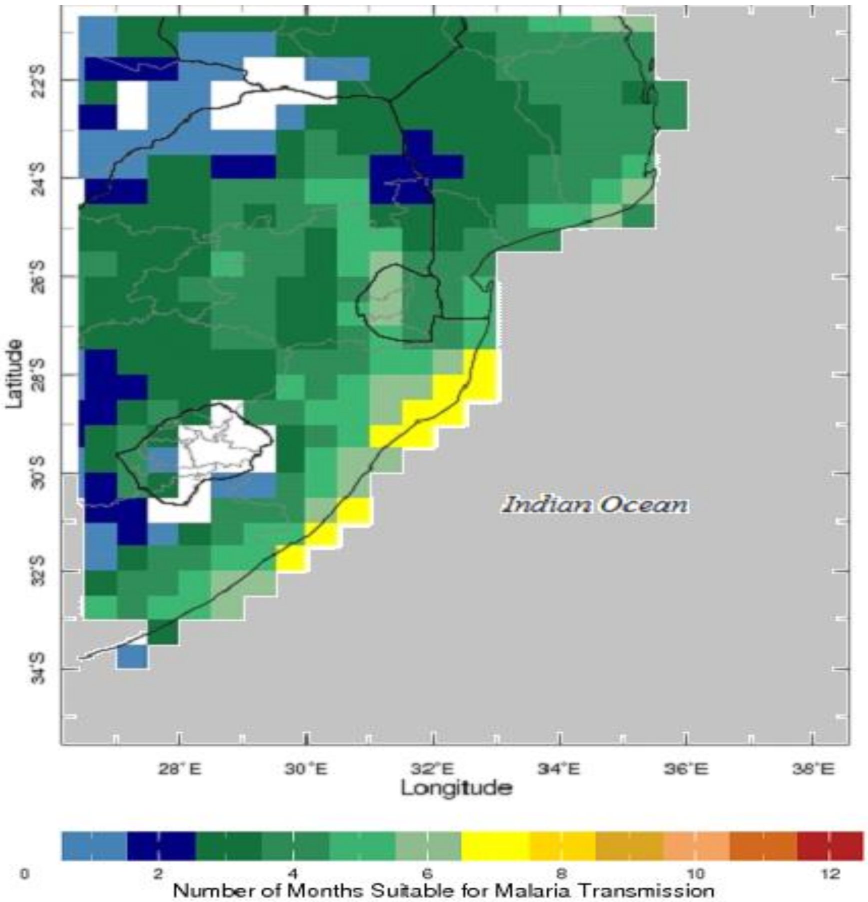



Figure 5.3. MARA seasonal climatic suitability for malaria transmission

A total of 79099 malaria cases were reported from 1998-2014, with the highest number of cases being reported in 2000, while the lowest number of cases was reported in 2010. There is an evident decreasing trend in the malaria incidences notably from 2006. Malaria shows an interannual variation of malaria with an alternation of low and high cases with a 2-year cycle. An epidemic typically occurs at the beginning of a cycle, followed by a slow downward trend to a minimum, then a sudden upswing (Figure 5.5).

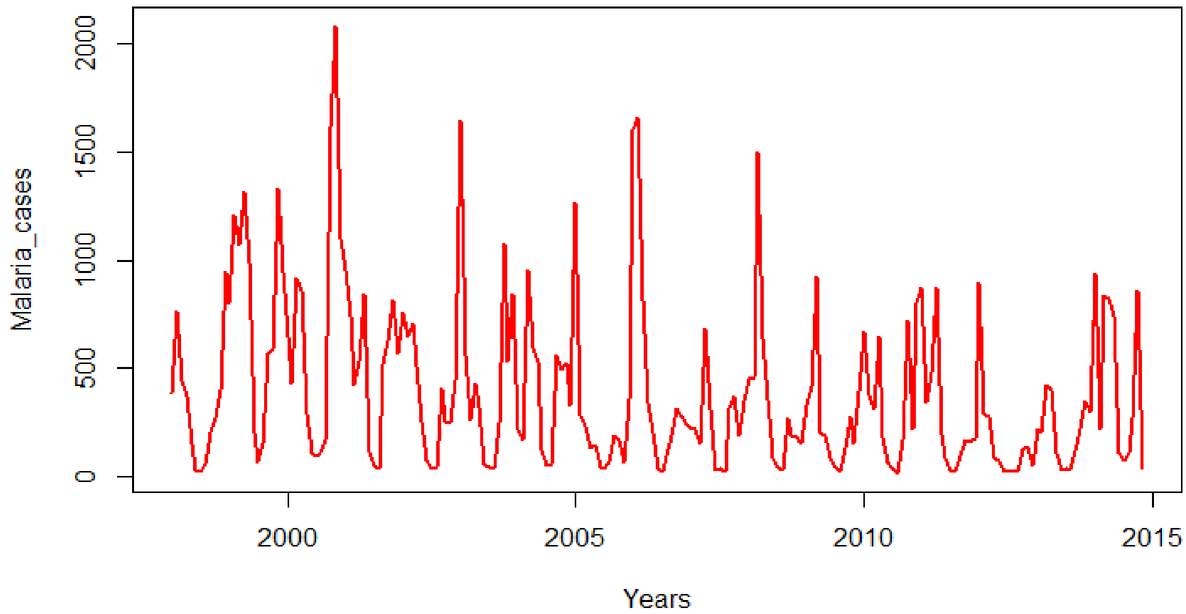



Figure 5.4. Interannual variability of malaria over Limpopo from 1998-2014.

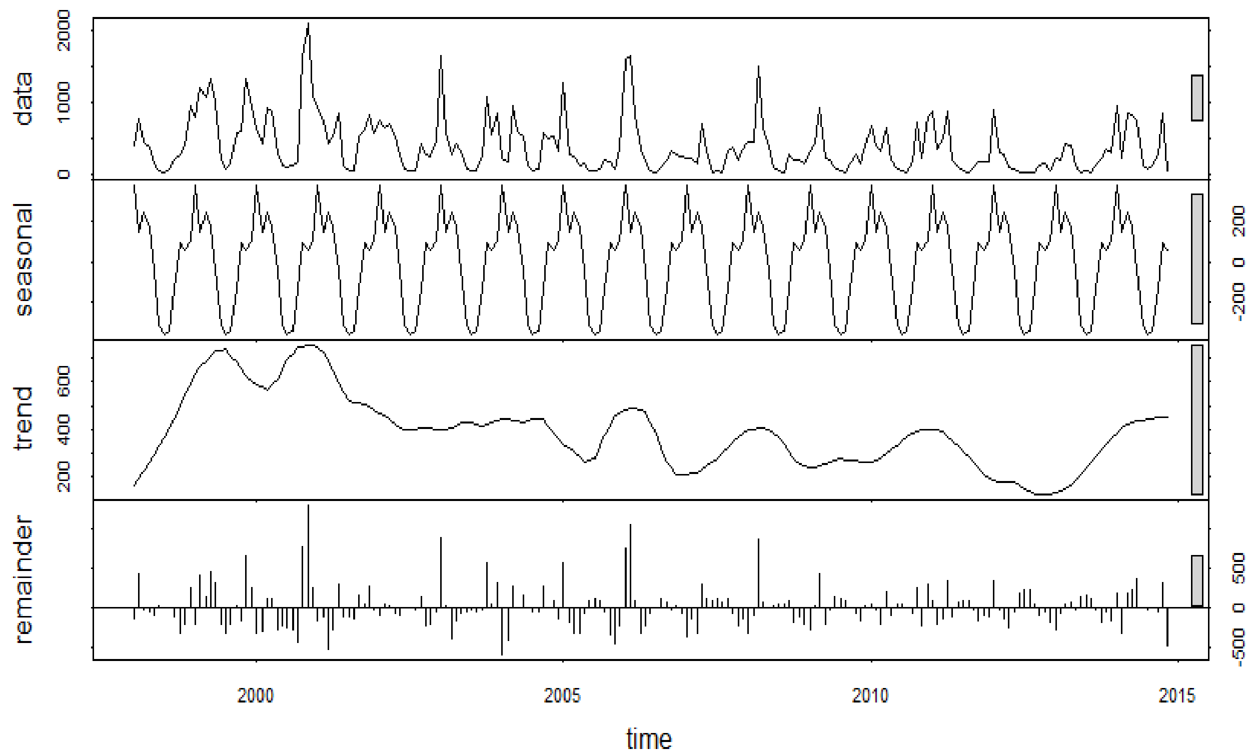



Figure 5.5. Seasonal decomposition of a malaria time-series of Limpopo from 1998-2014.

Seasonal decomposition of malaria interannual time series is shown in Figure 5.5. Here, malaria interannual variation time series is filtered into trends, seasonal and remainder/residual components. The second panel from the top show trends within the data, which is the low frequency variation in the data together with non-stationary and long term trends. The third panel shows seasonal cycles in malaria transmission. The remaining variation which is beyond that in seasonal and trend components is shown in the fourth panel.

## 5.4 Identification of malaria epidemics

Monthly malaria data (described in chapter 3) was de-trended and used to identify malaria epidemics. When data varies seasonally it helps to express it in terms of standardized anomalies. Standardized anomalies are calculated by dividing anomalies by the standard deviation to remove the influence of dispersion and provide more information about the magnitude. Malaria epidemics are identified using Equation 22. Malaria cases which are greater than two standard deviations from the mean were identified as epidemics. The identified epidemics are shown in table 5.1.

$$Mi = \frac{\sum_i^n (x-\mu)}{\sigma} \quad \text{......................................................} \quad (22)$$

Where: $Mi$= Malaria index, $x$= Malaria cases, $\mu$= mean malaria and $\sigma$= standard deviation

Table 5.1. Identified malaria epidemics in Limpopo

| Date (Year/month) | Malaria cases | Anomaly |
|---|---|---|
| 1999/03 | 1205 | 2.1 |
| 2000/11 | 2086 | 3.2 |
| 2003/02 | 1648 | 3.3 |
| 2005/02 | 1268 | 2.3 |
| 2006/02 | 1603 | 3.1 |
| 2008/04 | 1503 | 2.9 |

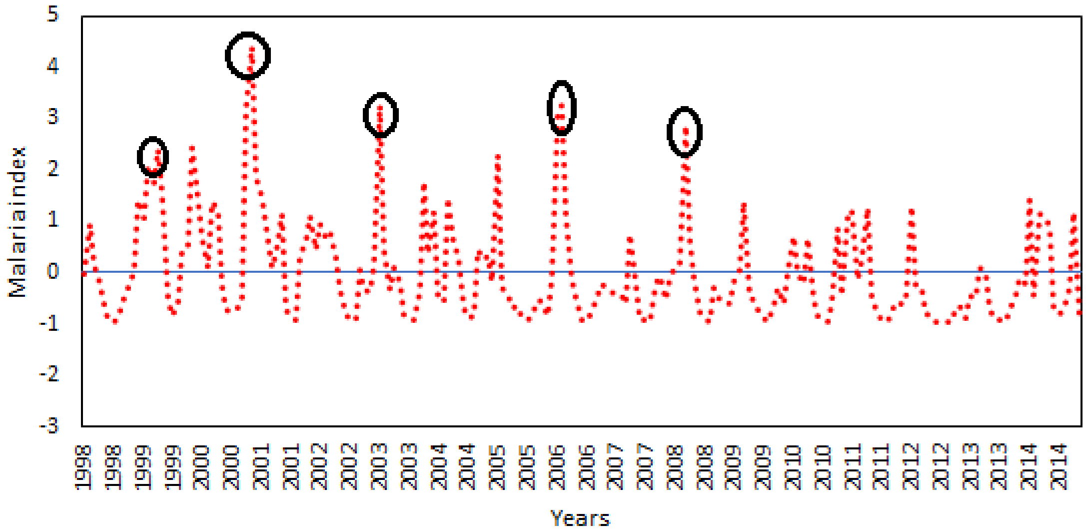



Figure 5.6. Departure from mean of malaria over Limpopo from 1998-2014.

## 5.5 Climate and malaria

The association between malaria and meteorological factors is complex due to the lagged and non-linear pattern. Without fully considering these characteristics, existing studies concluded inconsistent findings. Investigating the lagged correlation pattern between malaria and meteorological variables may improve the understanding of the association and possibly generate better prediction models (Zhao *et al.* 2014). From the explanatory analysis, lag times of up to three months for rainfall, temperature and humidity were considered.

More malaria cases were reported when the minimum temperature was above 16°C. This result is consistent with the findings of Alemu *et al.* (2011), who found that there is about 90% daily survival of *Anopheles* mosquitoes when the temperature is between 16°C and 36°C. They went on and argued that relative humidity greater than 60% combined with mean temperatures between 20°C and 30°C are ideal for the transmission of malaria.

A spatial correlation between December meteorological variables (rainfall, temperature and humidity) and malaria cases at one month lag time is shown in Figure 5.7. Meteorological variables depict positive relationship with malaria when meteorological variables are leading by one month. The spatial correlation between (a) malaria and rainfall ranges from 0.2 to 0.4; (b) malaria and temperature ranges from -0.3 to -0.5 and (c) finally ranges from 0.2 to 0.4 between relative humidity and malaria over the area of interest. The correlation between meteorological variables increases from west to east, with little or no relationship on the western regions of the Limpopo province.

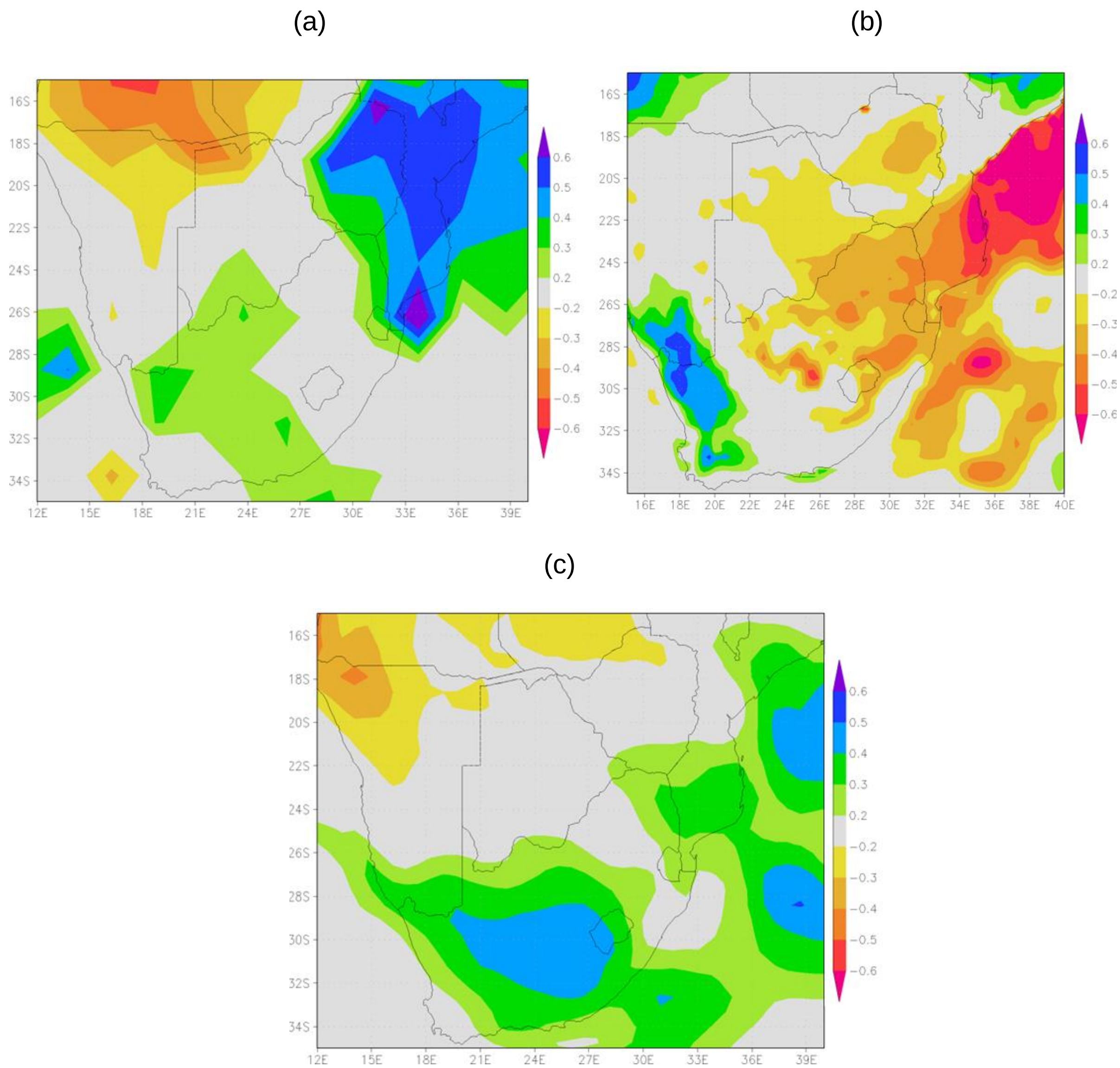



Figure 5.7. Spatial correlation of malaria index with (a) GPCP v2 precipitation, (b) NCEP/NCAR temperature and (c) CRU TS relative humidity for September-February from 1998-2014 at 1-month lag at 90% significant using 2-tailed t-test..

