

The copyright of this thesis vests in the author. No quotation from it or information derived from it is to be published without full acknowledgement of the source. The thesis is to be used for private study or non-commercial research purposes only.

Published by the University of Cape Town (UCT) in terms of the non-exclusive license granted to UCT by the author.

THE UNIVERSITY OF CAPE TOWN
Department of Oceanography

**MECHANISMS FOR THE WET AND DRY YEARS OVER
ERITREA DURING THE SUMMER RAINFALL SEASON**

Mussie T. Kidanemariam

A thesis paper submitted in partial fulfillment of the requirements for the
Masters degree in Applied Marine Science

July 2003

Acknowledgement

I would like to thank my supervisors Dr Mathieu Rouault and Prof Geoff Brundrit for their invaluable guidance, review, comment and encouragement throughout the work.

I would also like to thank the Eritrean Human Resource Development Project (EHRD) for providing me financial assistance and to study in South Africa.

I would like to take this opportunity to express my gratitude to Mrs Lula Gebreyesus, Executive Director of Africa Institute for Policy Analysis and Economic Integration (AIPA), for her guidance, moral support and the efficient manner she carried out the EHRD project.

Finally, I would like to acknowledge for the image provided by the NOAA-CIRES Climate Diagnostics Center, Boulder Colorado from their Web site at <http://www.cdc.noaa.gov/>

CONTENTS

<u>Acknowledgement</u>	2
<u>ABSTRACT</u>	4
<u>Section 1: INTRODUCTION</u>	5
a) <u>Geographical location</u>	6
b) <u>Climate of Eritrea</u>	6
c) <u>Seasons of Eritrea</u>	9
<u>Section 2: DATA AND METHODOLOGY</u>	13
<u>Section 3: RESULT AND DISCUSSION</u>	18
a) <u>Mean monthly and seasonal rainfall cycle</u>	18
b) <u>Wet and dry years</u>	20
c) <u>Atmospheric and oceanographic mechanisms for the wet and dry years</u>	23
d) <u>Correlation of Eritrean summer rainfall and SST</u>	38
e) <u>The relationship of ENSO and Eritrean rainfall</u>	40
<u>Section 4: CONCLUSION</u>	51
<u>LITERATURE CITATION</u>	54

ABSTRACT

The economy of Eritrea depends on rain-fed agriculture, which is highly sensitive to seasonal and interannual variations of rainfall. Adequate amount of rainfall is required every year for adequate agricultural production and drinking water. Therefore, the distribution of seasonal rainfall in space and time is critical to the country's economy. Drought has great influence on the socio-economic aspect and livelihood of the rural population. Drought occurs in Eritrea due to anomalous regional atmospheric circulation. This study focuses on the summer rainy season of June, July and August (JJA). It examines atmospheric and oceanographic mechanism patterns associated to summer rainfall anomalies.

The investigation mainly concentrates on wet and dry spells that occurred over Eritrea during the rainy seasons (June to August) of 1950's-1990's. Rainfall data was available from the Climatic Research Unit (CRU) Hulme dataset for a period of 1950 -1996 and this together with rainfall data from the Africa Data Dissemination Service was used to determine the characteristics of wet and dry spells. Finally, NCEP-NCAR reanalysis climate data was used to analyse the atmospheric circulation associated with wet and dry years.

It has been found that the pattern of the SST along the eastern Pacific and the Indian oceans seem to influence the occurrence of the anomaly rainfall years. Correlation analysis shows that Eritrean summer rainfall is more strongly correlated with the eastern Pacific and Indian Oceans SST. Thus, the drought records in Eritrea are mainly associated with El Niño events.

Section 1: INTRODUCTION

In Eritrea, rainfall is a significant climate variable playing an important role in socio-economic aspect of the country where its economic activity depends mainly on agricultural and livestock production. Variation in the normal rainfall regime can have large economic and social impacts on the country. Reduced rains during summer season (June-August) when crops are in their maximum need of water supply, can affect agricultural production, and lack of clean drinking water. Therefore, the distribution of seasonal rainfall in space and time is critical to the country's economy. Drought has great influence on the socio-economic aspect and livelihood of the rural population. Drought mainly occurs in Eritrea due to the anomalous regional atmospheric circulation. Based on this fact, this study aims to identify wet and dry years over Eritrea during the rainy season (June-August) for the period 1950's to 1990's and analyse the mechanisms associated and/or relation with large-scale atmospheric and oceanic conditions, in order to upgrade forecasting drought or wet spells.

Next, a review of the general climatic condition and rainfall pattern over Eritrea, and review of the literature is given. Data source and methodology used has been described in Section 2. In Section 3 results and discussion are presented with special emphasis to the mechanisms involved in producing the wet and dry spells. Section 4 presents summary of the study.

a) Geographical location

Eritrea is located in the Horn of Africa within the tropics of 12°22' to 18°02' latitude and 36°26' to 43°13' longitude. The country is bordering Djibouti and Ethiopia in the south, Sudan in the west and Red Sea in the east. Its total land covers around 124,300 km² and it has long coastline of approximately 1900 km.

b) Climate of Eritrea

Eritrea has high topography variation over short geographical distances. The average annual rainfall of the country which depends on geographic variation amounts to about 700 mm in some part and 100 mm in certain part of the country (Department of Environment of Eritrea 2001; Fig. 1). This leads to extreme variable annual precipitation. The most abundant precipitation falls along the Central and Northern highland, and Southwestern highland during the summer rainfall season (June to August). The amount of rainfall decreases eastward, from the Central and Northern highland, and Southwestern highland towards the sea. The precipitation is not evenly distributed throughout the year. Scarce precipitation and high temperatures result in reduced moisture, so that there is no area in Eritrea where the long-term average precipitation exceed potential evapotranspiration.

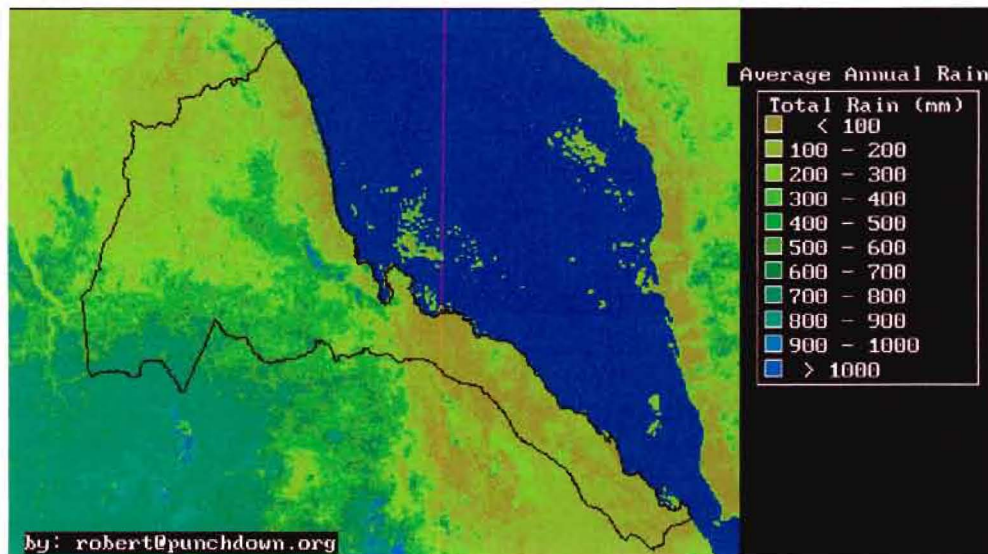


Figure 1: Eritrea Average Annual Rainfall

(Source: Buskirk RV <http://www.punchdown.org/rvb/rain/rainann.html>)

High topography variation makes the country to have various climatic zones. The country is divided into four zones (Fig. 2) based on climatic (rainfall) and physiographic (topography) criteria: the Central and Northern Highlands, the Southwestern Lowlands, the Northwestern, and the Coastal Zone.

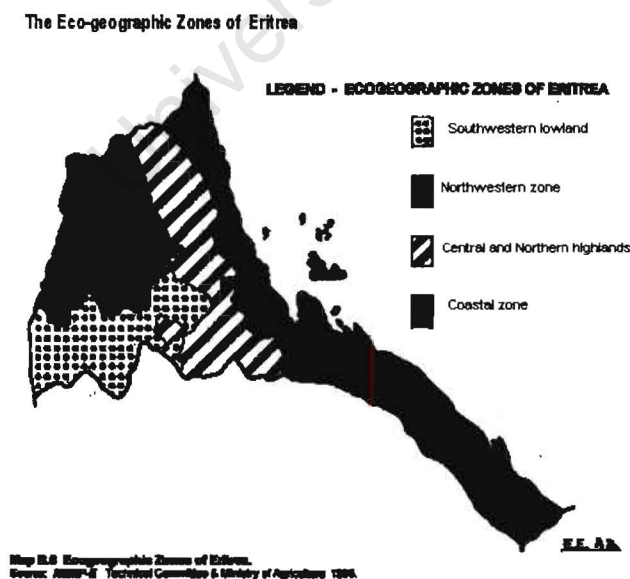


Figure 2: Eco-geographic zones of Eritrea (Source: Department of Environment of Eritrea 1999)

i) The Central and Northern Highlands Zone

This zone represents most of the high land region and the escarpment. Altitude ranges between 1800-2000m above mean sea level(a.m.s.l.). Annual rainfall ranges between 300 and 500 mm (Department of Environment of Eritrea 1999; Nurahmed 1998). Its 'big' rainy season (summer local referred as 'Kiremti') is from June-August. Due to its special feature if its topography, the escarpment region receives high annual rainfall.

ii). The Southwestern Lowlands Zone

The South Western Lowlands represents areas of west of the Central and Northern Highlands Zone and south of the North Western Lowlands of the country. Its main rainfall is between June-September (summer season). The annual average rainfall ranges approximately from 400 and 700 mm and its altitude ranges between 1500 to 2000 m (a.m.s.l.)(Department of Environment of Eritrea 1999; Nurahmed 1998).

iii). The Northwestern Zone

The North Western zone covers large part of the western semi-arid region, bordering Sudan. Its main rainy season is during Jun-August (summer season). Its annual average rainfall is below 400 mm with an altitude of 900-1500 m a.m.s.l. (Department of Environment of Eritrea 1999; Nurahmed 1998).

iv). The Coastal Zone

The Eastern Lowland includes the coastal plains zone which stretches along the Red Sea. This zone is the most arid region with hot, dry and humid coastal climate. The altitude range is generally below 900 m with annual average rainfall of less than 200 mm (Department of Environment of Eritrea 1999; Nurahmed 1998). Unlike the other zones, the coastal zone gets its rainy season, though it amounts small, from October-March.

c) Seasons of Eritrea

Eritrea has four seasons through out the year: summer (“*Kiremti*”), autumn, winter (“*Kiremti Bahri*”), and spring (“*Azmera*”).

Summer season commonly known as locally as “*Kiremti*” is the major rainy season which extends from June to August. Many parts of the climatic zones of the country get long rain during this season except the coastal zone. The “*Kiremti*” season commences during June when the ITCZ moves northward and terminates around late August when the ITCZ moves southward. Rainfall distribution during this season varies greatly (Fig. 3). Sometimes the season starts very late affecting the main economic sector of the country i.e. agricultural production.

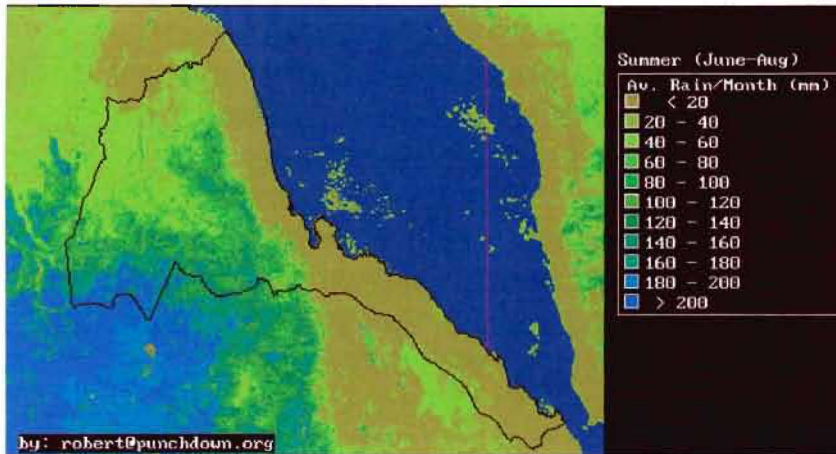


Figure 3: Average rainfall per month (in mm) for summer season (June –August)

(Source: Buskirk RV from <http://www.punchdown.org/rvb/rain/rainann.html>)

The winter (“*Kiremti Bahri*”) season stretches from October to March. During this season the coastal area gets rainfall though it is little in amount. During the spring (“*Azmera*”) season, Eritrea gets short rain from March to May.

d). Review of the literature

As Eritrea is a new nation and got its independence in 1991, very few study has been done on the rainfall condition of the country and almost nothing has been documented on the ocean-atmosphere mechanisms associated to wet and drought years during the major rainy season (June-August).

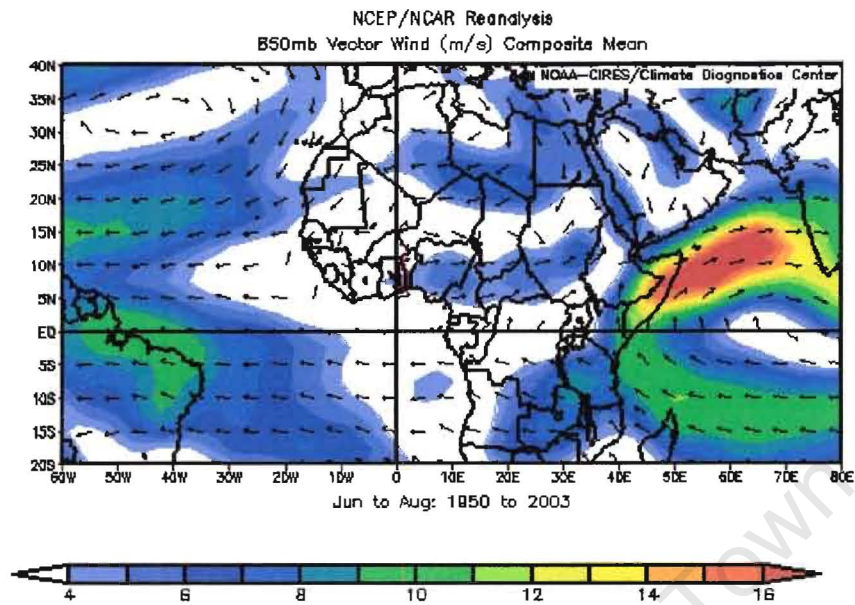
Nurahmed (1998) has noted that the summer rainfall is highly variable but he didn’t mention further the oceanic and atmospheric signal associated with it. Camberlin and Philippon (2001) mentioned that no study has been done yet on study of seasonal or interannual rainfall variability.

Department of Environment of Eritrea (2001), Nurahmed (1998) noted that the major factors for Eritrea's rainfall are: the Inter Tropical Convergence Zone (ITCZ), tropical cyclones over north Indian Ocean, orographic lifting, thermodynamic instability, and mid-latitude low pressure systems. Principal controlling factor for the summer rainy season (June-August) is the south -westerly winds, prevailing from the Atlantic Ocean. This can be observed from Figs. 4a and b of the composite image of mean of vector wind (at 850mb and 500mb) for summer season (June –August) from the NCEP-NCAR datasets from 1950-2003.

