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WRC Report No. 953/1/03

Water Research Commission

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Final Report to the Water Research Commission on Project 953, entitled **The Ocean's role in South Africa's Rainfall**

Project No 953/1/03
ISBN 1-77005-069-8

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Printed by Silowa Printers: 012 804 7565

Executive summary

The aim of this project was to investigate aspects of the role played by the Indian, the Atlantic and the Pacific Oceans as well as the Agulhas Current on rainfall over southern Africa. In doing this, this project built firmly on the foundations laid by previous WRC projects of this kind and also complemented projects run in parallel to it.

First, a comparison was made between dry summers occurring during El Niño/Southern Oscillation (ENSO) years and those occurring during non-ENSO years. During dry summers in ENSO years, anomalous upper tropospheric westerlies are dominant over most parts of the subcontinent and make the upper flow unfavourable for rain-bearing disturbances. High pressure anomalies exist over southern Africa, suppressing convection, while the ascending branch of the Walker circulation shifts offshore to the western Indian Ocean to lie over anomalously higher sea surface temperatures (SST) there. During non-ENSO dry summers, there is a less obvious indication of a significant increase in SSTs over the south-west Indian Ocean or of a coherent offshore shift in the Walker circulation. Instead, mid-latitude circulation anomalies tend to be more important so that increased advection of cool, dry South Atlantic air occurs over South Africa. The location of maximum westerly shear is thus shifted westwards and conditions are generally unfavourable for cloud band occurrence; hence, rainfall is reduced.

Next, an analysis of the 1946-1988 records from 149 rain gauges over South Africa was undertaken. It has shown the existence of a weak positive correlation between late summer rainfall (January to March) in tropical southern Africa and the Southern Oscillation Index (SOI). The correlation coefficients have been unstable since 1944. They were close to zero before 1970 and significant thereafter. Before 1970, southern African late summer rainfall was more specifically correlated with regional patterns of SST, mainly over the south-western Indian Ocean. After 1970, tele-connections with near-global SST anomaly patterns, i.e. over the central Pacific and Indian Oceans, were dominant. The increase in the sensitivity of southern African rainfall to the global SO-related circulation anomalies occurs simultaneously with the positive correlation between SOI and more extensive SST anomalies, particularly over the southern Indian Ocean.

Numerical experiments were then performed to test the impact of the observed SST increases in the Indian Ocean during ENSO events on southern African rainfall. Results show that ENSO events, which occurred against the background of the pre-1970 colder period in the South Indian and South Atlantic Oceans, had little effect on southern Africa climatic conditions. By contrast, more recent ENSO events, with higher SSTs over these ocean regions, lead to a climatic bipolar pattern between continental southern African and the western Indian Ocean. These results are consistent with the strong droughts observed over all of southern Africa during ENSO events since 1970.

To investigate the potential modifications of the associated ocean–atmosphere tele-connection patterns, a composite analysis has been performed on SST and National Center for Environmental Protection (NCEP) atmospheric parameters, according to the 5 driest years of both sub-periods. The 1950–1969 droughts were associated with regional ocean–atmosphere anomalies, mainly over the south-western Indian Ocean. By contrast, during the 1970–1988 droughts, near-global anomalies were observed in the tropical zone, corresponding to ENSO phenomenon. Significant correlations were found between the SOI and southern African rainfall for the periods 1900–1933 and 1970–

1998 when SOI and rainfall had high variability, and when southern Africa was affected by intense and extended droughts. During periods of low SOI (1934–1969), correlations became less significant and droughts were less intense.

In order to better understand precipitation over southern Africa, it is necessary also to consider those ocean effects on terrestrial rainfall which are, regionally, more restricted.Two such investigations were carried out.

First, ocean-atmosphere interaction above warm western boundary currents, such as the Agulhas Current, often leads to very high evaporation rates. Advection of moisture onshore may then conceivably lead to local intensification of storm systems. The evolution of a severe storm and flood event that occurred over the southern coastal regions of South Africa on 14-15 December 1998 was investigated. Heavy rainfall occurred in two widely separated locations and tornadoes were reported. Moisture flux transects through the storm region and back trajectories of air parcels suggest that low-level onshore flow of moisture from the Agulhas Current region played a significant role in the evolution and intensification of the storms.

Data available for estimating these particular moisture fluxes from the Agulhas Current are of coarse resolution and thus somewhat smoothed when compared to *in situ* ship observations. As part of a second regional project, it has been shown that the existing, and much used, NCEP and ECMWF model data tend to underestimate overall regional fluxes significantly, because they are unable adequately to represent the large sea-air fluxes over the core of the current. This has now been quantified for the first time.

The potential impact of the tropical Atlantic Ocean on southern African rainfall has also been investigated. From January to May 2001, several countries in southern Africa experienced above normal rainfall and floods to the extent that 23 000 people were displaced in southern Angola after a flood in April. Serious problems were concurrently experienced in Zambia and Zimbabwe. At the same time positive SST anomalies were measured off the Angolan and Namibian coast. These warm events are known as "Benguela Niños". In 1995, the warmest recorded Benguela Niño occurred with SST anomalies of up to 8°C extending 300 km offshore, with a southward extension to 27°S. During the 1984, 1986, 1995 and 2001 warm events, above average rainfall occurred near the SST anomalies and extended inland from the coast to an extent that appeared to depend on the intensity of the regional moisture convergence and atmospheric circulation anomalies. The significance of the warm events occurring during the February to April period is that this is the time when SST reaches its maximum in the annual cycle and this favours more intense local evaporation and convection and a greater impact on austral late summer rainfall. The crucial question remains regarding the source of Benguela Niño's and their predictability. Using the French OPA ocean general circulation model it was shown that they come about due to changes in the wind stress in the western tropical Atlantic. From here disturbances in the thermocline travel to the west coast of southern Africa where they outcrop as positive SST anomalies.

Conclusion and recommendations are presented in Chapter 7. This project ran for 5 years (1998-2002). From it came 20 research papers in peer-reviewed journals as well as 60 oral presentations at conferences, both national and international. Considerable collaboration with colleagues abroad was established and a number of these colleagues visited the University of Cape Town and took an active part in the research. A number of post-graduate students were trained as part of the project.

ACKNOWLEDGEMENTS

We would like to thank George Green and the steering committee of the project for pertinent inputs and guidance: Prof. Vere Shannon, Prof. Peter Tyson, Prof. Johan Van Heerden, Assoc. Prof. Bruce Hewitson, Dr Hannes Rautenbach, Dr Winifred Jordaan, Dr Cindy Bruyere, Prof. Mark Jury. Scientific contributions from Mark Majodina, Dr Michel Desbois, Dr Isabelle Jobard, Dr Jean Luc Melice, Dr Pierre Florenchie, Dr Pascal Roucou, Dr Isabelle Poccard, Sarah White and Fleur Couvreux are acknowledged. We would like to thank Lesley Staegeman and Leslie Elley for clerical support and Jeremy Main for technical support. Thanks to Prof. Geoff Brundrit and Assoc. Prof. Frank Shillington for stimulating exchanges of ideas; Hannekie Botha and Anne D'Albis on behalf of the France-South Africa cooperative project (NRF and CNRS); the South African Weather Service for providing rainfall data and the University of Cape Town, University of Dijon, IRD and CNRS for significant support. Thanks are due to the Water Research Commission for funding the project.

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1 Introduction

The influence of adjacent oceans on the rainfall of South Africa has attracted considerable research interest during the past few years. It has been demonstrated that anomalies of sea surface temperature in the Pacific, Indian and Atlantic Oceans are persistent and that these anomalies can be linked statistically to enhanced or reduced rainfall over South Africa. A proper understanding of the processes involved in exchanges of energy and water vapour between the ocean and the overlying atmosphere of these oceans is clearly essential to an understanding of the nature of those statistical links and to upgrade long-term rainfall and drought predictions. Progress towards a better understanding of the hydrological cycle, from ocean evaporation to moisture advection over the continent, forms a key element of what is required. Research on the influence of specifically the Agulhas Current on the overlying atmosphere has presented exciting initial results. This is of singular importance since it has been shown that the location of this current has a major influence on the rainfall along the east coast of South Africa.

To study this air-sea interaction over the current, a research project was sponsored by the WRC from 1993 to 1997 (WRC Rep. 374/1/99). This project was based on measurements of air-sea interaction from research ships. The data produced during that project produced a unique dataset that was used to validate many of the satellite and model data that are being used. The observations were, however, severely constrained in time and space. The large expanses of the Pacific, Indian and Atlantic Oceans have a greater influence on rainfall over South Africa than the Agulhas Current by itself. A new project was therefore accepted by WRC to investigate the ocean's role in South Africa's rainfall in a more extensive manner.

To this end, satellite data collected above the ocean and re-analysed climate data were used to make this geographically wider study possible. The current multiplicity of satellite missions and progress in numerical modelling offer a unique opportunity to study atmosphere-ocean interaction over large regions in a way not feasible before. Satellite missions from the European Space Agency, from the National Oceanic and Atmospheric Administration (NOAA), from the Defence Meteorological Satellite Program (DMSP) and from EUMETSAT (METEOSAT) allows one to measure sea surface temperature, wind, air temperature, atmospheric water content, clouds and rainfall on a regular basis. The Tropical Rainfall Measurement Mission, a satellite extremely well adapted to these observations was operational in 1998. This made possible the remote sensing of the intensity of convective systems and related rainfall above South Africa and adjacent oceans. We believe that this project has advanced the understanding of the mechanisms responsible for drought and the interdecadal variability of rainfall in South Africa and, thus, the increased ability to predict these with economically more valuable lead times.

The aims of the project were:

1. To gain a greater understanding of the role of ocean-atmosphere interaction in regulating rainfall and drought in South Africa

2. To develop a satellite based methodology to study and monitor the hydrological cycle from ocean evaporation to the advection of water vapour above South Africa

3. To carry out an in situ measurement program in order to validate satellite observations and model output that are useful in predicting rainfall over southern Africa

4. To gain more information on the mechanisms causing sea surface temperature variability in those regions where such anomalies are linked to drought in southern Africa

5. To develop, through the above aims, applications for the weather forecaster, the climate forecaster and water resource manager

In Chapter 2 we report on a study of the atmospheric circulation during dry summers occurring during El-Niño/Southern Oscillation (ENSO) years separately from those during non-ENSO years. It brings a better understanding of the mechanisms responsible for droughts during El Niño. Chapter 3 shows that the Agulhas Current region could play a significant role on coastal storm evolution and moisture fluxes. However, since the NCEP data on which these moisture fluxes are based are known to significantly underestimate the surface latent heat flux when compared to ship observations, it is demonstrated that the actual contribution of the Agulhas Current moisture could be in excess of that estimated using model data. Chapter 4 looks at the role of South-West Indian Ocean on southern African rainfall. Although the rest of the Indian Ocean has an important role, this ocean region has not received much attention in the past. Chapter 5 presents a study of the changes in the teleconnections linking southern African rainfall variability to oceanic and atmospheric conditions since the 70's. Numerical model experiments are used to investigate the mechanisms responsible for the drought post and ante the 70s. Chapter 6 is a preliminary study on the role of the tropical Atlantic on Southern African rainfall.

2 Dry summers over northeast South Africa and associated circulation

2.1 Introduction

The northeast South African region of interest (Figure 2.1) in this study is prone to significant drought and flood events. It borders southern Mozambique, which also experienced devastating floods in February 2000. It is an important agricultural region with a relatively large rural subsistence population and also contains the Kruger National Park. Significant drought and flood events in this region can therefore impact severely at both the local and national level. The purpose of the study was to investigate the atmospheric circulation changes associated with ENSO and non-ENSO related droughts over northeast South Africa in great detail. This leads us to a better understanding of the physical mechanisms linking ENSO and droughts. Since ENSO is primarily a tropical Indo-Pacific phenomenon, the main hypothesis is that ENSO droughts over southeastern Africa essentially arise from modulations to the local Walker circulation and SST anomalies in the neighboring tropical Indian and Atlantic Oceans. Non-ENSO droughts might involve greater influences from the midlatitudes. Much of southeastern Africa's summer rainfall arises from tropical-extratropical cloudbands and associated disturbances; hence both a tropical and a midlatitude influence on regional rainfall may be considered. Widespread South African rain typically occurs when the cloudband stretches NW-SE from its tropical source (heat low over southern Angola / northern Namibia) to a midlatitude disturbance southeast of South Africa (Harrison 1984). Thus, factors that change the location and intensity of the tropical and midlatitude systems are therefore likely to influence cloudband occurrence and hence rainfall. Regional drought may therefore arise from either local or remote forcing (or a combination) that acts to shift preferential areas of tropical and midlatitude weather, suppresses convection or otherwise makes conditions less favorable for cloudband occurrence across South Africa. Most of the conclusion reached in that study could be extended to others Southern African region influenced by ENSO.

2.2 Data and Methods

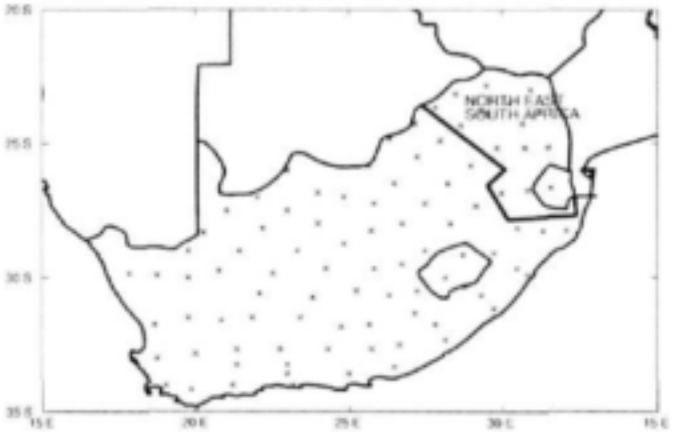

Figure 2.1 The study region of northeast South Africa.

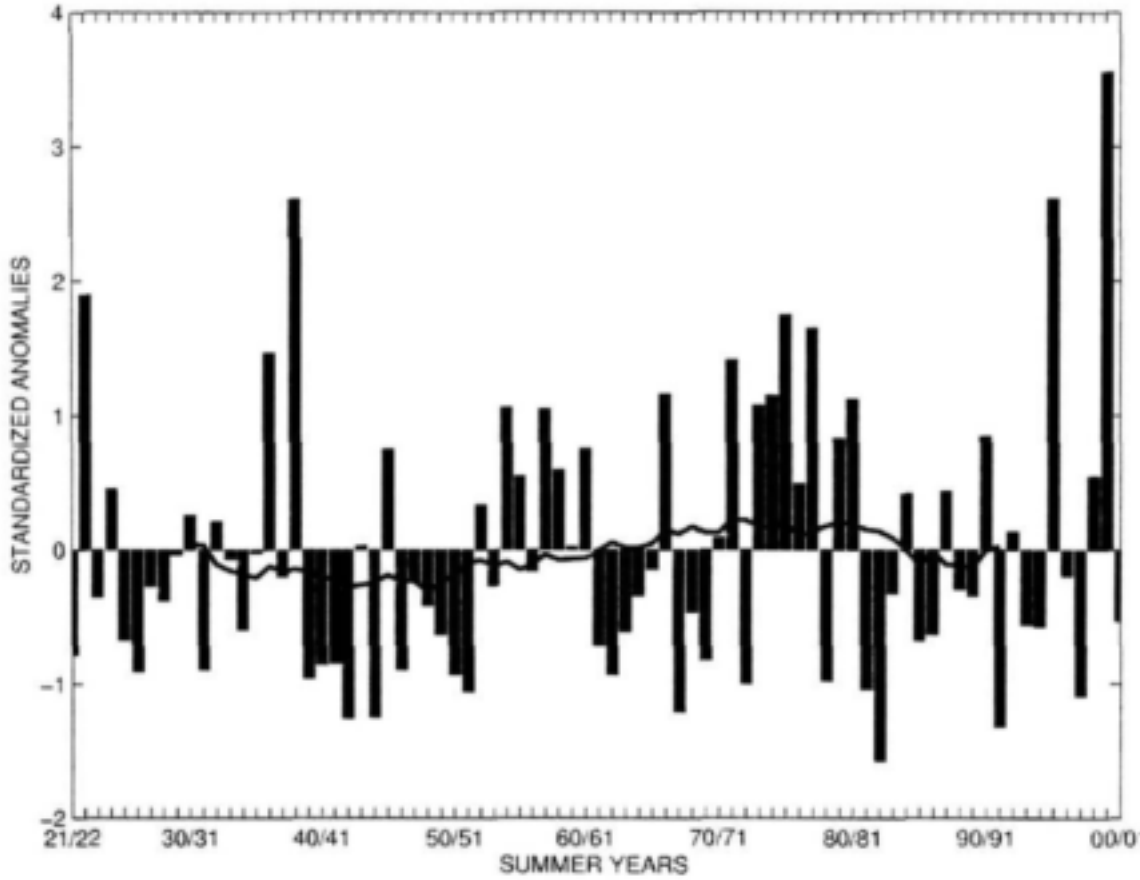

Figure 2.2 Time series of standardized summer rainfall (DJF) anomalies over northeast South Africa (Area 8) with 9 year running mean. El Nino Year are 23/24, 25/26, 30/31, 32/33, 39/40, 41/42, 51/52, 57/58, 63/64, 65/66, 69/70, 72/73, 76/77, 82/83, 86/87, 91/92, 94/95, 97/98. La Nina 24/25, 28/29, 31/32, 38/39, 42/43, 50/51, 54/55, 55/56, 64/65, 70/71, 73/74,75/76, 84/85, 88/89, 95/96, 99/00 according to Trenberth (1997) after 1950, and Compagnucci et al (2002) before 1950.