Correlation amongst independent variables are shown in Table 5.2. There is a high positive correlation between all the variables, except rainfall. Monthly maximum temperature and minimum temperature (r = 0.92, $p$ < 0.001) showed a highest correlation, followed by monthly minimum temperature and relative humidity (r = 0.75, $p$ < 0.001), monthly maximum temperature and relative humidity (r = 0.55, $p$ < 0.001). Rainfall is negatively correlated with all variables. An association between monthly malaria cases and meteorological variables (rainfall, maximum temperature, minimum temperature, relative humidity) was observed and further checked by

Pearson's correlation at zero to three months lagged periods. At zero-month effect, none of the variables showed negative correlation. Highest correlation was shown by minimum temperature and relative humidity (r = 0.52; $p < 0.001$, r = 0.52; $p < 0.001$, respectively) followed by maximum temperature (r = 0.4; $p < 0.001$), and rainfall (r = -0.304; $p < 0.001$). This result suggests that periods of high rainfall are associated with lower maximum temperatures due to amongst others, the effect of cloud cover on shortwave radiation. Further, higher amount of relative humidity can be expected to be associated with higher minimum temperatures because water vapour acts as a greenhouse gas. Low rainfall severely restricts potential vector breeding sites, with a major impact on vector abundance and vectorial capacity. There is a negative but statistically significant relationship between rainfall and malaria at 0-month lag in Limpopo. However, the relationship between malaria and rainfall is positive at a 3-month lag time (Table 5.3).

Monthly meteorological factors dynamically correlated with monthly malaria incidence during the period of the study. Examining of correlations showed statistically significant association between meteorological factors behind malaria incidence time series. However, meteorological variables generally did not show strong correlation with malaria incidence at zero-month lag time. Statistical significant correlations between the meteorological variables and monthly malaria incidence were observed when climate factors time-series lagged malaria time series by at least one month (Figure 5.8-5.11).

This indicates that changes in meteorological factors prior to malaria outbreak are an important influencing factor and at least one-month time is needed for meteorological factors to have a strong effect on the occurrence and transmission of malaria. This is with the exception of rainfall which only show a positive correlation at three-month lag time (Figure 5.12). This can be explained by the fact that wide spread rainfall destroys mosquito sites. However, water pools which results from that rainfall form conducive avenue for mosquito breeding.

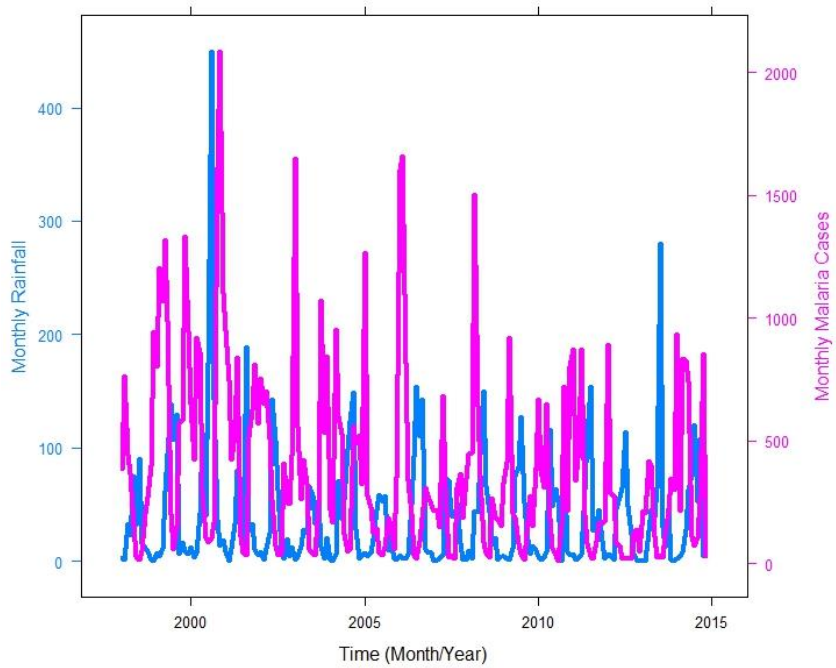



Figure 5.8. Relationship between monthly rainfall and malaria cases over Limpopo from 1998-2014.

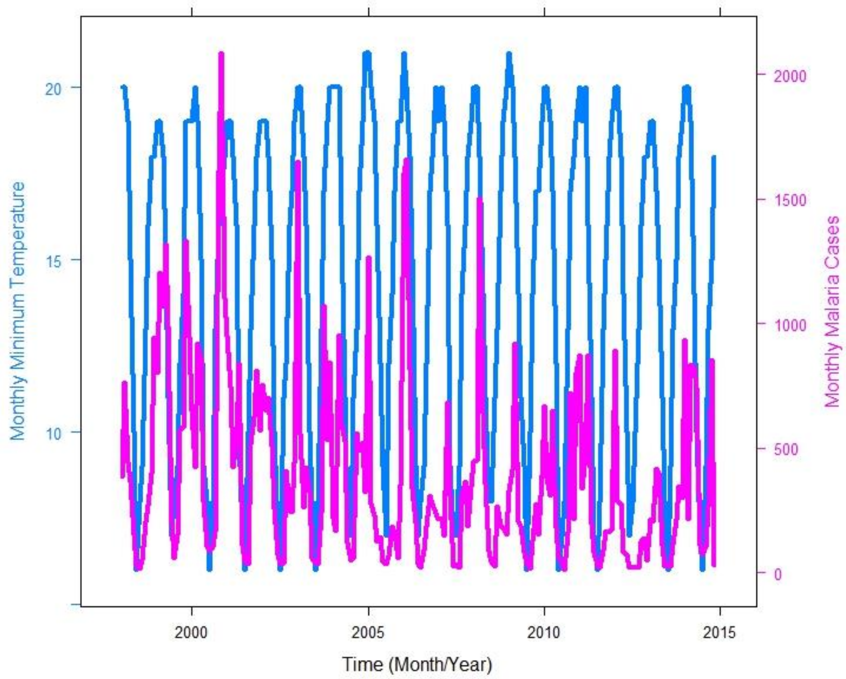



Figure 5.9. Relationship between monthly minimum temperature and malaria cases over Limpopo from 1998-2014.

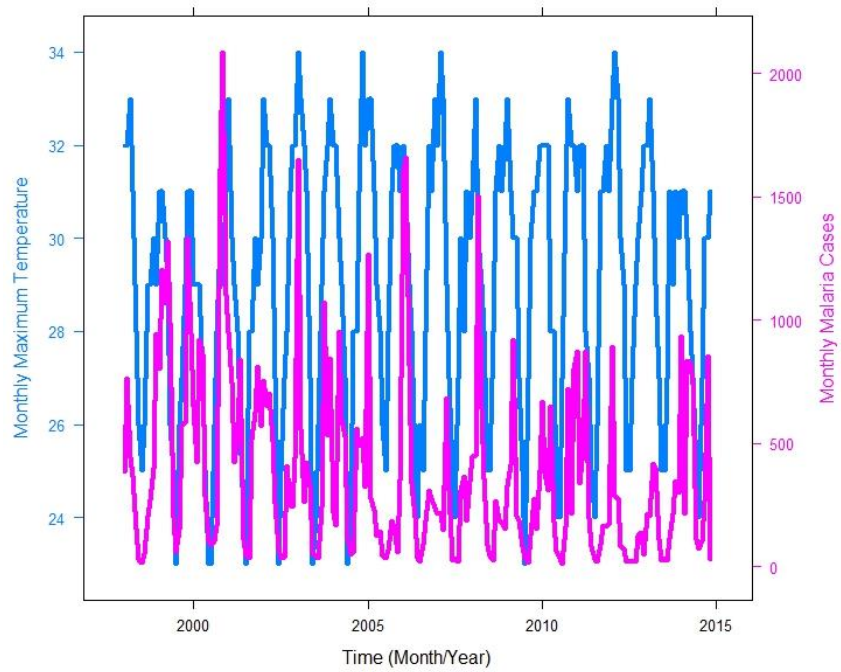



Figure 5.10. Relationship between monthly maximum temperature and malaria cases over Limpopo from 1998-2014.

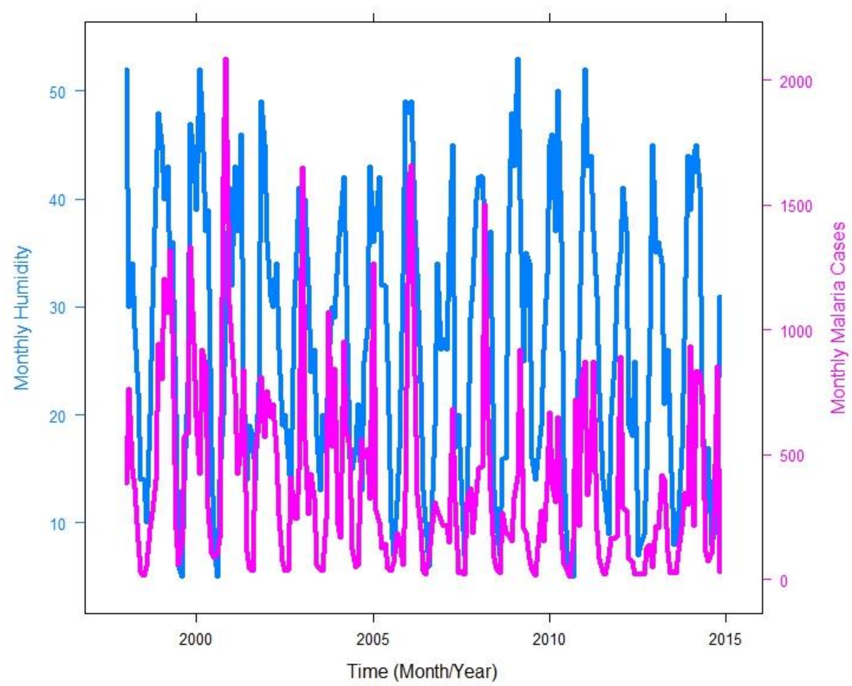



Figure 5.11. Relationship between monthly relative humidity and malaria cases over Limpopo from 1998-2014.

Table. 5.2. Auto-correlation between meteorological variables

| | Tmax | Tmin | RH | Rainfall |
|---|---|---|---|---|
| Tmax | 1 | 0.92 | 0.55 | -0.58 |
| Tmin | 0.92 | 1 | 0.75 | -0.64 |
| RH | 0.55 | 0.75 | 1 | -0.51 |
| Rainfall | -0.58 | -0.64 | -0.51 | 1 |

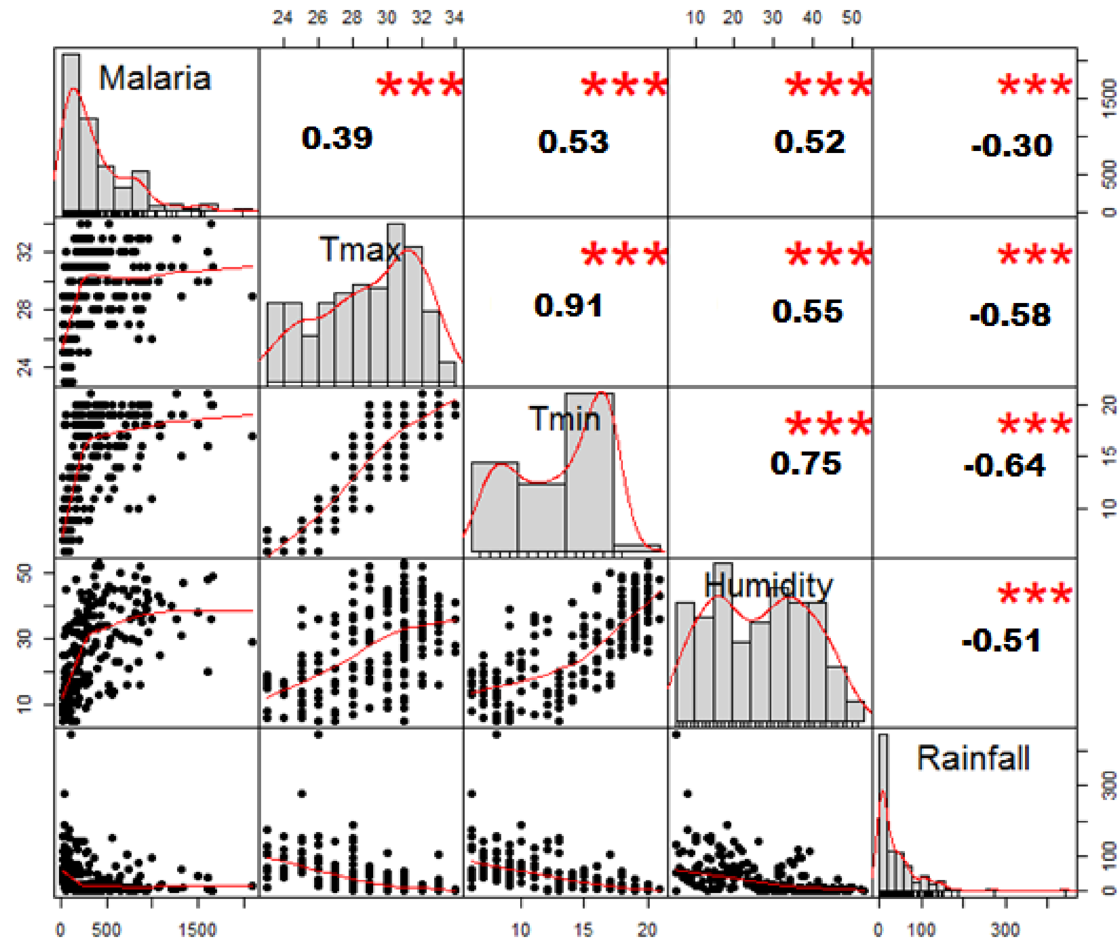



Figure 5.12. Spearman's correlation analysis between climatic variables (Tmax, Tmin, Humidity and rainfall) and malaria counts.