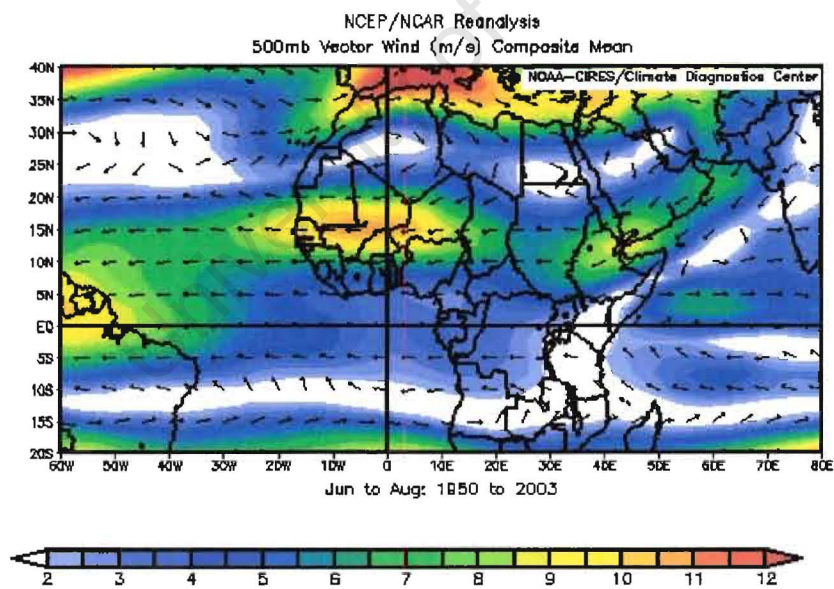
Large-scale fluctuations in the monsoon flow are a major source of temporal climatic variability over Eritrea. This has been noticed by the peculiar characteristics of monsoon wind over Eritrea. According to Nurahmed (1998) the northeasterly wind will be replaced by south westerly during the Southern Hemisphere summer and Northern Hemisphere summer, respectively.

Starting from 1960's weather patterns in Eritrea have been fluctuating very much. It has been observed that since 1965, Eritrea has been suffering from drought at approximately every 5-7 years (Department of Environment of Eritrea 2001). Catastrophic drought has been recorded from 1972 to 1987, and in 1993 (Department of Environment of Eritrea 2001). Eritrean summer rainfall has been very poor and arrived very late in the year 2001 and 2002. The consequence of the below-normal rainfall and dry spells during this season results in sever drought in the country.

Nurahmed (1998) noted that ENSO might have an impact on Eritrean rainfall. He recommended further study is needed.



a) at 850mb



b) at 500mb

Figure 4: Composite NCEP-NCAR summer season (June-August) mean vector wind at 850mb (a) and 500mb (b)

Section 2: DATA AND METHODOLOGY

A monthly precipitation data set for Eritrea from 1950 to 1996 is extracted from 2.7x2.7 degree grided rainfall data set of Climatic research unit (CRU) Hulme precipitation and this together with rainfall data from Africa Data Dissemination Service was used to determine the characteristics of the wet and dry years. The African Data Dissemination Service (ADDS) compiles and updates rainfall database. The data is collected from the host countries. The ADDS provides public access to African data sets archived by the U.S. Agency for International Development (USAID) Famine Early Warning System Network (FEWS NET).

In using the CRU data set, coordinates 35° to 45° E and 11° to 20° N are used to show the geographic position of Eritrea from June-August (rainy season) period each year to form an Eritrean summer rainfall index for the data set. Correspondingly, years for which the normalised summer rainfall anomaly (normalized anomaly is equal to the anomaly divided by the standard deviation for the period) above or below approximately one standard deviation were then defined as wet and dry years, respectively. This analysis has been done along with the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) data set.

Observational rainfall data for the period 1979's–00's for Eritrea were obtained from Africa Data Dissemination Service for different meteorological stations. After obtaining the rainfall data for the period of 1979 to 2000, normalized summer rainfall has been plotted. This plot helps to identify the wet and dry years and compare with

the data from CRU data set. The Africa Data Dissemination Service has some data gaps and some of the stations were not operating for many years due to war for independence of the country.

The study includes various gridded fields of atmospheric parameters from NCEP-NCAR reanalysis to describe typical conditions associated with wet and dry years over Eritrea. An analysis of the fields is based on compositing techniques, which involve the selection of meteorological events with similar characteristics and then obtaining the averaged characteristics of these events at seasonal scale. Though NCEP-NCAR reanalysis includes a comprehensive set, only the following variables have been selected: zonal and meridional components; geopotential height, air temperature, relative humidity, cloud cover, and precipitation.

To analyse the relationship of El Niño-Southern Oscillation (ENSO) and Eritrean rainfall, as an index of ENSO, Southern Oscillation Index (SOI), which has been used as derived by the climatic prediction model (Table 1) and El Niño events as defined by SST anomalies in Niño 3.4 Region by Trenberth (1997) (Table 2) have been used. Extreme El Niño events have been selected based on the Southern Oscillation Index (SOI) and SST anomalies in Niño 3.4 Region which synchronize to the Eritrean summer rainfall season (June-August). The NCEP-NCAR reanalysis was used to assess the mean fields and anomalies associated with the extreme El Niño events. Composites of warm anomalous years (El Niño events) for the different atmospheric fields were plotted. Correlation analysis of those parameters and ENSO index has been done.

Year	JFM	AMJ	JAS	OND	Year	JFM	AMJ	JAS	OND
1950	C	C	C	C	1976	C	N	N	W-
1951	C	N	N	W-	1977	N	N	N	W-
1952	N	N	N	N	1978	W-	N	N	N
1953	N	W-	W-	N	1979	N	N	N	N
1954	N	N	C-	C	1980	W-	N	N	N
1955	C	C-	C-	C+	1981	N	N	N	N
1956	C	C	C	C-	1982	N	W-	W	W+
1957	N	W-	W-	W	1983	W+	W	N	C-
1958	W+	W	W-	W-	1984	C-	C-	N	C-
1959	W-	N	N	N	1985	C-	C-	N	N
1960	N	N	N	N	1986	N	N	W-	W
1961	N	N	N	N	1987	W	W	W+	W
1962	N	N	N	N	1988	W-	N	C-	C+
1963	N	N	W-	W	1989	C+	C-	N	N
1964	N	N	C-	C	1990	N	N	W-	W-
1965	C-	N	W	W+	1991	W-	W-	W	W
1966	W	W-	W-	N	1992	W+	W+	W-	W-
1967	N	N	N	N	1993	W-	W	W	W-
1968	N	N	N	W-	1994	N	N	W	W
1969	W	W-	W-	W-	1995	W	N	N	C-
1970	W-	N	N	C	1996	C-	N	N	N
1971	C	C-	C-	C-	1997	N	W	W+	W+
1972	N	W-	W	W+	1998	W+	W	C-	C
1973	W	N	C-	C+	1999	C+	C	C-	C
1974	C+	C	C-	C-	2000	C	C-	N	C-
1975	C-	C-	C	C+	2001	C-	N	N	

Table 1: cold (La Niña) and warm (El Niño) Episodes by Season (as defined by SOI); weak periods are designated as C- or W-, moderate strength periods as C or W, strong periods as W+ or C+, and neutral periods as N. (source: NOAA web site, climatic prediction model http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.html)

El Niño Events		
Begin	End	Duration
Aug, 1951	Feb, 1952	7
Mar, 1953	Nov, 1953	9
Apr, 1957	Jun, 1958	15
Jun, 1963	Feb, 1964	9
May, 1965	Jun, 1966	14
Sep, 1968	Mar, 1970	19
Apr, 1972	Mar, 1973	12
Aug, 1976	Mar, 1977	8
Jul, 1977	Jan, 1978	7
Oct, 1979	Apr, 1980	7
Apr, 1982	Jul, 1983	16
Aug, 1986	Feb, 1988	19
Mar, 1991	Jul, 1992	17
Feb, 1993	Sep, 1993	8
Jun, 1994	Mar, 1995	10
Apr, 1997	Apr, 1998	13

Table 2 lists of El Niño events after 1950 as defined by SST anomalies in Niño 3.4 Region and exceeding $\pm 0.4^{\circ}\text{C}$ threshold. The starting and ending month of each event is given with the duration in months (Source: Trenberth 1997).

Regarding the validity of NCEP-NCAR reanalysis dataset; Smith et al. (2001) suggested that the uncertainties of NCEP-NCAR are not known yet. He found that NCEP-NCAR underestimates significantly near-surface wind speed, but it underestimates slightly pressure and momentum flux while it overestimates sensible and latent heat fluxes. Further he noted that NCEP-NCAR temperature and specific humidity relatively valid to wind and pressure. Pocard and Janicot (1998), Camberlin et al. (2001) noted NCEP-NCAR reanalysis is data set essential for climatic studies despite some limitations. Further Yan et al. (2002) suggested that “NCEP-NCAR data are dynamically homogeneous as they are gridded outputs of identical modeling based on worldwide meteorological observations.”

University of Cape Town

Section 3: RESULT AND DISCUSSION

a) Mean monthly and seasonal rainfall cycle

Mean monthly of Eritrea's rainfall from 1950-1996 which were extracted from the Climatic Research Unit (CRU) data set using 35° to 45 ° East and 11° to 20 ° North coordinates that includes the geographical position of Eritrea. The data has been plotted in to bar graph showing the major rainy season (summer) the months of June, July and August (Figs. 5 and 6). Nurahmed (1998) noted that major rainy season, summer season, extends from June to August

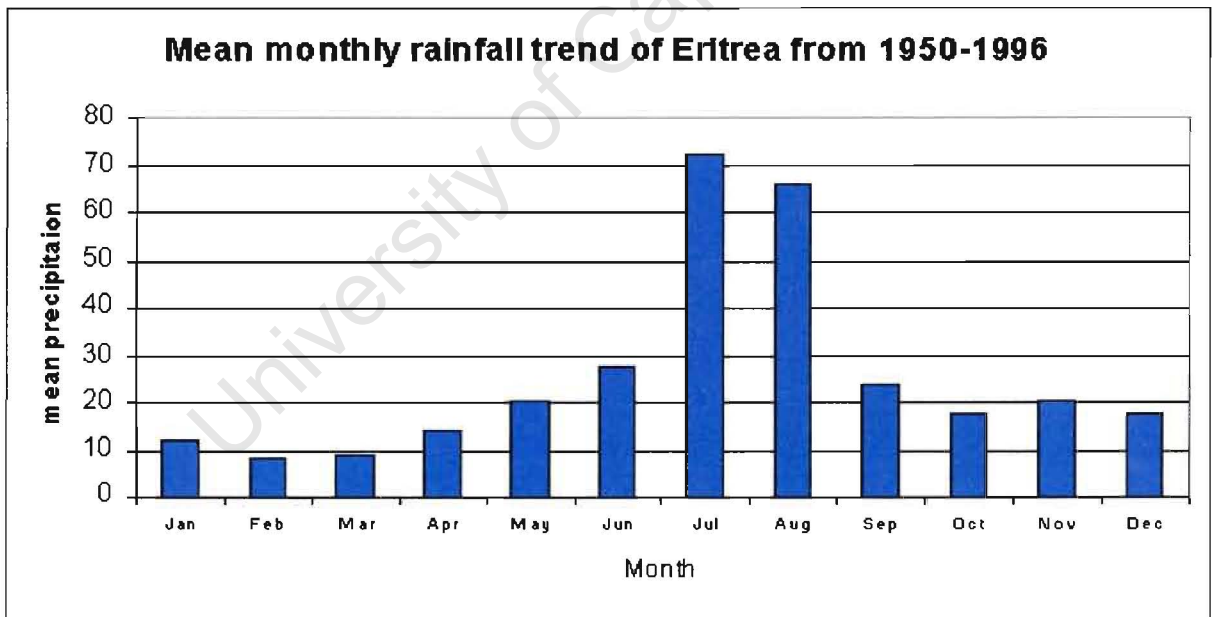


Figure 5: Mean monthly rainfall based on data from the CRU dataset showing the months of June-August as major rainy months (summer season)

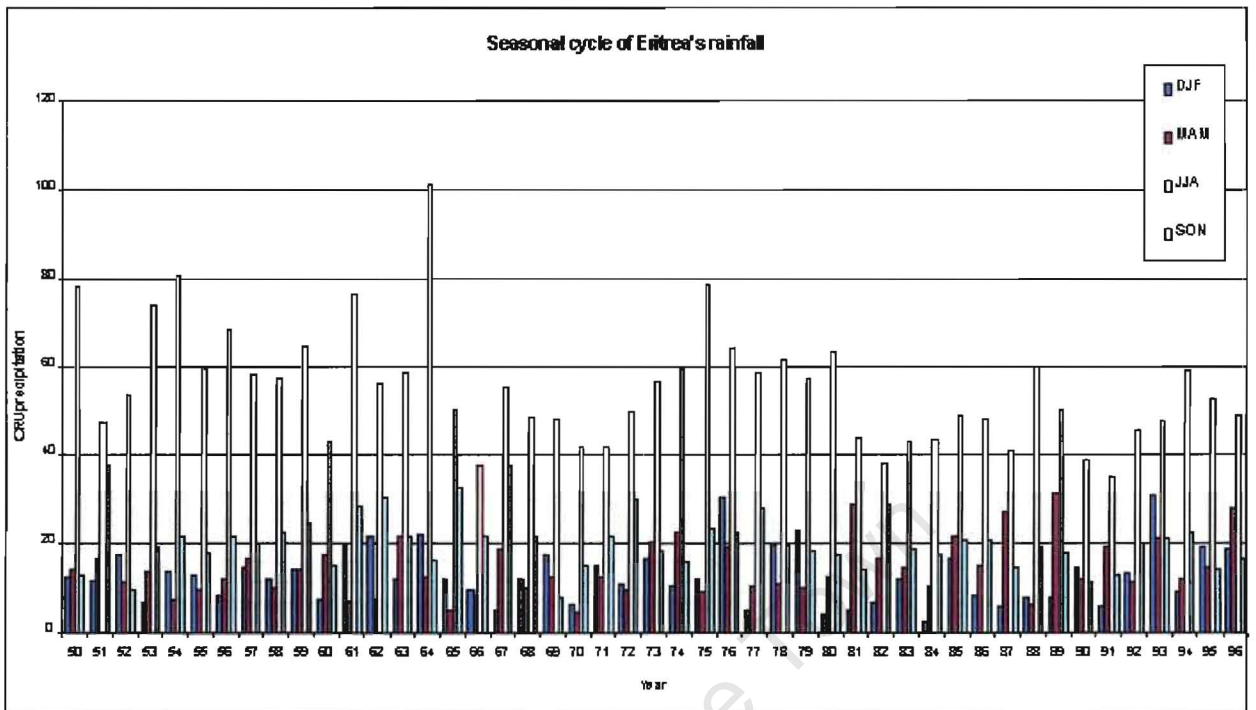


Figure 6: Inter-annual mid-year rainfall based on data from the CRU dataset showing June-August.