Summer (DJF) rainfall data for northeast South Africa (Fig. 2.1) was obtained from the South African Weather Service for the 1921-2000 period. The region considered is known as a homogeneous rainfall area based on a cluster analysis of South African rainfall (South African Weather Bureau, 1972). These data were then area-averaged to form a northeast rainfall index for each austral summer and standardized anomalies (summer anomaly divided by standard deviation) are plotted in Fig. 2.2. National Center for Environmental Prediction (NCEP) re-analyses (Kalnay et al., 1996) are used to assess atmospheric circulation changes associated with ENSO and non-ENSO droughts. . El Nino Year are 23/24, 25/26, 30/31, 32/33, 39/40, 41/42, 51/52, 57/58, 63/64, 65/66, 69/70, 72/73, 76/77, 82/83, 86/87, 91/92, 94/95, 97/98. La Nina 24/25, 28/29, 31/32, 38/39, 42/43, 50/51, 54/55, 55/56, 64/65, 70/71, 73/74,75/76, 84/85, 88/89, 95/96, 99/00 according to Trenberth (1997) after 1950, and Compagnucci et al (2002) before 1950. Nevertheless the definition of El Nino and La Nina is still debated especially before 1950 when data sampling was scarce Trenberth (1997). Some of those events finished during the summer season (i.e. the 1951 event was weak and finished in February 1952. The general tendency for those events is to mature during South African summer rainfall. The magnitude and duration of each event is variable. This study uses the NCEP data with a monthly time resolution and spatial resolution of 2.5 ° latitude and 2.5° longitude. Some problems have been identified in the reliability of NCEP data since the data are not homogenous in time due to, for example, the availability of satellite data after the 70s. The quality and validity of the NCEP data has been discussed in a recent monograph on Southern Hemisphere meteorology (Karoly and Vincent, 1998). Over Africa, regional advantages and disadvantages of the data have been documented (Grist and Nicholson, 2001; Camberlin et al 2001; Trenberth and Guillemont, 1998, Poccard et al, 2001). The data before 1968 should be treated with caution. However, for the purposes of analysing interannual rainfall variability over southern Africa and associated large scale circulation anomalies, as is the intent here, the NCEP re-analyses are believed to be appropriate.

Severe ENSO and non-ENSO droughts are then defined as those for which the summer rainfall equals or falls below one standard deviation. Circulation changes for those droughts during the 1949-2000 period that NCEP re-analyses are available are then investigated. It is also noteworthy that the region has experienced some significant wet years, most notably in the 70's and in 1995/6 and 1999/00. Fig. 2.2 indicates that the region experienced severe drought as defined above during the post-1949 ENSO summers of 1972/3, 1982/3, 1991/2, 1997/8 while significant non-ENSO dry summers after 1949 were 1950/1, 1951/2, 1962/3, 1967/8 and 1981/2. Investigation of the circulation and SST fields during these years indicated that a composite approach to the analysis of the ENSO droughts was warranted, consistent with previous ENSO studies (e.g., Rasmusson and Carpenter, 1982; Ropelewski and Halpert, 1989; Allan et al., 1996; Reason et al., 2000). To assess the sensitivity of this analysis, composites were also formed with the 1986/7 season included and little difference was found. Note that the 1986/7 summer was the next closest dry ENSO case (about 0.75 sigma) for northeast South Africa during the 1949-2000 period.

While the ENSO summers already mentioned appeared to have sufficient commonality in the circulation and SST fields for a compositing approach to be a useful way of focusing on the salient features, this was not the case for the various non-ENSO drought years. These years tended to show strong midlatitude influences on the rainfall, particularly via shifts in the ridges and troughs of wavenumber 3 (Karoly and Vincent, 1998; Tyson, 1986). Compositing tended to smear out these shifts and it is preferable to consider the cases individually so as to demonstrate how these midlatitude differences can also significantly impact on northeast South African rainfall. Focus is placed on the three most severe post-1949 non-ENSO droughts, namely 1951/2, 1967/8 and 1981/2.

2.3 Circulation changes associated with ENSO droughts

In this section, circulation changes associated with the ENSO drought years are considered. Previous work (e.g., Lindesay, 1988; Jury, 1992; Reason et al., 2000; Cook, 2000) has found evidence for an offshore shift of the ascending branch of the local Walker circulation to lie over the western Indian Ocean rather than over southern Africa during ENSO. Such a shift tends to result in dry conditions since it is favorable for the offshore shift of tropical extra-tropical cloudbands that are important for South African summer rainfall (Harrison, 1984; Preston-Whyte and Tyson, 1988). Thus, when the local Walker circulation ascends over tropical southern Africa, the cloudbands extend southeast from southern Angola and out over the southeast coast of South Africa giving good rains over northeast region. Idealized modeling studies by Cook (2000) suggest that some droughts over southern Africa could possibly be linked to ENSO-driven warm sea surface temperature over Pacific Ocean through atmospheric teleconnections via the propagation of Rossby wavelike features. Upper level convergence over the tropical eastern Indian Ocean / Indonesian region acts as a source for these Rossby wave features that propagate the signal southwestwards across the Indian Ocean to impact on southern Africa. By the ENSO mature phase (January-March season or austral summer following the first significant warming in the equatorial Pacific), large scale positive pressure anomalies extend across the Indian Ocean / southern African region (e.g. ENSO composites of mean sea level pressure (MSLP) and 500 hPa geopotential anomalies shown in Kiladis and Mo (1998) and Reason et al. (2000)). The 500hPa geopotential anomaly (Fig. 2.3) for the ENSO drought is consistent with these results and suggests unfavourable conditions for tropical convection and cloud band alignment over southern Africa. The positive height anomalies would tend to weaken the continental Angola/Botswana low, thus reducing the development of easterly waves and the formation of cloud bands in the southeast Atlantic Ocean region. The 500hPa geopotential and the MSLP composite (not shown) suggest an equatorward expansion of the midlatitude westerlies and increased tendency for a drier South Atlantic airmass to be advected over South Africa consistent with the earlier conceptual model of Tyson (1986) that was derived from station data. While these circulation changes suggest an increased westerly influence over the southeast Atlantic region, they also suggest that, south and southeast of South Africa, the midlatitude systems are more likely to track further offshore from the landmass (i.e., poleward), thus weakening the midlatitude link over this part of the South West Indian Ocean that is needed for extensive cloud band formation.

The South Atlantic inflow which feeds into the generally anticyclonic circulation over subtropical southern Africa is clearly evident at the 850 hPa level (Fig. 2.4) or just above the height of the interior plateau. At 700hPa, the anticyclonic anomaly (not shown) is found to be centered over Botswana, again discouraging tropical convection and cloud band formation. At 200 hPa (not shown), the westerly anomalies over Angola and Zambia reflect a weakening of the mean flow associated with the location of the ITCZ here while the stronger westerlies southwest of South Africa and weaker to the southeast are consistent with the unfavorable shifts in midlatitude storm tracks already mentioned. The analyses presented so far essentially confirm the circulation anomalies occurring during ENSO events that were inferred by previous workers from the limited data sets available at the time (e.g. Harrison, 1986; Lindesay, 1988). To extend this further, we consider anomalies in moisture flux and convergence in this moisture over southern Africa. The low to midlevel anticyclonic circulation over subtropical southern Africa weakens the input of moisture from the relatively warm South West Indian Ocean as confirmed by the 700 hPa moisture flux anomalies. Increased moisture flux is seen over the tropical western Indian Ocean consistent with the ascending branch of the local Walker circulation being located there rather than over tropical southern Africa during ENSO and with high pressure anomalies extending out over the Indian Ocean from Australasia. The enhanced divergence (convergence) at 700hPa and upper level convergence (divergence) across the NW-SE oriented band from Angola across Botswana, Zimbabwe and eastern South Africa (in the tropical western Indian Ocean) is consistent with the anticyclonic circulation over the subcontinent, and with the offshore shift of the Walker circulation and associated convection.

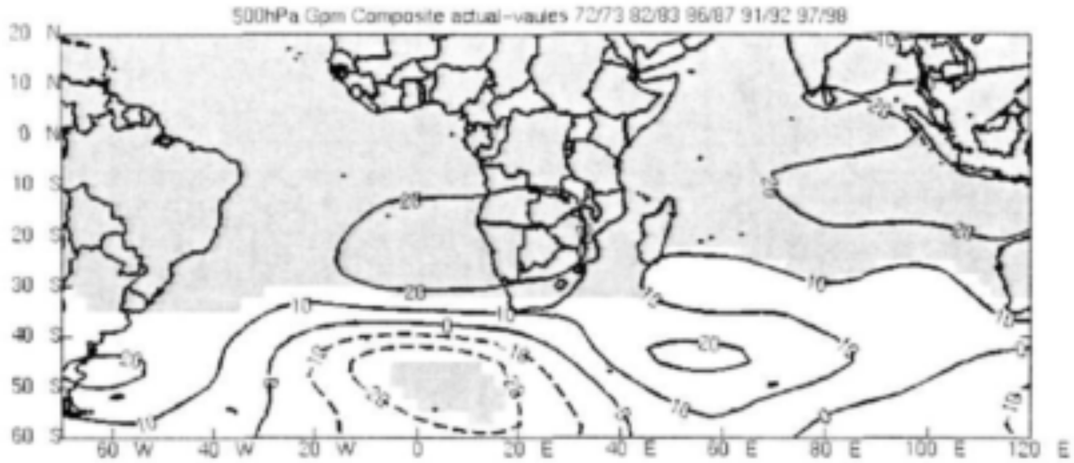

Figure 2.3 Composite DJF 500 hPa geopotential height anomalies based on recent El Nino droughts (72/73, 82/83, 86/87, 91/92 and 97/98). The contour interval is 10gpm. In the shaded regions the anomalies are significant at 95%. Negative values are indicated by dashed contours. Shading indicates statistical significance at 95 %.

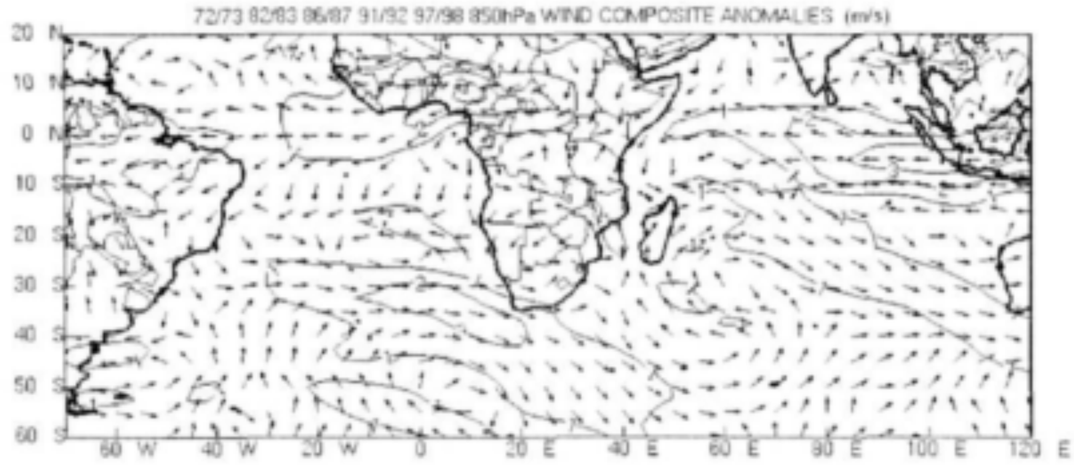

Figure 2.4 Composite DJF 850 hPa wind anomalies based on recent El Nino droughts (72/73, 82/83, 86/87, 91/92 and 97/98). The contour interval of the wind speed is 1m/s.

Further evidence for the unfavorable conditions for cloud band formation and rainfall is provided by the changes in vertical shear (baroclinic instability) and in the criterion for barotropic instability. The barotropic instability criteria is given as $\beta\text{-}d^2U/dy^2=0$. β isthe gradient of Coriolis parameter and d^2U/dy^2 is the second partial derivative of the zonal wind. The distribution of vertical shear (the difference between 200 and 850hPa zonal wind) for the ENSO years shows easterly shear in the equatorial region and westerly shear in the subtropics. During ENSO years, there is a westward shift (20ºE, 40ºS) in position of the maximum shear (> 25 m/s) compared to the long term mean position (30ºE, 40ºS). This shift suggests a tendency for the baroclinic waves and hence the midlatitude part of the cloud band (i.e. the frontal system) to be located further west, thus not favoring cloud bands across South Africa. The 200 hPa barotropic instability criterion is met over Democratic Republic of Congo, Tanzania and Ethiopia, consistent with the tendency for above average rainfall in those areas during ENSO. Over southern Africa, the increased westerlies means that the criterion is generally not met and there are fewer barotropic disturbances and less chance of easterly waves / tropical depressions and hence cloud bands.

In summary, the anomalous circulation patterns during ENSO dry summers, which discourage convection, and cloud band formation across southern Africa are:

(1) Anticyclonic conditions centered over Botswana with associated stable conditions and regional subsidence.
(2) Low-level divergence and upper level convergence along a NW-SE oriented band across southern Africa associated with an eastward shift of the Walker circulation and cloud band occurrence.
(3) Increased westerly flow in the midlatitudes favoring more frontal systems over southwestern South Africa and advection of dry South Atlantic air over northern South Africa.
(4) Increased upper level westerlies and the jet core positioned further westward.
(5) Reduced upper level easterlies over low latitude southern Africa, which decreases the frequency and growth rate of tropical disturbances that are needed to promote the source of the cloud bands over this region.

2.4 Circulation anomalies associated with non-ENSO droughts

The previous section has discussed how circulation anomalies during northeast South African ENSO dry summers act to suppress convection and hence rainfall. These anomalies arise out of the re-organization of the global tropical circulation that occurs during ENSO. Fig. 2.2 shows that there are several noticeably dry non-ENSO summers in northeast South Africa and the purpose of this section is to investigate their associated circulation patterns and mechanisms that may lead to reduced rains during these seasons. Given the greater midlatitude influence that was found to occur for these droughts, it is preferable to look at specific cases individually rather than present composites, which tend to smear out the extra-tropical features of influence. The three driest non-ENSO summers since 1949 (1951/52, 1967/68 and 1981/82) are considered below although there is still some debate for 50/51 being en ENSO year or not.

Case 1: 1951/2

Like the ENSO composite, the low to midlevel circulation over southern Africa during the 1951/2 summer was also anticyclonic (Fig. 2.5), however, more pronounced negative anomalies are evident in the midlatitudes and these extend into the tropical South Atlantic. Wind anomalies at 850 hPa (not shown) suggest increased advection of dry South Atlantic air over much of South Africa and there was little low level inflow of moisture from the South West Indian Ocean or Congo basin consistent with what one would expect for a dry season. Moisture inflow from the western Indian Ocean over southern Africa occurred much further north during this season. Over southern Angola, moisture was transported off the continent rather than being imported from the tropical South East Atlantic as would have occurred if the heat low was strong and cloud band generation was favored.

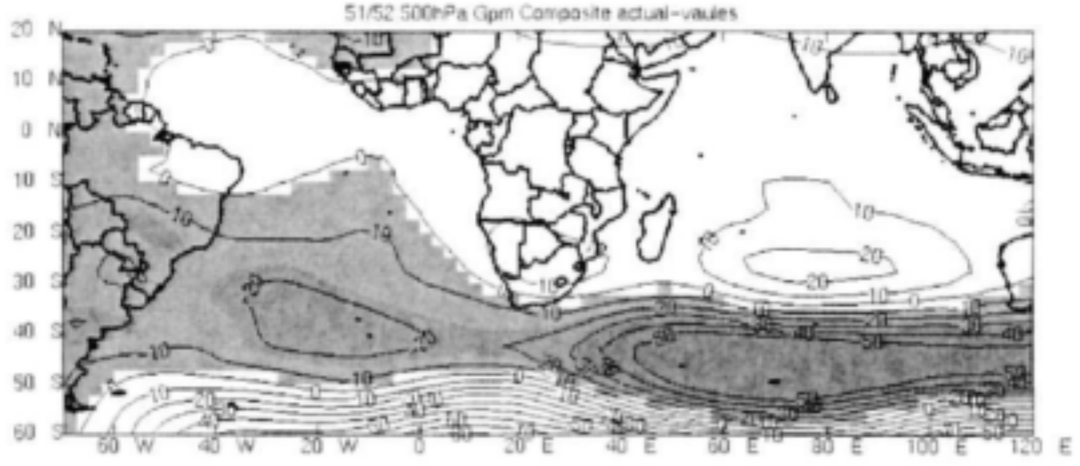

Figure 2.5 Geopotential height anomaly at 500 hPa for the DJF 1951/2 dry summer. Contour interval is 10 gpm and negative anomalies are shaded.

Calculation of the barotropic instability criteria over the region indicated that these were only possibly satisfied over Madagascar and not on the mainland (not shown). The midlatitude wind shear between 850 and 200 hPa showed the maximum to be displaced westward to 22.5° E, 40°S, again unfavourable for cloud bands across South Africa. Upper level wind anomalies were westerly in both the tropics and midlatitudes suggesting a weakening of tropical convection over southern Africa and increased midlatitude influence. The actual 200hPa flow itself is more reminiscent of a winter pattern with maxima just east of South Africa. Relatively strong convergent anomalies were found (not shown) at 200 hPa over the NW-SE Angola to South Africa zone implying reduced tropical convection and cloud band occurrence.

Case 2: 1967/8

The 1967/8 summer is the driest non-ENSO season and is also drier than all the ENSO droughts identified in Figure 2.2 except for 1982/3 and 1991/2. Circulation anomalies associated with the 1967/8 summer are also quite different from those shown for the ENSO composite or for the 1951/2 season. The most prominent feature is a large cyclonic anomaly immediately south of South Africa with associated advection of cool, dry South Atlantic air over South Africa (Fig. 2.6) and little inflow of moisture over NE South Africa from the Indian Ocean or the Congo basin. Relative divergence was evident at the 850 hPa level over the NW-SE Angolan-eastern South African zone (not shown), discouraging tropical convection and cloud band occurrence. Barotropic instability criteria were found to be unfavorable over South Africa (not shown) and the vertical shear maximum occurred west (20°E, 40° S) of its mean longitude, discouraging cloud bands over South Africa. The existence of a pronounced midlatitude westerly influence over South Africa is also marked at the 200 hPa level where a strong westerly trough extends into low latitude southern Africa.

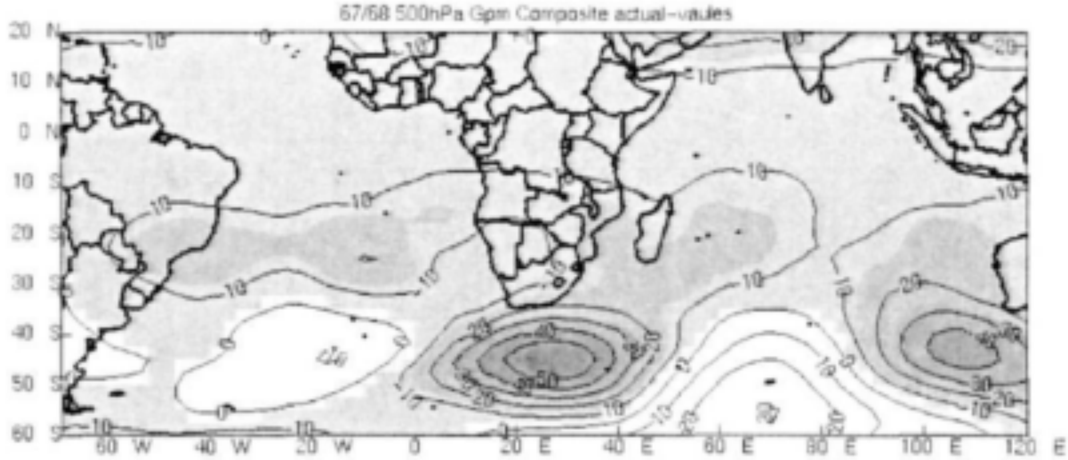

Figure 2.6 500hPa geopotential anomaly for the 1967/8 dry summer.