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Table 5.3. Correlation between malaria cases and climatic variables at 0-3 months lags.

| Climatic variables | Lag time | R | *p*-Value |
|---|---|---|---|
| **Rainfall** | 0 month | -0.304 | <0.001 |
| | 1 month | -0.28 | <0.001 |
| | 2 months | -0.08 | >0.025 |
| | 3 months | 0.17 | <0.017 |
| **Tmax** | 0 month | 0.4 | <0.001 |
| | 1 month | 0.42 | <0.001 |
| | 2 months | 0.27 | <0.001 |
| | 3 months | -0.31 | >0.011 |
| **Tmin** | 0 month | 0.52 | <0.001 |
| | 1 month | 0.53 | <0.001 |
| | 2 months | 0.35 | <0.001 |
| | 3 months | -0.18 | >0.012 |
| **RH** | 0 month | 0.52 | <0.001 |
| | 1 month | 0.45 | <0.001 |
| | 2 months | 0.2 | <0.004 |
| | 3 months | 0.09 | >0.187 |

Forecasting may rely on several techniques related to statistics and mathematical modeling. The forecasting method used in this study is based on a statistical method known as Seasonal Auto-Regressive Integrated Moving Average (SARIMA), with use of external regressor variables (SARIMAX). SARIMA(X) models are designed to account for serial autocorrelation in seasonal time series (Adeola *et al.* 2017). Model selection was automated using the auto arima function, which performs a stepwise regression on the data and selects the best model based on the Akaike Information Criterion (AIC).

The time series plot of monthly incidence was examined to check for seasonal effects using an Augmented Dickey-Fuller (ADF) test. To achieve a stationary time series, monthly incidence was seasonally differenced by replacing each observation by the difference between itself and the observations of a previous. The climatic variables were also seasonally differenced. The residuals were further examined to check for seasonal effect and help identify model parameters using Autocorrelation function (ACF) and partial autocorrelation function (PACF).

Augmented Dickey-Fuller test (ADF test) was used to determine the requirement of differencing with in the model. The ADF test results indicate that the transformed malaria cases time series is stationary, the p-value is less than 0.05 ($p$ = 0.01). Therefore the ADF test rejects the null hypotheses of non-stationarity with in the data. The T-value (obtained by ar1/se) is greater than 3 which suggest that the co-efficient is significant. Ljung-Box test was also performed to evaluate auto correlation within the data, the $p$-value of greater than 0.05 ($p$ = 0.203 is obtained suggesting there is no auto-correlation).

The plots suggest SARIMA (2,1,2) $(1,0,0)_{12}$ confirmed with the auto-Arima function as the best forecasting model that fit the training dataset well. The AIC values for the SARIMA models fitted to the malaria cases data are shown in Table 5.4.

Table 5.4 Akaike Information criterion (AIC) values for Seasonal Autoregressive Integrated Moving Average (SARIMA) models.

| **Model Type** | **AIC Values** |
|---|---|
| (0,1,0)(2,0,0)[12] | 114.17 |
| (1,1,0)(2,0,0)[12] | 106.166 |
| (2,1,0)(2,0,0)[12] | 93.9264 |
| (2,1,1)(1,0,0)[12] | 81.2097 |
| (1,1,2)(1,0,0)[12] | 77.5727 |
| **(2,1,2)(1,0,0)[12]** | **76.6838** |

From the coefficients obtained, the equation below was formulated and it can be written as:

$$\gamma_t = 1.4398^* \, \gamma_{(t-1)} - 0.5429^* \, \gamma_{(t-2)} + 0.1210\varepsilon_{(t-1)} + 0.0879\varepsilon_{(t-2)} \ldots\ldots\ldots\ldots (23)$$

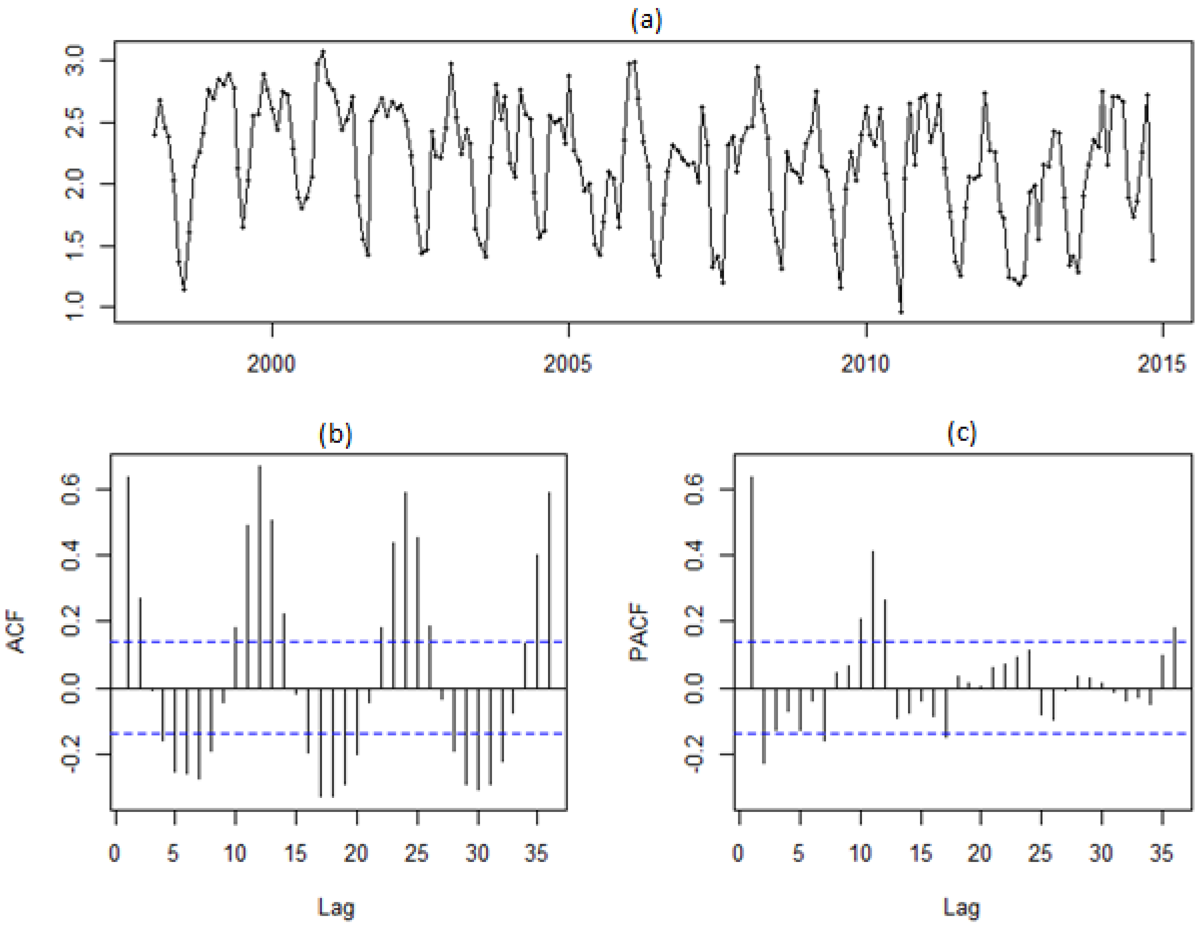


Figure 5.13. (a) Time series of logarithmic and differenced malaria cases between January 1998 and November 2014, (b) the Autocorrelation function (ACF), and (c) Partion Autocorrelation function (PACF) were used to identify the appropriate order of Autoregressive (AR) and Moving Average (MA).

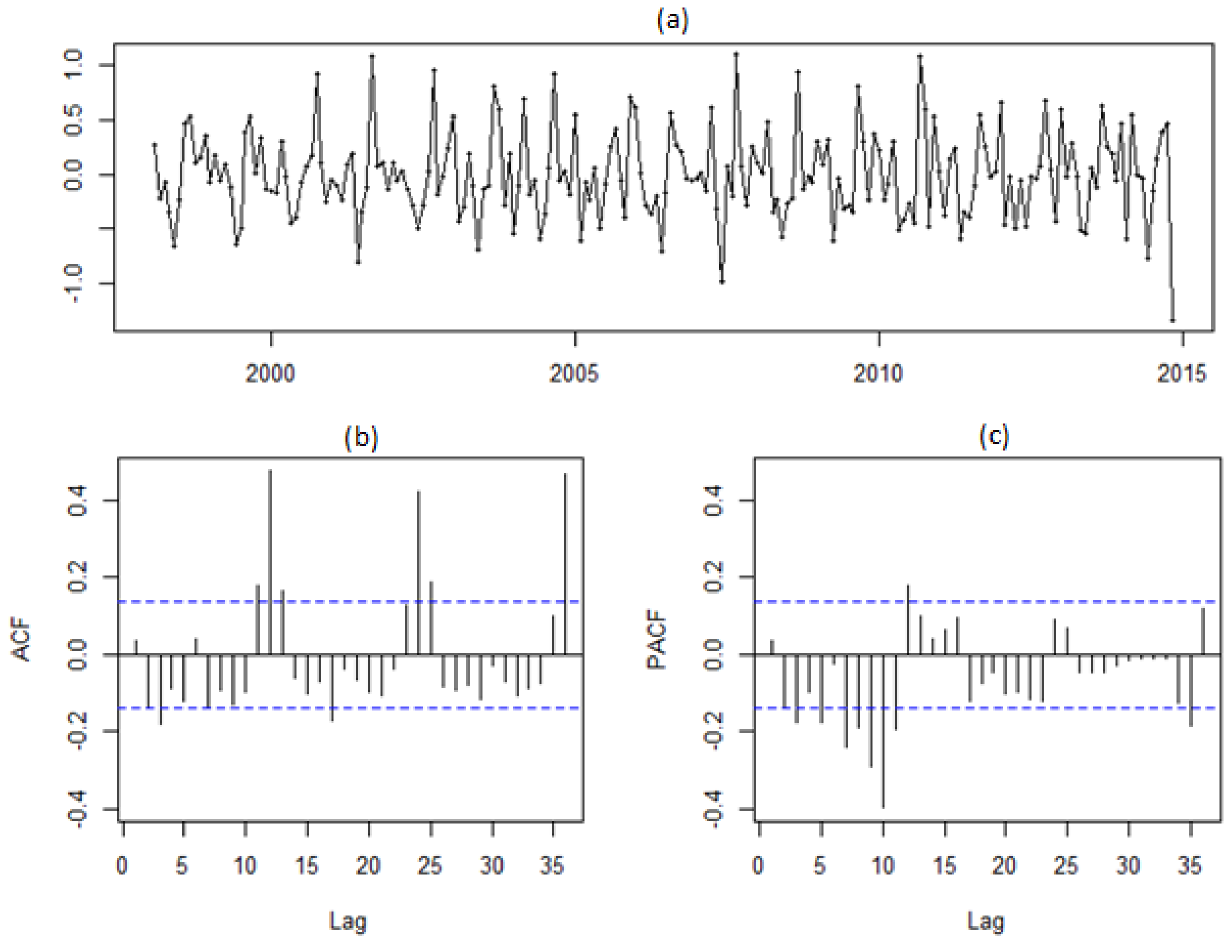


Figure 5.14. (a) Residual of the time series between January 1998 and November 2014, (b) the Autocorrelation function (ACF), and (c) Partion Autocorrelation function  (PACF) were used to identify the appropriate order of Autoregressive (AR) and Moving Average (MA).

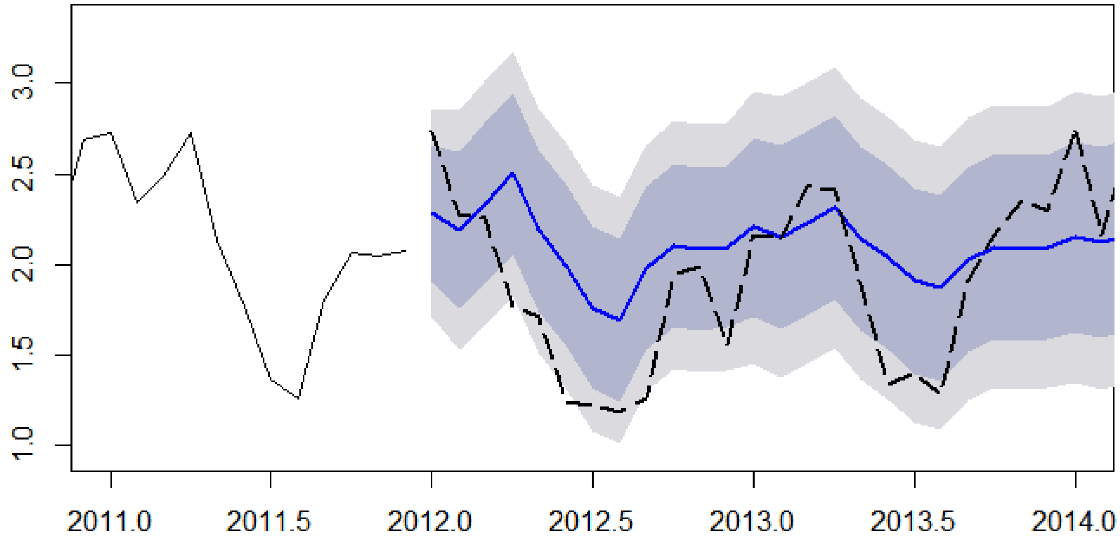


Figure 5.15. Actual (observed-dashed black line) and predicted (fit-blue line) transformed values of malaria cases from January 2012 to November 2014 without climatic variables.

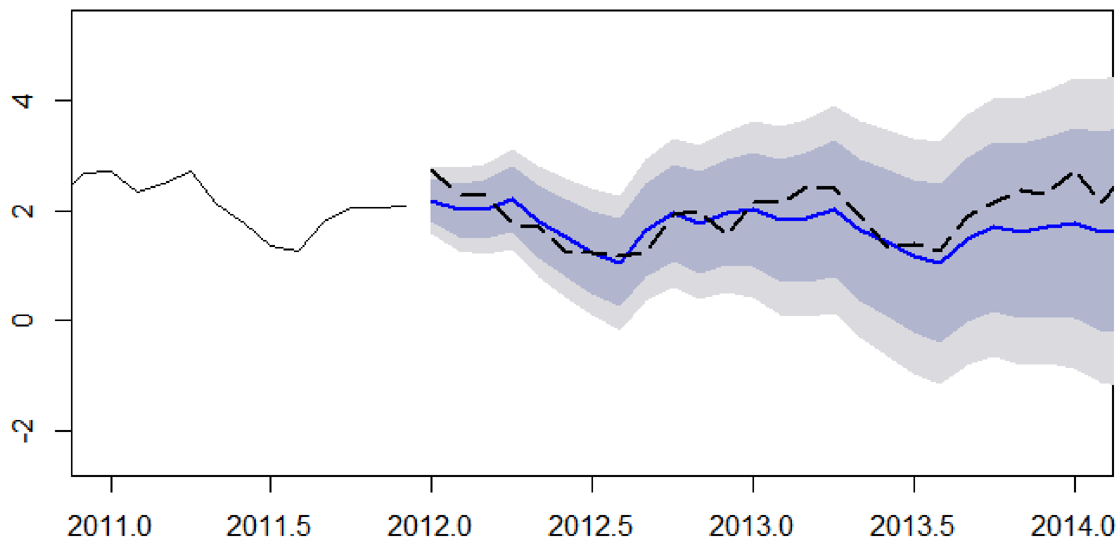


Figure 5.16. Actual (observed-dashed black line) and predicted (fit-blue line) transformed values of malaria cases from January 2012 to November 2014 with exogenous variables.

## 5.6 Remote influences

The location of Limpopo in the malaria distribution fringe concentrated in the subtropics which are influenced by the large-scale oscillation of the Pacific Ocean and the Indian Ocean (Craig *et al*. 1999). SST changes in the equatorial pacific have been linked with interannual climate variability in these regions. In fringe areas malaria transmission is epidemic prone case incidences show substantial inter-annual variation. Interannual variability in the incidences of malaria has been linked with interannual climate variability associated with ENSO (Mabaso *et al*. 2007) and possibly to climate change (Bouma *et al*. 1994). This has led to a suggestion that interannual climate data and ENSO index can be used to monitor and provide malaria epidemics early warning system at least three months in advance to help health managers to plan interventions (Hay *et al*. 1998; Thomson *et al*. 2000).