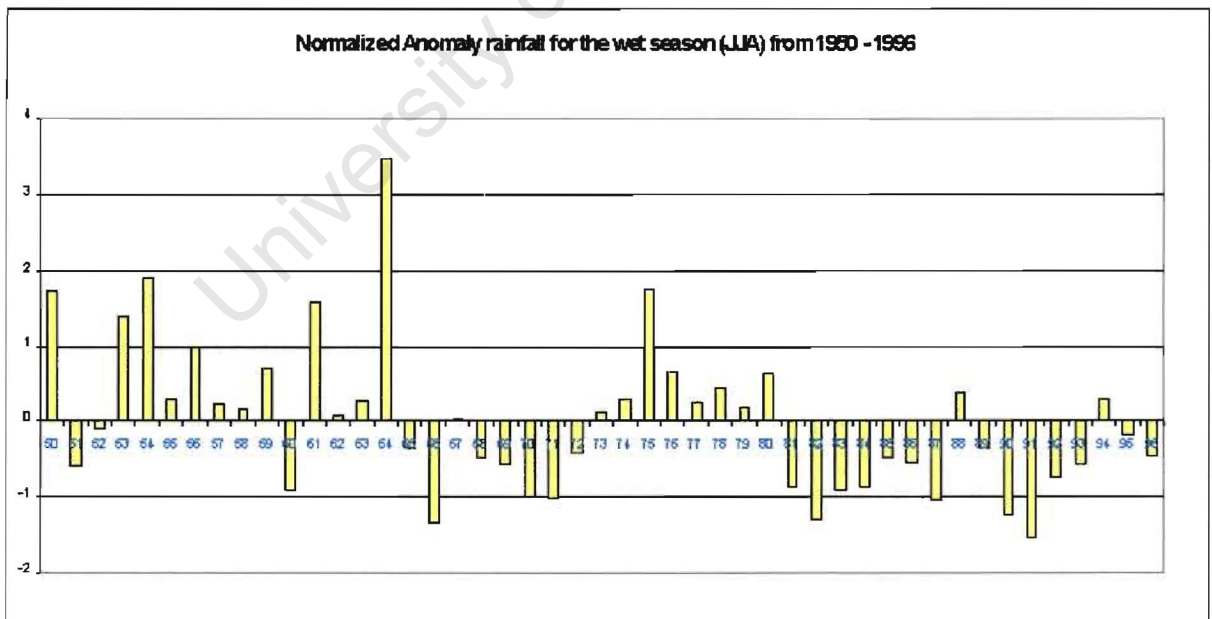


Figure 7: Normalised summer rainfall season based on data from the CRU dataset

b) Wet and dry years

Based on the normalised summer rainfall anomaly (normalized anomaly is equal to the anomaly divided by the standard deviation of the anomaly) derived from the CRU dataset for the period of 1950-1996 (June-August), the most extreme seasons which are above or below one standard deviation were then defined as wet and dry years, respectively (Fig. 7).

Thus the wet and dry years selected are:

Wet years	1950	1953	1954	1956	1961	1964	1975
Dry years	1966	1970	1971	1982	1987	1990	1991

Further, normalized summer rainfall anomaly (Fig. 8) of the observational data from the African Data Dissemination Service (ADDS) showed similar result with the CRU data set. The normalized summer rainfall anomaly from ADDS (Fig. 8) showed that that 1982, 1984, 1987, 1990 and 1991 were dry years. But the normalized anomaly plot (Fig. 7) from the CRU data set showed that the year 1996 was a dry year whereas the normalized anomaly plot from the ADDS showed that the year 1996 was extreme wet. Global Precipitation Climatology Project (GPCP) data set has been used to compare the reliability of the two data set (CRU and ADDS). The GPCP data set comprises of precipitation data from low-orbit-satellite microwave data, geosynchronous-orbit satellite infrared data, and rain gauge observations. This data set contains monthly gridded area-mean rainfall with 2.5x2.5 degree resolution. Long-term

precipitation record for all over the globe is available from the data set. The data set is essential for verification of climate model simulations.

GPCP data shows that the JJA months of the year 1996 were wet season (Fig. 9). Comparing the precipitation data from the tree data sets for this particular year indicates that the GPCP and ADDS (Figs. 8 and 9) data sets have similar result whereas the CRU data (Fig. 6) showed the summer season of the year 1996 was dry. Thus the CRU data set should have to consider such kind of inconsistency. In this study the year 1996 has not been chosen neither as dry year nor wet year.

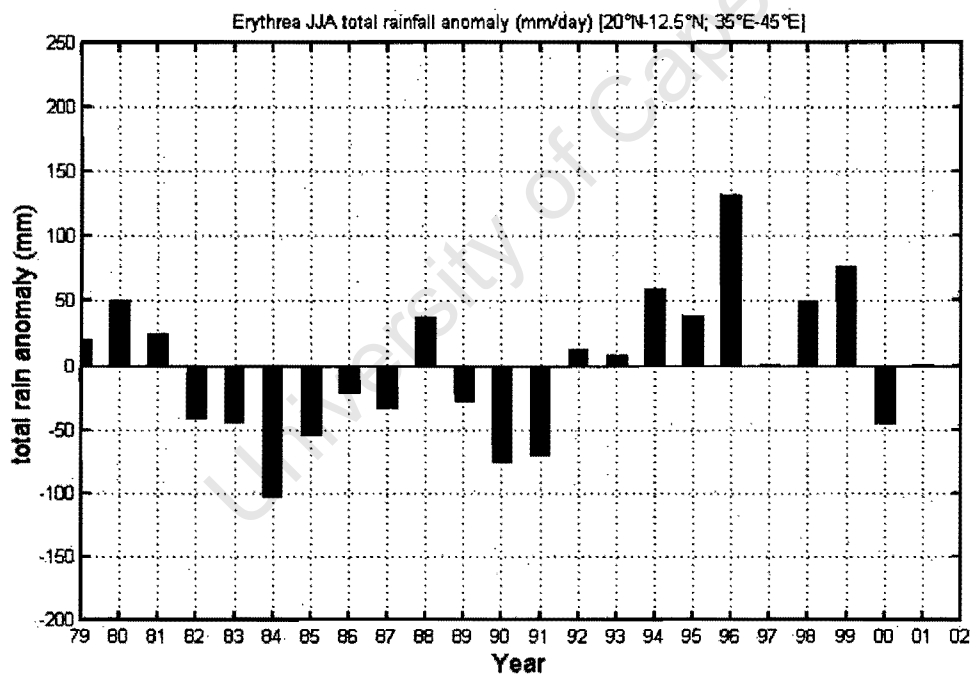


Figure 8: Normalised anomaly of Eritrean summer rainfall based on data from African Data Dissemination Service

In the past many dry years have been recorded. For instance drought occurred in major part of the Horn of Africa, including Eritrea, in 1968-1973, 1982 and 1990-1991 (UNEP 1991; Andrew and Mustafa 1992). Sever drought occu 21

in Eritrea in the year 1984 (Andrew and Mustafa 1992; Fig. 8). This extreme dry year has been clearly shown in the ADDS normalized plot but not strongly in the CRU data set (Figs. 7 and 8). According to the Department of Environment of Eritrea (2001), since 1965 Eritrea has been suffering from drought at approximately every 5-7 years. Catastrophic drought has been recorded from 1972 to 1987, and in 1993 (Department of Environment of Eritrea 2001). From normalized summer rainfall anomaly (Fig. 7 and 8), it can be observed that there were extended dry years from 1982 -1987 and 1990/91 which in fact drought hit the country adversely during those years.

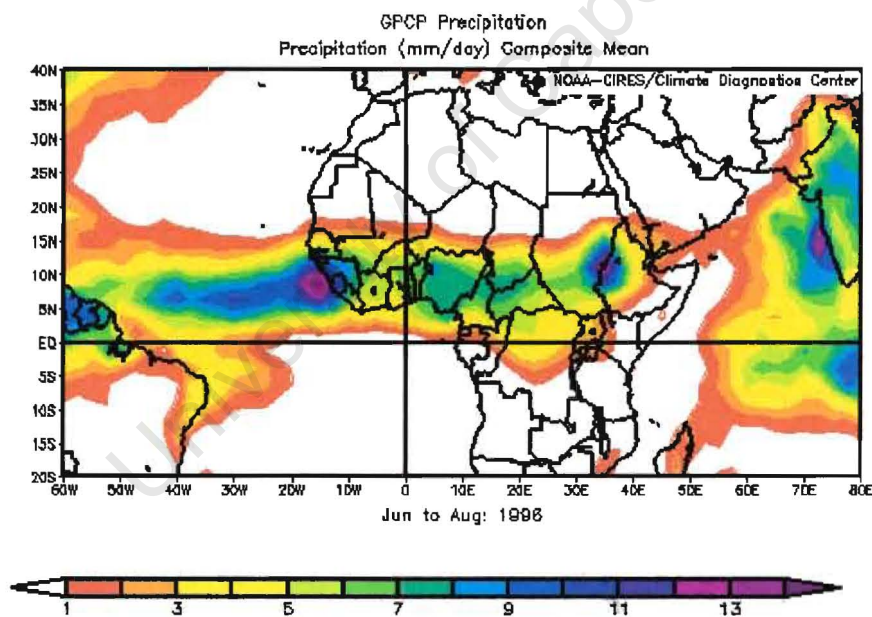


Figure 9 GPCP precipitation image for summer season of 1996

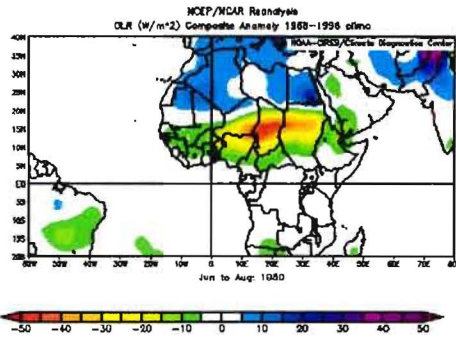
c) Atmospheric and oceanographic mechanisms for the wet and dry years

Using the NCEP reanalysis data, the atmospheric dynamics associated with the wet and dry years are further analysed by compositing. The following composites of meteorological fields are performed at different pressure levels: Outgoing longwave radiation (OLR), Sea Surface Temperature (SST), Air temperature, Relative humidity, Vector wind, and Geopotential height

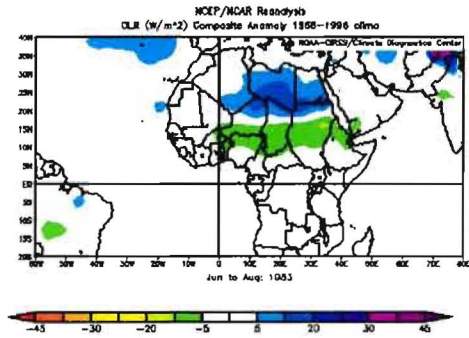
Outgoing longwave radiation (OLR):

Analysis of distribution and cover of clouds is important to understand rainfall patterns (Preston-whyte and Tyson 1988; Peixoto and Abraham 1992). Whether any region around the globe is covered by cloud or not can be identified by outgoing longwave radiation (OLR). OLR is usually used as a proxy for rainfall.

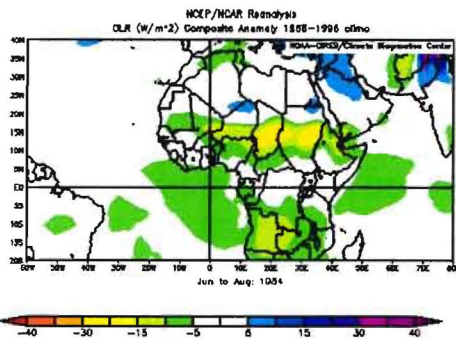
The large negative OLR values over Eritrea (Fig. 9) during wet anomaly years implies more extensive or deeper cold cloud tops. This corresponds to a positive anomaly in deep convection (above normal convection), i.e., enhanced rainfall. While large positive OLR value (Fig. 10) for the dry anomaly years implies below normal convection (reduced rain) except for the years 1966, 1970 and 1971. As observed from Fig.10 anomalous OLR value have been bigger and widespread since 1980's which corresponds with the dry years as it has been shown from Figs 7 and 8. Thus the OLR values showed similar results with that of the CRU Hulme precipitation data.



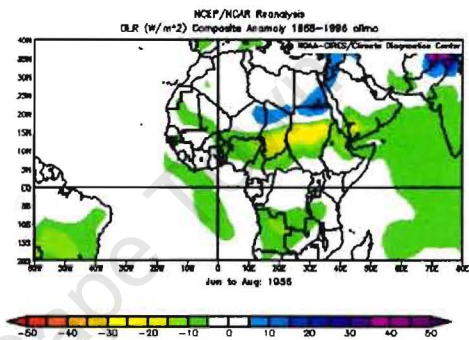
Year 1950



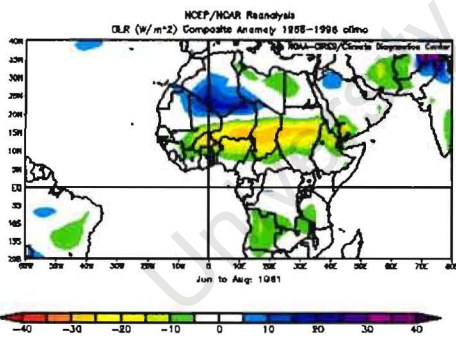
Year 1953



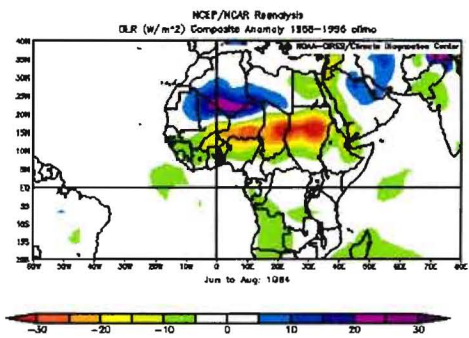
Year 1954



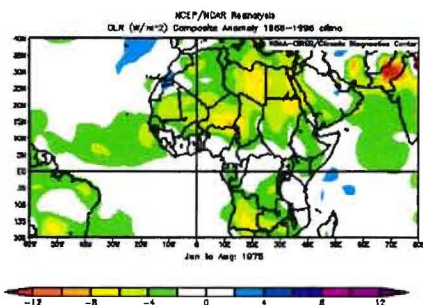
Year 1956



Year 1961

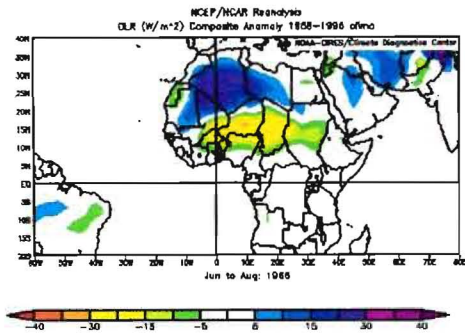


Year 1964

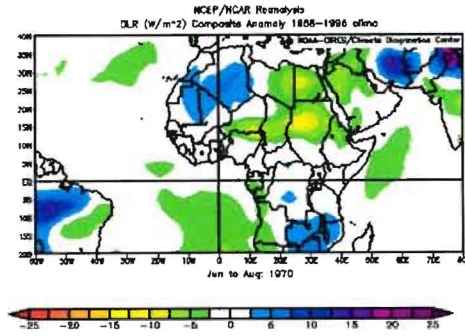


Year 1975

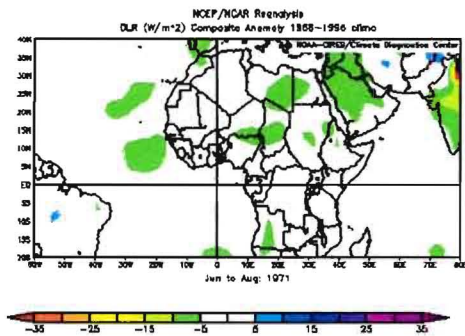
Figure 9: OLR for Wet years (all wet years show negative OLR values over Eritrea)