Case 3: 1981/2

Like the ENSO composite, this season shows positive pressure anomalies over southern Africa (Fig.2.7) however, there are also very strong anticyclonic anomalies over the neighboring midlatitude oceans, which are still apparent at 200 hPa (not shown). These midlatitude anticyclonic features are reflected in the moisture flux with relatively cool, dry South Atlantic air over western South Africa and a weakening of the onshore flow of moisture from the South West Indian Ocean. Given the poleward shift of the South Indian Ocean anticyclone, the winds over the waters just east of South Africa become more northerly and less onshore; hence reducing the onshore advection of moisture. Furthermore, low level divergent anomalies are again present over the NW-SE Angola-eastern South African zone and there are marked convergent anomalies at 200 hPa (not shown) consistent with the dry conditions observed. The computed barotropic instability criteria at 200hPa (not shown) suggests reduced barotropic disturbances over South Africa. The wind shear maximum (>25m/s) was again found to be west (20° E, 40°S) of its mean position during this season, discouraging cloud bands over South Africa. A common feature of the non-ENSO droughts seems to be an increased midlatitude influence on the circulation in the South African region and increased advection of cool, dry air from the south or southwest over the country. In the midlatitudes, the maximum wind shear is shifted west from its average position thereby discouraging the midlatitude component of the cloud bands from lying across South Africa. Relative divergence across the NW-SE Angola to eastern South African zone at the 850 hPa level with a weakened or absent tropical low over Angola/northern Botswana is also noted. These common features are unfavourable for convection and cloud band occurrence across northern South Africa leading to the dry conditions observed. The enhanced inflow of South Atlantic air and low level divergence come about through different large scale circulation patterns and hence do not stand out when composited together.

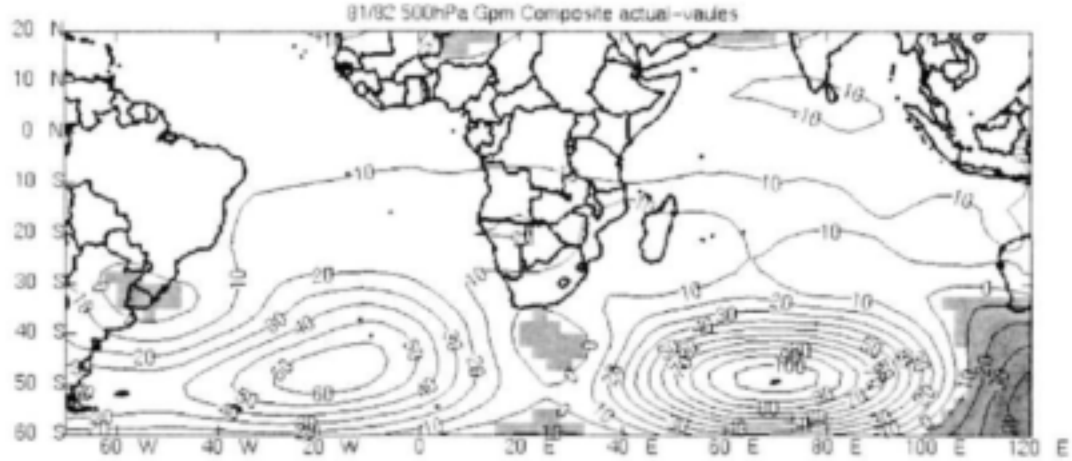

Figure 2.7 500hPa geopotential height anomaly for the 1981/2 dry summer.

A common feature of the non-ENSO droughts seems to be an increased midlatitude influence on the circulation in the South African region and increased advection of cool, dry air from the south or southwest over the country. In the midlatitudes, the maximum wind shear is shifted west from its average position thereby discouraging the midlatitude component of the cloud bands from lying across South Africa. Relative divergence across the NW-SE Angola to eastern South African zone at the 850 hPa level with a weakened or absent tropical low over Angola/northern Botswana is also noted. These common features are unfavourable for convection and cloud band occurrence across northern South Africa leading to the dry conditions observed. The enhanced inflow of South Atlantic air and low level divergence come about through different large scale circulation patterns and hence do not stand out when composited together.

2.5 Discussion

This study has considered the circulation anomalies and mechanisms potentially associated with dry years in the summer rainfall region of north-east South Africa. This region is important to southern Africa for agriculture, tourism and natural diversity and also contains a relatively large rural population. However, severe drought (as defined by the seasonal rainfall being at least a standard deviation below the long term mean) was also found to occur during several non-ENSO years. It was therefore decided to separately investigate dry summers during ENSO years from those that occurred during non-ENSO years. This investigation was restricted to the 1949-2000 period given the reliance herein on NCEP re-analyses to derive the circulation anomalies. Composite analysis was found to be appropriate for the ENSO dry summers while the greater midlatitude influence during non-ENSO dry summers necessitated dealing with these cases on an individual basis.

Tropical-extratropical cloud bands that extend from an easterly disturbance over low latitude southern Africa to a westerly disturbance southeast of South Africa are responsible for a large proportion of the summer rainfall of the region (e.g., Harrison, 1984; Preston-Whyte and Tyson, 1988). During dry summers, these systems tend to be shifted offshore over the South West Indian Ocean or be suppressed. This may happen if the ascending branch of the local Walker circulation shifts offshore and/or if positive pressure anomalies and associated subsidence exist over southern Africa. Another important factor that is commonly associated with dry summers over northeast South Africa is advection of relatively cool, dry South Atlantic air over South Africa rather than inflow of moist warm air from the north or the east.

During ENSO dry summers, the large area of positive pressure anomalies that extends out across the Indian Ocean / southern African / South East Atlantic region from its center over tropical Australasia leads to local subsidence and suppression of convection over southern Africa and weakening of the tropical low over southern Angola that is the source region for cloudbands. This ridging also leads to an equatorward expansion of the westerlies over the southeast Atlantic and South Africa, again unfavourable for cloudband occurrence over South Africa. Upper level westerly anomalies represent a weakening of the flow over low latitude southern Africa, reducing the tendency for barotropic instability and convection. South and southwest of South Africa, the upper level westerly anomalies may act to steer frontal systems more towards southwestern South Africa and less to the southeast of the country, which further discourages cloud bands to extend NW-SE across South Africa. The neighboring tropical oceans show warm anomalies (Reason et al., 2000) tending to attract convection away from southern Africa and reducing its rainfall.

While the ENSO dry summers result from significant changes in the tropical circulation and SST, the analysis suggests that midlatitude influences play a much bigger role in the non-ENSO dry seasons. Like the ENSO dry seasons, there is relative advection of cool, dry South Atlantic air over South Africa which is unfavorable for cloud bands; however, this tends to come about more from relatively large pressure anomalies situated in the midlatitudes rather than from changes centered in the tropics as occurs during ENSO years. SST changes over the neighboring tropical and subtropical oceans are much smaller than during ENSO years and there is little evidence of an influence on rainfall. Over tropical southern Africa, the low to midlevel circulation is generally, but not always, anticyclonic further suggesting that it is the midlatitude influence that is more important for dry summers during these non-ENSO years.

The significant midlatitude influence during the non-ENSO dry summers may pose greater difficulties in their forecasting than during the ENSO dry years due to the weaker coupling between the ocean and atmosphere in the extra-tropics, less coherent signals in SST and potentially a greater role of internal atmospheric instabilities during non-ENSO cases. However, it should also be remembered that the ENSO signal over southeastern Africa tends to be less strong and coherent than that nearer the core tropical Indo-Pacific region (e.g., northern Australasia; Allan et al., 1996) and indeed there are several ENSO years when conditions over north-eastern South Africa were not particularly dry (e.g., 1966, 1993 – Figure 2). Unfortunately, this implies that South African seasonal forecasting is challenging during both ENSO and non-ENSO seasons and that a multitude of factors needs to be considered. These include regional and remote SST patterns, Antarctic sea-ice extent and thickness, pre-season soil and vegetation conditions over southern Africa as well as near-global circulation anomalies associated with phenomena like ENSO and the interdecadal Pacific Oscillation. Future work is aimed at assessing these influences as well as considering the nature of wet seasons over the region.

3 Role of the Agulhas Current

3.1 Effect on extreme weather

3.1.1 Introduction

Ocean atmosphere interaction above warm western boundary currents such as the Gulf Stream, the Kuroshio Current and the Agulhas Current often leads to very high evaporation rates. The influence of the Gulf Stream on regional weather has been investigated previously. For example, Bosart and Lin (1984) found this current to be partially responsible for the intensification of the well documented President Day storm of 1979. The potential effect of the Gulf Stream on transient weather has been studied mainly for winter storms and cold air outbreaks (Bane and Osgood 1989). Subsequent modelling studies (e.g. Holt and Raman, 1992) showed that the Gulf Stream had a role in the development or intensification of winter storms along the U.S. east coast. The Frontal Air Sea Interaction Experiment (FASINEX) showed the modification of the marine boundary layer above the Gulf Stream (Friehe et al. 1991) and that the warm water of the Gulf Stream could trigger mesoscale and secondary circulations (Khalsa and Greenhut, 1989). The large heat fluxes off the Gulf stream have been found to have an important role in coastal frontogenesis (Doyle and Warner, 1993) and cyclogenesis (Holt and Raman, 1990; Bosart and Lin, 1994. In the case of the Agulhas Current, high latent heat fluxes may lead to increased low level advection of moisture onshore and local intensification of storm systems. Observational evidence for the significant latent heat fluxes in the Agulhas region was obtained during the Agulhas Current Air Sea Exchange Experiment (ACASEX) of autumn 1995, the first dedicated air-sea interaction research cruise in this current (Rouault et al. 1995). Most of the measurements showed that the core of the Agulhas current, about 80 km wide, transfered about 5 times as much water vapor to the atmosphere as the surrounding water (Rouault et al. 2000). A maximum latent heat flux of up to 600 Wm^{-2} was measured during the cruise. Other high fluxes have been measured above the current during various cruises made at different times of the year (Walker and Mey, 1988; Mey et et al. 1990; Rouault and Lee-Thorp, 1997; Rouault et al, 1998; Rouault and Lutjeharms, 2000). Given these large heat fluxes just off the South African coast, the numerical model results of Reason (2001), and the evidence from the above cited studies concerning the role of the Gulf Stream, it is conceivable that the Agulhas Current may influence local storms.

3.1.2 The storm of 14-15 December

The austral summer of 1998/9 was one in which the Eastern Cape experienced an unusual number of storms, floods and tornadoes (De Coning et al., 2000) of which the storm in question was particularly prominent. Since most of South Africa's population lives in precarious conditions, the consequences of such floods and storms are often devastating to both people and property. Using NCEP re-analyses, Meteosat and Tropical Rainfall Measurement Mission (TRMM) satellite data, local raingauges station and radiosonde observations, this study analyses the generation and evolution of a severe storm that produced flooding over a region in the southwestern part of South Africa (Western Cape) and heavy rainfall and tornadoes in various locations in the southeast (Eastern Cape) during December 14-15, 1998. Heavy rainfall occurred in two widely separated locations and two tornadoes were reported. Moisture flux transects through the storm region and back trajectories of air parcels suggest that low-level onshore flow of moisture from the Agulhas Current region played a significant role in the storm evolution. However, since the NCEP data on which these moisture fluxes are based are known to significantly underestimate the surface latent heat flux when compared to ship observations, it is suggested that the actual contribution of the Agulhas Current moisture source to the storm may have been even greater than is documented below.

The synoptic situation during the 14-15 December 1998 storm analysed in this study appeared to involve interaction between a continental heat low, a South West Indian Ocean anticyclone and an approaching westerly trough and therefore was somewhat different to the heavy rainfall synoptic patterns mentioned above. This interaction resulted in large regions of organised convection forming over the south of South Africa in the Western Cape and later the Eastern Cape during the storm's lifespan. Initial organisation was circular while the subsequent convection was more linear in form as the storm evolved further. Flooding was experienced on December 14 at Tygerhoek, Western Cape. On December 15, the storm tracked into the Eastern Cape with heavy rainfall occurring at East London as well as tornadoes at several locations. In particular, a tornado at Umtata resulted in extensive loss of life and damage.

Heavy rainfall events over South Africa's interior seem to be fueled by tropical moisture from the north (D'Abreton and Tyson 1995; D'Abreton and Tyson 1996) whereas along the Eastern Cape, events are fueled by the South West Indian Ocean (Crimp and Mason 1999). However, these results are based on a limited number of events and further research is necessary to confirm these apparent regional differences in moisture source. In the case studied here, evidence is presented that low level moisture originating from the Agulhas Current region contributed towards the evolution of the storm.

3.1.3 Rainfall

South African Weather Service (SAWS) raingauge data indicates that heavy rainfall occurred near the South and Southeast coast of Africa on 14 and 15 December 1998 (Fig. 3.1). Flood-producing rainfall occurred over the Western Cape at Tygerhoek (34° 9' S, 19° 5' E) on 14 December (93 mm) and the next day (98 mm) at East London (33° S, 27° 5' E) in the Eastern Cape of South Africa. Tygerhoek is a predominantly winter rainfall area and heavy summer rains are rare. The flood-producing rainfall of 93 mm on 14 December represents about 500 percent of Tygerhoek's December climatological rainfall. The heavy rainfall (98 mm) on 15 December at East London represents 150 % percent of December's climatological rainfall at this station. Unlike Tygerhoek, East London receives more rain in summer than in winter on average. Rainfall estimated from TRMM and half-hourly Meteosat images processed at the SAWB during the event indicates that most of the rainfall occurred above the bordering coastal regions and the core of the Agulhas current on 14-15 December. The core of the current is the area with Sea Surface Temperature greater than 21 C. Another source of rainfall data was provided by the Tropical Rainfall Measurement Mission (TRMM). Only the TRMM surface and vertical profile of rain rate and the subsequent latent heat release are used in this study.

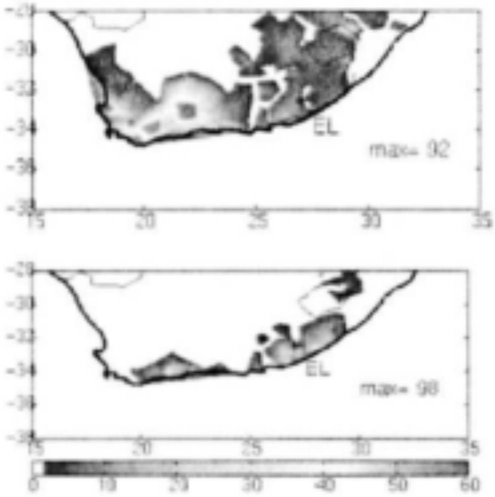

Figure 3.1 SAWB rainfall for 14 (top) and 15 (bottom) December from 100 stations in mm/day.

TRMM provides systematic visible, infrared, and microwave measurements of rainfall between 35 N and 35 S and passes over the Agulhas Current region and coastal South Africa four times daily. The two principal rain-measuring instruments used in that study are the Precipitation Radar (PR) and the TRMM Microwave Imager (TMI). The PR has a horizontal ground resolution of approximately 4 km and a swath width of 220 km. It can provid vertical profiles of the rain from the surface up to a height of about 20 km. The TRMM Microwave Imager (TMI) is a passive microwave sensor designed to provide quantitative rainfall information over a wide swath width of 760 km. An important feature of microwave retrievals is that SSTs can be measured through clouds, which are nearly transparent at 5 GHz. This is a great advantage over the infrared SST observations that require a cloud-free field of view. This advantage is particularly important in the Agulhas Current region since cloud lines have been shown to commonly occur above this current (Lutjeharms et al. 1986; Lee-Thorp et al. 1998b; Lutjeharms and Rouault 2000). TRMM's low altitude (350 km) results in TMI having improved ground resolution, which ranges from 5 km for the 85.5 GHz channels to 45 km for the 5 GHz channels. Rainfall estimates from TMI at about 10:05 UTC and 11:40 UTC on 14 December and at 07:15, 08:50 UTC and 10:25 UTC on 15 December (Fig. 3.2) confirm the Meteosat estimate rates of about 10 to 30 mm/h. In addition to this heavy rainfall and local flooding, tornadoes were reported at Hogsback (32° 35' S, 26° 56' E) and in the city of Umtata (31° 32' S, 28° 40' E) on December 15. Eleven people were killed and buildings were destroyed in a 70-km radius. Van Niekerk and Sampson (1999) have classified the tornado as F2 on the Fujita scale. Satellite images in the visible frequency band for southern Africa and adjoining ocean regions for 14 and 15 December 1998 from METEOSAT. Clouds are in white.

3.1.4 Synoptic setting and storm development.

Mean Sea Level (MSL) synoptic charts and Meteosat visible and infrared imagery (Fig.3.3) show the general development and dissipation of the storm system. Half hourly infrared, visible and water vapor Meteosat data, TRMM Precipitation Radar and Tropical Microwave Imager, NCEP Reanalysis data and ECMWF trajectories were also used to document its evolution. On 13 December a weak cold front was present south of the continent with a heat low over the interior. A well-developed anticyclone was present in the South West Indian Ocean with associated easterly advection of moist air that went above the Agulhas Current along the southeast coast.

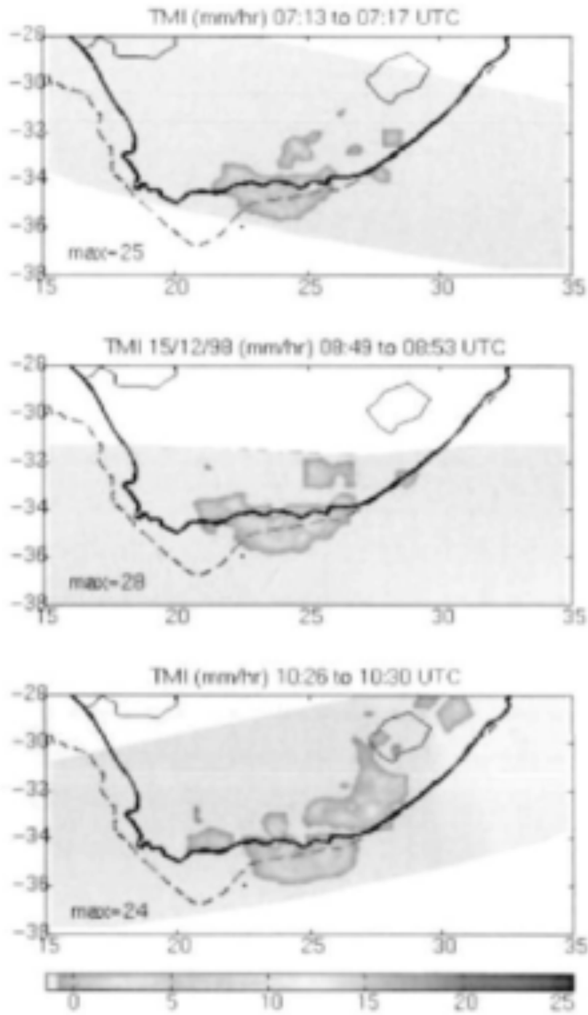

Figure 3.2 TRMM-derived surface rain rates from TMI on 15 December 1998 for three consecutive orbit passes (mm/h).