The warmer than average patterns of SSTs in the western equatorial Indian Ocean with cooler than average conditions in the east (positive phase of Indian Ocean Dipole) can sometimes be triggered by ENSO events. Positive phase of IOD is a pattern of warmer than average SSTs in the western equatorial Indian Ocean with cooler than average conditions in the east. Because of interactions between the IOD and ENSO, the impacts of ENSO may be altered by the IOD phase. Therefore, the best guidance for seasonal mean climate is from regional forecasts that are available 3-6 months in advance of the season of interest. It is therefore important to investigate the influence of the Indian Ocean and Atlantic Ocean on the transmission of malaria.

This section examines the remote influences on malaria transmission. The correlation between climate indices is shown in table 5.4. Niño3.4 index appears to influence significantly to other climate indices, a positive relationship is observed between Indian Ocean Dipole index and ENSO Modoki Index (EMI) (r = 0.37 and r = 0.25 respectively) and negative relationship with Arctic Oscillation (AO) and Indian ocean subtropical dipole (IOSD) (r = -0.32 and r = -0.24 respectively). It appears ENSO disturbs the relationship between other climate modes. Therefore, partial correlation of the other climate modes when the influence of ENSO is performed and is shown in table 5.5. EMI was found to have greater influence on other indices followed by IOD when Niño3.4 index is removed.

The correlation between climate modes and malaria transmission in Limpopo is shown in table 5.6. Negative phase of IOD influences greatly on the occurrence and transmission of malaria (r = 0.449, $p < 0.052$) when the influence of ENSO is removed.

Table 5.5 Climate modes correlation.

| | IOD | IOSD | AAO | Nino3.4 | EMI |
|---|---|---|---|---|---|
| IOD | 1 | -0.07 | -0.14 | 0.37 | -0.24 |
| IOSD | -0.07 | 1 | 0.09 | -0.24 | 0.13 |
| AAO | -0.135 | 0.09 | 1 | -0.32 | -0.18 |
| Nino3.4 | 0.37 | -0.24 | -0.32 | 1 | 0.25 |
| EMI | -0.24 | 0.13 | -0.18 | 0.25 | 1 |

Table 5.6 Partial correlation of climate modes with Nino 3.4 excluded.

| | IOD | IOSD | AAO | EMI |
|---|---|---|---|---|
| IOD | 1 | -0.015 | -0.19 | -0.27 |
| IOSD | -0.07 | 1 | 0.12 | 0.14 |
| AAO | -0.14 | 0.09 | 1 | -0.24 |
| EMI | -0.27 | 0.14 | -0.24 | 1 |

Table 5.7 Correlation of malaria and climate modes

| | R | P-value |
|---|---|---|
| IOD | -0.449 | <0.052 |
| IOSD | -0.112 | <0.011 |
| AAO | -0.019 | <0.079 |
| EMI | -0.061 | <0.039 |

## 5.7 Summary

Malaria in Limpopo is strongly seasonal and occurs in a form of epidemics. This chapter presented spatial and temporal patterns of malaria in Limpopo. A summary of the findings of this chapter is as follows:

a) A total of 79099 cases of malaria were reported during the study period (1998-2014), with the highest number of cases per month (2086) reported in November 2000.
b) More malaria cases were reported when the minimum temperature is above 15°C.
c) There is a decreasing trend in malaria transmission in Limpopo.
d) More malaria cases are reported during austral summer months, with a peak in January.
e) When considering suitability of malaria based on meteorological variables, most parts of Limpopo are suitable for malaria transmission, but the eastern low veld, in Mopane and Vhembe districts are the most suitable regions.
f) Malaria epidemics are identified using a standardized index, where cases which are greater than two standard deviation from the mean are identified as epidemics.

g) Using Pearson correlation, malaria transmission appears to be strongly associated with minimum temperature($R = 0.53$, $p < 0.001$) and relative humidity ($R = 0.52$, $p < 0.001$).

h) The highly significant positive correlations between meteorological variables and monthly malaria incidence is observed at least one month lag time. Except rainfall which shows positive correlation at three months lag time.

# CHAPTER 6

# THE INFLUENCE OF PRECURSOR METEOROLOGICAL CONDITIONS ON MALARIA TRANSMISSION IN LIMPOPO

## 6.1 Introduction

In some regions (e.g. Kwa-Zulu Natal) several factors such as extrinsic parasite development, mosquito abundance, survival and biting rate were found to be dependent upon climatic factors. Such that high malaria seasons are preceded by warm and moist winters thus high mosquito population at the beginning of the malaria season. Whilst wet winters rises water table thus providing early water pooling and availability of breeding sites during rainy season. Early onset of the rainy season and/or early seasonal temperature rise are conducive for early growth of vector population and early completion of extrinsic parasite development or if there is a delayed cessation of the rainy season and warmer conditions persist to autumn allowing for transmission season persist for longer there might be high probability for epidemics to occur (Craig *et al.* 2004). Therefore, it is of great importance to analyse the precursor meteorological conditions prior the outbreak of malaria.

Rainfall provides mosquito breeding sites, temperature determines the development of vector and parasites. The combination of humidity and temperature determine the survival of malaria vector. Climate forecasts and climatic indicators can be used to detect malaria epidemics. In climatic conditions that are marginally suitable for transmission, severe epidemics may follow extreme climatic conditions (Craig *et al.* 2004).

The main aim of this chapter is to investigate the influence of meteorological conditions before the occurrence of malaria epidemics. Therefore, an understanding of the malaria data is critical. At event scale (considering several cases for verification), the precursor meteorological structure is determined. Six cases of malaria epidemics are identified in chapter 5 between 1998 and 2014. Remote influences and meteorological structure of previous winters are also investigated.

## 6.2 Precursor meteorological structure

### 6.2.1 Composites of previous winters

This section provides analysis of the meteorological structure of winters prior malaria transmission season through composite analysis of six identified malaria epidemics, following the methods of Craig *at al.* (2004). In malaria transmission system, several factors like extrinsic parasite development, mosquito survival, abundance and biting rate are climate dependent.

Winters preceding malaria epidemics are associated with above normal sea surface temperatures (SSTs) of the south west Indian Ocean, the Mozambique Channel and south east Atlantic Ocean about 3°C above normal (Figure 6.1). A continental high pressure at 500 hPa is located east of South Africa associated with a westerly wave to the south, the Botswana high which usually dominates the circulation at this level north is weakened (Figure 6.2 e).

This high pressure might be as a result of the extension of the mascarene high in its westward propagation and is responsible for moisture influx from the SWIO (Figure 6.2 d) to north-eastern regions of the country resulting in above normal temperatures (Figure 6.2 b & f) and relative humidity (figure 6.2 c). Relatively warm and moist conditions are experienced during winters prior the occurrence of malaria epidemics. Above normal rainfall is received in winters preceding the epidemics of malaria (Figure 6.2 a).

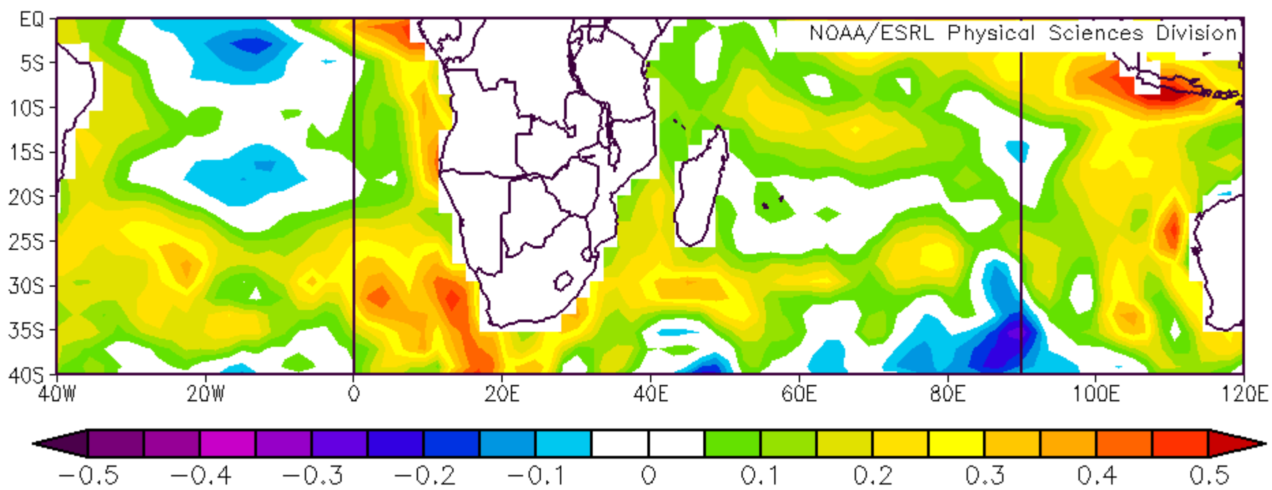


Figure 6.1 Composite anomalies of June-July-August (JJA) SSTs (°C) of the Atlantic and Indian Oceans for 1998, 2000, 2002, 2004, 2005 and 2007.

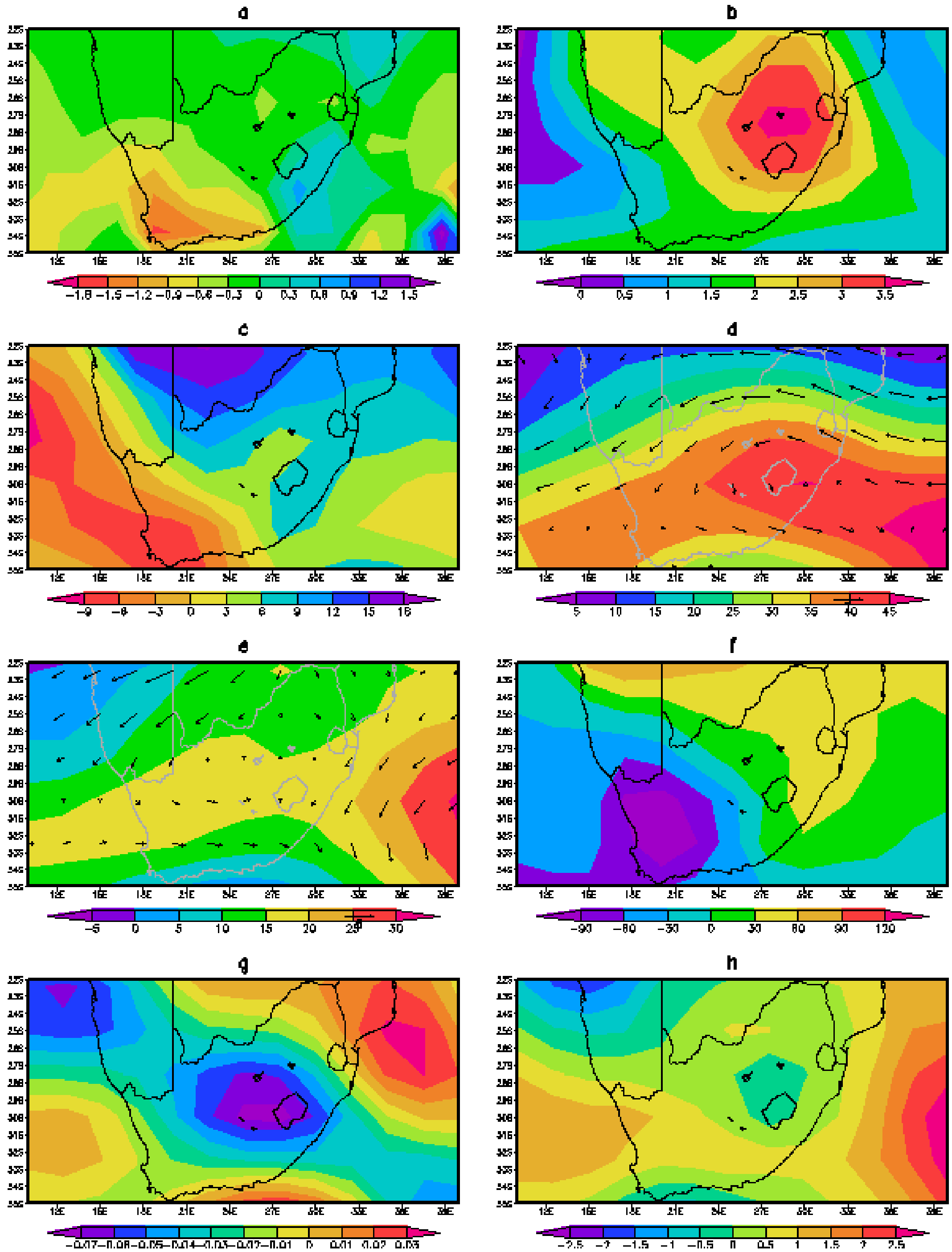


Figure 6.2. Composite JJA of composite anomaly of (a) rainfall (mm), (b) surface air temperature (°C), (c) relative humidity (shaded, %), (d) geopotential heights at 500 hPa (shaded, m) and wind (vector, m.s-1) (e) geopotential heights at 850 hPa (shaded, m) and wind (vector, m.s-1), (f) OLR (Wm-2),(g) vertical velocity (shaded, Pa/s and (h) Sea level pressure (hPa) for 1998, 2000, 2002, 2004, 2005 and 2007.

### 6.2.2 Precursor conditions three months prior the epidemic of malaria.

Three months prior the occurrence of malaria epidemic, above normal SSTs (0.3°C) are observed in the south west Indian Ocean and Mozambique Channel, while below normal SSTs are observed over south-east Indian Ocean west of Australia. This phenomenon is known as a positive phase of Indian Ocean Subtropical Dipole (Figure 6.3), and is associated with above normal rainfall over southern Africa. Warm SSTs in equatorial Atlantic and the Benguela Niño region may result in relaxation of the St. Helena high thus changes in sea level pressure over the South Atlantic Ocean while shifting rainy weather from Madagascar to southeast Africa (Jury and Kanemba 2007).

The presence of a low pressure over the interior (Figure 6.4 e) and anticyclonic circulation (Figure 6.4 d) over south east Indian Ocean induces low level tropical moisture flux to south east Africa, which than rises against the eastern escarpment. The uplift of moisture (Figure 6.4 c) is conducive for the occurrence of above normal rainfall (Figure 6.4 a) in most parts of southeast Africa. During this time, there is a presence of high humidity (moist air) (Figure 6.4 c) and lower temperatures (Figure 6.4 b) in south east Africa due to the presence of clouds (Figure 6.4 f).