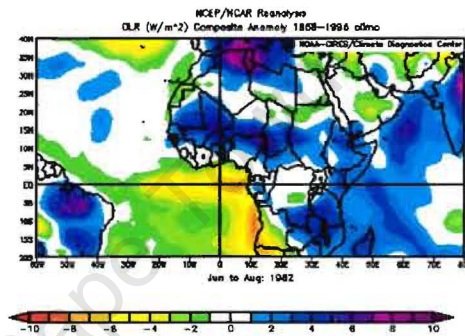
Year 1966



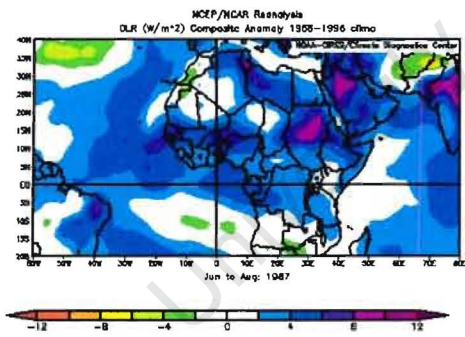
Year 1970



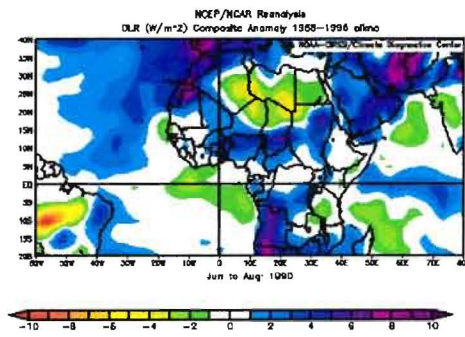
Year 1971



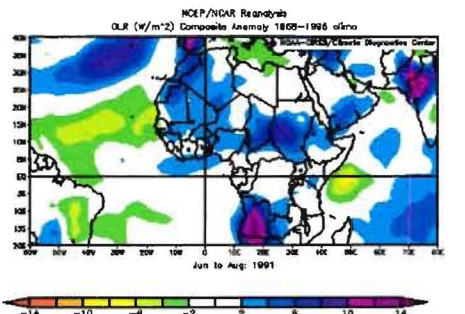
Year 1982



Year 1987



Year 1990

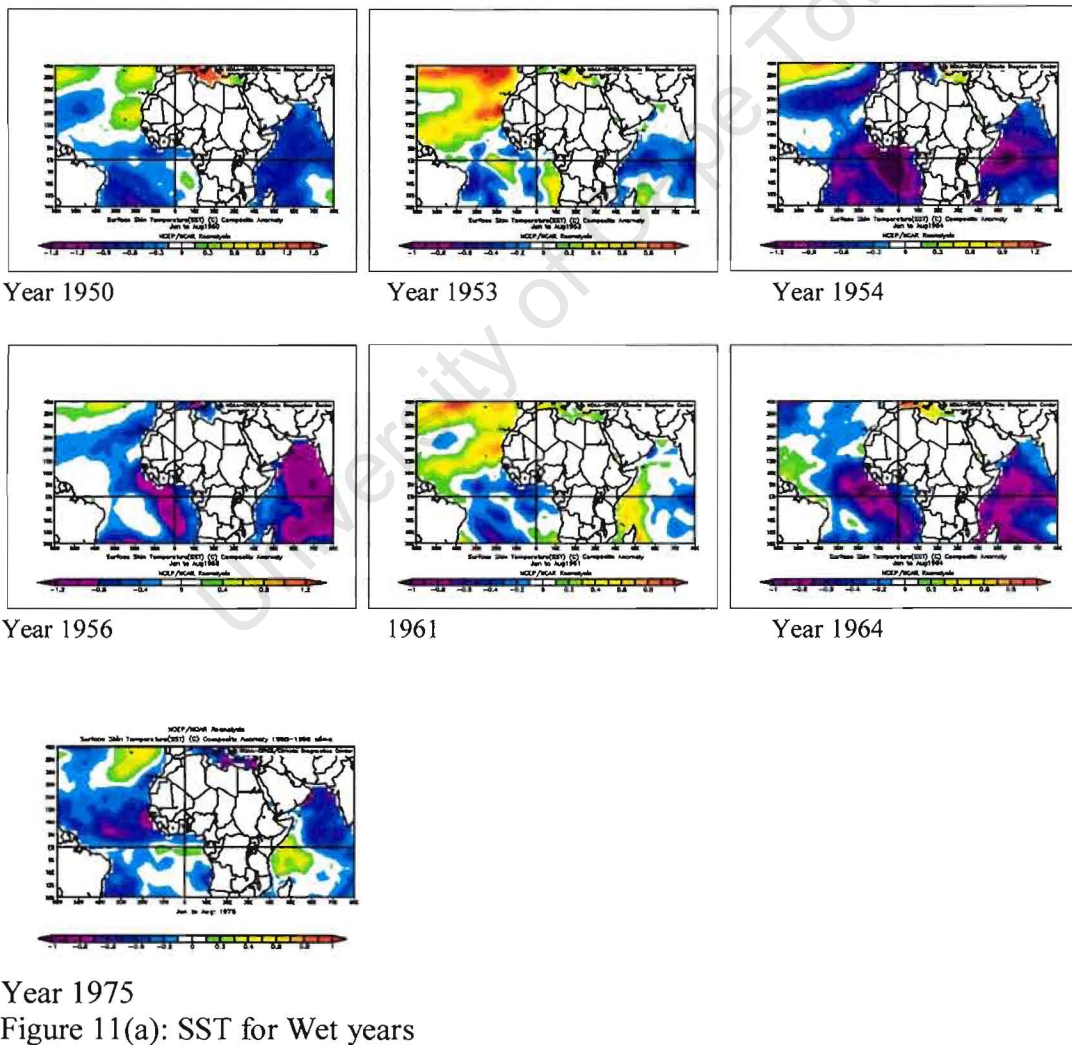


Year 1991

Figure 10: OLR for Dry years (shows from 1980's the anomalous OLR value gets bigger)

Sea Surface Temperature (SST)

The pattern of the SST along the tropical Atlantic and the Indian oceans seems to be linked to the occurrence of the anomaly years (Figs. 11a and 12). During wet years, the presence of warmer northern tropical Atlantic Ocean and colder southern tropical Atlantic, and colder Indian Ocean SST has been observed from the composite image (Fig. 11b). While during most of the dry anomaly years, particularly in 1987, 1990 and 1991 (Fig. 12a) and the composite image if these anomalous years, warm SST of Indian Ocean has been observed (Fig.12b).



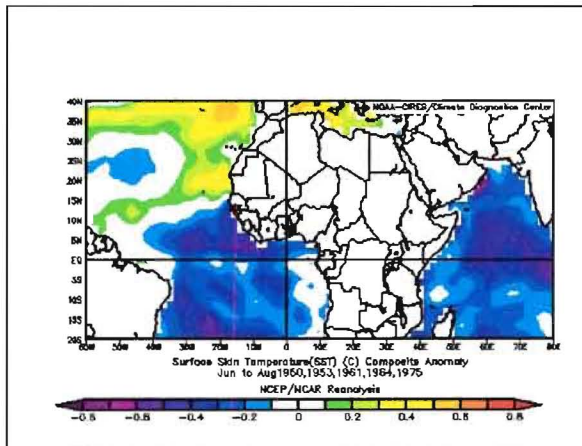


Figure 11(b): SST composite image for Wet years (1950, 1953, 1961, 1964, 1975) which prevail similar SST pattern

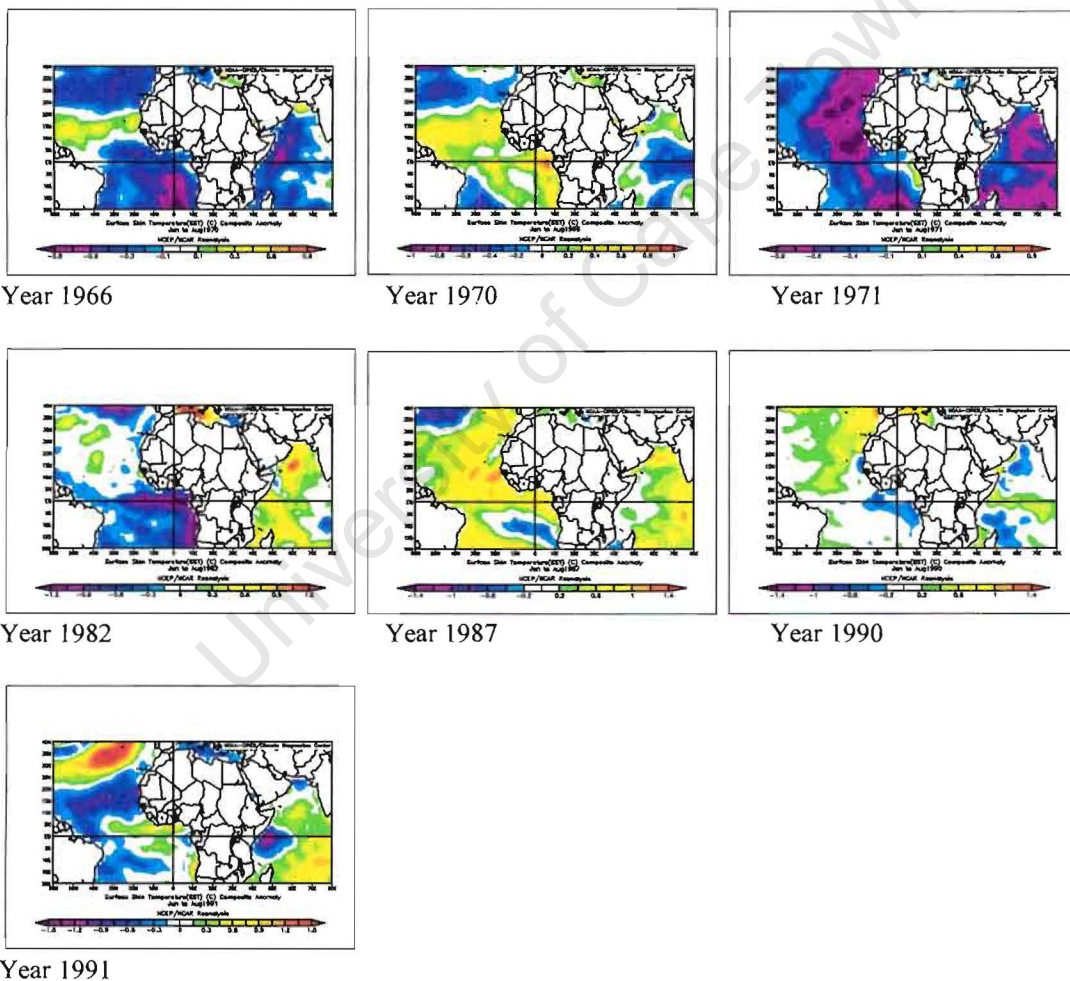


Figure 12(a): SST for Dry years

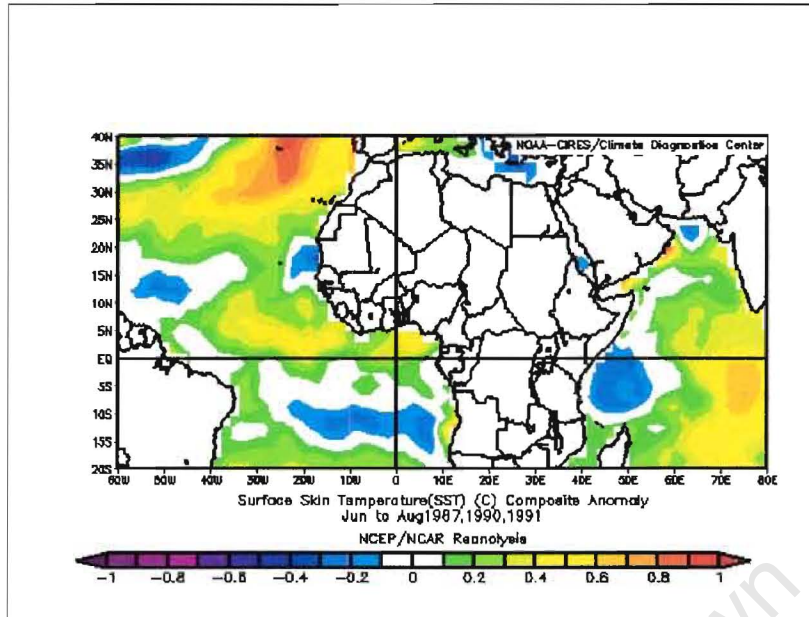
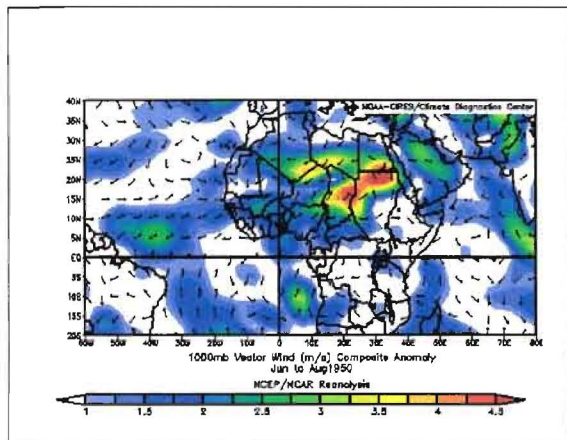


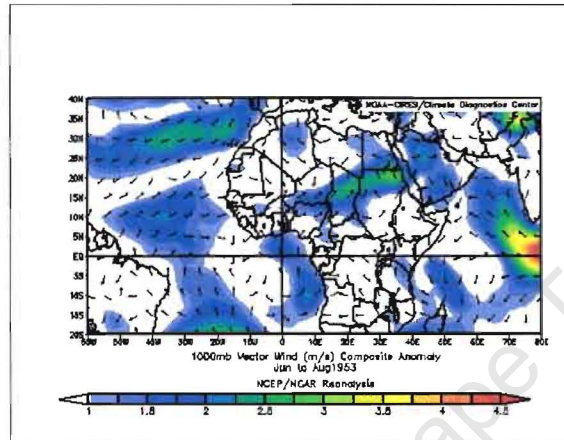
Figure 12(b): SST composite image for dry years (1987, 1990, and 1991) which prevail similar SST pattern

Vector wind

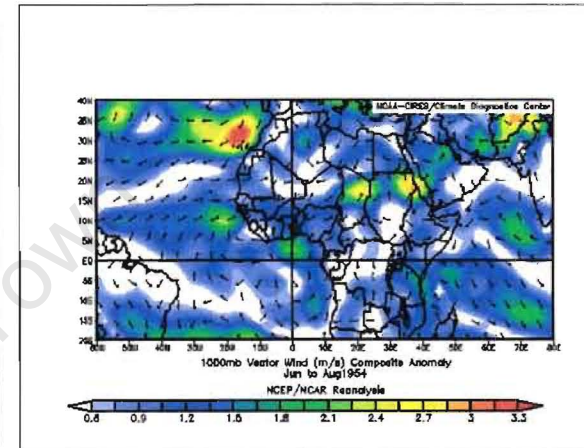
The composite images for the wet years (Fig. 13a) showed that the vector wind were more westerly. The westerly winds, which bring moisture from tropical Atlantic, are good for enhanced rain during the wet years in Eritrea. From Fig. 13b of the composite images for the wet years at different pressure levels, it can be seen that at the upper tropospheric (200mb) the wind flow is anomalously easterly. At the lower atmosphere wind flow becomes anomalously westerly (Fig. 13b). Whereas, during dry years the pattern of wind anomalies is the opposite (Fig. 14b). During the dry years, the composite images (Fig.14a) showed that the winds were anomalously easterly which affirmed that there were less westerly with reduced rain during those dry years.