Cloud lines over the Agulhas Current (Fig. 3.3) moving in an eastwards direction along the coast on 13-14 December provide further evidence of the low level moisture available along the southeast coast of South Africa. On 14 December, the inland heat low deepened from 1010 hPa to 1008 hPa as it shifted eastward. Interaction between this heat low, the midlevel trough that tracked over the region on 14-15 December with associated cold air advection aloft and the low level inflow of warm moist air from the Agulhas Current produced very favorable conditions for intense storm development. According to Meteosat derived rain rate data, Meteosat cloud top temperature and Meteosat water vapor brightness temperature, the beginning of the heavy rainfall over the Tygerhoek region of the Western Cape occurred at about 10:00 UTC on 14 December as the storm spun up with associated deepening and entrainment of the surrounding air. Meteosat visible infrared and water vapour imagery show a slow eastward moving system of organized convective thunderstorm cells and squall lines.

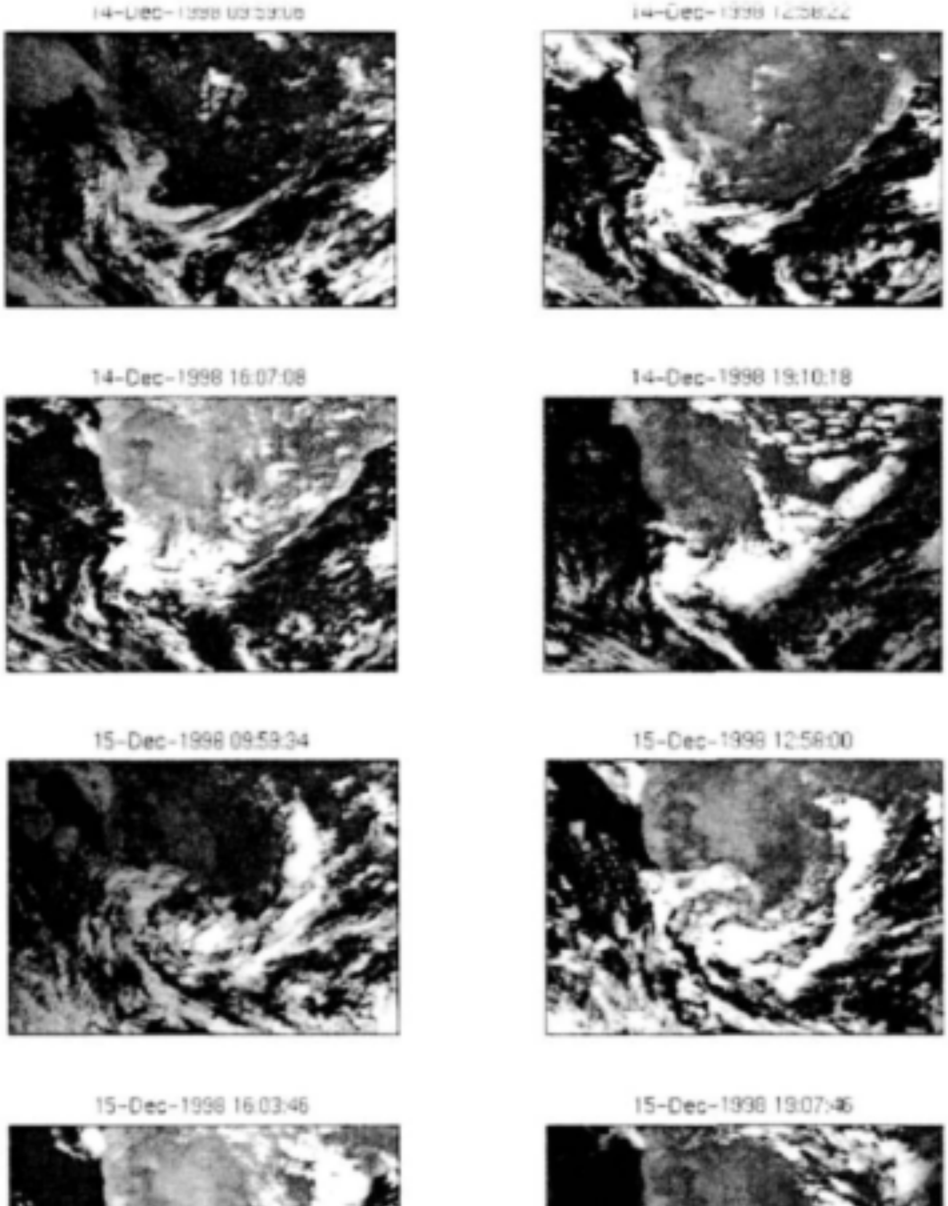

Figure 3.3 Meteosat visible image of the storm development

A large circular area of convection was present during the late afternoon and evening hours of 14 December. Later on 14 December (around 21:00 UTC), the organised convection became linear in form and lasted long enough and was sufficiently extensive to be classified as a squall line (at least 6 h and 650 km long). On 15 December the storm deepened and shifted slightly eastward. The single squall line that was observed propagating east across South Africa until around 15:00 UTC 15 December was joined by a second squall line feature that appeared to develop around this time from the storm center over the south coast and neighboring warm waters to the south Meteosat water vapor and NCEP Reanalysis data indicate that dry air in the mid to upper troposphere that was advected over the region by the westerly wave on 14 December was now transported to the north and north east of the storm center. Heavy rainfall occurred mainly over the Agulhas Current and coastal region releasing large amounts of latent heat according to TRMM. The maximum surface rain rates (Fig. 3.2) occurred during all three TRMM orbit passes between 25-26° E and 34-36° S where the SST ranged from 22° to 25° C. We note that the maximum rain rates at the surface occurred in line with the tongue of warm Agulhas Current water. The second TRMM pass over the Agulhas Current region on 15 December occurred between 08:49 and 08:53 UTC and showed heavy rainfall over a region of about 45000 km^2 with a maximum surface rain rate of 28 mm/h. Longitudinal profiles of the vertical rain rate were analyzed with sections across the heavy rainfall event to show that convective rainfall was found at a maximum height of 6000 m and that the bulk of the precipitation ranged from 1000 to 5000 m. The area of heavy rain between 34 and 34.5° S corresponds well with the high SST region of the Agulhas. The interaction between the latent heat release associated with this convective rainfall and the advection of cool, dry air aloft was presumably favorable for tornado occurrence in the eastern Cape at Hogsback at about 10:30 UTC on 15 December and at Umtata two hours later. Brightness temperature from the infrared Meteosat channel at 10:30 UTC indicates the extent of the storm at the time of the Hogsback tornado with the penetration of dry air aloft from the north. As shown later, the contrast between this dry air aloft and low level moist air advecting into the region from the Agulhas Current created a strong moisture gradient over the coastal area which was favorable for the development of the storm on this day. On 16 December, the next anticyclone ridged in from the South Atlantic with associated advection of cooler, drier air into the region as the midlevel trough tracked further east. As a result, the surface low over the eastern Cape was displaced well out into the South West Indian Ocean and rainfall over land ceased. The synoptic and satellite information suggests that low level moisture input from the Agulhas Current region to the south played a very significant role in the development of this storm event. This is in contrast to previously studied South African flood events which have tended to emphasize moisture input from the north or northeast. Another unusual feature was the interaction between the continental heat low, the trailing anticyclone over the South West Indian Ocean and the midlevel trough approaching from the west, documented here for the first time. Other documented floods in South Africa have resulted from either cut off lows (southern parts of the country) or tropical cyclones (northeastern South Africa).

NCEP re-analysis temperature data confirm the presence of the intense near-surface thermal low over the interior previously seen in the MSL charts. On 13-14 December the temperatures at 1000 hPa reached a maximum of 34° C with a strong thermal gradient of approximately 16° C existing between 30° S and 45° S that enhanced the baroclinicity of the approaching trough. This strong gradient weakened by 5 degrees on 15 and 16 December. At the 850 hPa level, the heat low was still evident. It showed a similar pattern of dissipation on 15 and 16 December at 1000 hPa as at 850 hPa. No evidence of the heat low was seen at the 500 hPa level consistent with the fact that thermal lows have small vertical extension and usually are confined below 700 hPa (Preston-Whyte and Tyson, 1988; Theron and Harrison, 1991). NCEP geopotential height data at the

850 and 500 hPa levels show a weak westerly trough tracking above the surface heat low (Fig. 3.4) from 13 until 16 December.

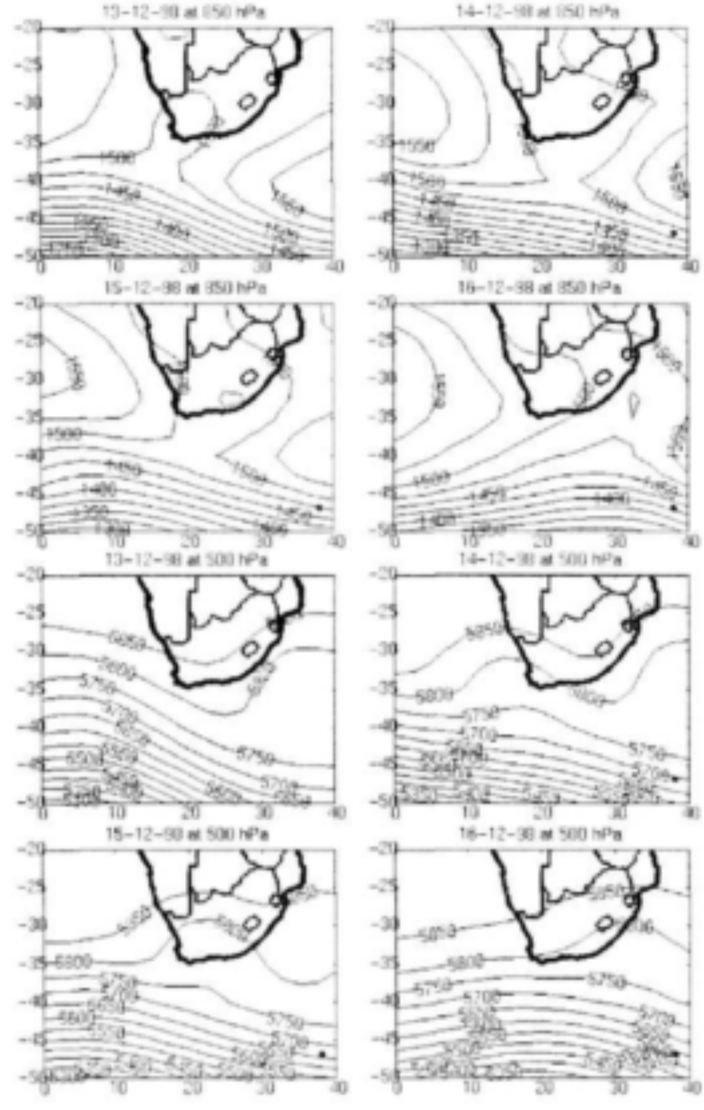

Figure 3.5 NCEP daily geopotential height (m) for 13 until 16 december 1998 values for (a) 850 hPa and (b) 500 hPa levels

The heat low moved approximately 5 degrees eastward between 13 and 14 December with the trough axis displaced west of the heat low during the 14-15 December. Vertical velocity (NCEP) values at 925 hPa indicated that a closed pattern of strong ascent developed over western South Africa on 14 December which then tracked east on 15 December as the storm evolved. A maximum vertical velocity of 0.11 Pa/s was reached on both days in the region of the trough axis. Distinct ascending and descending limbs were present at all levels, reflecting the subsidence in the South Indian Ocean and South Atlantic anticyclones and the uplift in between them that is associated with the trough. It is interesting to note the greatest vertical velocity (0.13 Pa/s) was reached at great vertical extent (the 300 hPa level) on 15 December, which is consistent with deep convection and satellite images from that day. from 13 until 16 December.

3.1.4 Moisture fluxes

Moisture flux diagrams were constructed from NCEP specific humidity and wind data. They show that about 140 g.m/kg.s of moisture was advected into the storm region at the 1000 hPa level on 13 and 14 December (Fig. 3.5a). Part of this moisture was advected from above the Agulhas Current by the easterly to northeasterly winds around the trailing edge of the anticyclone located in the South West Indian Ocean. Although NCEP specific humidity data shows relatively large amounts of moisture in the tropics little was advected towards the storm region (Fig. 3.5a). The winds in the tropical regions of greatest specific humidity were weak and not consistently in the same direction over a large fetch area as those in the South West Indian Ocean. At 850 hPa, there was still anticyclonic motion over the Indian Ocean but the moisture at that level does not appear to have been contributing as much to the storm as the near-surface flux on 13 and 14 December. Again, little moisture originated from the tropics because of the light and variable winds at this level. A greater tropical contribution of moisture to the storm region was evident at the 700 hPa level (Figure 3.5b) although its magnitude of 50 g.m/kg.s was still considerably less than that originating near the surface of the greater Agulhas Current system (140 g.m/kg.s). At 500 hPa, there was negligible moisture available and the winds reflect a westerly wave motion associated with the passage of the midlevel trough. The water vapour estimated from Meteosat essentially shows the same feature. Latitudinal cross sections of moisture flux along 35° S and 30° S (Fig. 3.7) provide further evidence of the moisture input to the storm region. On December 13 a moisture flux of about 40-60 g.m/kg.s moved north towards the Western Cape between 15° E and 20° E and was mostly confined to the surface layers. East of 20° E (the longitude of Cape Agulhas), there was a southward flux of moisture with magnitude increasing east with distance over the South West Indian Ocean. The general pattern remained the same on 14 and 15 December although there was a substantial increase in the magnitude and vertical extent of the moisture flux from the Agulhas Current on these days as the boundary between the northward and southward moisture flux shifted from 20° E to 25° E. As confirmed in trajectories shown later, east of about 25°E, low level moisture was advected south over the Agulhas Current region by the winds on the trailing edge of the anticyclone, and then further west were turned north to feed into the cyclonic circulation of the heat low . Since the boundary shift between the southward and northward transports represents a substantial increase of about 500 km in the fetch of the winds above the Agulhas Current, it suggests that on 15 December the Agulhas Current moisture that was advected from the south played a larger role than on the previous days. On 16 December, the wind shifted from easterly to southwesterly, this can be seen in the latitudinal profile as an eastward shift to 30° E of the boundary of the northward moving moisture. The latitudinal cross sections discussed above show horizontal shear in the moisture fluxes over the region. Horizontal shear in the atmosphere increases the vertical vorticity of the system and thus enhances upward motion. These cross sections also show the presence of vertical shear. This change in direction of the moisture flux with height in the atmosphere increases the horizontal vorticity, which is also favorable for atmospheric instability. As a result, it is not just the flux of moisture that contributes to the storm development but also the horizontal and vertical shear in these fluxes that is significant. NCEP moisture flux transects have shown that moisture was available to this storm from both the north and from the South West Indian Ocean including the Agulhas Current region. At low levels, the most

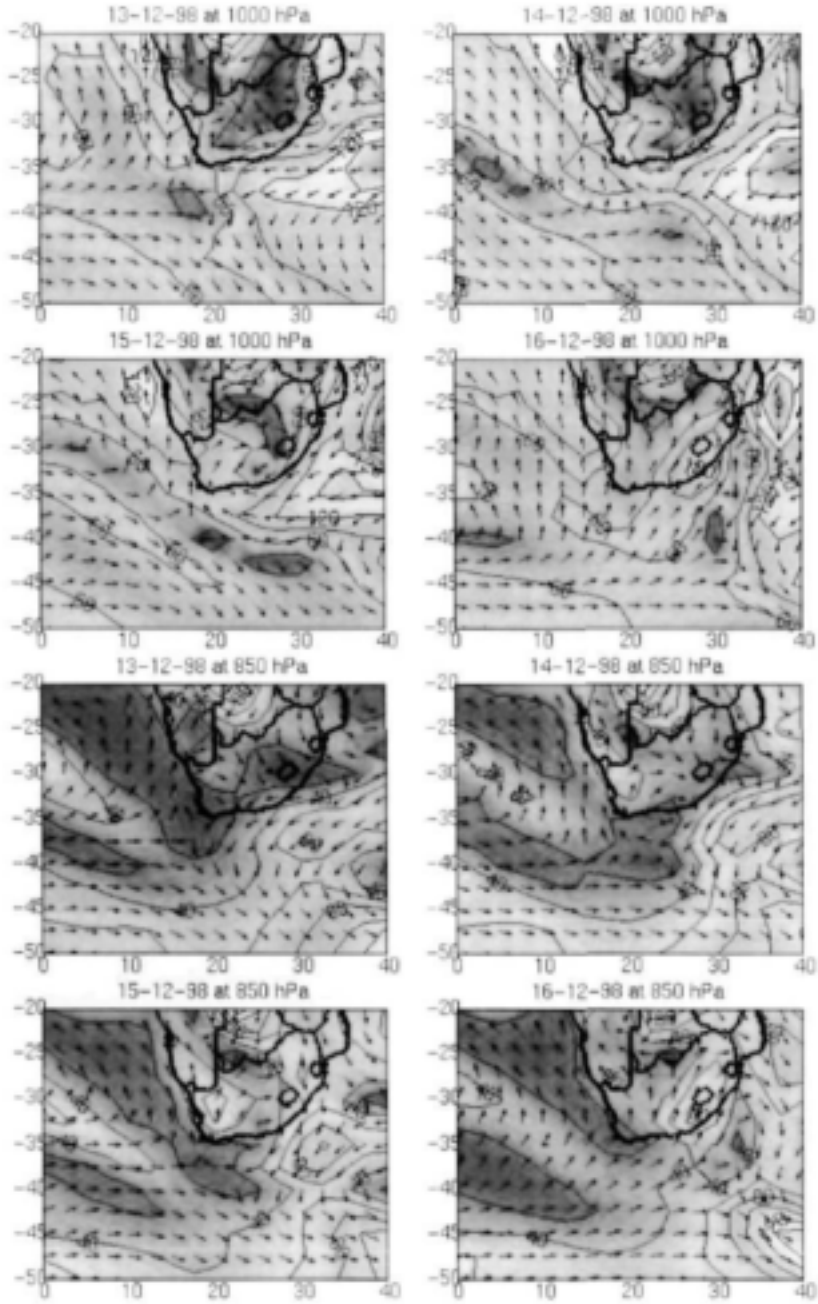

Figure 3.6 (a) NCEP daily moisture flux values (g*m/kg*s) for 13 until 16 December 1998 for (a) levels 1000 hPa (top) and 850 hPa (bottom).