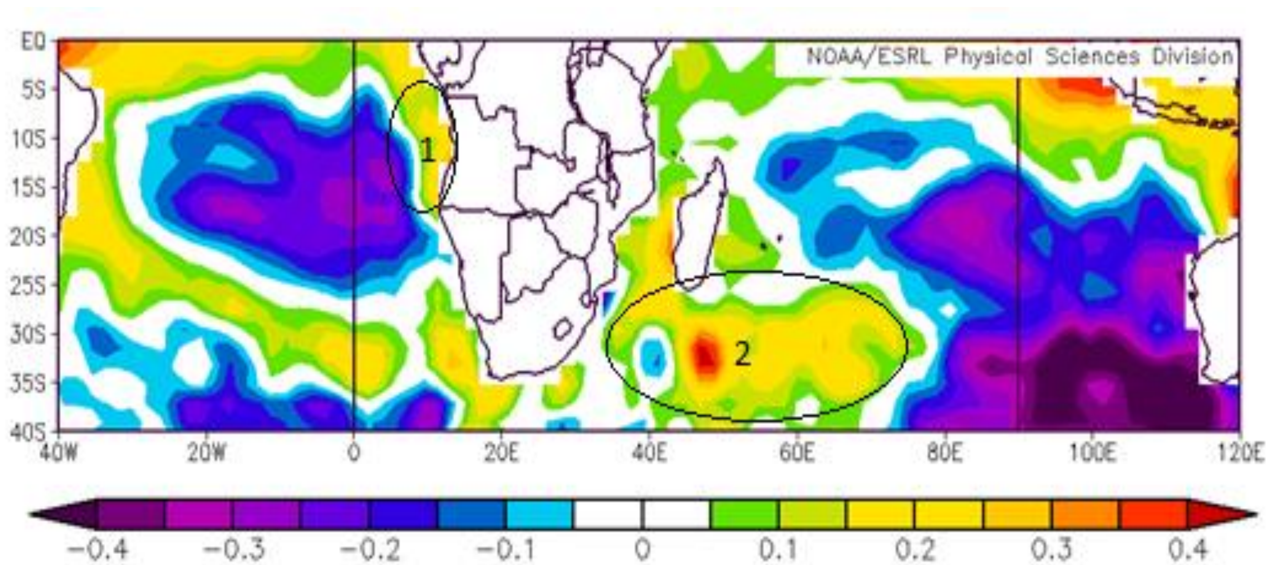


Figure 6.3. October-November-December (OND) composite SSTs (°C) of the Atlantic Ocean and Indian Ocean for 1998, 2000, 2002, 2004, 2005 and 2008.

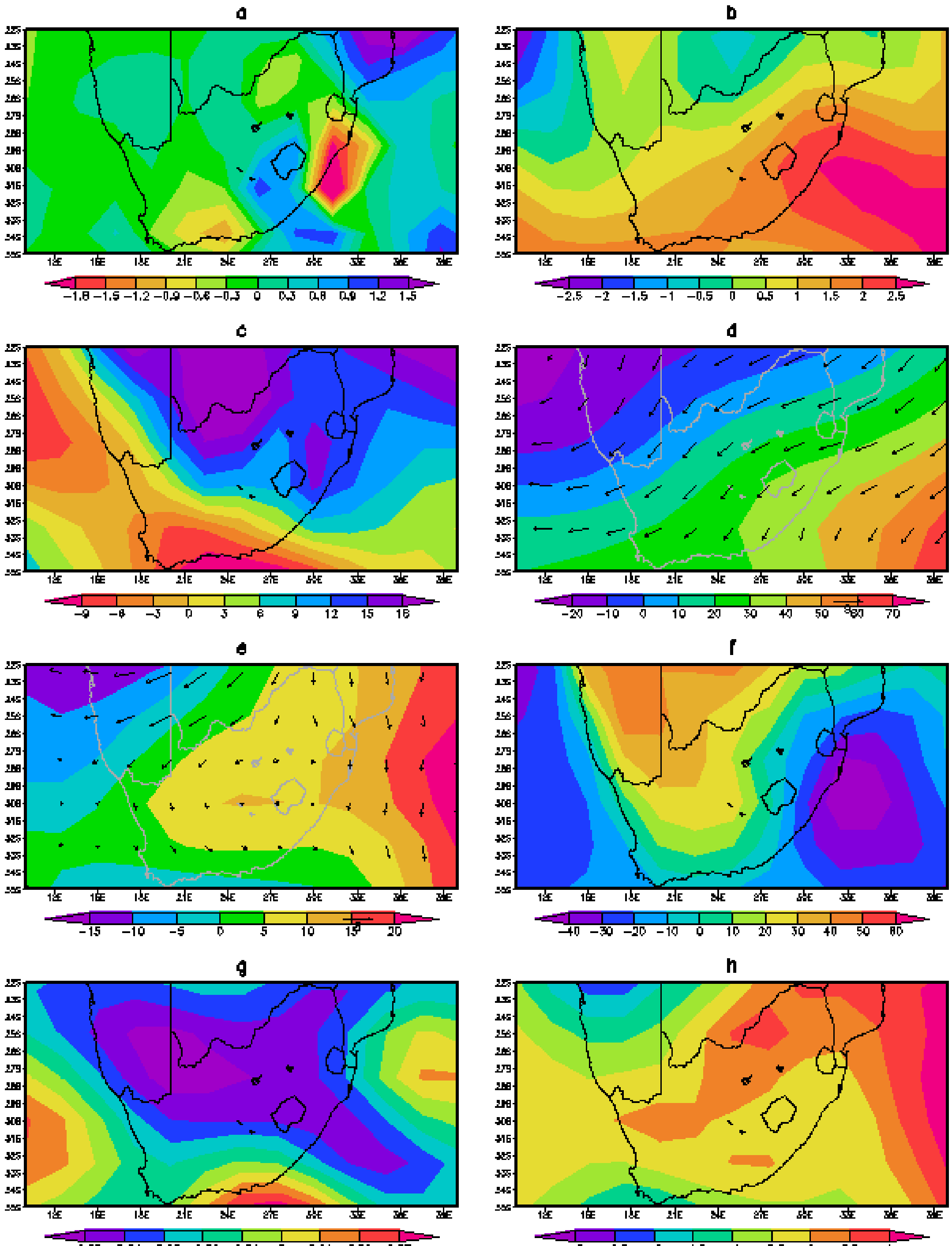


Figure 6.4. Composite OND of composite anomaly of (a) rainfall (mm), (b) surface air temperature (°C), (c) relative humidity (shaded, %), (d) geopotential heights at 500 hPa (shaded, m) and wind (vector, m.s-1) (e) geopotential heights at 850 hPa (shaded, m) and wind (vector, m.s-1), (f) OLR (Wm-2),(g) vertical velocity (shaded, Pa/s and (h) Sea level pressure (hPa) for 1998, 2000, 2002, 2004, 2005 and 2007.

### 6.2.3 Seasonal precursor meteorological conditions

Case 1: December 1998- February 1999

SSTs of the Indian Ocean are shown in Figure 6.5, above normal SSTs are observed over much of the Indian Ocean, with the exception of the south reaches of the Mozambique Channel where the temperatures were below normal. Precursor meteorological structure three months prior the malaria epidemic that occurred in November 1999 are shown in Figure 6.6.

Higher surface temperatures (Figure 6.6 b) and north-easterly winds were found over the east coast and Mozambique Channel with respect to high malaria seasons. The onshore flux of tropical air is drawn into a low-pressure cell situated over southern Mozambique, Zimbabwe and northeast South Africa (Figure 6.6 d & e). The warm moist air rises over the eastern escarpment (Figure 6.6 g), cools and precipitates (Figure 6.6 a & c). When a season is dominated by such a circulation, communities in south-east Africa usually experience increased malaria. The lack of a temperature signal over the malaria impact zone (warmer to the east and cooler to the west) may explain why some researchers fail to find the expected relationship (Jury and Kanemba 2007).

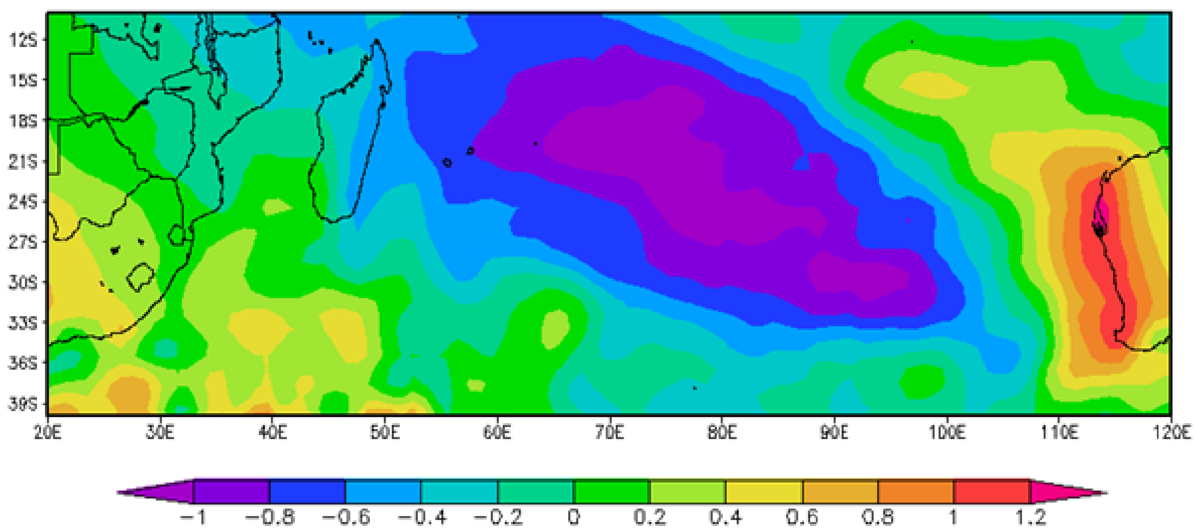


Figure 6.5. December-January-February (DJF) SSTs (°C) of the Indian Ocean for 1998/99 season.

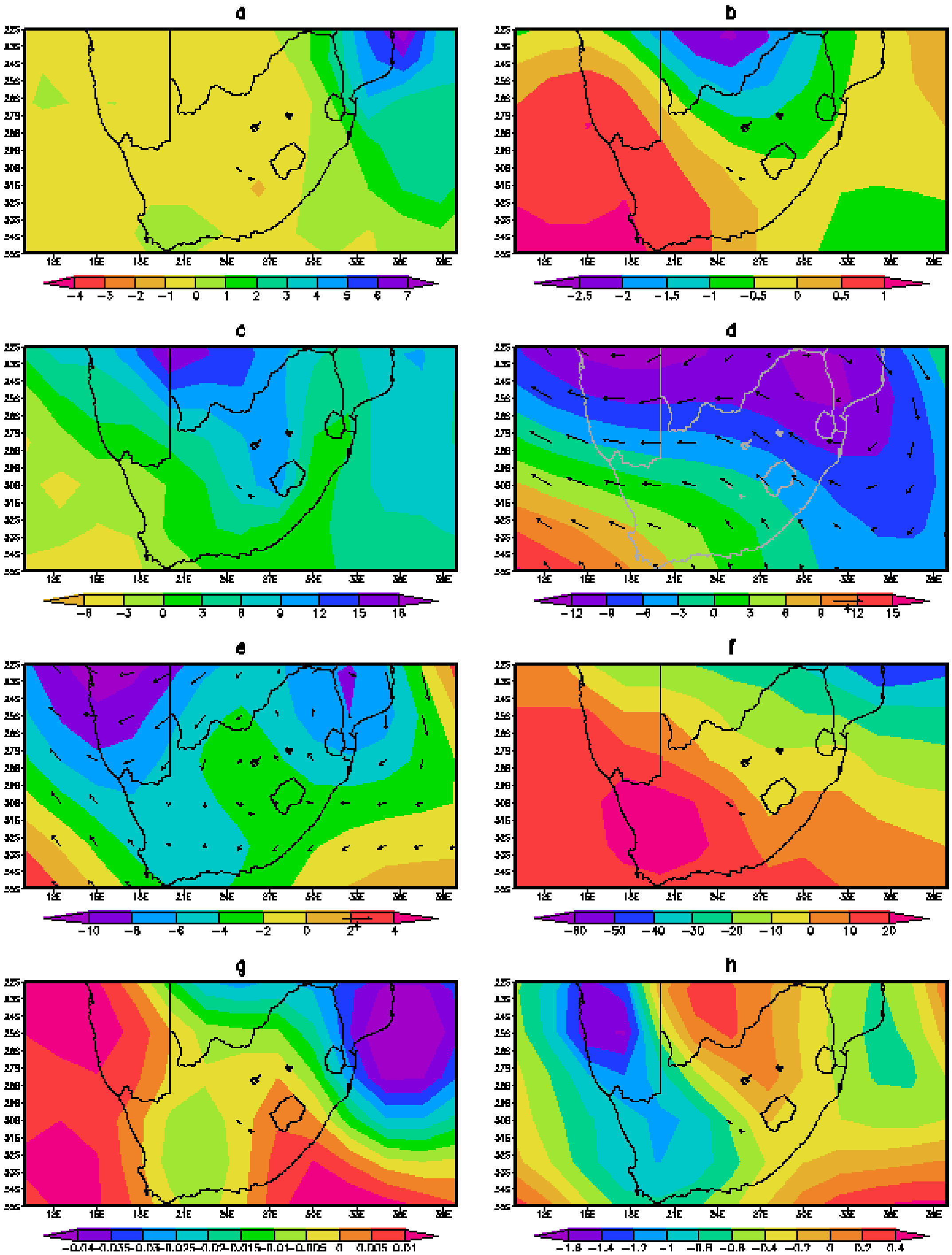


Figure 6.6 December-January-February (DJF) composite anomaly of (a) rainfall (mm), (b) surface air temperature (°C), (c) relative humidity (shaded, %), (d) geopotential heights at 500 hPa (shaded, m) and wind (vector, $m.s^{-1}$) (e) geopotential heights at 850 hPa (shaded, m) and wind (vector, $m.s^{-1}$), (f) OLR ($Wm^{-2}$),(g) vertical velocity (shaded, Pa/s and (h) Sea level pressure (hPa) for 1998/99 season.

Case 2: August-October 2000

Year 2000 was a La Niña, during this phenomenon the ascending limb of the Walker cell is centred over central southern Africa resulting in above normal rainfall. During this time, tropical lows form over central to western southern Africa and easterly wave comes into conjunction with tropical lows. Cloud band which are associated with major energy and momentum flux form over southern Africa, resulting in ample rainfall. Above normal SSTs were observed over the south east Indian Ocean west of Australia and SWIO along the east coast of South Africa, while below normal SSTs were observed over the central Indian Ocean east of Madagascar and the Mozambique channel (Figure 6.7).

A region of divergence observed along the south and east coast up to Zimbabwe to the north (Figure 6.8 g) may result from frequent ridging of anticyclones to the south of the country (Figure 6.8 h, d & e). Increased moisture content (Figure 6.8 c), low OLR (Figure 6.8 f), below normal temperature (Figure 6.8 b) and above normal rainfall (Figure 6.8 a) are observed in the malaria prone regions of Limpopo. This conditions may be linked with onshore moisture flux from the SWIO induced by the ridging of the St. Helena high to the south.

The presence of a ridging anticyclone south east of South Africa driving moisture from the SWIO resulting in above normal rainfall amounts during this time of the year. Ridging anticyclones are usually associated with light rainfall. This kind of rainfall combined with high relative humidity is conducive for *an. arabiensis* and *an. funestus* vectors (which are the primary malaria vectors in South Africa) as they prefer semi-permanent little pool of water.

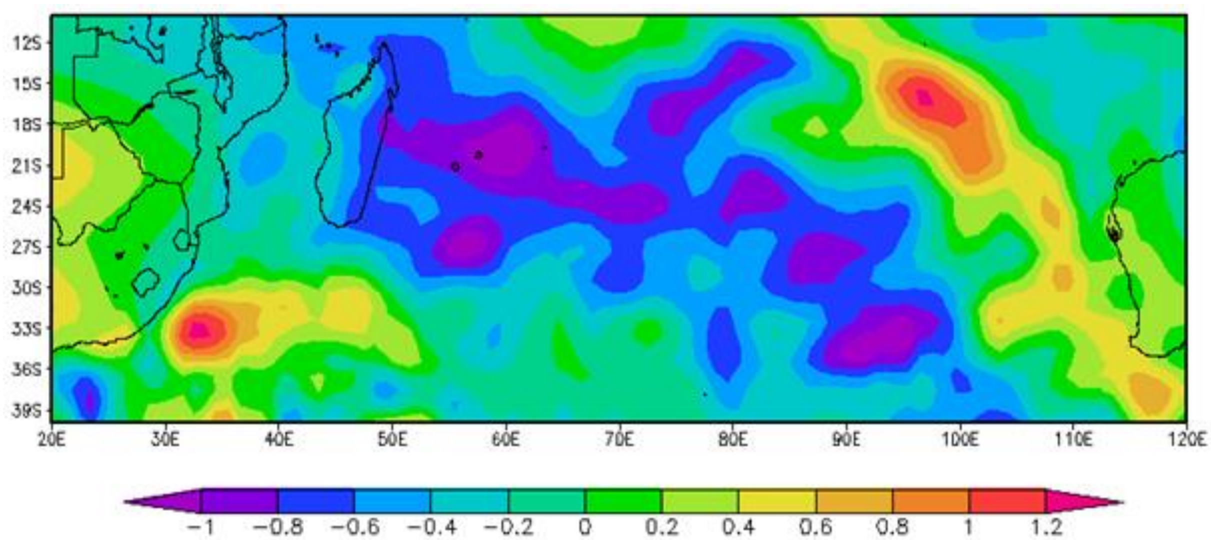


Figure 6.7. August-September-October (ASO) SSTs (°C) of the Indian Ocean for 2000.