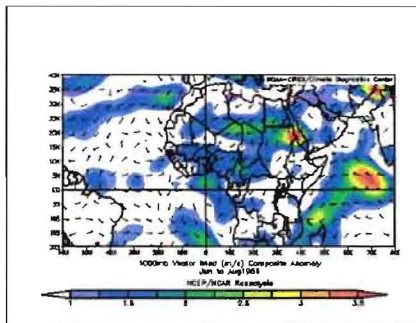
Year 1950



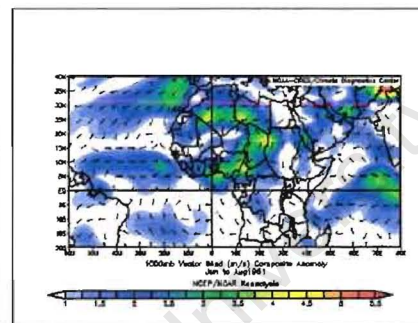
Year 1953



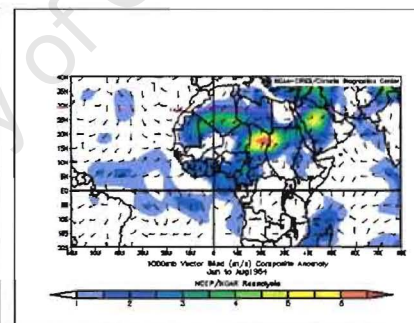
Year 1954



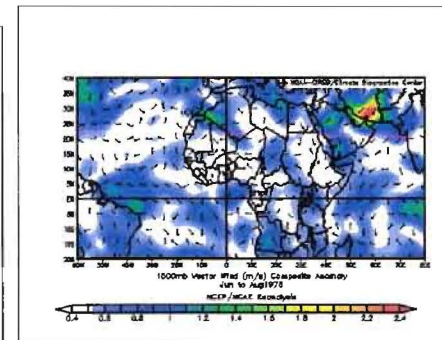
Year 1956



Year 1961

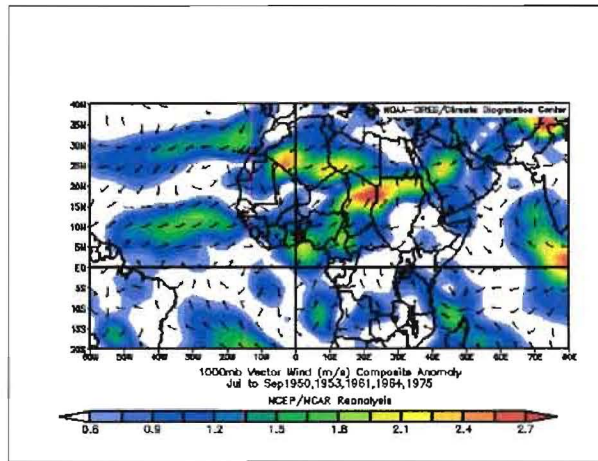


Year 1964

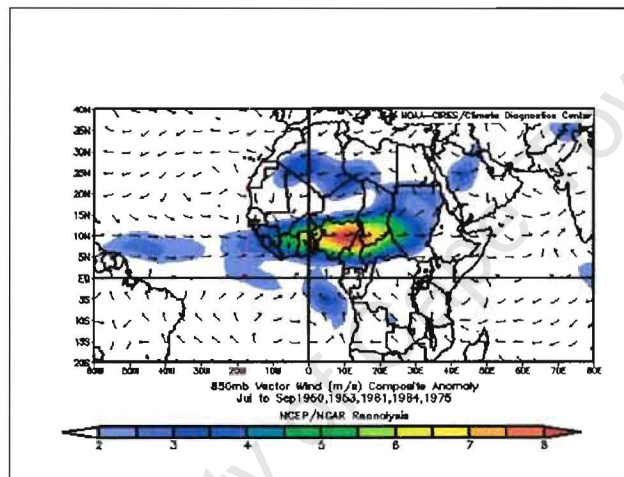


Year 1975

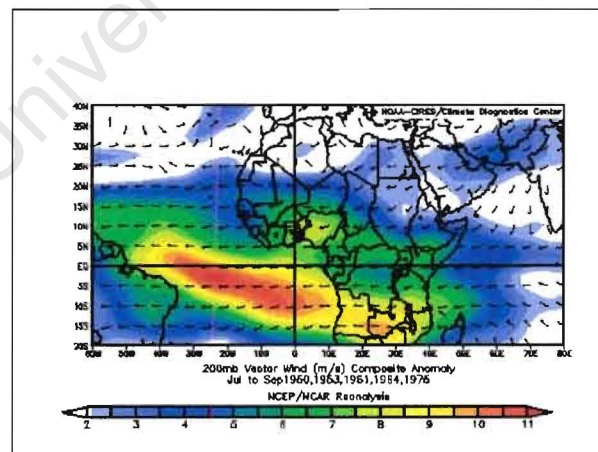
Figure 13(a) Vector wind anomaly for dry years



at 1000mb

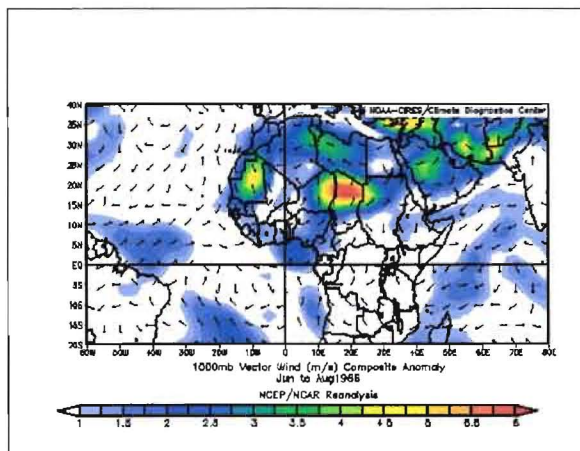


at 850

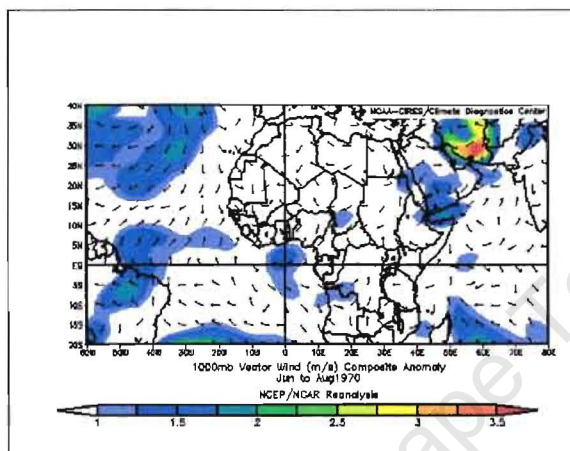


at 200 mb

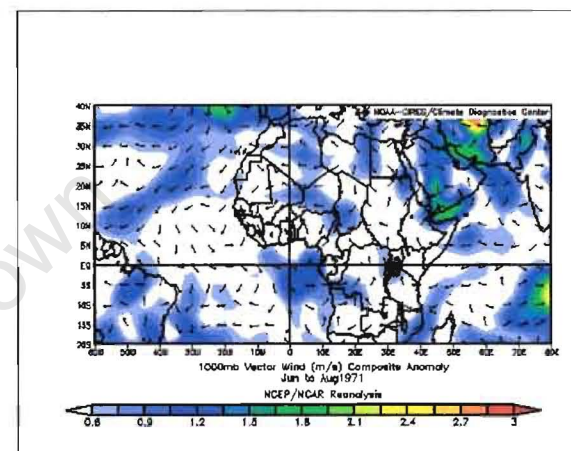
Figure 13(b): composite of vector wind anomaly for wet years 1950, 1953, 1961, 1964 and 1975 at 1000 mb, 850 mb and 200 mb



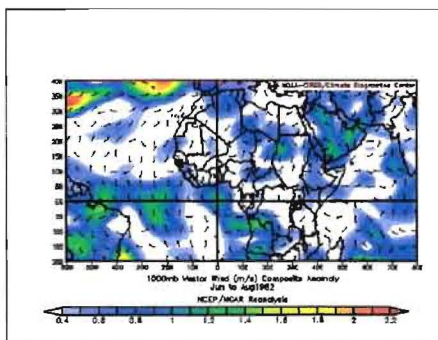
Year 1966



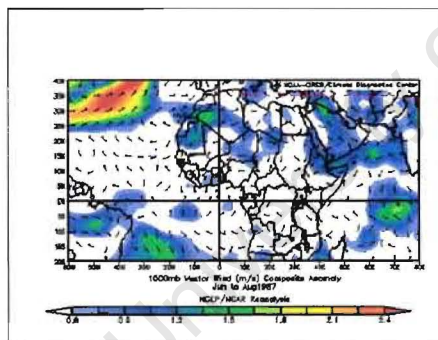
Year 1970



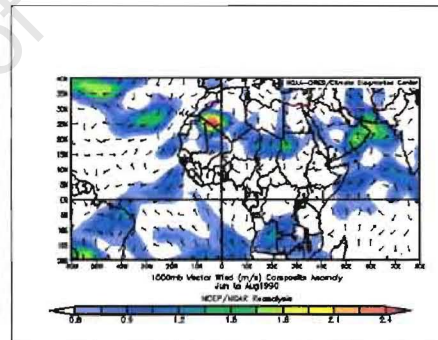
Year 1971



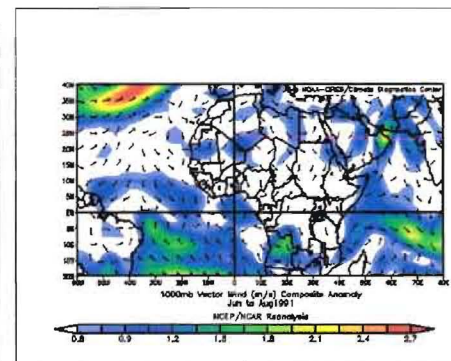
Year 1982



Year 1987

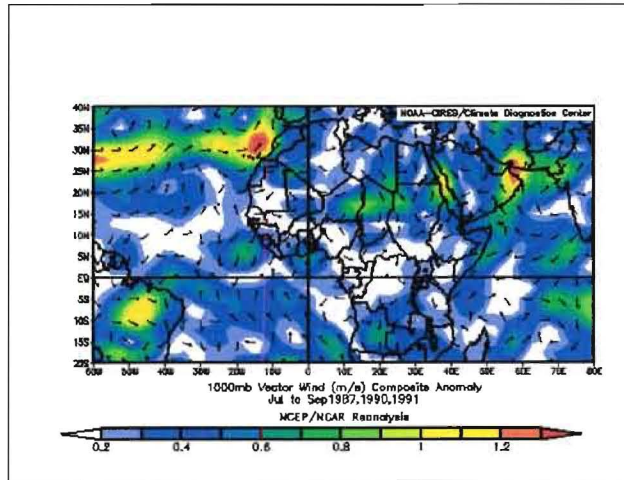


Year 1990

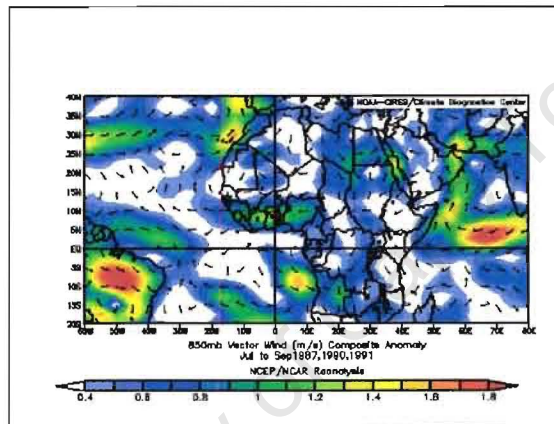


Year 1991

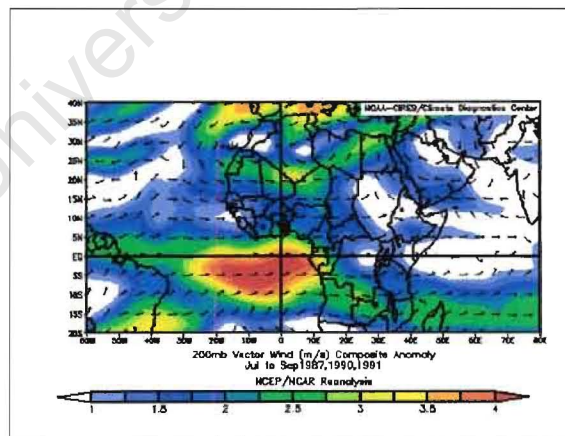
Figure 14(a) Vector wind anomaly for dry years



at 1000mb



at 850mb



at 200mb

Figure 14(b): composite of vector wind anomaly for dry years 1987, 1990 and 1991 at 1000 mb, 850mb and 200mb

Air temperature

Air temperature composite anomalies for wet years (1950, 1953, 1961, 1964 and 1975) at 1000 mb (Fig. 15) shows cold anomalies (below normal temperature) that arose from the rainy season. While composite of air temperature for dry years shows warm air temperature anomaly years (Fig. 16), which is anticipated during dry years.

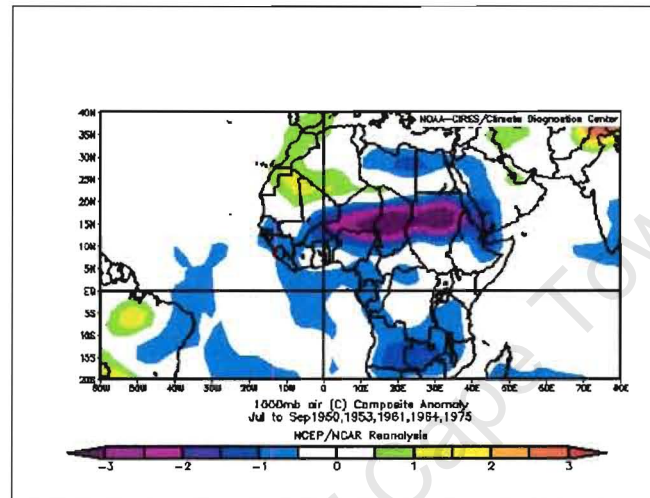


Figure 15: composite of air temperature for wet years

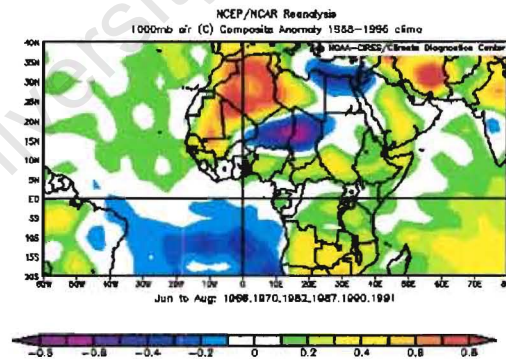


Figure 16: composite of air temperature for dry years

Relative humidity

Composite images of relative humidity from Figs. 17 and 18 show that during wet years, there was high higher relative humidity over Eritrea due to more rain and during the dry years it was the opposite in respects. From the composite image of the dry years (Fig. 18a), especially from the composite image of the most extreme drought years (Fig. 18b) can be observed that high moisture content over southern tropical Atlantic Ocean. This high humidity could affect indirectly the flow of westerly winds resulting in less rain over Eritrea.