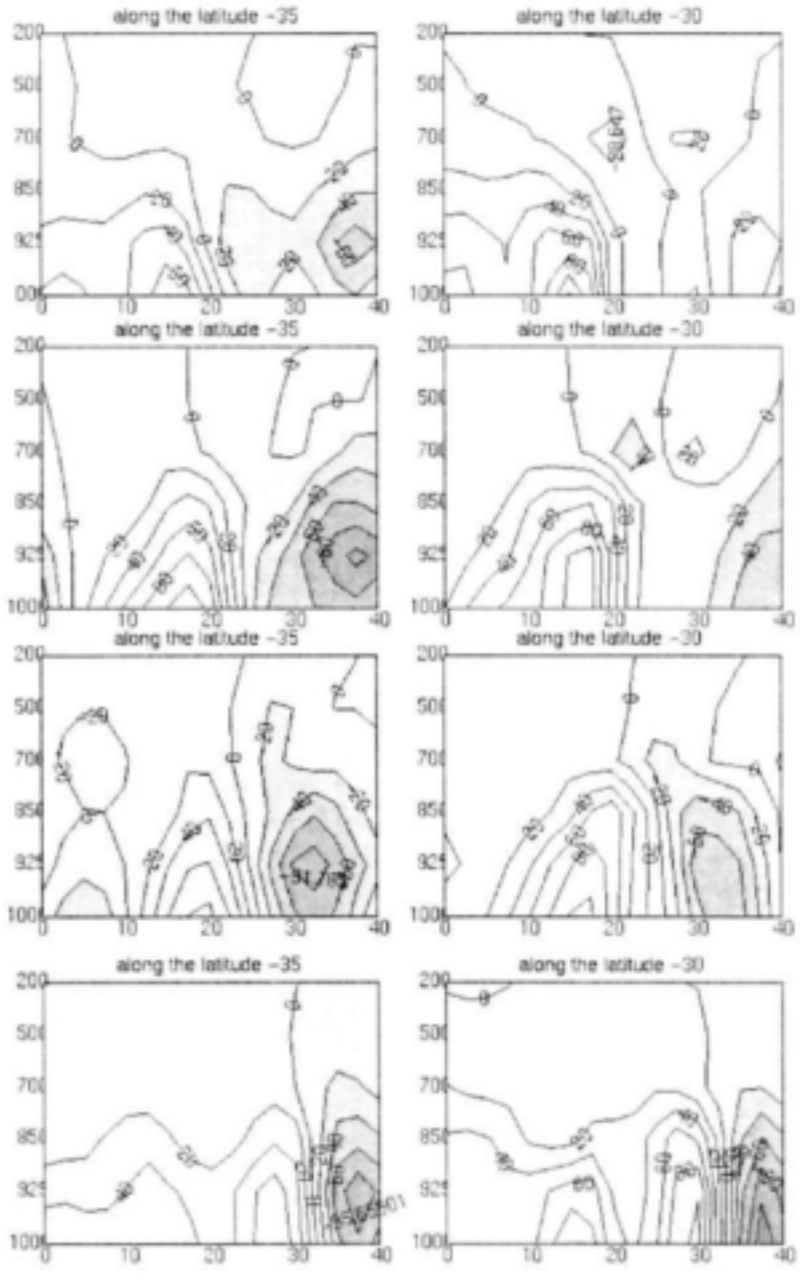

Figure 3.7. NCEP moisture flux vertical profiles (g*m/kg*s) across latitude 35° S (left) and 30° S (right) for 13 until 16 December 1998 (top to bottom). Grey shading indicates southward moving moisture: white is northwards.

significant moisture source appears to originate from the south, i.e., tracking over the Agulhas Current region. At the 700 hPa level (Figure 3.5b), smaller amounts of moisture were advected towards the storm from the north. Although there were large amounts of tropical moisture available at the 700 hPa, the relatively weak winds were unable to advect much of it into the storm region. To examine the tropical and Agulhas Current sources in greater detail, backward air parcel trajectories have been obtained from ECMWF data. Numerous backward trajectories were done at different locations of the coast and different time of the storm. These trajectories were obtained from the British Atmospheric Data Centre (BADC) and are calculated using ECMWF 6 hourly winds. The trajectory model used by BADC is a parcel advection code based on the contour dynamics/advection algorithm of Norton (1994) and Waugh and Plumb (1994). Backward trajectories have been performed from the storm's center to give 3 day backward trajectories for each air parcel analyzed. In general, these trajectories show that the low level flux of moisture advected by the Indian Ocean Anticyclone tracked over the Agulhas Current, sometimes running above it for a few days parallel to the coast. More importantly, the trajectories indicate that moist air was deflected towards the coast on December 14 following passage of the cold front. The trajectories suggest a continuous low level onshore influx of moisture to the west of the storm with the influence of the westerly trough apparent in the mid- to upper levels. This trajectory study through moist air at 900 hPa (or within the marine boundary layer) further suggests that the the Agulhas Current system could have added moisture to the system. It also confirms the Meteosat visible and infrared images that show a large low level cloud band moving parallel to the coast, above the Agulhas current and in the direction of the weak eastwards moving cold front. At the 500 hPa level, the trajectory shows that air was derived from the north west of the country, suggesting that it may be part of the descending branch of the westerly. The air at 200 hPa is also part of the westerly wave which is evidence of the cold dry air advection aloft. These trajectories therefore suggest that air parcels over the storm region traveled through a warm, moist surface layer at 900 hPa with an influx of cold dry air between the 500 and 200 hPa level. It also suggests that the air arriving at the storm was coming from the north to northwest at midlevels. More important, the trajectories at 500 and 200 hPa show the approaching westerly trough. At the same time the water vapor Meteosat images show dry air advecting above the region of the tornadoes, consistent with the NCEP derived moisture fluxes.This situation is one favorable to instability and convection, namely, warm moist air near the surface with cold dry air aloft.

3.2 Underestimation of water vapor fluxes above the Agulhas Current

Contrary to experience for the Gulf Stream and Kuroshio (Renfrew et al. 2001, Moore and Renfrew 2001), the data presented here suggest that both the NCEP and the ECMWF re-analyses significantly underestimated the in situ latent and sensible heat fluxes for the Agulhas Current during the ACASEX and ACE cruises and may well do so in general. We believe that this consistent underestimate mainly results from the models being unable to adequately represent the 80-100 km wide core of the Agulhas Current or the sharp SST gradients associated with it (Fig 3.8).

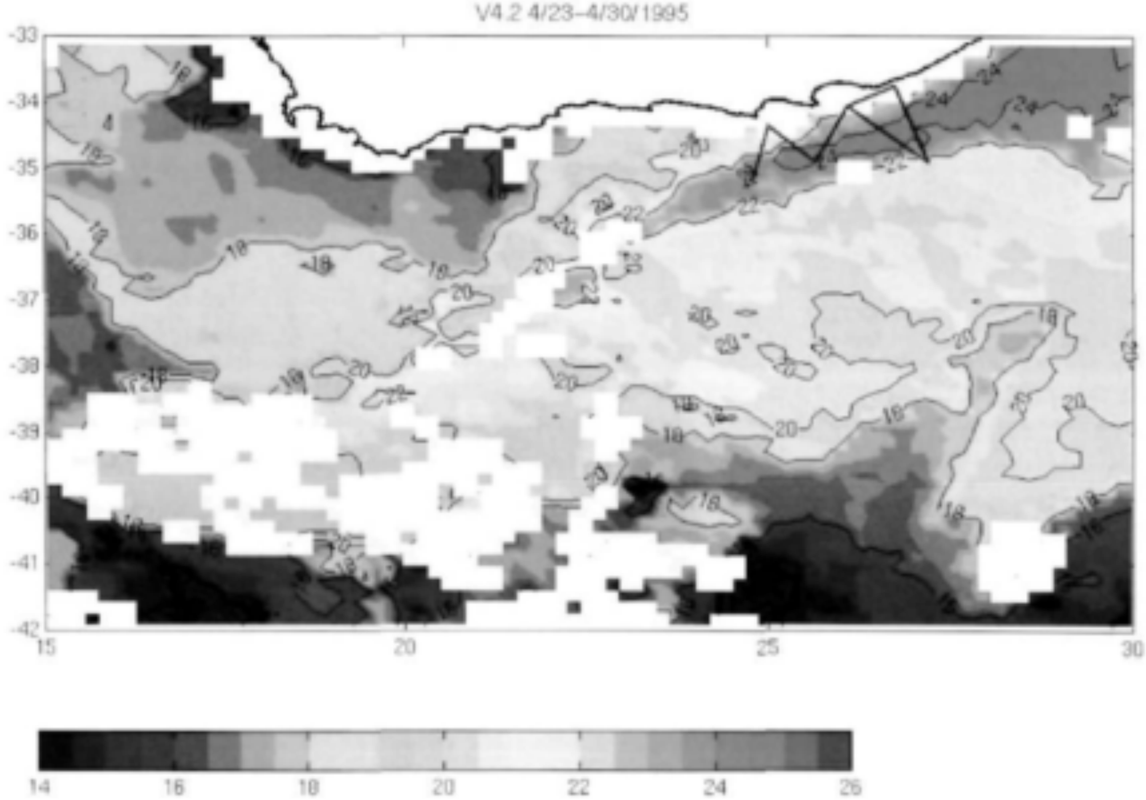

Figure 3.8 18 km resolution AVHRR Pathfinder SST (Reynolds and Smith, 1994) averaged over the period 23-30 April 1995 during which the ACASEX field expedition took place. The ACASEX cruise track is shown in blue. The core of the Agulhas Current has SST > 22°C. White areas over the ocean correspond to those for which there was persistent cloud cover during the cruise.

The ECMWF products have been taken from the ECMWF operational archive which are short range forecasts for the time range from 12 to 36 hours. Data is available from ECMWF at http://www.ecmwf.int. The idea behind using these forecasts is to be sufficiently close to the analysis time to have an accurate representation of the atmospheric fields but to avoid the rapid model adjustment to the data just after this time. The 1995/6 ECMWF data used here have a spectral resolution of triangular wavenumber 213 (T213) which corresponds to a grid spacing in physical space of about 60 km. However, the effective resolution is of order 100 km since half a wavelength is about 100 km in a T213 spectral resolution. For the NCEP re-analyses used here, the resolution is lower (triangular wavenumber T62) or about 210 km grid. Both models use the sea surface temperature analyzed daily by NCEP and provided on a 1x1 degree regular grid. This SST field is then interpolated to the model grids consistent with their land sea mask. SST is kept constant during the ECMWF forecast. Surface flux computations are part of the ECMWF turbulence scheme, which is described by Beljaars and Viterbo (1998). The algorithm for air sea interaction is based on Monin-Obukhov similarity extended with a gustiness formulation for low wind speed (Beljaars, 1995). The roughness length for momentum has a Charnock term (with a Charnock parameter of 0.018) and smooth surface term (scaling with friction velocity and kinematic viscosity). The roughness lengths for heat and moisture have a smooth surface term only. In the NCEP re-analyses, the flux algorithm is detailed in Zeng et al. (1998) and is a simplification of the TOGA-COARE algorithm described in Fairall et al (1996). Fluxes from these models over the Agulhas Current are compared below with those obtained in situ from various cruises, principally the ACASEX cruise. Figure 3.9 shows a comparison between the ECMWF and in situ fluxes estimated above the core of the Agulhas Current (SST> 23°C) during the 24 April – 1 May 1995 period. This represents 445 points or 90 hours of measurement during various meteorological conditions. It is clear that the ECMWF significantly underestimates the latent heat fluxes (and also sensible heat fluxes - not shown) during this period. The mean latent heat flux estimated by the ship instrumentation during ACASEX was 210 Wm^{-2} while that for the ECMWF was 167 Wm^{-2}. For sensible heat, the mean flux obtained from the ship measurements during ACASEX was 42 Wm^{-2} while the ECMWF value for this period was only 27 Wm^{-2}. Similar large discrepancies exist between the NCEP and the in situ fluxes as well.

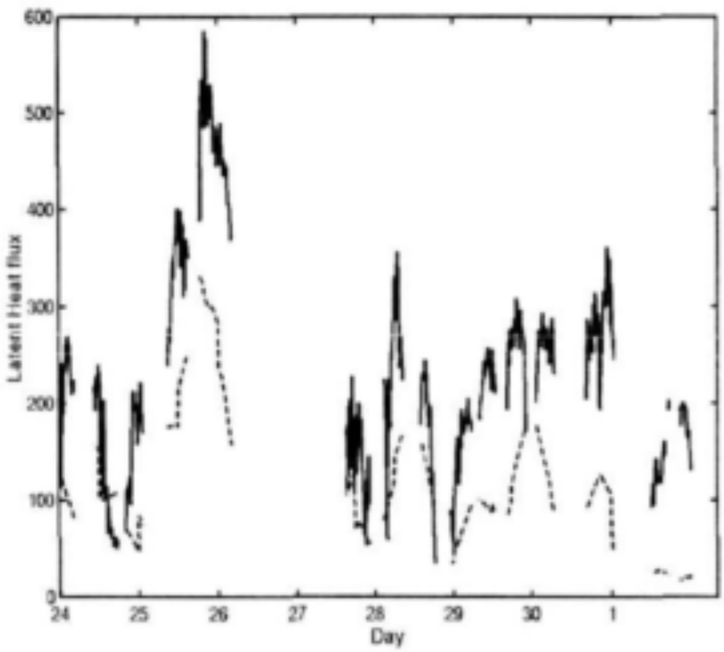

Figure 3.9 Comparison between latent heat fluxes estimated during the ACASEX cruise (thick) and the 4 times daily values (dashed) from ECMWF operational

Figure 3.10, which is the Agulhas Current SST used by the ECMWF, indicates the likely source of the flux discrepancies. The narrow core of the current is not well represented and the SST gradients are considerably less well defined than those in Fig. 3.8. There is also little evidence of any eddy, meander or filament SST structure in Fig. 3.10 unlike what is typically observed. The mean AVHRR SST for the core of the model. The ECMWF values are interpolated from the grid to the location of the measurements. Comparison is for measurements taken in the core region of the Agulhas Current only.

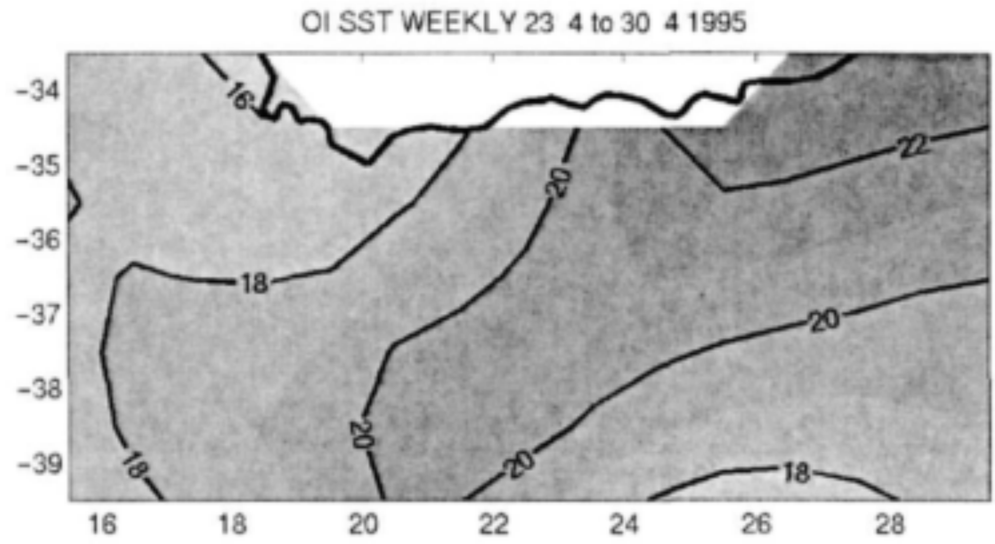

Figure 3.10 Optimal interpolation (1 × 1 degree resolution) of the weekly mean SST used by NCEP for the cruise period.

According to cruise data Agulhas Current was about 23.5°C with a maximum of 24.5°C. By comparison, the corresponding interpolated mean ECMWF SST for the current core was 1.5-2 degrees lower (21.9°C). Further evidence supporting the suggestion that SST underestimation is the main cause for the discrepancies between the in situ and model latent and sensible heat fluxes comes from comparing fluxes calculated using the Fairall et al (1996) bulk algorithm. Using the mean meteorological parameters measured in situ for the core of the Agulhas Current (wind speed = 8.6 m/s, SST= 23.5 °C, air specific humidity at 10 m = 10 g/kg, air temperature at 10 m = 18.2 °C, saturated specific humidity at the sea surface = 18 g/kg and air pressure = 1020 hPa), a latent heat flux of 240 Wm^{-2} and a sensible heat flux of 65 Wm^{-2} are obtained. Reducing the SST by 2 °C to 21.5 °C and the corresponding saturated specific humidity at the sea surface to 15.8 g/kg, results in a latent heat flux of 172 Wm^{-2} and a sensible heat flux of 37 Wm^{-2}, values that are much closer to the ECMWF operational model values of 167 and 27 Wm^{-2} respectively.Other cruise data (not shown here) at different times of the year (e.g. the ACE cruises; Bryden et al. 1995) or those previous cruises to Marion Island (Rouault and Lee-Thorp, 1997) that cross the Agulhas Current and during which flux measurements have been made lead to the same conclusion - the underestimation of the latent and sensible heat fluxes by the models most likely results from the SST being too cool, either because of the coarse resolution of the models or the SST products used. The results from these other cruises further support the claim that operational models and their re-analyses tend to underestimate the latent and sensible heat fluxes over the Agulhas Current.