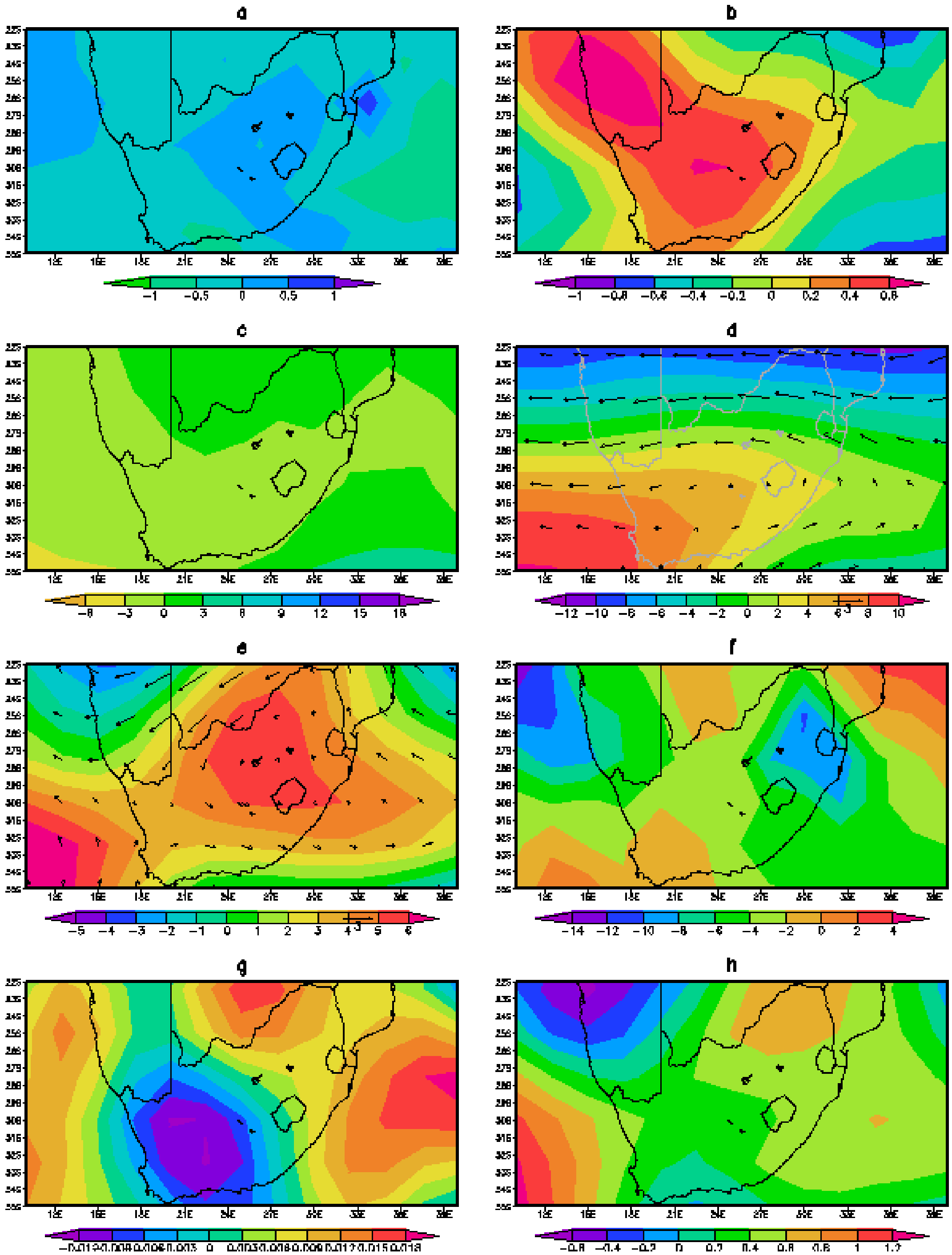


Figure 6.8. August-September-October (ASO) anomalies of (a) rainfall (mm), (b) surface air temperature (°C)  (c) relative humidity (%), (d) geopotential heights at 500 hPa (shaded, m) and wind (vector, m.s$^{-1}$), (e) same as (d) but 850 hPa, (f) OLR (Wm$^{-2}$), (g) vertical velocity (shaded, Pa/s) and (h) Sea level pressure (hPa) for 2000.

Case 3: November 2002 - January 2003

2002/03 was a relatively dry season, characterised by warm and dry off shore winds. The effect of the Angola low is supressed by the intensification of the Botswana upper high. During low ENSO phase (El Niño) the descending limb of the walker cell falls over central southern Africa, forming the region of high pressure with reduced meridional flux of energy. Tropical easterly lows and waves form over east Africa or western Indian Ocean, and the convergence zone of the cloud bands which bring rainfall during summer is displaced eastwards to lie over the Indian Ocean east of Madagascar (Figure 6.10 e).

Above normal pressure (Figure 6.10 d&e) and above normal temperatures (Figure 6.10 b) are observed over the Karoo region spreading across South Africa at 500 hPa. There is a region of higher than normal vertical velocity (Figure 6.10 g), below normal rainfall (Figure 6.10 a) and below normal relative humidity (Figure 6.10 c) observed over the malaria prone regions and the southeast coast of South Africa.

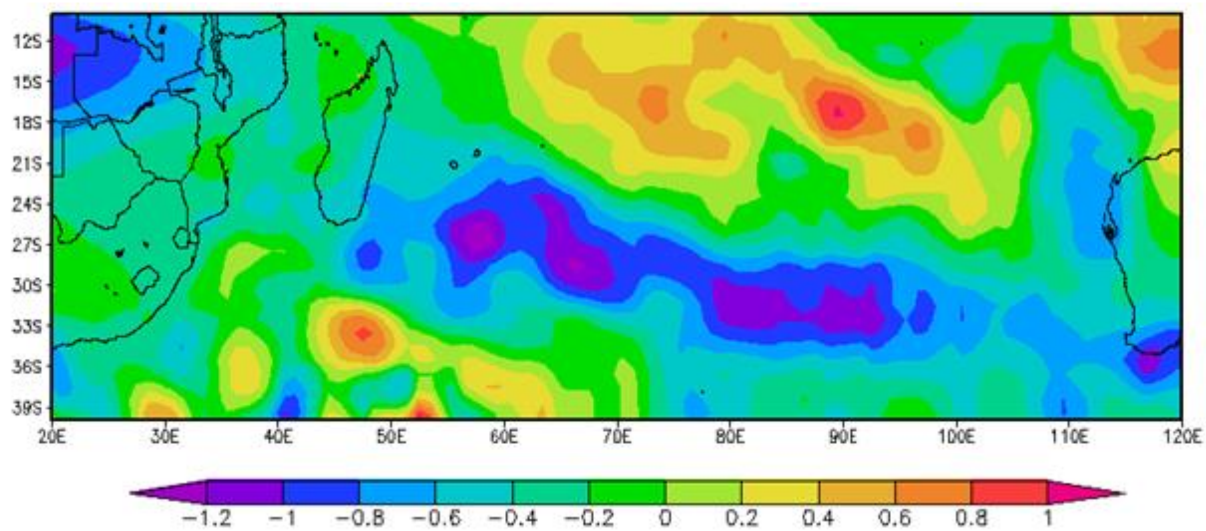


Figure 6.9 November-December-January (NDJ) SSTs (°C) of the Indian Ocean for 2002/03 season.

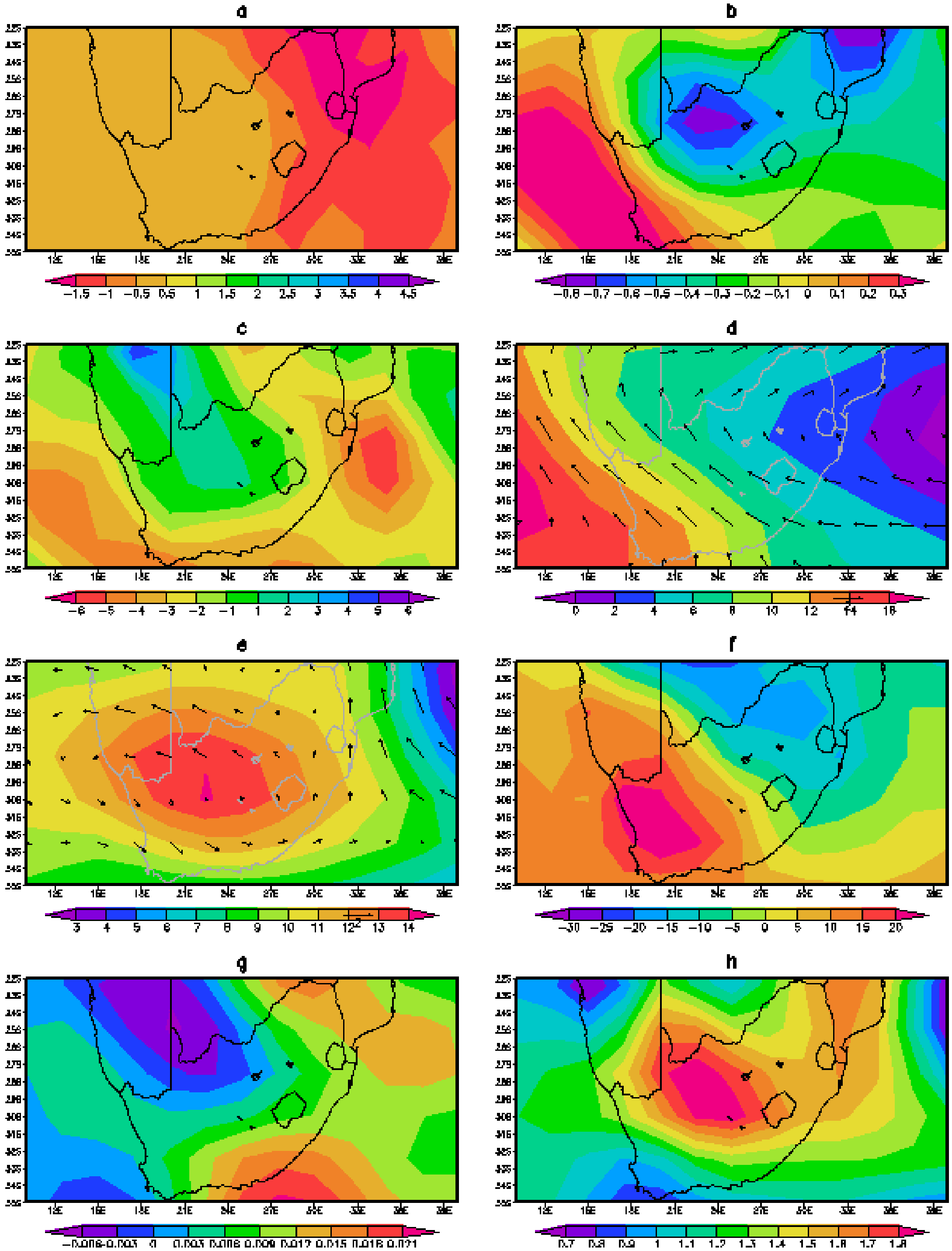


Figure 6.10. November-December-January (NDJ) anomalies of (a) rainfall (mm), (b) surface air temperature (°C), (c) relative humidity (shaded, %), (d) geopotential heights at 500 hPa (shaded, m) and wind (vector, m.s$^{-1}$), (e) geopotential heights at 850 hPa (shaded, m) and wind (vector, m.s$^{-1}$), and (f) OLR (Wm$^{-2}$), (g) vertical velocity (shaded, Pa/s) and (h) Sea level pressure (hPa) for 2002/03 season.

Case 4: November 2004-January 2005

Figure 6.12 shows the meteorological structure 3 months before the malaria epidemic of January 2004. The 2004/05 was a relatively dry season (Figure 6.12 a), characterised by warm and dry off shore winds (Figure 6.12 b; Figure 6.12 e). During this time the descending limb of the Walker cell falls over central southern Africa, forming the region of high pressure with reduced meridional flux of energy. The austral summer rain bearing systems migrate to lie over the Indian Ocean east of Madagascar taking rainfall with them.

Below normal rainfall conditions were experienced in most parts of southern Africa, particularly the malaria prone regions of Limpopo. Yet the surface air pressure was above normal during this time of the year coupled with below normal atmospheric moisture content (Figure 6.12 c), the condition was still conducive for the survival of mosquito vectors thus increased transmission of malaria. Weak onshore winds from the Indian Ocean driven by a low-pressure sitting southeast Africa and Mozambique Channel and the intensification of Mascarene high over the SWIO (Figure 6.12 d) were also observed. The sea surface temperatures of the central and south west Indian Ocean were well above normal (Figure 6.11). A region of convergence is observed over the SWIO and southeast Africa (Figure 6.12 g).

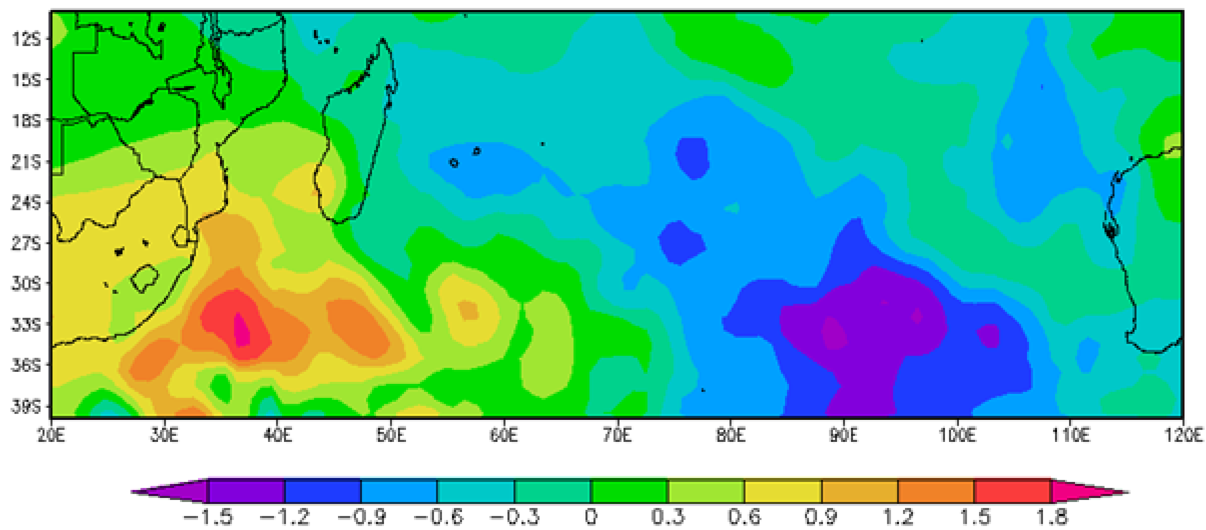


Figure 6.11. November-December-January (NDJ) SSTs (°C) of the Indian Ocean for 2004/05.