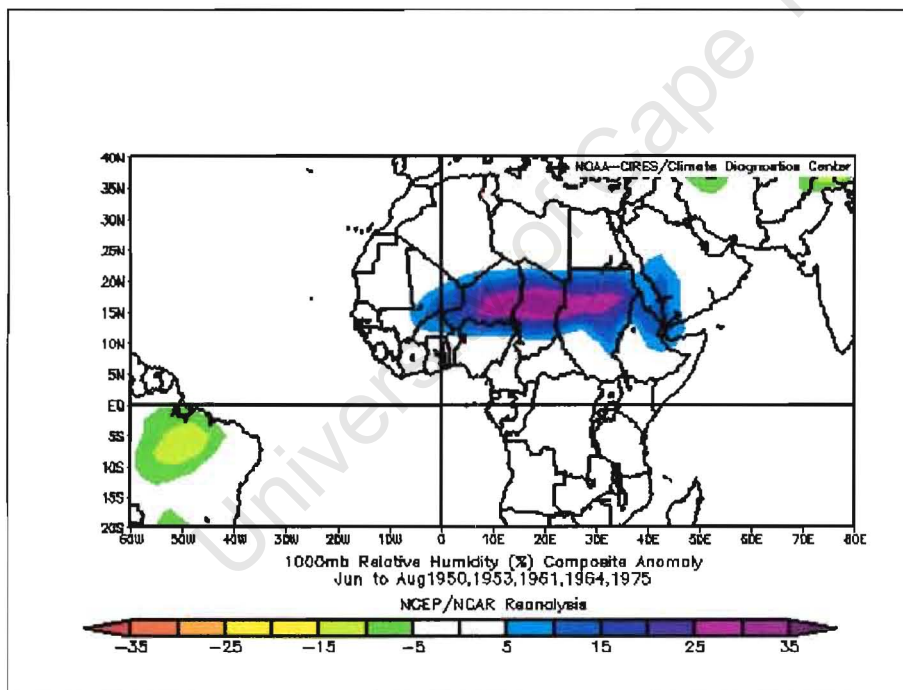


Figure 17: composite of relative humidity for wet anomalous years

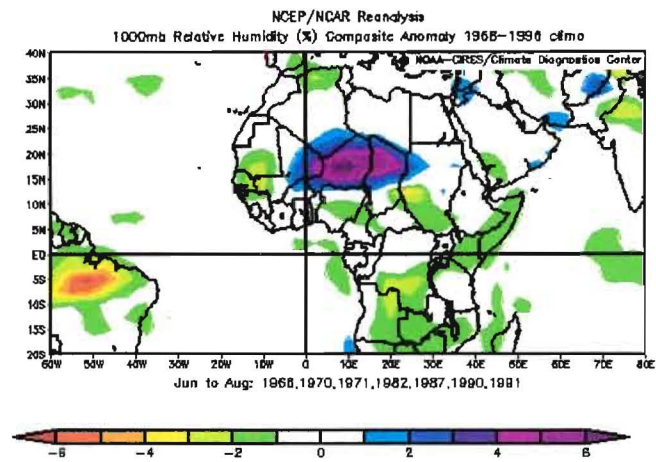


Figure 18(a): composite of relative humidity for dry anomalous years (1966, 1970, 1971, 1982, 1987, 1990 and 1991)

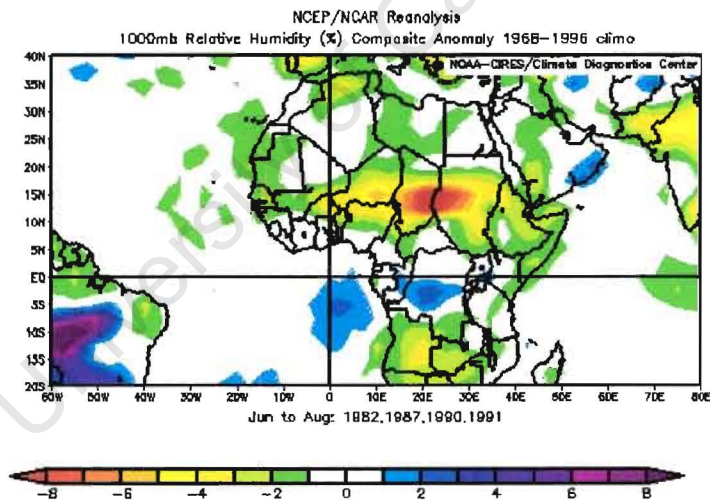
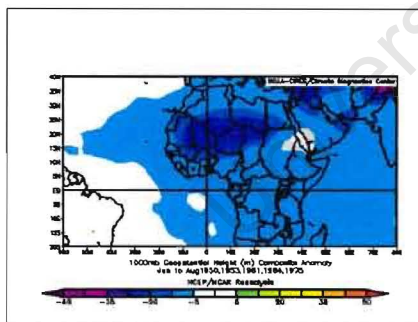


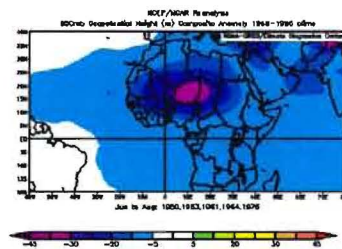
Figure 18(b): composite of relative humidity for dry anomalous years extreme drought years (1982, 1987, 1990 and 1991)

Geopotential height

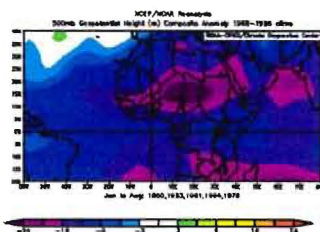
Negative values (low pressure) are observed for wet anomaly years associated with ascending air and cloudy skies resulting in wet conditions (Fig. 19) at different pressure levels. This low pressure could be induced due to the more south westerly wind (Figs. 13a and 13b) associated with more humidity (Fig. 17) from the tropical and equatorial Africa. Positive composite value of the Geopotential height (high pressure) is observed during the dry anomaly years (particularly for the composite images of extreme dry anomalous years: 1982, 1987, 1990 and 1991) that are associated with descending air, clear skies resulting in warming of the lower levels (Fig. 20). This wide spread high-pressure anomalies associated with less westerly during dry years (Figs. 14a and 14b) result in less rain. Further, it can be observed from Figs. 19 and 20 that the pressure dropped rapidly with height during wet years as compared during the dry years. This is mainly due to density difference of cold and warm air.



a) at 1000mb

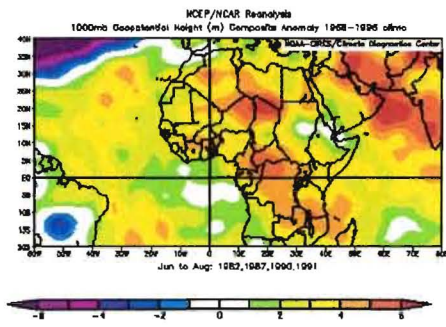


b) at 850mb

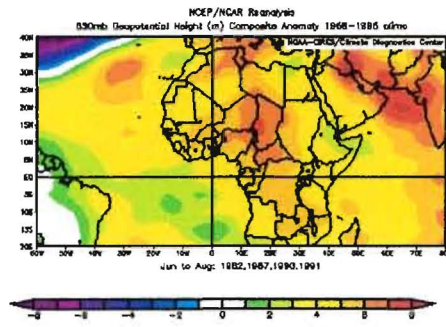


c) at 500mb

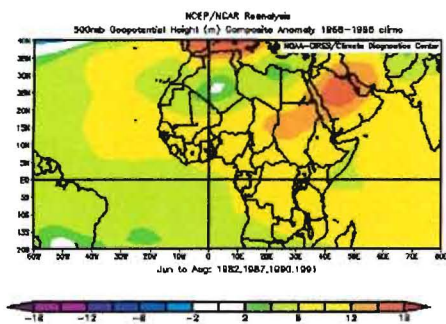
Figure 19: composite of geopotential height for wet anomalous years 1987, 1990 and 1991 at 100mb, 850mb and 500mb



a) at 1000mb



b) at 850mb



c) at 500mb

Figure 20: composite of geopotential height for dry anomalous years 1982, 1987, 1990 and 1991 at 1000mb, 850mb and 500mb

d) Correlation of Eritrean summer rainfall and SST

Having the establishment of the mechanism leading drought and wet period, SST anomalies were announced during the wet and dry years. The *Koninklijk Nederlands Meteorologisch Instituut* (KNMI) climate explorer, which is used to correlate station data, climate indices, gridded observations, and NCEP-NCAR reanalysis fields, has been used in this study to analyse correlation at different lags between Eritrea rainfall (CRU precipitation) and SST (NCDC (Reynold & Smith) SST reconstruction). Fig. 21 shows that summer rainfall over Eritrea is correlated to tropical Atlantic, Indian and eastern Pacific Oceans SST. Nurahmed (1998) indicated that the South Atlantic high pressure cells over the South Atlantic Ocean is one of the major controlling factors for the flow of lower tropospheric during the main rainy season (June-August). Further he added that “..the South Atlantic Ocean is the main source of moisture for summer rainfall over most parts of the country. Northeasterly dry and continental wind is a prevalent flow during dry spell within the season.”

It was seen from Fig. 21 that the Eritrean summer rainfall is correlated with the eastern Pacific Ocean SST (0.5-0.6) and Indian Ocean SST (0.5). The warm SST of Indian Ocean along with extreme high SST in eastern Pacific Ocean seems to influence the occurrence of the anomalous dry years. Further in this section, i investigated the relationship between the eastern Pacific Ocean (ENSO) and Eritrea summer rainfall.

corr Jun-Aug averaged CRU precipitation 35:45E 11:20N index
with Jun-Aug averaged NCDC SST

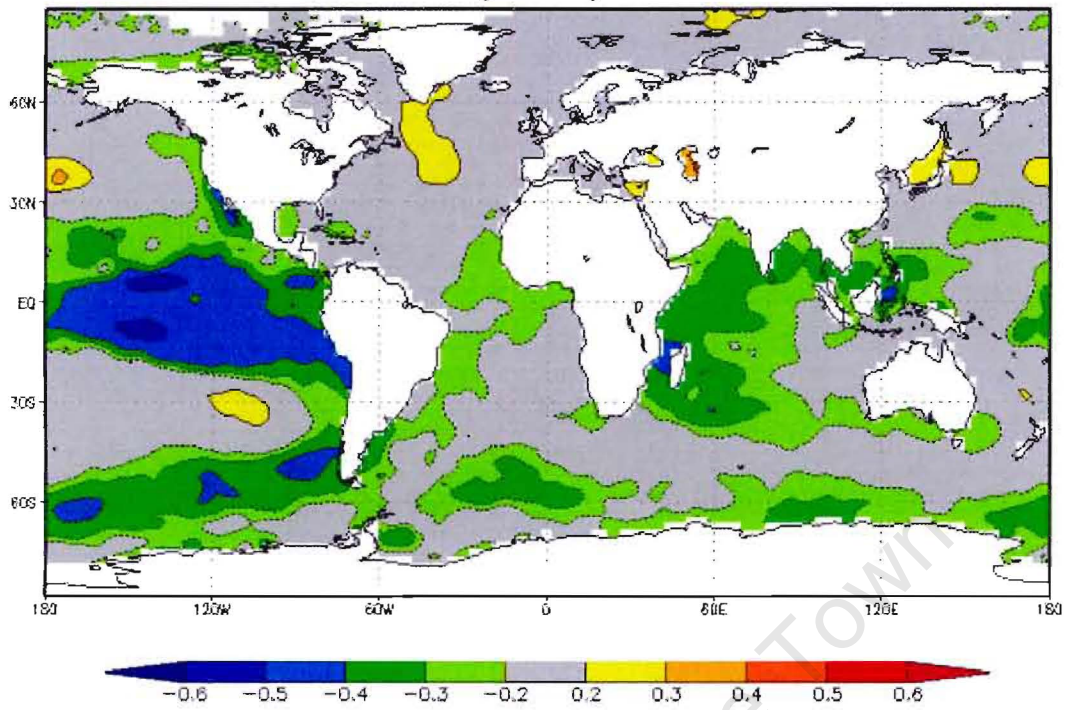


Figure 21: Correlation of Eritrean summer rainfall and NCDC (Reynold & Smith) SST reconstruction (for the time period of 1950-1996)

e) The relationship of ENSO and Eritrean rainfall

Because El Niño is a global phenomenon, this study also analyse the relationship between ENSO and Eritrean rainfall. The strong El Niño events, which coincide with the Eritrean summer rainfall seasons (June-August), were selected, as it has been described in the methodology section, based on the Southern Oscillation Index (SOI) and SST anomalies. El Niño events selected are: 1957, 1972, 1982, 1987, 1991, 1997 and 2001. NCEP-NCAR reanalysis data set was used to assess the mean fields and anomalies associated during the extreme El Niño events. The analysis of the fields is based on compositing techniques.

Sea Surface temperature (SST)

Understanding interannual variability of SST is essential because it significantly influences evaporation, thermal wind, moisture convergence, and indicates stability of the atmosphere.

During El Niño, the Indian Ocean along with eastern Pacific Ocean tends to warm (Fig. 22). The warm periods of the Indian Ocean (Fig. 12a and 12b) and eastern Pacific Ocean correspond to reduced rainfall over Eritrea. This implies that the rhythm of Eritrean summer rainfall is governed by large-scale SST patterns. Particularly, anomalous warm SST acts to reduce rainfall over Eritrea. ENSO events highly expressed the SST anomalous. ENSO is playing a dominant role in modulating rainfall over much of the Continent; mainly on northeastern (including Eritrea), eastern equatorial and southeastern Africa (Campbelin et al. 2001;

Nicholson and Kim 1997). As Eritrea is part of this region, ENSO could play a role in fluctuating rainfall of the country.

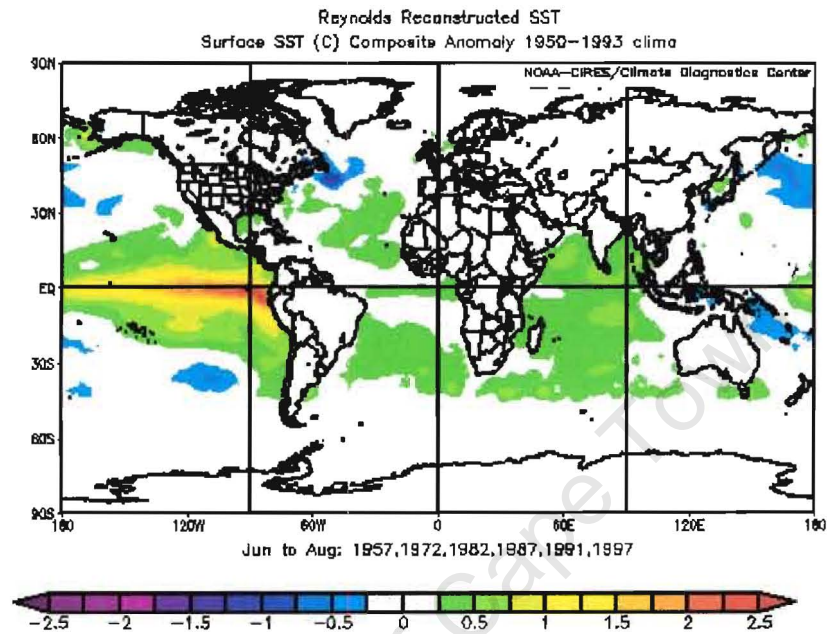


Figure 22: composite of SST anomalies during El Niño years

Thus, the SST over the Indian Ocean is strongly correlated with the ENSO event such that anomalous warm water in the Ocean tends to occur with extreme warm (El Niño) event. Thus, SST Indian Ocean along with the eastern Pacifica Ocean may impact on the Eritrean summer rainfall.