Because the core of the Agulhas Current is often covered with clouds (Lutjeharms and Rouault, 2000, Lee-Thorp et al., 1998b), SST estimated by the Tropical Rainfall Measuring Mission (TRMM) is likely to be more accurate than that derived from AVHRR data. The TRMM Microwave Imager (TMI) can measure SST at a resolution of 35 km through clouds and the TRMM satellite orbits the Earth between 15 and 16 times daily with the Agulhas Current region in the field of view of the TMI instrument from two to four times a day. This is a great advantage over the infrared SST observations that require a cloud-free field of view. Taking account of TRMM derived SST estimates in flux calculations for cloudy ocean areas is likely to help reduce discrepancies between model and in situ values. We note that NCEP has been using a 0.5 degree resolution SST product since May 2001 improving SST gradients in the Gulf Stream and Kuroshio regions for example (Thiebaux et al., 2001) - however, the model is not run at this resolution. The ECMWF resolution has now been increased to T511 or about 40 km in grid point space (during the 1995-6 period of interest here it was T213 or roughly 60 km in grid point space) with the lowest vertical level moved down from 30 m to 10 m and this 0.5 degree SST data is also being used. ECMWF have also been using a fully coupled wave model (Janssen and Viterbo, 1996) since June 1998 which provides a sea state dependent Charnock parameter to the air-sea flux algorithm every hour - this may well improve matters in the Agulhas region given the frequency of rough sea state in this location. While such model improvements could mean that the differences between ECMWF/NCEP fluxes for 2001 and later and those estimated in situ could be less than reported here for 1995-6, it is likely that to resolve the fluxes over the Agulhas Current in a large scale data assimilation system, a SST analysis at 35 km resolution or better and a model that is capable of maintaining this horizontal resolution in the boundary layer is needed. This relatively high resolution is needed due to the tight gradients in SST between the Agulhas Current core and ambient waters and the associated fluxes (e.g., the ACASEX cruise showed that the latent heat flux over the core was about five times greater than that over the ambient). Such an increase in resolution is considerable and introduces other considerations such as computational resources. It may well be that a preferable approach is to nest a limited area model over sensitive heat flux regions like the Agulhas Current.

4 Role of the Indian Ocean

Several studies have shown that the Indian Ocean plays an important role in the association between ENSO and southern African rainfall. Our contribution concerning the Indian Ocean stems from cooperation with the Centre de Recherche Climatologique (CRC) France and Chris Reason from UCT.

4.1 South West Indian Ocean

We explored links between sea surface temperature (SST) anomalies in the Southwest Indian Ocean for rainfall variability over South Africa Warmer SST in the Southwest Indian Ocean tends to be associated with wetter conditions over eastern and central South Africa and vice versa. An ensemble of experiments with an atmospheric general circulation model forced by an idealization of the warming in the Southwest Indian Ocean leads to statistically significant rainfall increases over large areas of eastern South Africa and neighbouring regions. The mechanism appears to involve changes in the convergence of moist air streams originating from the Indian Ocean and from tropical southern Africa. The magnitude of the rainfall anomalies accumulated over a 90 day season was of the order of 90-300 mm and, therefore, represents a significant fraction of the annual total. These model results reinforce the observational work suggesting that SST anomalies in the Southwest Indian Ocean are linked with significant rainfall anomalies over eastern South Africa. Results are developed in Reason and Mulenga (1999).

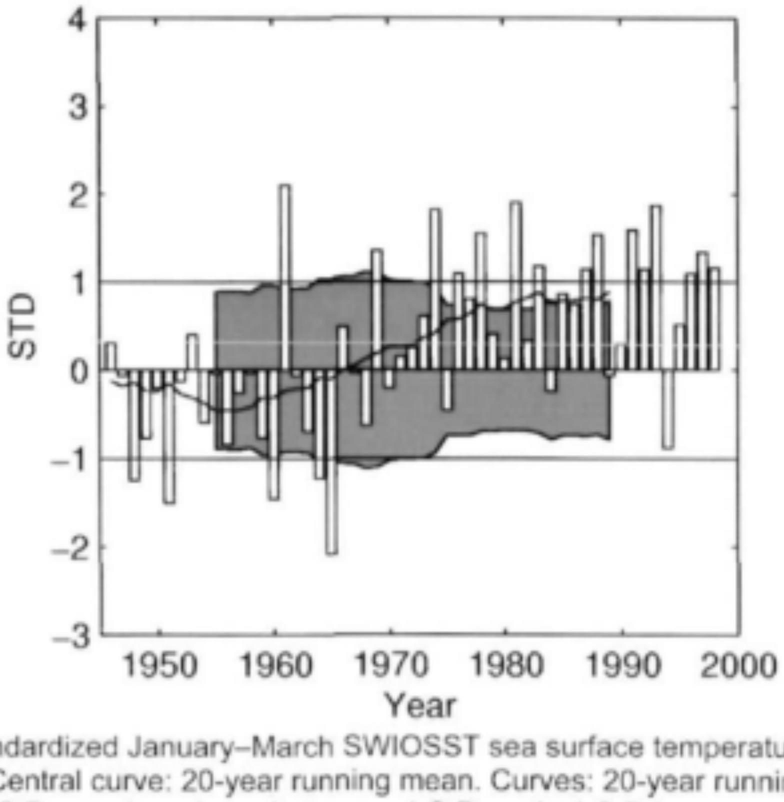

Figure 4.1 Standardized January–March SWIOSST sea surface temperature anomalies (1946–1998). Central curve: 20-year running mean. Curves: 20-year running standard deviation. red: S.D. envelope (area between -1 S.D. and +1 S.D.)

We constructed a SST anomaly index for the southwest Indian Ocean (referenced as SWIOSST). This area corresponds to the negative anomaly area for 1950–1969 dry years. January–March SST is averaged between 20° and 30°S and between 30° and 60°E. This index can only be considered to be reliable for the second part of the century. There is a decrease in observations during World War II and 1945 has been discarded from the sample. Figure 4.1 shows the evolution of the standardized index SWIOSST for 1946–1998. SWIOSST's 20-year running mean and standard deviation envelopes are superimposed. There is a marked increase of the mean values, consistent with the temperature increase in the subtropical and extra-tropical latitudes of the Southern Hemisphere (Fontaine *et al.*, 1998). As for SOI, correlation coefficients between southern African rainfall index (SARI) and SWIOSST are calculated over the 1946–1998 period and for the 1946–1969 and 1970–1998 sub-periods. For the global period, the correlation is significant at the 95% confidence level but the value is weak because SARI is not characterized by a trend, contrary to SWIOSST. However, the correlation for both sub-periods and the evolution of those correlations underline several points. For the 1946–1969 sub-period, the association between southern African droughts and cold southwest Indian Ocean SST is almost systematic, especially for intense droughts. After 1970, the association between droughts and cold SST does not occur, and the correlation coefficient drops. A possible reason is a decrease in the amplitude of the cold events due to an increase of mean Indian Ocean SST. Another possibility is that stronger southern African droughts associated with ENSO events mask the relatively dry periods of January–March 1984 and 1994 which occurred in association with cold SWIOSST.

5 Role of the Pacific Ocean

The collaboration with CRC was very important in that endeavor.

5.1 Interdecadal modification of ENSO/rainfall relationship

For Southern Africa south of 12° S as a whole, an index of rainfall variability (SARI for « Southern Africa Rainfall Index) was constructed based on Principal Component Analysis results. Details concerning the computation of this index can be found in Richard et al. (2000). December to April (hereafter DJFMA) rainfall amounts are considered since this season has been shown to be the most coherent spatially and temporally relatively to the interannual variability (Richard et al., 2001). Fig. 5.1 shows the time evolution of DJFMA SARI over 1901 - 1998 computed from the Climate Research Unit gridded dataset (Hulme, 1992a and 1996).

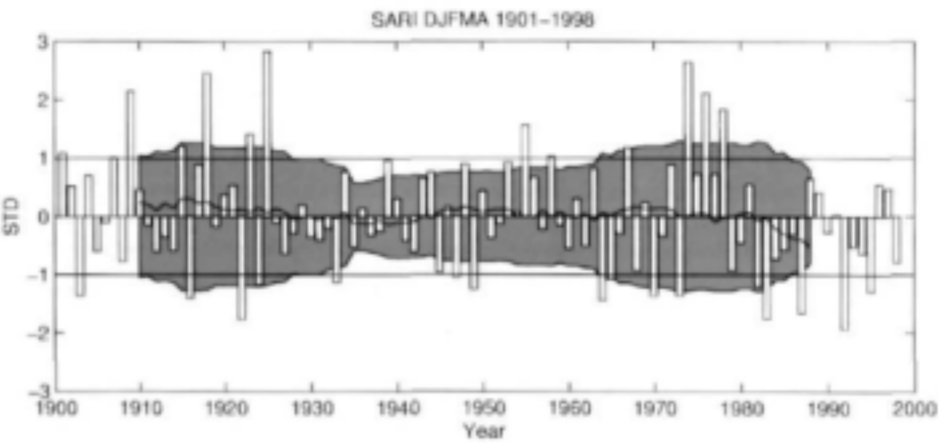

Figure 5.1 Changes in rainfall amounts and variance for Southern African summer rainfall index (SARI) from 1901 to 1998. bars: standardised December to April (DJFMA) rainfall amounts for SARI. Central curve : 20-year running mean. External envelopes and shading: 20-year running standard deviation, Richard et al. (2000).

No significant trend is evident from SARI during the century, in agreement with many previous studies of long term rainfall variations over the region (Tyson, 1991; Hulme, 1992b). However, decadal-scale changes in the magnitude of the interannual rainfall variability are evident from the standard deviation envelope (Fig. 5.1). Three major sub-periods emerge: stronger rainfall variability is found at the beginning of the century and during recent decades beginning in the late 1960's, while weaker variability is apparent in-between (1940's and 1950's decades) Accordingly, composite rainfall anomalies have been computed relatively to the five driest years in each of the "low variability" and "high variability" post-World War II periods (roughly before and after the 1970 s). The dry composite sample for the 1950-1969 period includes 1960, 1962, 1964, 1965 and 1968. For the 1970-88 period, it includes 1970, 1973, 1982, 1983 and 1987. The rainfall dataset used in the composite analysis is the original « Centre de Recherches de Climatologie » (CRC) which has a fairly good spatial resolution over Southern Africa (Bigot et al., 1994 and 1995). During the low variability period (1950-1969, Fig 5.2a), the spatial extent of droughts affecting Southern Africa is not homogeneous: the most important deficits are found mainly over Zimbabwe, while they are less significant over Zambia and South Africa. Compared to the former, droughts of the 1970-88 period (Fig. 5.2b) are more extended and intense and spread widely northward. They affect northern Zambia and Mozambique more significantly and are also more intense in Namibia and South Africa. Thus drought features have experienced regional changes.

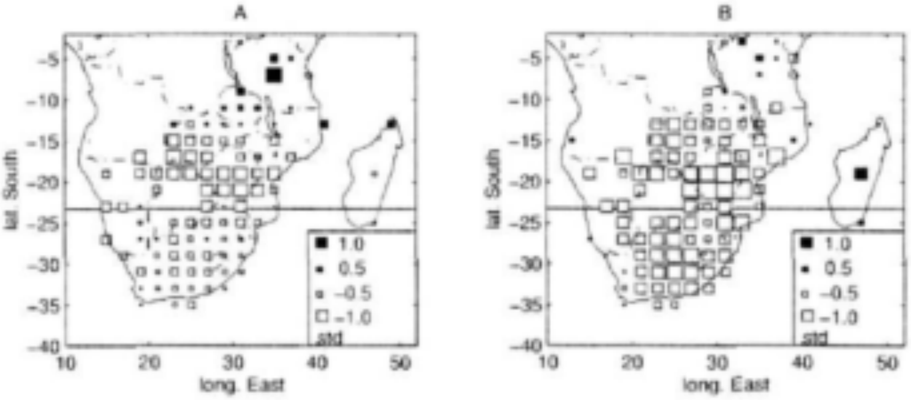

Figure 5.2 Composite rainfall patterns associated with droughts before (a) and after (b) 1970 Composite of DJFMA Southern African rainfall anomalies and Student T test:
A: Standard deviation anomalies 1950-1969 dry quartiles
B: Standard deviation anomalies 1970-1988 dry quartiles

One of the reasons for the seasonal persistence of extended rainfall anomalies in the tropics and subtropics lies in the atmospheric circulation and moisture supply modifications by slowly varying surface boundary conditions and most notably Sea Surface Temperatures (SST). The best example of such SST forcing is the El Niño Southern Oscillation (ENSO) phenomenon involved in rainfall variability of surrounding regions but also leading to rainfall anomalies in remote locations (Ropelewski and Halpert, 1986; 1989; 1996). Fig. 5.3a presents the SST anomaly composite for the droughts of the « low-variability » sub-period (1950-69). There are few significantly related areas, mainly in the surrounding Atlantic and Indian Oceans, especially abnormally cold SST in the subtropical Southwest Indian Ocean (spanning the Mozambique current, the Agulhas current and its retroflection region). This is consistent with the results of Walker (1990), Reason and Lutjeharms (1998) and Reason and Mulenga (1999), who showed that cold Southwest Indian Ocean SST are often associated with dry conditions over Southern Africa. The atmospheric signals for the same sample are consistent with this SST anomaly pattern and mainly indicate a reduction of deep convection over the continent. Unlike for the 1950-69 period, the « high variability» period droughts are associated with warm and widespread SST anomalies in the tropics (Fig. 5.3b) corresponding to the ENSO pattern. In the 1970-88 period, four among the five driest years are associated with peaks of the ENSO cycle. 1982 cannot be related to ENSO since warm SST anomalies started in boreal spring i.e. only at the very end of the DJFMA season. During the 1950-69 period, none of the droughts coincided with significant ENSO anomalies. Thus SST and atmospheric anomaly patterns associated with the most severe regional scale droughts in Southern Africa changed from regional before the late 60's to near global afterwards. This increasing influence of ENSO on Southern African rainfall can also be diagnosed through changes in the statistical association with various ENSO indices along the century. Fig.5.4 displays the correlation coefficients between SARI and the Southern Oscillation Index (SOI) in DJFMA computed over 20-years running windows from 1900 to 1998. ENSO - Southern African rainfall variability relationship is clearly not stationary over the century, with correlation close to zero during the 40's and the 50's, and significant after the late 1960 's. This result is also consistent with findings of Mason and Mimmack 1992.

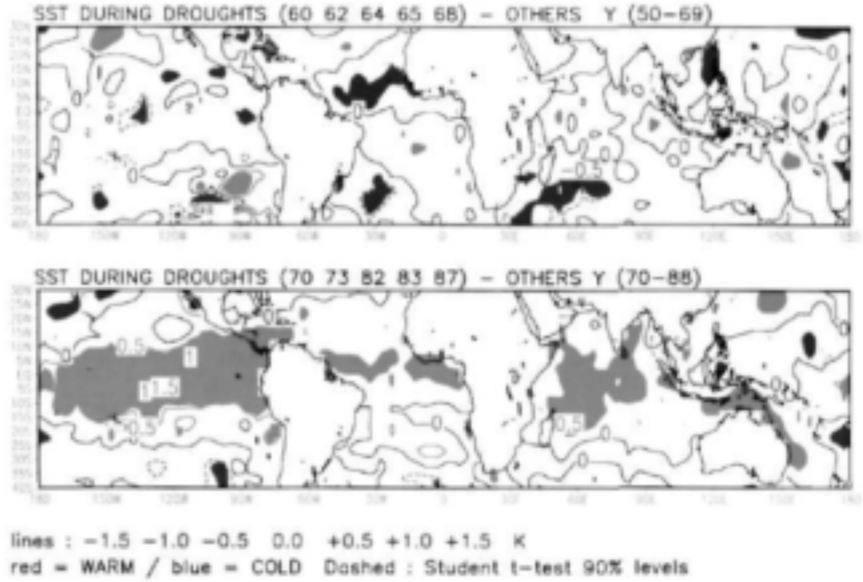

Figure 5.3 Composite SST anomalies patterns associated with droughts before (a) and after (b) 1970 Solid line: positive anomalies. Dashed line: negative anomalies. Shading denotes the statistical significance at the 95% level.

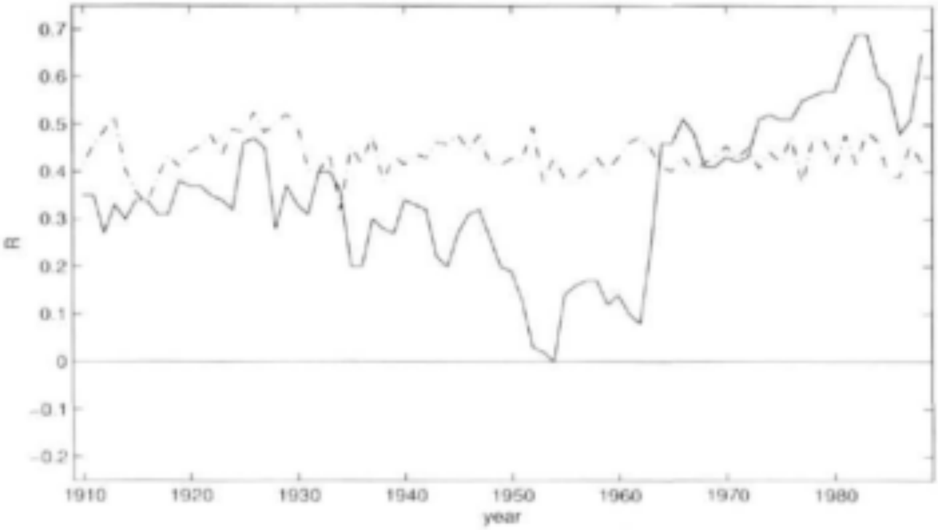

Figure 5.4 Changes in the correlation between SARI (DJFMA) and SOI (DJFMA) time evolution of correlation between SARI and the Southern Oscillation Index for DJFMA from 1900 to 1998 with a 20-year running window mean. Years are for the middle of the 20-year period. The dotted line displays the 5% significance level according to Monte-Carlo simulations performed for each 20-year period.

Some atmospheric and/or oceanic phenomena have been put forward to account for the occasional failure of the ENSO-rainfall relationship in Southern Africa (cf. for example Mason and Jury 1997 for the review) but only few studies (Kruger 1999) focused on changes on longer time-scales. The hypothesis explored in the next section involves the observed long-term modifications in the SST background.

Rasmusson et al. (1994) amongst other noticed substantial changes in the amplitude of SO-related anomalies in the Pacific Ocean over the last century. Wang and Ropelewski (1995) related these changes to the slowly (decadal scale) evolving background SST state. Richard et al. (2001b) pointed out the coincidence between modifications of the SOI and SARI running variances. The SST variability from 1945 to 1994 can be decomposed in orthogonal modes through Empirical Orthogonal Functions (EOF) analysis with VARIMAX rotation (Trzaska et al., 1996). Details concerning the EOF analysis and the Varimax criterion can be found in Richmann (1986). The first mode (10.2 % of variance, Figure 5.5a,b) depicts a global tropical mode (GT) and corresponds to the ENSO pattern, its temporal evolution displays significant interannual variability in the range of 4-7 years and is correlated at R=-0.68 (significant at 95%) with the standard Southern Oscillation Index. The second and fourth modes depict respectively SST variability in the Northern and Southern Tropical Atlantic and are not discussed here.