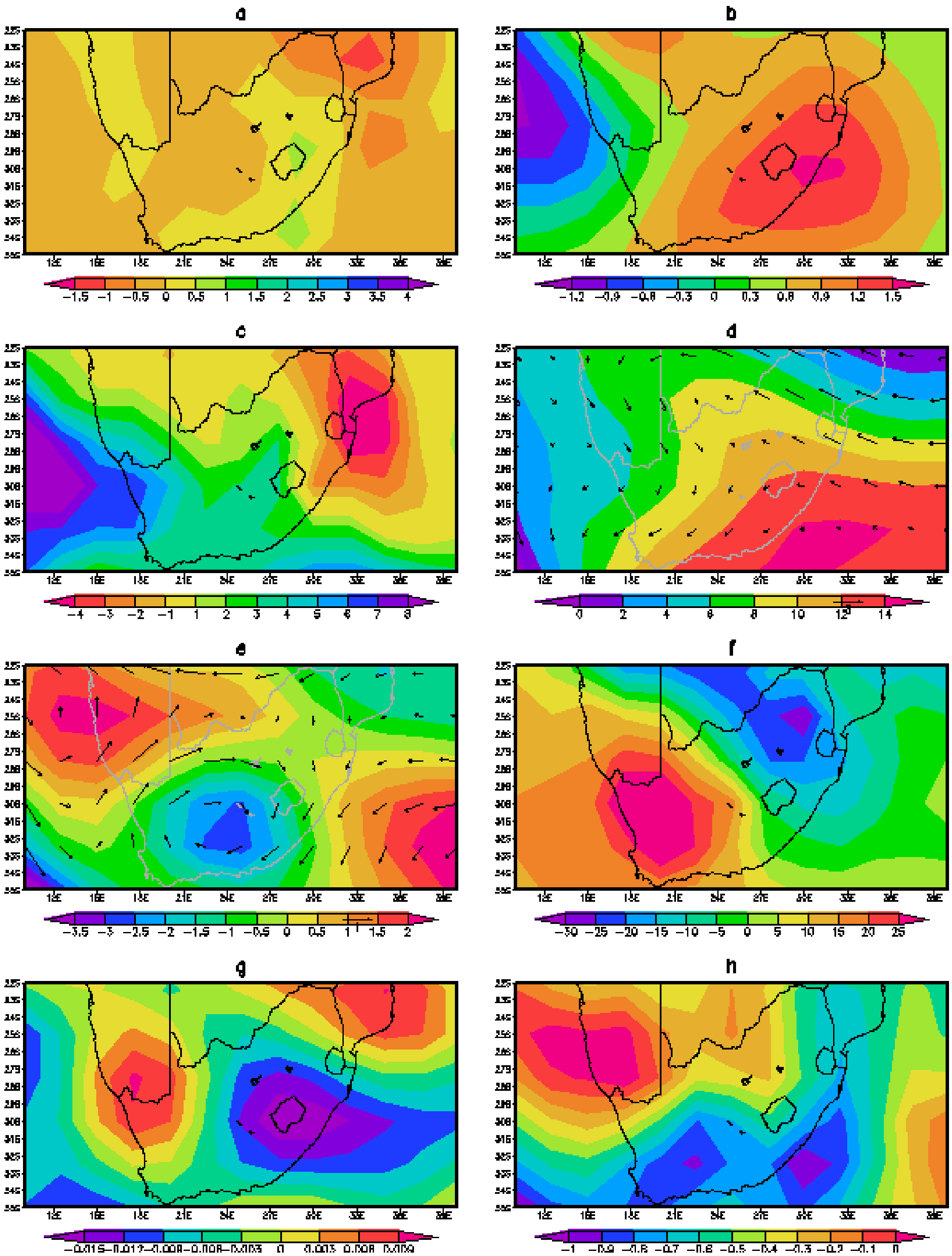


Figure 6.12. November-December-January (NDJ) anomalies of (a) rainfall (mm), (b) surface air temperature (°C), (c) relative humidity (%), (d) geopotential heights (shaded, m) and wind (vector, m.s$^{-1}$), (e) same as (d) but at 850 hPa (f) OLR (Wm$^{-2}$), (g) vertical velocity (shaded, Pa/s) and (h) Sea level pressure (hPa) for 2004/05 season.

Case 5: November 2005-January 2006

During the 2005/06 neutral ENSO season, three months prior the occurrence the epidemic of malaria in April 2006. Above normal SSTs are observed in southwestern Indian Ocean and below normal SSTs are observed in the South-eastern Indian Ocean (Figure 6.13). The intensification of the Mascarene High provides strong prevailing winds along its eastern edge resulting in reduced seasonal latent heat loss and therefore increased temperature in the southwestern Indian Ocean. Tropical moisture transfer induced by a high-pressure system (Figure 6.14 d, e & h) sitting over the Mozambique Channel resulted in increased rainfall in the eastern parts of southern Africa (Figure 6.14 a).

Above normal temperature and humidity are observed over the north-eastern South Africa (Figure 6.14 b & c), which are the conditions conducive for development, activity and survival of mosquitoes.

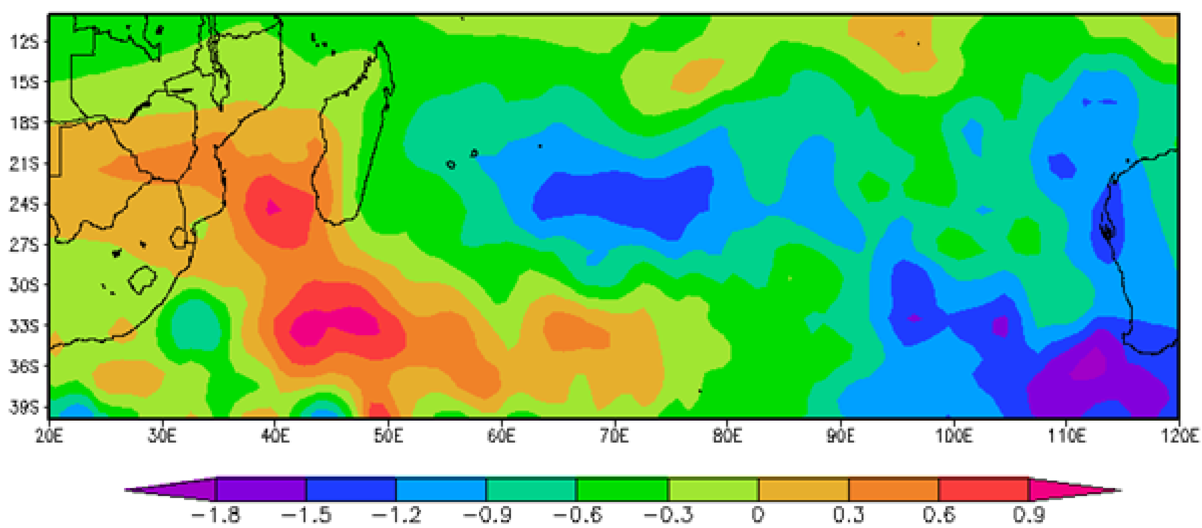


Figure 6.13. November-December-January (NDJ) SSTs (°C) of the Indian Ocean for 2005/06 season.

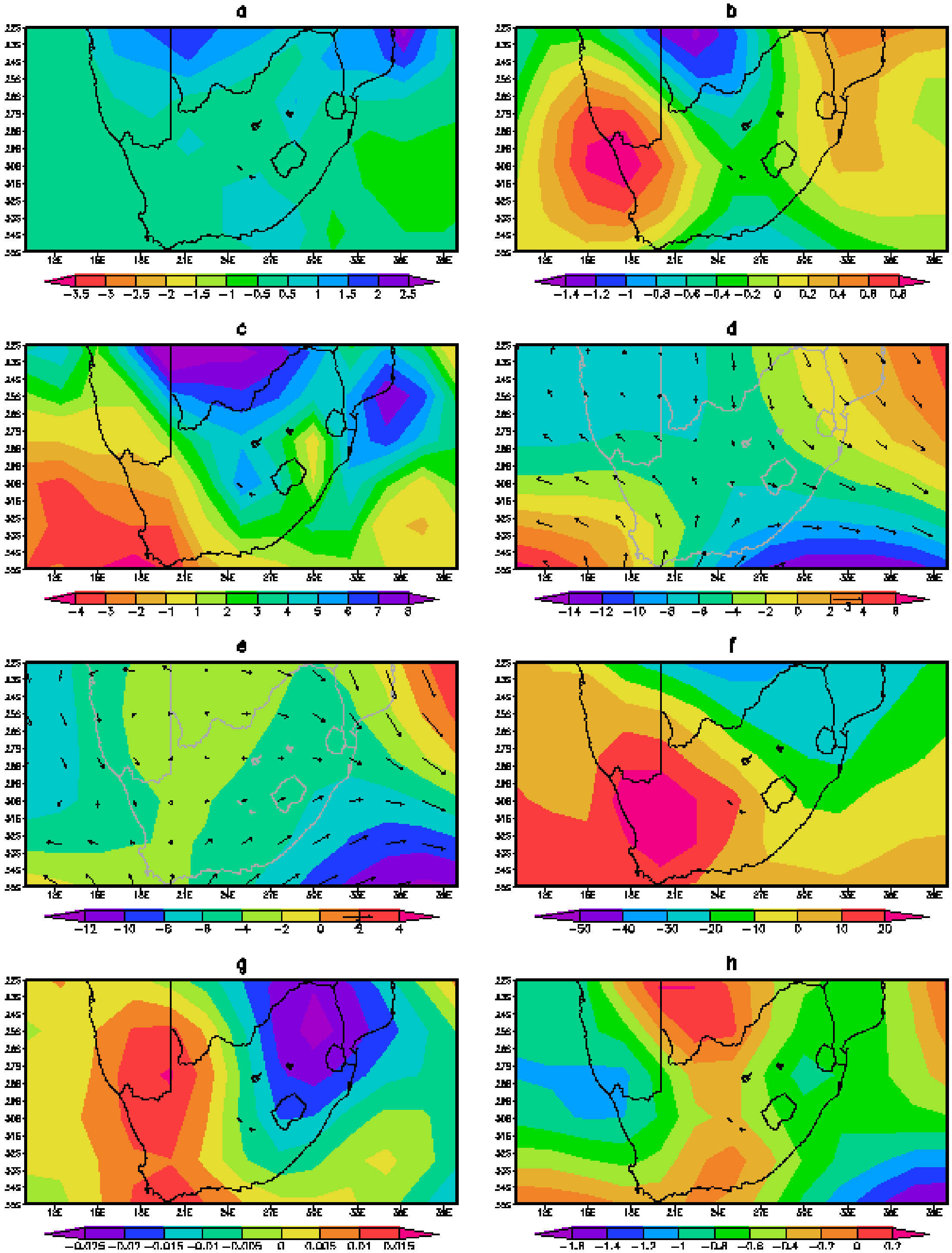


Figure 6.14. November-December-January (NDJ) anomalies of (a) rainfall (mm), (b) surface air temperature (°C), (c) relative humidity (%), (d) geopotential heights at 500hPa (shaded, m) and wind (vector, m.s$^{-1}$), (e) same as (d) but at 850 hPa and (f) OLR (Wm$^{-2}$), (g) vertical velocity (shaded, Pa/s) and (h) Sea level pressure (hPa) for 2005/06 season.

Case 6: January to March 2008

Yet 2007/2008 was a moderate La Niña season when one might expect relatively higher rainfall amounts especially during late summer (JFM), the south westerly wind diffluence in the Mozambique Channel might have been responsible for below normal rainfall. SSTs of the Indian Ocean and the Mozambique Channel were about 1°C below normal (Figure 6.15). Low SSTs are not conducive for cyclogenesis thus very minimal chances of tropical cyclone landfall which generally peaks during late summer.

Repeated ridging of the high-pressure systems in the south-east coast of South Africa, played a significant role in driving marine time air into the subcontinent (Figure 6.16 d & e). At the surface over the Indian Ocean and adjacent inland areas, steep pressure gradients promote strong advection of moist air over the land (Figure 6.16 d). Weakening inland pressure gradients, the changing curvature of the flow, meso-scale orographic forcing, and upper level divergence in the westerly wave combine to produce uplift over the eastern regions (Figure 6.16 h). Circulation type associated with ridging anticyclones brings rainfall to eastern South Africa from October to May but with a slight tendency for maximum frequencies of occurrence in October and February.

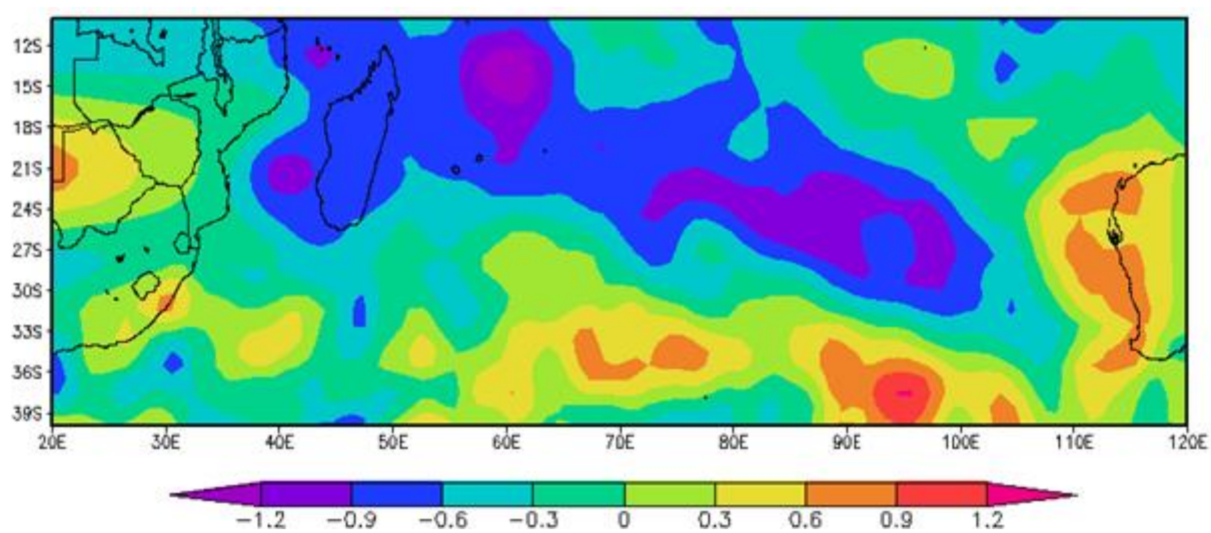


Figure 6.15. January-February-March (JFM) SSTs (°C) of the Indian Ocean for 2008.