Wind

i) *Zonal winds*: easterly anomalies (less westerly) and/or more north easterly wind is observed in lower troposphere (Figs. 23 and 24) over Eritrea. The postive zonal winds anomalies (Figs. 23 and 24) indicate there were easterly anomalies, representing anomalous anticyclonic circulation.

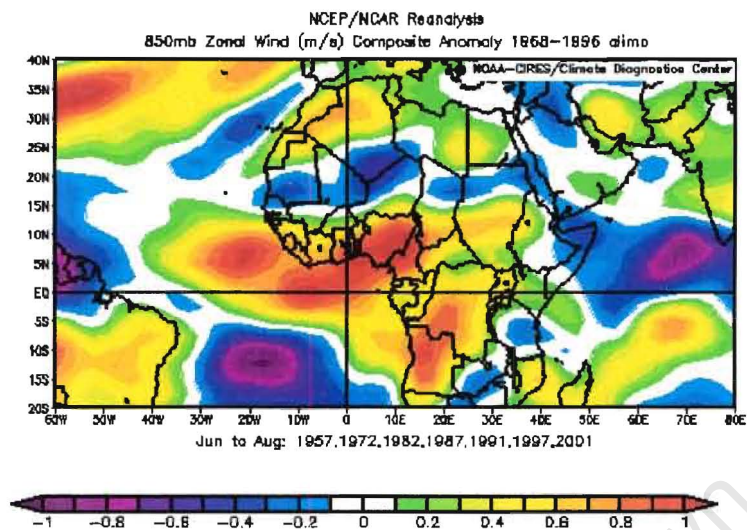


Figure 23 Composite of Zonal wind anomalies (850hPa) for El Niño years

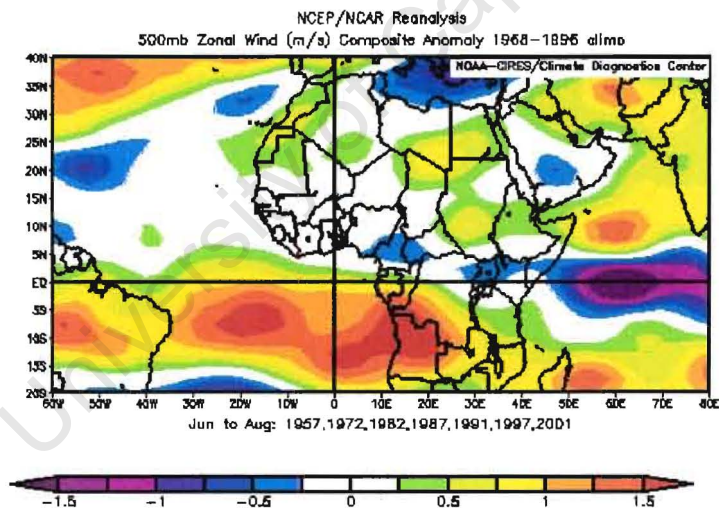


Figure 24 Composite of Zonal wind anomalies (500hPa) for El Niño years

ii) *Meridional wind*: though southerly winds blow during the El Niño events over Eritrea, almost all over the continent of Africa, the anomalous northerly winds are expressed by the ENSO events (Figs. 25 and 26). Cambelin et al. (2001) suggested that in addition to SST, other atmospheric forcing mechanisms: Africa Easterly Jet, or

northerly wind anomalies across the Sahara, is related to drought conditions (Cambelin et al. 2001).

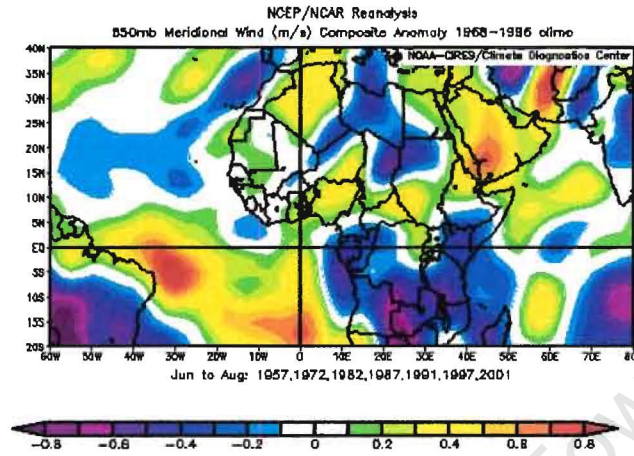


Figure 25 Composite of Meridional wind (850hPa) for warm anomalous years

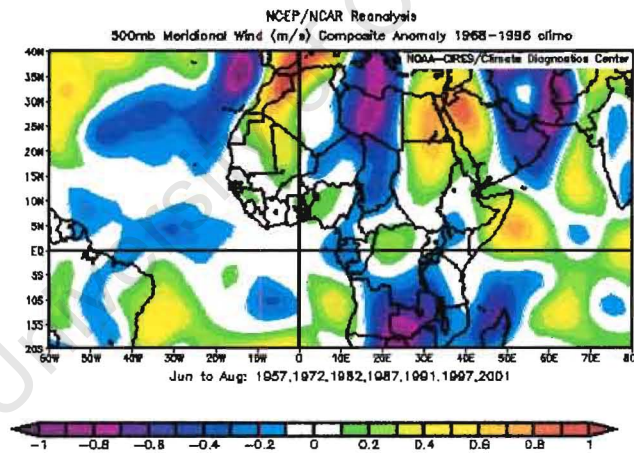


Figure 26 Composite of Meridional wind (500hPa) for warm anomalous years

Air temperature

Works of Horel and Wallace (1981), Pan and Oort (1983) showed that during El Niño events most of the troposphere is anomalously warm. Fig. 27 shows that almost the entire level of troposphere over Eritrea become warm during El Niño phases. The

anomalous warm low-level temperature could be the result of lowered cloud cover complemented by increased insolation.

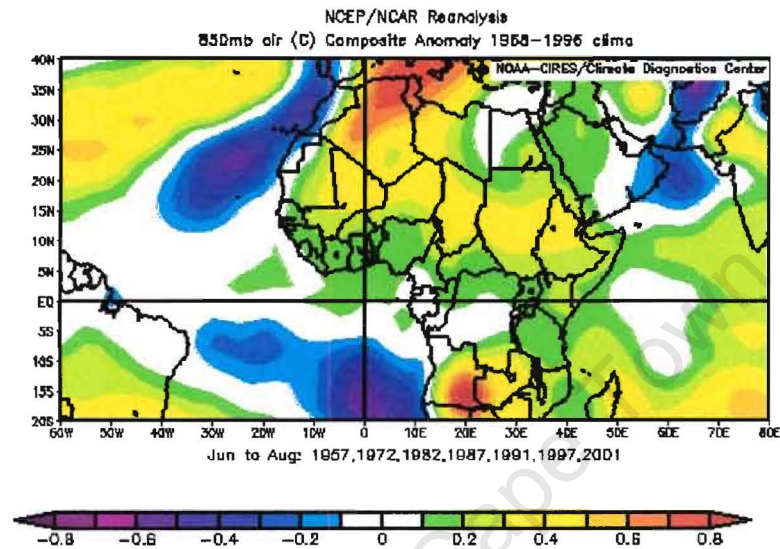


Figure 27 Composite of Air temperature for El Niño anomalous years

Relative humidity

During El Niño event, relative humidity at 850hPa is lower than normal over Eritrea and vast region of East Africa (Fig. 28). Rocha and Simmonds (1997) explained relative humidity anomalies, during the dry years in the north-eastern of Africa pressure enhanced over the continent weakening the thermal low. Thus, the weaker vertical motion related with the pressure anomalies would discourage convection.

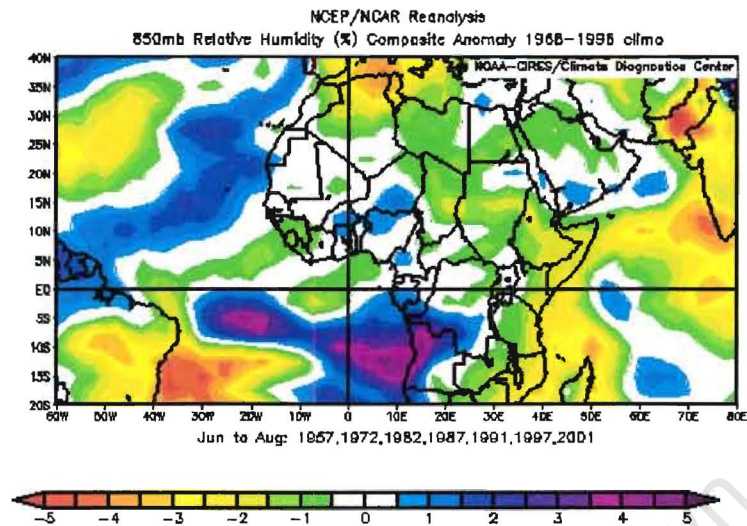


Figure 28 Composite of relative humidity for El Niño anomalous years

Geopotential height

During the dry anomalous years, over the Indian Ocean, positive composite values of the geopotential height (high pressure) at 850hPa are observed (Fig. 29). These dry anomalies years are associated with descending air, clear skies resulting in warming of the lower levels, and hence decrease rainfall. At 500hPa (Fig. 30) a band of positive pressure anomalies extends from almost central Africa to the south and south-western Indian Ocean, including Eritrea, explaining the warm events.

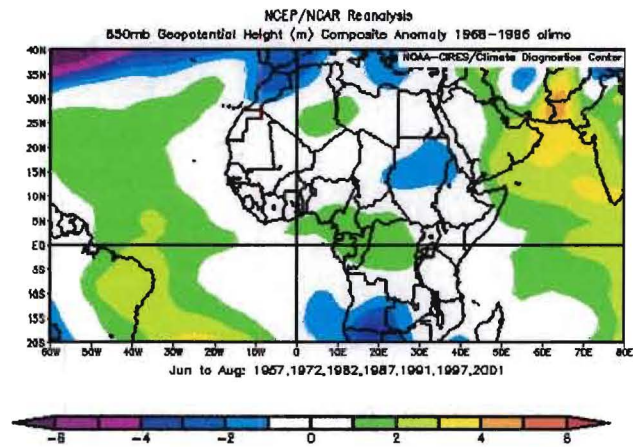


Figure 29: Composite of geopotential height (at 850hPa) for El Niño anomalous years

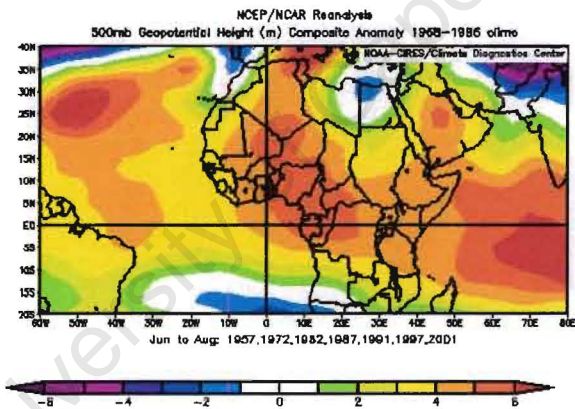


Figure 30 Composite of geopotential height (at 500hPa) for El Niño anomalous years

Precipitation rate

Though precipitation anomalies derived from NCEP-NCAR analysis are not best estimates but are used in this study to enlarge the domain of the study. From Figs. 31a and 31b of precipitation anomalies, it has been observed that during the 1957 and 1972 El Niño events, the impact of ENSO was not well pronounced over Eritrea. Whereas, during 1982 (Fig. 31c), 1987 (Fig. 31d), 1991 (Fig. 31e).

1997 (Fig. 31f), and 2001 (Fig. 31g) El Niño events, it showed marked decrease of rainfall over Eritrea. Reverse condition happened during the 1957 and 1972 El Niño phase (Figs. 31a and 32b). Thus, in Eritrea the extreme drought records of the year 1982 to 1984, 1990/91 and 2001 could be mainly associated with the El Niño events.

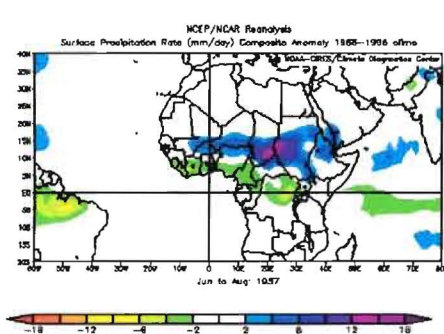


Figure 31(a): Precipitation rate anomaly for 1957

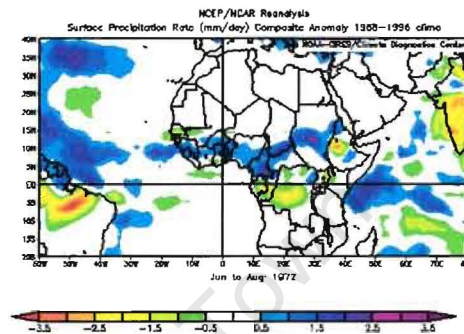


Figure 31(b): Precipitation rate anomaly for 1972

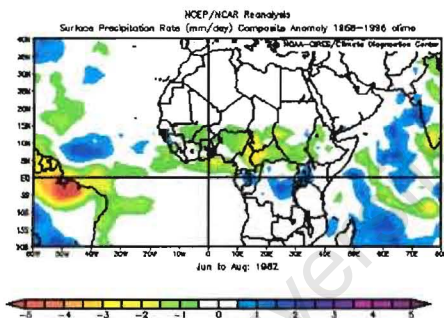


Figure 31(c): Precipitation rate anomalies for 1982

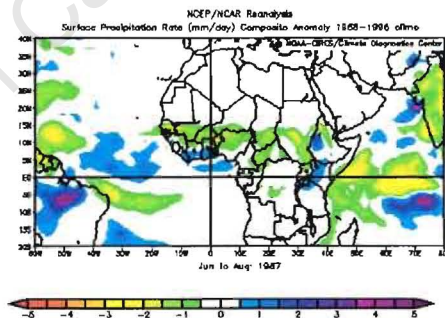


Figure 31(d): Precipitation rate anomaly for 1987

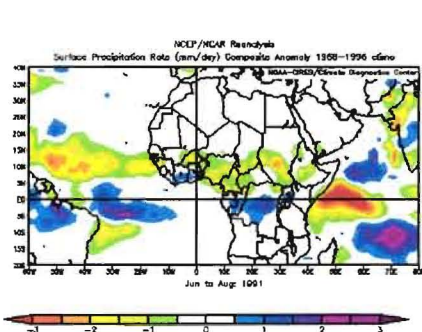


Figure 31(e): Precipitation rate anomaly for 1991

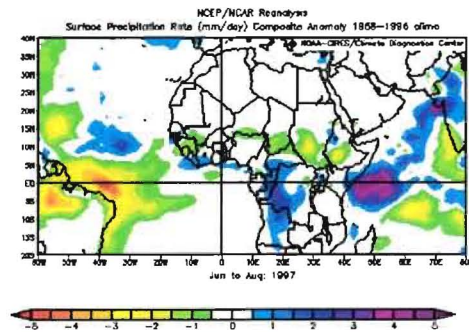


Figure 31(f) Precipitation rate anomaly for 1997

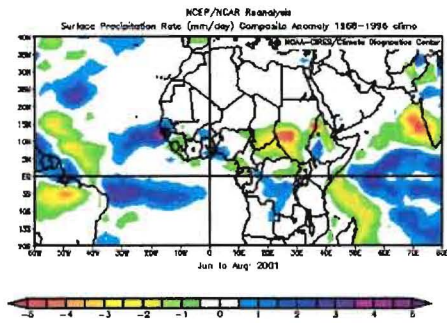


Figure 31(g): Precipitation rate anomaly for 2001

From Figs. 32 and 33, it can be seen that there is a correlation of ENSO and summer rainfall of Eritrea.