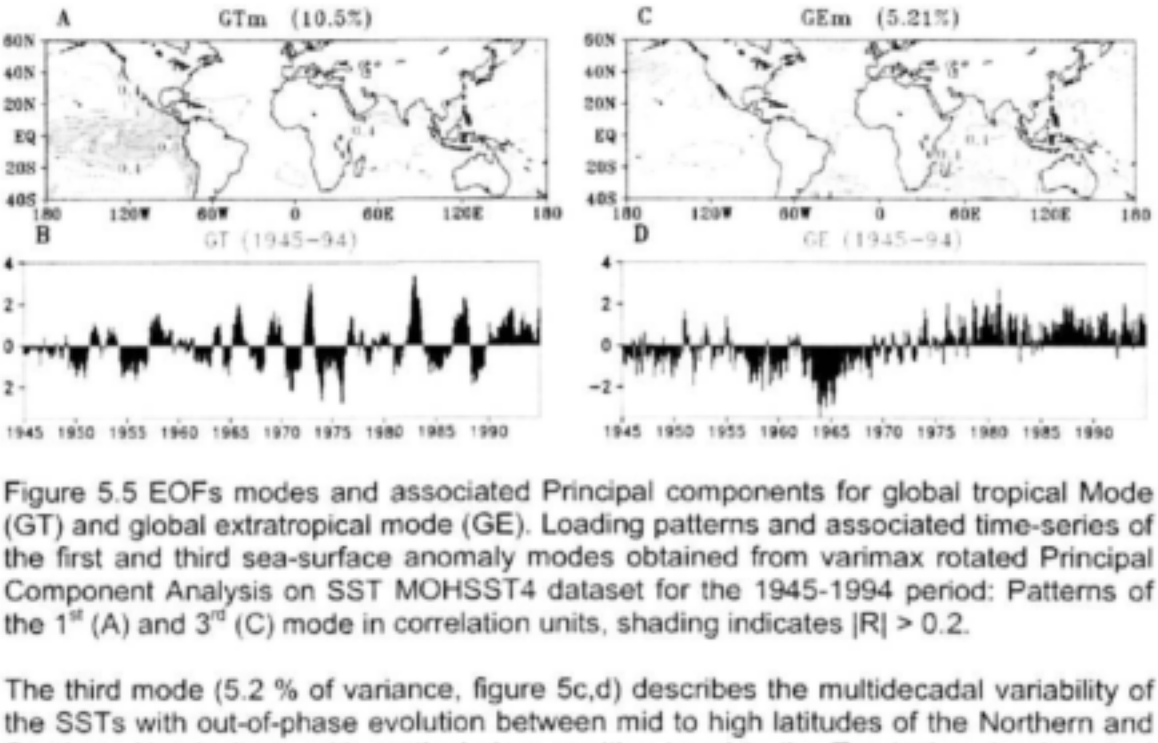

Figure 5.5 EOFs modes and associated Principal components for global tropical Mode (GT) and global extratropical mode (GE). Loading patterns and associated time-series of the first and third sea-surface anomaly modes obtained from varimax rotated Principal Component Analysis on SST MOHSST4 dataset for the 1945-1994 period: Patterns of the 1st (A) and 3rd (C) mode in correlation units, shading indicates |R| > 0.2.

The third mode (5.2 % of variance, figure 5c,d) describes the multidecadal variability of the SSTs with out-of-phase evolution between mid to high latitudes of the Northern and Southern Hemisphere, with particularly a positive trend in the Tropical and subtropical Indian Ocean. Folland et al. (1991) and Kawamura (1994) have already pointed out this mode (GE, global extratropical). It is also quite similar to low frequency EOF3 with the same sign reversal about 1970 in a longer period study (1860-2000) of Folland et al. (1999). The possibility that some of the features of this mode could reflect modifications of the data availability (Parker et al. 1994) can not be ruled out. In addition, it could be a part of long-term natural variability involving deep ocean (Weaver et al. 1994, Rahmstorf 1995). However, GCM experiments strongly suggest that this pattern and its time evolution are in fact the signal of the combined radiative effects of the continuously increasing anthropogenic greenhouse gases in one hand, and changes in aerosols emissions on the other hand (Mitchell et al., 1995; Le Treut, 1995; Boucher, 1997; among others). To assess the potential links between these long term changes in SST background and the modification of the Southern African Rainfall - ENSO association, two sets of sensitivity experiments with the French ARPEGE-Climat AGCM (Météo-France, Déqué et al., 1994) have been conducted using linear combinations of the first (ENSO-like) and third (SST-background long-term changes) modes as boundary conditions. The first set, referred as « early ENSO » experiment, reflects notably ENSO warm events embedded in a relatively « cold » Southern Hemisphere and Indian Ocean SST background. The second set is referred as « recent ENSO » experiment and represents ENSO in the relatively warmer southern and Indian Ocean SST context. Only the « recent ENSO » experiments successfully simulate abnormally low rainfall over subtropical Southern Africa (Fig. 5.6). In the « early ENSO » experiments, rainfall is close to the mean and no significant deficits appear over the subcontinent. On the contrary, in the « recent ENSO » experiments, rainfall is below normal over large parts of the subcontinent while the central and SW Indian Ocean experience above normal rainfall: this bipolar feature in precipitation has been widely noticed to be associated with droughts over Southern Africa (see e.g. Jury et al., 1994, Mason and Jury 1997). Simulated Outgoing-Longwave-Radiation (OLR) anomalies, which is a proxy for deep convection, demonstrate it even more clearly (Fig. 5.7). These results strongly suggest that modifications of the association between Southern African rainfall and the ENSO phenomenon are related to long term changes in the sea surface temperature background.

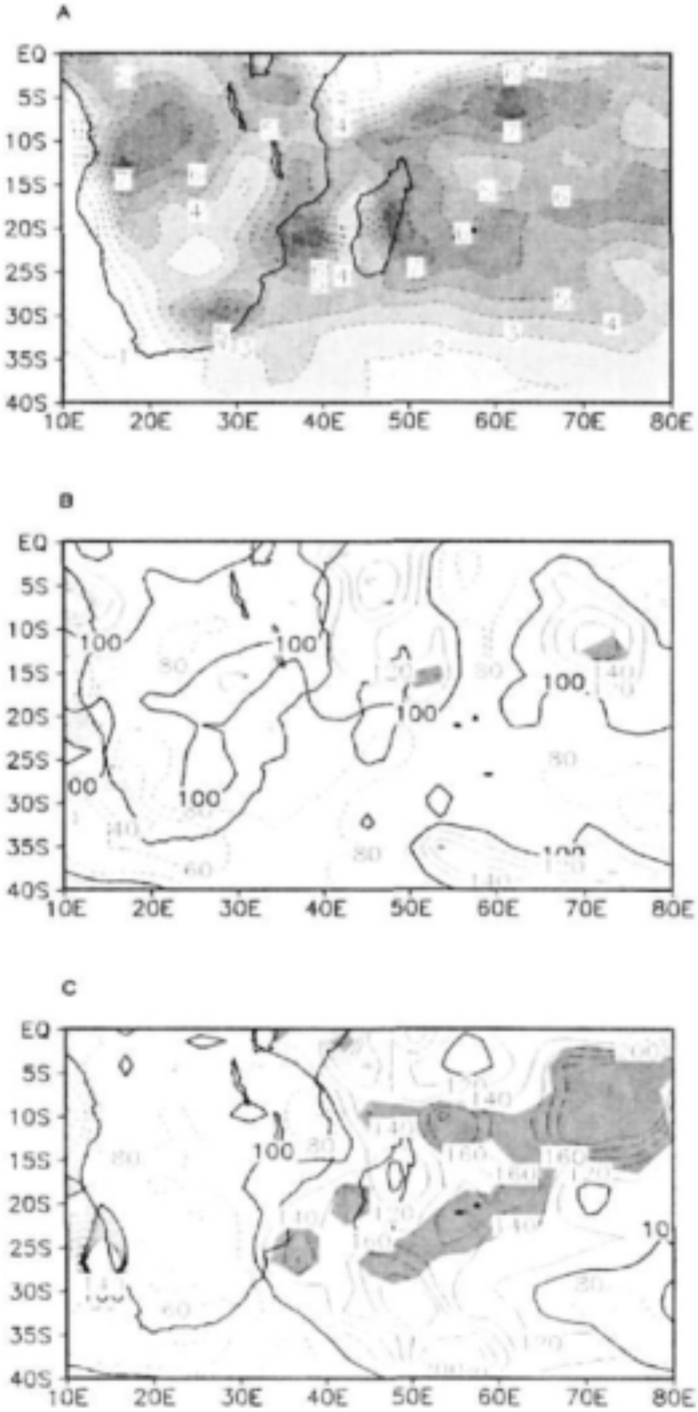

Figure 5.6 Simulated rainfall anomalies :

a) March monthly means values (AMIP 1979-1988) in mm/day.

b) « early ENSO » experiment: % of the 1979-88 AMIP average.

c) « recent ENSO » experiment: in % of the 1979-88 AMIP average.

Shaded areas are for the significant values at the 95% confidence level (t-test). Light shading for below normal, dark shading for above normal

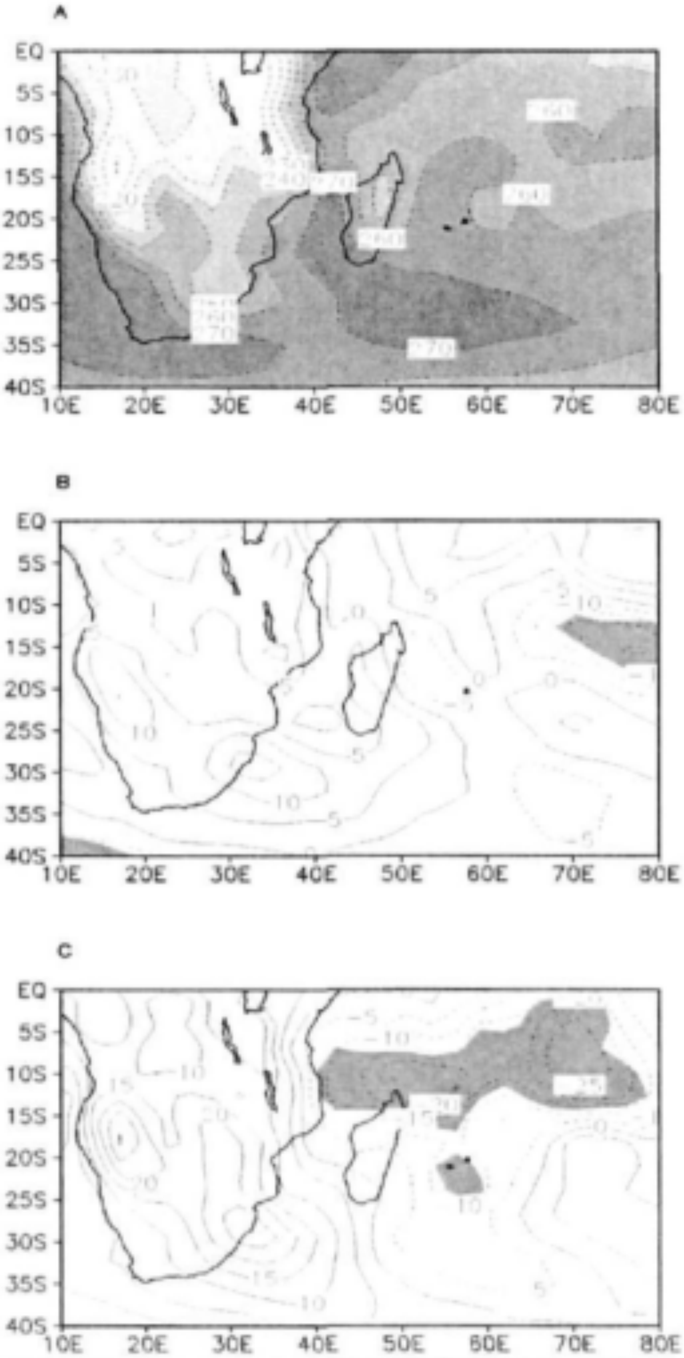

Figure 5.7 Simulated OLR anomalies March

a) monthly means values (AMIP 1979-1988) in W/m^2s^{-1}

b) « early ENSO » experiment minus the 1979-88 AMIP average.

c) « recent ENSO » experiment minus the 1979-88 AMIP average.

Shaded areas are for the significant values at the 95% confidence level (t-test). Light shading for below normal, dark shading for above normal

6 *Role of the Atlantic Ocean*

6.1 South East Tropical Atlantic Warm Events and Southern African Rainfall

The influence of the Tropical Atlantic Ocean on Brazilian and West African rainfall has been the subject of numerous studies but less has been done to understand the effect of tropical and equatorial Atlantic variability on Southern African rainfall in the peak rainy season of austral summer and autumn. Using data from 1940-1975, Hirst and Hastenrath (1983) established a positive correlation between tropical South East Atlantic coastal SST and Angolan coastal rainfall for late summer (March–April) and noted that some of the warm events along the Angolan coast were preceded by reduced tradewinds in the tropical and equatorial Atlantic Ocean. Subsequently, Nicholson and Entekhabi (1987) showed that during warm South East Atlantic events, above average rainfall occurred along the Angolan (6°S to 17.5°S) and Namibian (17.5°S to 29°S) coasts as well as inland. The occurrence of these warm events in late summer is at the time of the peak in the annual march of SST, hence amplifying the local effects on atmospheric instability and rainfall. The occurrence of warming of around 2°C to 6°C along the southwestern Africa coast between 10°S and 25°S appears to be an aperiodic phenomenon. Some of these warm events have been described and named "Benguela Ninos" by Shannon et al. (1986) because of their similarities with anomalous warming occurring in the upwelling area off Peru and high rainfall in the usually arid Peru during the Pacific El Niño. The warm events appear to arise as warm water of equatorial origin propagates poleward along the southwest coast of Africa as far as 25°S where cold upwelled Benguela Current waters are usually found, hence the term Benguela Ninos. It is thought that these warm events are remotely forced since they follow ENSO-like warm events in the equatorial Atlantic and a sudden relaxation of the trade winds near Brazil (Carton and Huang, 1994, Delecluse et al., 1994). This trade wind relaxation could leads to the generation of equatorial Kelvin waves as well as a strengthening of the South Equatorial Counter Current (SECC), thereby producing a depression of the thermocline along the equator. Warm waters then accumulate in the eastern South Atlantic and coastal Kelvin waves propagate the anomalies southward along the coast. ENSO-like warm events in the equatorial Atlantic do not lead all the time to Benguela Ninos (Binet et al, 2001). Shannon et al. (1986) identified Benguela Ninos in 1934, 1963, 1984 with associated high rainfall (1934, 1963) and flooding (1984) in the usually arid Namibian area. More recent warm events occurred in 1986 (Boyd et al, 1987), 1995 and probably 2001. The 1984 events is the best documented (Philander, 1990). During the 1995 event, ocean temperature anomalies of up to 8°C were measured below 30 m. Cruise data showed these anomalies extending 300 km offshore with a southward extension to 27°S (Gammelsrød et al, 1998). This, and other warm events, has had a strong influence on local fish distribution and abundance in Angolan and Namibian waters (Binet et al., 2001). We have documented the impact of recent warm events of 1984, 1986, 1995 and 2001.

During these events, positive anomalies reached a maximum during March/April with monthly mean SST reaching as high as 30°C along the coast of Angola. It also seems that cold events (1982, 1992 and 1997) are met with below average rainfall. The precipitation anomaly fields shown in Figs 6.1, 6.2 and 6.3 were constructed from the Global Precipitation Climatology Project (GPCP) Version 2.5x2.5 gridded combination of gauge measurements and satellite estimates of rainfall (Huffman et al., 1997). This product is very useful for Southern Africa where little rain gauge data are available. Due to the high mean SST off the Angolan coast (Figure 6.1) and the timing at the peak of the annual cycle (23°C to 29°C in March), we have reason to believe that these warm anomalies could have an effect on the overlying atmosphere as was suggested by Hirst and Hastenrath (1983). Indeed, Figs 6.2 and 6.3 suggests a relationship between local SST and precipitation averaged over the coastal region and above the oceanic region off Angola during the late austral summer. Figs 6.3 plots the precipitation anomalies divided by the standard deviation at each grid point and highlights the relatively homogeneous rainfall responses to the warm events in which seasonal anomalies of up to 2 standard deviations occur above the SSTA and neighbouring areas of Angola and Namibia. Integrated moisture flux shown in Fig 6.4 indicates that western Indian Ocean is the principal source of moisture for summer rainfall over southern Africa but a secondary source is situated in the Atlantic Ocean off Angola. During January and February the mean flux is westerly off the tropical SE Atlantic with convergence over Zambia with the mean easterly flux originating from the tropical Indian Ocean. Figure 6.4 shows the mean moisture flux for January February, March, and April while the middle panel of Figure 6.3 shows the anomaly from this mean for 1984, 1986, 1995 and 2001. In 1995, the SE Atlantic SSTA was largest but the inflow into Angola / Namibia from the Indian Ocean was weaker than average and the rainfall was enhanced only by the Atlantic source. For 2001, there was convergence in southern Zambia / northern Zimbabwe between the enhanced moisture flux from the SE Atlantic SSTA and that coming from the western Indian Ocean. Hence, the largest precipitation anomalies occurred over central southern Africa with those in western Angola / Namibia influenced only by the SE Atlantic moisture flux. By contrast, the moisture flux from the western Indian Ocean across low latitude southern Africa was enhanced in 1984 and 1986 with relative convergence over western Angola / Namibia. This, together with the increased evaporation and unstable lower atmosphere over the warm SE Atlantic SSTA, led to relatively large precipitation anomalies in this region. Benguela Niño events are associated with above average rainfall over the tropical SE Atlantic and western Angola / Namibia. If the large scale circulation is favourable, then the precipitation anomalies may extend further into southern Africa. While warm events may be associated with unwelcome floods along the Angolan and Namibian coast, increased rainfall elsewhere can sometimes alleviate droughts in other regions of Southern Africa. These rainfall impacts the fact that they are an oceanographic phenomenon with relatively long lead times, suggests that better monitoring of the tropical SE Atlantic region is important and could have significant societal benefits. Monitoring of the warm event upstream could provide an early warning forecast system that could be beneficial to society.