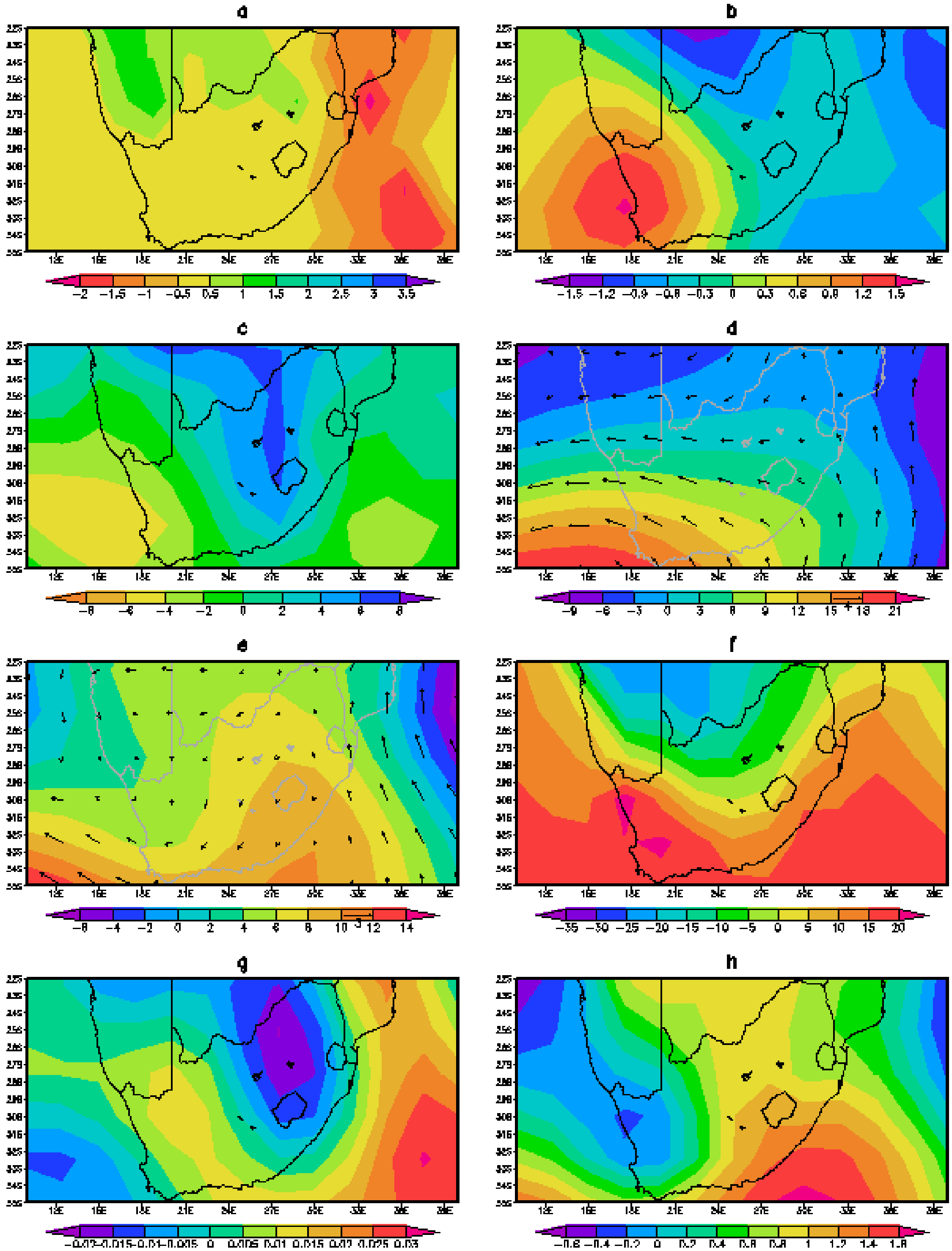


Figure 6.16. January-February-March (JFM) anomalies (a) rainfall (mm), (b) surface air temperature (°C), (c) relative humidity (%), (d) geopotential heights at 500hPa (shaded, m) and wind (vector, $m.s^{-1}$), (e) same as (d) but at 850 hPa and (f) OLR ($Wm^{-2}$), (g) vertical velocity (shaded, Pa/s) and (h) Sea level pressure (hPa) for 2008.

## 6.3 Summary

This chapter investigated the meteorological structure of previous winters and three months prior the epidemics of malaria to identify predictors of malaria epidemics over the Indian Ocean and Atlantic Ocean. Two dominant indicators were identified which are: above normal SSTs of the equatorial Atlantic Ocean, Benguela Niño region and SWIO.

a) Warm and moist winters preceding the malaria transmission season is likely to allow for high mosquito survival and the availability of the breeding sites in winter thus high population in the beginning of the transmission season thus resulting in the occurrence of outbreaks and epidemics.
b) Warm SSTs in the tropical Atlantic and the Benguela Niño region prior the epidemics of malaria may result in relaxation of the St. Helena high thus changes in sea level pressure fields over the Atlantic Ocean while shifting rainy weather from Madagascar to southeast Africa.
c) The eastward ridging St. Helena high to the south tend to influence greatly on the occurrence of the epidemics of malaria as it induces onshore flux of moisture from the Indian Ocean thus producing rainfall over the malaria prone regions of Limpopo and also modulate the temperature over the region.
d) We investigated sea surface temperatures of the Indian Ocean three months prior the occurrence of the epidemics. Three occurred during La Niña season, one during normal ENSO and two occurred during El Niño season. The sea surface temperatures of the SWIO were relatively higher than normal for almost all the events, with the exception of 2002/03 and 2008 season.

# CHAPTER 7

# DISCUSSION OF KEY FINDINGS AND FUTURE WORK

## 7.1 Introduction

The aim of this work was to determine the influence of meteorological parameters on malaria transmission in Limpopo from 1998-2014. The malaria prone regions of Limpopo are found in the eastern low velds of Vhembe and Mopane Districts. The transmission in this region is strongly seasonal and prone to epidemics. There are many factors that play a role in the temporal and spatial distribution of malaria over a region, this include meteorological and non-meteorological factors. This work however focuses greatly on meteorological factors (rainfall, temperature and humidity) in particular.

This chapter provides a summary of key findings of this work and recommendation for future work.

## 7.2 Discussion of key findings

### 7.2.1 Climate of the malaria prone regions of Limpopo

Weather and climate are major determinants of the geographical distribution, seasonality, interannual variability and longer term trends of malaria transmission. Periods of anomalously high rainfall, temperature and humidity result in modified distribution, duration and transmission of malaria even in areas where control is strong. Prolonged droughts can reduce the transmission of malaria. Climate variability including the El Niño phenomena and other long-term meteorological cycles have been found to be strongly related to trends in malaria transmission and periodic upsurges in cases, including epidemics (van Lieshout *et al*.  2004; Noor *et al*. 2014).

Weather and climate of the malaria prone regions of Limpopo vary considerably on a number of time scales. Droughts and floods are a pronounced feature at interannual time scale and influenced by revolving wet and dry spells at intra-seasonal time scale. Rainfall and relative humidity exhibit a strong gradient from west to east, more pronounced in the eastern region due to orographic effect forced by the Soutpansberg mountain ranges and from the land falling tropical systems from the Indian Ocean that affect this region from time to time. The strong mean anticyclonic circulation draws moisture from the SWIO into the interior. There is a distinct seasonality with approximately 95% of rainfall occurring between October and April, usually intruded by dry periods known as mid-summer dry spells (M'marete 2003).

### 7.2.2 Spatio-temporal characteristics and trends of malaria

A combination of high monthly minimum temperature, relative humidity of ≥ 60% and the availability of breeding sites provide suitable conditions for malaria transmission. The negative association attained by rainfall at zero-two months lag time, indicates a delayed response which results from water bodies being washed away. High relative humidity is observed when temperature and rainfall are also high resulting in conducive conditions for parasite development and survival of mosquito population.

The transmission windows of malaria based on both temperature and relative humidity could play a significant role in the transmission of malaria. When the average monthly relative humidity is below 60%, it is believed that the life of the mosquito is so shortened that there are minimal chances for malaria transmission. There appears to be an inverse relationship between the length of malaria transmission season and the risk of epidemics. The shorter the transmission season, the higher the risk of the epidemics (Jury and Kanemba 2007).

There has been a decrease in malaria incidences in Limpopo since the year 2000. Despite the significant decrease in the incidences, Limpopo remain the largest contributor in South Africa. However it appears that there has been an increase in imported cases of malaria in recent years (Opie *et al.* 2014). On average above 700 cases of malaria are reported during January. This coincides with a peak number of humans returning from Christmas holidays from the neighbouring malaria prone regions. It can then be argued that a considerable percentage of the reported cases are imported.

There has been an increasing number of imported malaria cases in recent years. According NICD (2017), of the 27392 cases of malaria that were reported in South Africa between 2014/15 and 2016/17 seasons alone, 15971 cases (58 %) were imported. 2015/16 season saw a low number of malaria cases (6375 cases) due to strong El Niño drought. However, about 74.5% (4752) were imported cases (Figure 7.1).

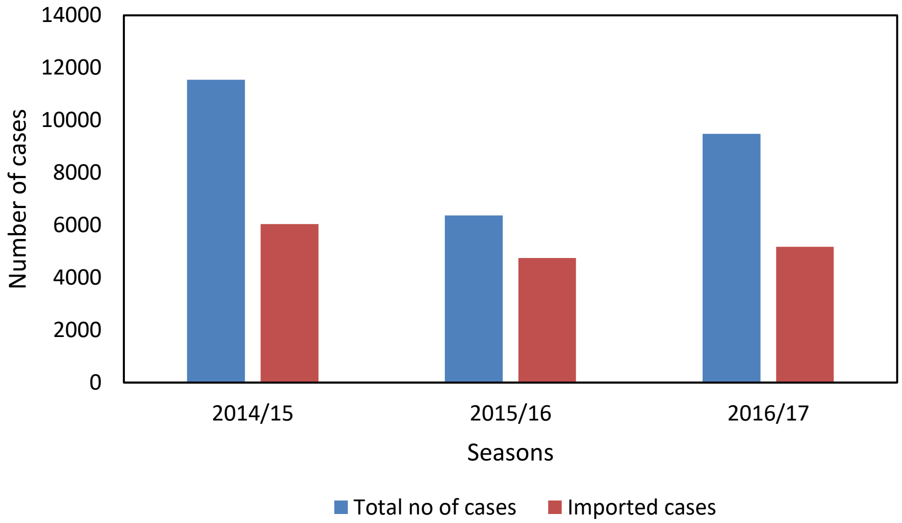


Figure 7.1 Malaria cases in South Africa for 2014/15, 2015/16 and 2016/17.

### 7.2.3 Climate and malaria

There is a higher positive correlation between monthly malaria cases and monthly minimum temperature, relative humidity and maximum temperature at zero-two months lag effect. The correlation coefficient for the association between monthly minimum, relative humidity and monthly incidence of malaria was found greater than that of maximum temperature and malaria incidence. This indicates that minimum temperature and relative humidity seems to play a significant role in the transmission of malaria in Limpopo compared to maximum temperature and rainfall, these results are in line with the findings of Ikeda *et al.* (2017). Like all the insects, mosquito have a limited range of tolerable humidity and temperature. The high surface area to volume ratio of mosquitoes makes them especially sensitive to desiccation at low humidity levels. Relative humidity influences biological and feeding behavior of mosquitoes. At higher humidity, mosquitoes generally survive for longer and disperse further (Prieto and Rojas 2013). Higher humidity also affects the rate of replication of bacterial and protozoan pathogens and their survival in the environment. Based on the time required for parasite development and survival, at temperatures below 18°C few parasites can complete the development within the lifetime of the mosquito (Craig *et al.* 1999).It can then be said that minimum temperature and relative humidity are the main precipitating factors of malaria transmission in Limpopo.

The findings with respect to zero-two month lag effect of relative humidity, minimum temperature and maximum temperature are supported by earlier work of Devi and Jauhari (2013), who observed the same relationship with vector abundance in Dehradun, India. However, here a positive relationship between rainfall and malaria cases is observed on a time lag of three-four months. This can be explained by that the human pool of infection takes time to build each year. Hence, the malaria peak lags rainfall by at least three-four months.

*Anopheles* mosquitoes require the right amount of rainfall for breeding purpose but rainfall above that or rainfall accompanied by storm conditions can flush away breeding sites. Not only the amount and intensity of rainfall, but also the time in the year, whether in the wet or dry season, affects *Anopheles* mosquito survival. Different species of *Anopheles* mosquitoes prefer different water bodies for breeding. The possible explanation could be that the rainfall plays a vital role in malaria epidemiology because water not only provides the medium for the aquatic stages of the mosquito's life but also increases the relative humidity and thereby the longevity of the adult mosquitoes. Without sufficient rainfall or water collections, mosquitoes cannot proliferate and infect humans. This indicates that the malaria transmission is clearly associated with the rainy season.

It was previously thought that rainfall controls the transmission of malaria in south-east Africa (e.g. Jury and Kanemba 2007). However, due to the nature of biological processes malaria and their dependence on other physical factor such as humidity and temperature, it seems probable that the influence of meteorological variables varies from region to region. Studies have found that rainfall is the only factor that has a significant association with malaria transmission in Mpumalanga (Ngomane and de Jager 2012), while there was no link found in Northern Kwa-Zulu Natal (e.g. Craig *et al.* 2004b). However, the findings of this study suggest that malaria transmission in Limpopo is mainly controlled by minimum temperature and relative humidity.

This study investigated sea surface temperatures of the Indian Ocean three months prior the occurrence of the epidemics between 1998 and 2014. Three occurred during La Niña season, one during normal ENSO and two occurred during El Niño season. Sea surface temperatures of the SWIO were relatively higher than normal for almost all the events, with the exception of 2002/03 and 2008 season.

Warm and moist winters preceding the malaria transmission season are likely to allow for high mosquito survival and the availability of the breeding sites hence high population in the beginning of the transmission season thus resulting in the occurrence of outbreaks and epidemics (Craig *et al.* 2004b). Warm SSTs of the SWIO and Benguela Niño region east of Angola are the dominant predictors of malaria in Limpopo. Warm SSTs of equatorial Atlantic and Benguela Niño region results in relaxation of the St. Helena resulting in a shift in rainy weather to southeast Africa. La

Niña have been linked with increased malaria transmission over Southeast Africa. However, during El Niño when rain bearing systems have migrated east of Madagascar, continuous ridging of St. Helena high may produce conducive conditions for malaria transmission in Limpopo. In the absence of El Niño or La Niña, the Indian Ocean becomes an important source of predictability as it plays a significant role in malaria transmission.

The SARIMA (2, 1, 2) $(1, 0, 0)_{12}$ model was found to be the best fit model for a reliable forecast. The model without climatic variables has an accuracy of 53%, while the model with all the climatic variables show 78% accuracy.

Seasonal transmission and spatial distribution of malaria in the prone regions of Limpopo is largely controlled by meteorological factors and the remote influences as predictors. Therefore, close monitoring of this factors can provide a guide for establishing an early warning system to manage epidemics. The lag effect between malaria cases and climatic variables is crucial for the prediction of malaria transmission, intervention and control.

## 7.3 Future work

This work has focused on the influence of the meteorological factors on the transmission of malaria. Therefore, it is recommended that the influence the non-meteorological factors are studied separately considering the human migration particularly during Easter and Christmas holidays when the vector population and hours of exposure to mosquitoes is high. The future study should also include failure in malaria control programs and drug rotation. A study that will incorporate both meteorological and non-meteorological factors in Limpopo is therefore recommended.

Malaria epidemic forecasting model which incorporates both ENSO-driven climate anomalies and non-ENSO factors relative influence on epidemic risk potential can be made possible (Mabaso *et al*. 2007). It can be more advantageous to also include factors like wind speed and direction for mapping malaria in Limpopo. Midega (2012) showed that the relationship between distance from a larval site and malaria risk is highly dependent on the wind direction and wind speed. Studies on the effect of wind direction and wind speed can possibly be useful in studying malaria transmission in South Africa.

Systems for reporting malaria epidemics needs to be strengthened. Long term high resolution data set (up to at least 30 years) are needed for developing climate-malaria model. The development of forecasts for some diseases has stalled because of a shortage of epidemiological data. More commonly, disease-climate modelling has been restricted due to short data sets representing small areas. The implication is that models should be tested against health data from countries sharing the same signal. In some cases, viable surveillance system may exist but require modification to ensure timely analysis. Further work needs to be carried out to determine the extent to which the quality of diagnosis affects our ability to predict epidemics.

Climatic variables can be incorporated into a conceptual model to describe malaria transmission. This process based dynamical models may not only facilitate greater understanding drivers of transmission but may better address the effect of complex feedbacks and non-linear processes underlying malaria transmission (Parham and Michael 2010). The dynamic models may also help with the modelling of the transmission of malaria in future warming climate.

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