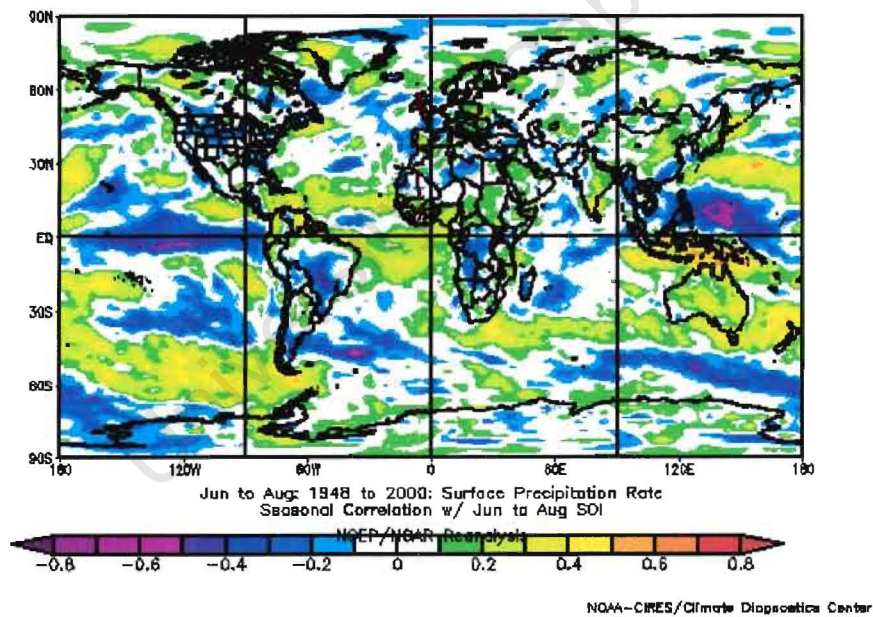


Figure 32 Precipitation rate anomalies-SOI correlation for El Niño years

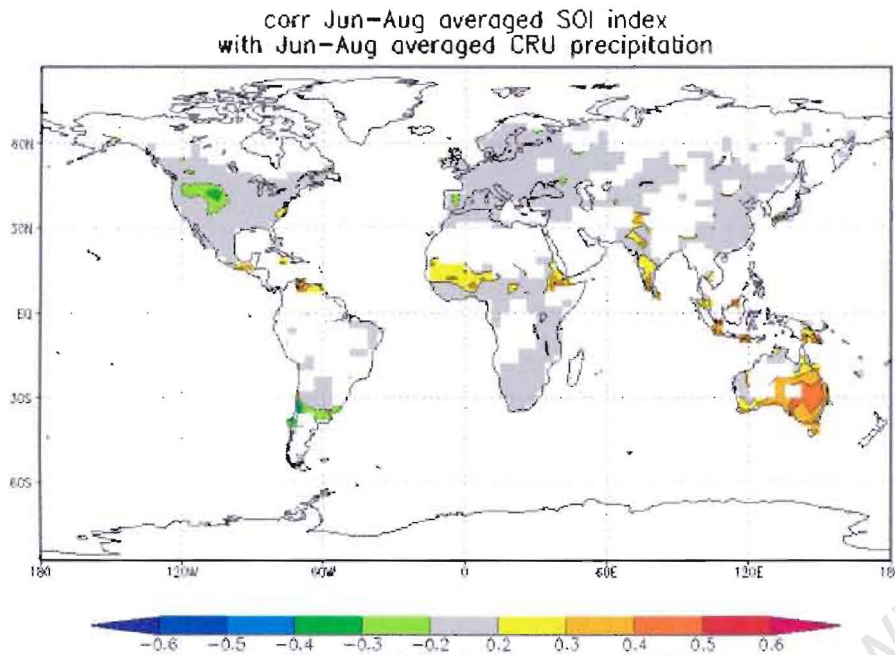


Figure 33: Correlation of precipitation rate and SOI index

Outgoing Long wave Radiation (OLR)

From the above composite of precipitation anomalous years, it has been observed that the 1982, 1987, 1991, 1997 and 2001 El Niño events have also similar anomalies of precipitation rate pattern with regarded to Eritrea. The 1957 and 1972 El Niño events have similar but different from the other anomalies precipitation rate pattern. Depending on this similarity, OLR composite anomalies has been done for those El Niño events exhibit similar precipitation rate anomaly.

During 1957 and 1972 El Niño events, decreased OLR values (anomalous negative OLR) over Eritrea has been shown on Fig. 34. This implies that there was above normal convection associated with the abnormal precipitation (high rainfall) (see Figs. 31a and 31b)) during those El Niño events. While during the 1982, 1987, 1991, 1997 and 2001 El Niño events, the large positive OLR values (anomalous increased

OLR) (Fig. 35) implied below normal convection, resulting in decreased rainfall (see Figs 31c-g).

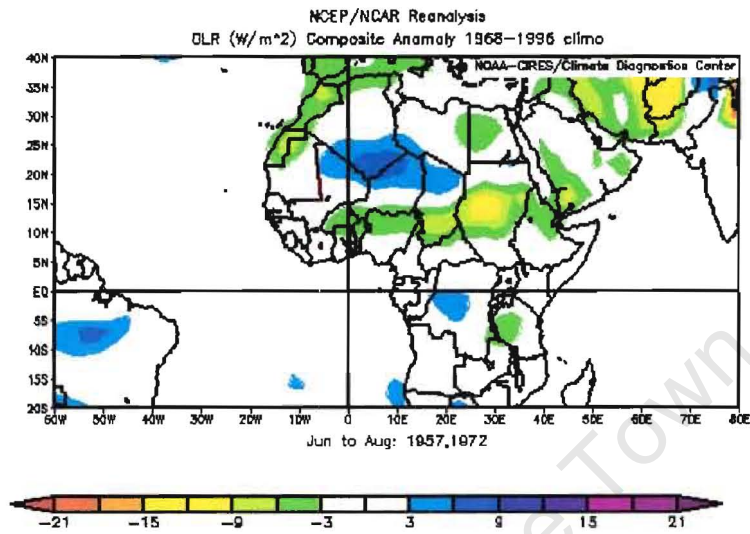


Figure 34 Composite of OLR anomalies for 1957 and 1972 El Niño events

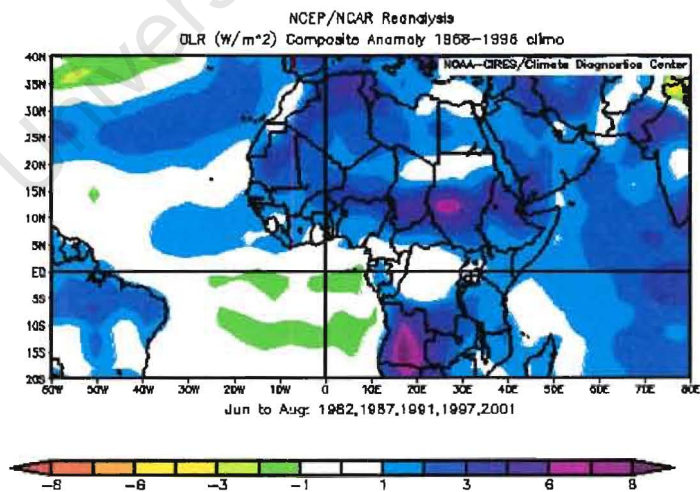


Figure 35 Composite of OLR anomalies for 1982, 1987, 1991, 1997 and 2001 El Niño events

Section 4: CONCLUSION

Rainfall plays an important role in the socio-economic aspect of Eritrea where its economic activity depends mainly on agricultural production. Fluctuation in the normal rainfall regime can have large economic and social impacts on the country. Decreased rains during summer season (June-August) when crops are in their maximum need of water supply, can affect agricultural production, and lack of clean drinking water. Distribution of seasonal rainfall in space and time is critical to the country's economy.

In this study, wet and dry years (during summer rainfall season) have been identified and analysed using the three independent datasets: CRU (Climatic Research Unit, University of East Anglia, UK) Hulme dataset, the Africa Data Dissemination Service, and NCEP-NCAR reanalysis. Wet years are 1950,1953,1954, 1956,1961,1964, and1975. Dry years are 1966, 1970, 1971, 1982, 1987, 1990 and 1991. Using NCEP-NCAR reanalysis, composite analysis of various gridded fields of atmospheric parameters (zonal and meridional components; geopotential height, air temperature, relative humidity, cloud cover, and precipitation) and SST has been done for wet and dry years separately. During wet years it has been observed that low-pressure system and more westerly wind. While during dry years, high-pressure system and less westerly (more northeasterly) winds have been prevailing.

Drought mainly occurs in Eritrea due to the anomalous regional atmospheric circulation which accompanied by an abnormal summer rainfall season. There are a number of influences on the pattern of Eritrean drought and rainfall. Analysis of

different atmospheric and SST data showed that the tropical Atlantic, Indian and Pacific Oceans are correlated with the Eritrean summer rainfall. These oceans are not separate influences but linked together. ENSO which provides the link between the influences and correlates well with the Eritrean summer rainfall. Correlation analysis showed there is a relationship between eastern Pacific Ocean and Eritrean summer rainfall. Though it is not strong, there is a relationship also between Eritrean major rainfall and the Indian Ocean. Overall the Indian Ocean and eastern Pacific Ocean have a good correlation with the Eritrean summer rainfall. This shows that El Niño could have strong impact on Eritrean summer rainfall along with the fluctuation of Indian Ocean SST.

The impact of El Niño-Southern Oscillation (ENSO) (as measured by SOI and SST anomaly) on climatic variability of Eritrea has been found important during summer rainfall season (JJA). During the 1982, 1987, 1991, 1997 and 2001 El Niño events, dry conditions (less precipitation) tend to prevail over Eritrea. The SST over the Indian Ocean is strongly correlated with the ENSO event such that anomalous warm water in the Ocean tends to occur with extreme warm (El Niño) event. This anomalous SST of Indian associated with El Niño events may have an impact on Eritrean summer rainfall but it needs further study.

Anomalous atmospheric features occurring during the warm ENSO events have been identified: north-easterly low level wind anomalies prevail over Eritrea, anomalous warm temperatures occurred at low level, decreased relative humidity, weak low-level convergence and high pressure anomalies were observed. Nurahmed (1998) suggested that ENSO might have an impact on pattern of Eritrean rainfall. This study has

investigated the influence and has confirmed its importance and has quantified the strength of the influence.

Thorough study is needed to understand the role and mechanism of ENSO and incorporate it into forecast and prediction of rainfall which is helpful to management decisions so that the people of Eritrea can better adapted to the unusual perturbation of rainfall pattern induced by ENSO.

University of Cape Town

LITERATURE CITATION

Andrew W, Mustafa Khogali (1992) Assessment of desertification and drought in the Sudano-Sahalian region, 1985-1995. United Nations Sudano-Sahalian Office (UNSO)

Buskirk RV () Eritrea Average Annual Rainfall. Retrieved May 15, 2002, from <http://www.punchdown.org/rvb/rain/rainann.html>

Cambelin P, Janicot S, Pocard I (2001) Seasonality and atmospheric dynamics of the teleconnection between African rainfall and tropical sea-surface temperature: Atlantic Vs ENSO. *Int J Climatol* 21:973-1005

Camberlin P, Philippon N (2001) The East African March–May Rainy Season: Associated Atmospheric Dynamics and Predictability over the 1968–97 Period. *J Climate* 15:1002–1019

Climatic prediction model (2002) Cold (La Niña) and warm (El Niño) Episodes by Season. Retrieved May 15, 2002, from http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.html

Climatic Research Unit (CRU, University of Anglia, UK) Hulme analysis retrieved on June 20, 2003 from web site source <http://www.cru.uea.ac.uk/cru/data/>

Department of Environment of Ministry of Land, Water and Environment of Eritrea
(2001) Eritrea's initial national communication. Department of Environment of
the Ministry of Land, Water and Environment, Asmara, Eritrea, pp. 1-50

Department of Environment of Ministry of Land, Water and Environment of Eritrea
(1999) Eritrea Biodiversity Stocktaking Assessment Report. Department of
Environment of Ministry of Land, Water and Environment, Asmara, Eritrea,
pp. 1-12

Horel JD, Wallace JM (1981) Planetary scale atmospheric phenomena associated with
the Southern Oscillation. In Rocha A, Simmonds I (1997) Interannual variability
of south-eastern Africa summer rainfall. Part 1: Relationships with air-sea
interaction processes. *Int J Climatol* 17: 235-265

Kalnay E, Coauthors (1996) The NCEP/NCAR 40-Year Reanalysis Project. *Bull
Amer Meteor Soc* 77:437-471

Nicholson S, Kim J (1997) The relationship of the El Niño –Southern Oscillation to
African rainfall. *Int J Climatol* 17:117-135

Nurahmed M (1998) Satellite based rainfall estimation over Eritrea, MSc Thesis,
University of Reading, UK, pp. 1-45

Pan YH, Oort AH (1983) Global climatic variations connected with sea surface temperature anomalies in the eastern equatorial Pacific Ocean for the 1958-73 period. In Rocha A, Simmonds I (1997) Interannual variability of south-eastern Africa summer rainfall. Part 1: Relationships with air-sea interaction processes. *Int J Climatol* 17: 235-265

Peixoto JP, Oort AH (1992) *Physics of climate*. American Institute of Physics, New York, p. 175

Poccard I, Janicot S (1998) Interannual variability of SST-tropical circulation relationships on the period 1968-1997: Focus on west Africa. In Cambelin P, Janicot S, Poccard I (2001) Seasonality and atmospheric dynamics of the teleconnection between African rainfall and tropical sea-surface temperature: Atlantic Vs ENSO. *Int J Climatol* 21:973-1005

Preston-whyte RA, Tyson PD (1988) *The atmosphere and weather of Southern Africa*. Oxford university press, Cape Town, p. 43

Rocha A, Simmonds I (1997) Interannual variability of south-eastern Africa summer rainfall. Part 1: Relationships with air-sea interaction processes. *Int J Climatol* 17:235-265

Smith SR, Legler DM., Verzone KV (2001) Quantifying Uncertainties in NCEP Reanalyses Using High-Quality Research Vessel Observations. *J Climate* 14:4062-4072

Trenberth KE (1997) The Definition of El Niño. Bull Amer Met Soc 78:2771-2777

United Nations Environment Programme (UNEP) (1991) Status of desertification and implementation of the United Nations Action Plan to combat desertification. Nairobi, Kenya: United Nations Environment Programme

Yan Z, Bate S, Chandler RE, Isham V, Wheeler H (2002) An Analysis of Daily Maximum Wind Speed in Northwestern Europe Using Generalized Linear Models. J Climate 15:2073-2088

University of Cape Town