An extension of the PIRATA array of moorings (Servain *et al.*, 1999) at key locations in the tropical SE Atlantic is therefore recommended to understand the dynamics of warm and cold events events and their effect on the overlying atmosphere. The variables measured by PIRATA moorings are surface winds, SST, sea surface salinity, air temperature, relative humidity, incoming short-wave radiation, rainfall, and subsurface temperature, salinity and pressure in the upper 500 meters. In addition to benefits such as calibration of satellite products in a cloudy oceanic region and assimilation/verification of oceanographic circulation models, the suggested extended PIRATA measurements could provide a better understanding of the evolution of warm and cold events and the role that upper layer heat content plays in influencing regional rainfall.

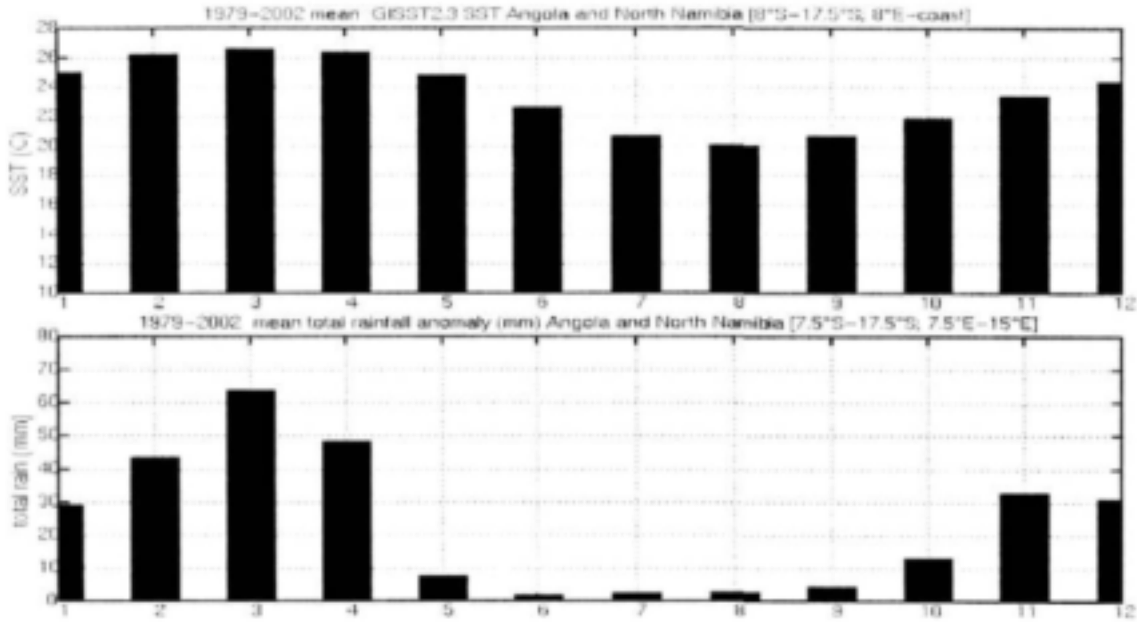

Figure 6.1 Top, mean SST off Angola and North Namibia averaged in [8°S-17.5°S; 8°E-Coast]; bottom: Total rainfall (mm) averaged in [7.5°S-15.5°S; 7.5°E-15°E];

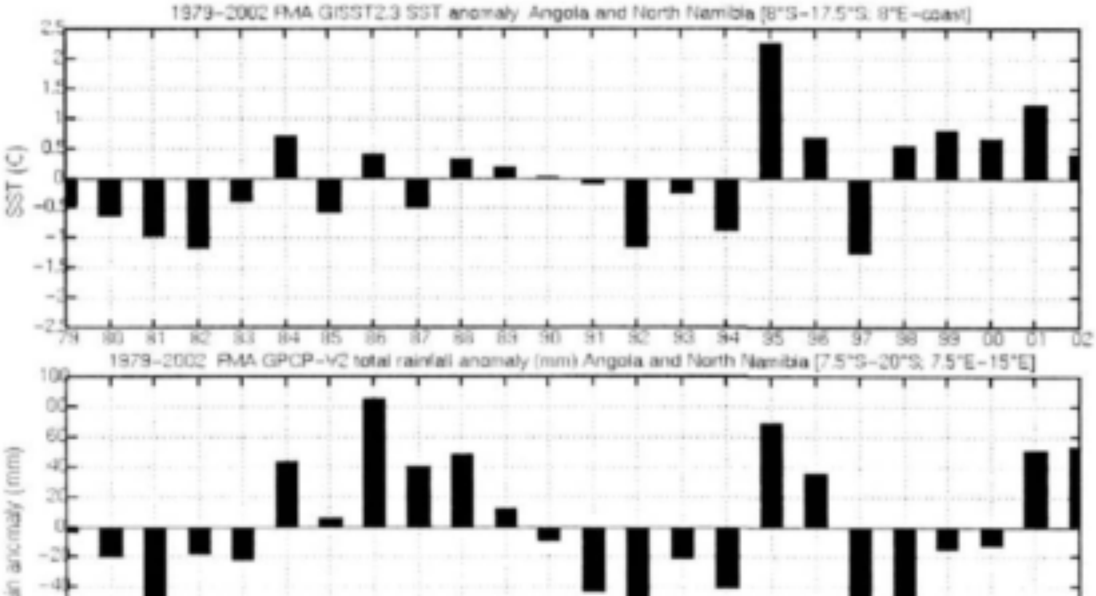

Figure 6.2 mean FMA SST anomalies off Angola and North Namibia averaged in [8°S-17.5°S; 8°E-Coast]; bottom: mean FMA total rainfall anomalies (mm) averaged in [7.5°S-15.5°S; 7.5°E-15°E];

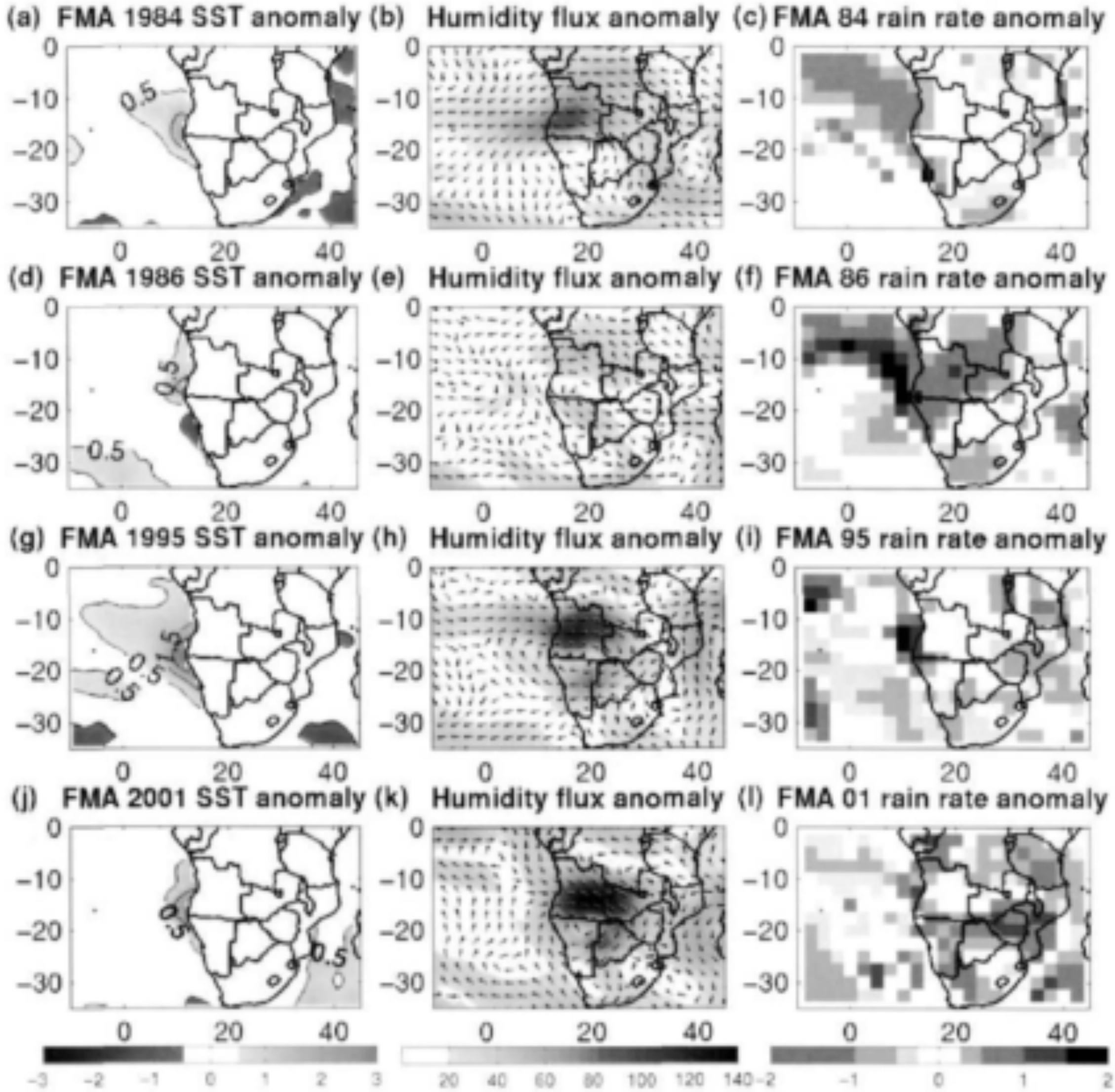

Figure 6.3 Left: mean FMA OI SST anomalies for 1984 (a); 1986(d) 1995(g) and 2001 (j) isocontour at 0.5°C, 1.5°C and 2.5°C. Middle: mean FMA integrated moisture anomalies from the surface to 300 hPa flux anomalies for 1984 (b), 1986 (e) 1995 (h) and 2001 (k) in g/kg.m/s. Right: mean FMA rain rate normalized anomalies for 1984 (c), 1986(f) 1995 (i) and 2001 (l). (rain rate divided by standard deviation).

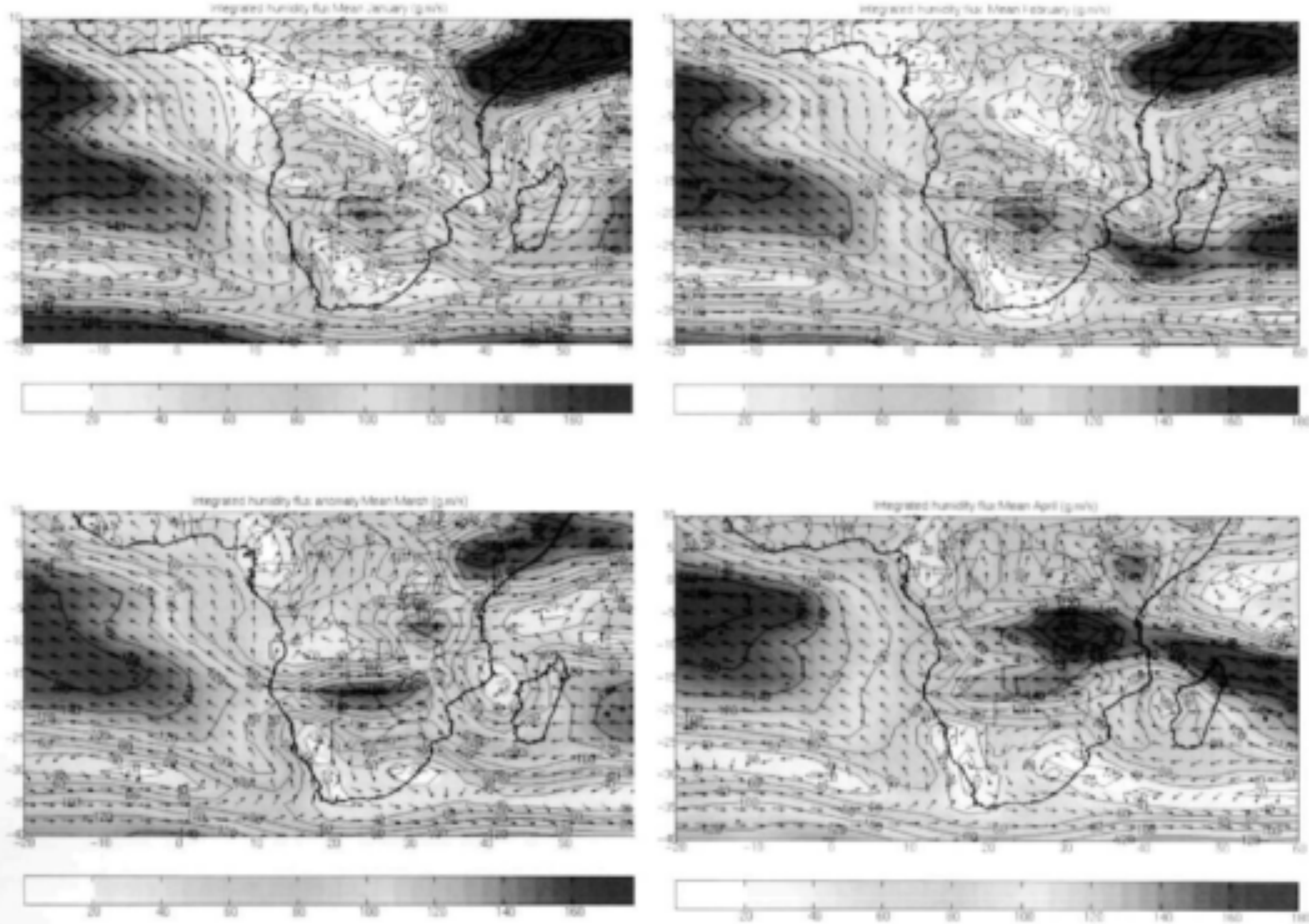

Figure 6.4 Mean 1968-2001 January, February, March and April integrated moisture flux from the surface to 300 Hpa from NCEP reanalysis (g/kg.m/s).

7 Conclusions and Recommendations

This project has unravelled some of the physical mechanisms linking the ocean and climate variability in South Africa. This constitutes but one small step on the road to such a complete understanding of these mechanisms that it would allow realistic and reliable seasonal forecasts of the rainy season.

We have shown that the Indian and Pacific Oceans have a considerable effect on the yearly variation of rainfall over South Africa. The Agulhas Current also has a most important role, more so than previously envisaged, due to the large rate of moisture transfer above it. However, the latter may be restricted to enhancing local weather systems and storms. We have shown this in one special case.

Observational and modelling studies show a link between rainfall variability in southern Africa and the Pacific El Niño, as well as the SSTs in the Indian. These links have changed during the last century. During an El Niño, abnormally high SSTs appear in the Indian and Atlantic Oceans. In turn, these oceans then have a more direct effect on South African rainfall. A direct link with El Niño comes about through an atmospheric response to the Pacific high SST anomalies. During ENSO dry summers, anomalous upper tropospheric westerlies are dominant over most parts of the subcontinent and make the upper flow unfavourable for rain-bearing disturbances over South Africa. High pressure anomalies exist over southern Africa, suppressing convection, while the ascending branch of the Walker circulation shifts offshore to the western Indian Ocean to lie over anomalously warm SSTs there.

In this work we have highlighted the significant changes in the teleconnections linking southern African rainfall variability to oceanic and atmospheric conditions. In particular, the most severe droughts affecting the region between 1950 and the 1970's were associated with regional oceanic-atmospheric anomalies, involving mainly the South-West Indian Ocean, whereas since the 1970's they are mostly related to ENSO events. A stronger relation to ENSO is also diagnosed through an overall correlation between rainfall variability over southern Africa and ENSO indices. Numerical experiments suggest that this enhanced relation to ENSO is linked to the long term evolution of the SST background, which is a part of the observed global warming trend.

We have shown that models significantly underestimate the *in situ* latent and sensible heat fluxes from the Agulhas Current because they are unable to represent adequately the 80-100 km wide core of the Agulhas Current or the sharp SST gradients associated with it. Because the core of the Agulhas Current is often obscured by persistent cloud cover, SST estimated by the Tropical Rainfall Measuring Mission (TRMM) is likely to be more accurate than that derived from AVHRR data.

We are starting to understand the physical mechanisms responsible for drought in southern Africa, the first step before producing accurate forecast of the rainy season with sufficient lead time. Little is yet known on the impact of the Southern Ocean on our rainfall or the effect of the Atlantic Ocean. We need to study the link between surface oceanic heat content anomalies and local or remote ocean atmosphere interaction processes in the oceans. Although SSTs have been shown to influence African rainfall variability, it is the heat content of the upper ocean that is more important for generating and sustaining atmospheric circulation patterns favourable or unfavourable to rainfall. Progress in ocean model and satellite remote sensing now will allow one to quantify the heat content of the ocean with a much better accuracy. We also need to extend the areas of study to the entire southern African region since circulation and moisture flux anomalies north of South Africa have a direct impact on the country's rainfall variability

We furthermore need to link these types of research projects more closely with international programmes such as CLIVAR (Climate Variability), GEWEX (Global Energy and Water cycle Experiment), GOOS (Global Ocean Observing System), PIRATA (Pilot Research moored Array in the Tropical Atlantic) and GODAE (Global Ocean Data Assimilation Experiment). This would be of decided benefit to the projects and to the mission of the WRC by involving greater numbers of foreign researchers at the cutting edge of this research.

Last, we need more direct observations, either with dedicated ship cruises or with ocean moorings. We therefore recommend the deployment of ATLAS moorings in the tropical and South-West Indian Ocean and in the tropical South-East Atlantic Ocean off Angola. ATLAS buoys can monitor, telemeter and thus help to understand the evolution of sea surface temperatures, upper ocean thermal and saline structures, the net heat budget, air-sea fluxes of momentum, latent and sensible heat and fresh water. Besides gaining much needed information on the physics of the seasonal cycle of SST and other key parameters, ATLAS moorings could also be used to monitor abnormal oceanic phenomenon upstream of the event thus providing an early warning system that could be beneficial to agriculture as well as fisheries.

8 Dissemination of knowledge

8.1 Peer rewieved papers in Journals

20 papers in peer rewieved international or national Journals.

Fauchereau N, S. Trzaska , M. Rouault , Y. Richard (2003) Rainfall Variability and Changes in Southern Africa during the 20th Century in the Global Warming Context, Natural Hazards, Volume 29, Issue 2, pp. 139-154

Florenchie, P., JRE Lutjeharms, C.J.C Reason, S. Masson and M. Rouault, Source of the Benguela Ninos in the Atlantic Ocean, *Geophysical Research Letter*, Vol. 30 No. 10 10.1029/2003GL017172

Rouault M, C. J. C. Reason, J.R.E. Lutjeharms and A. Beljaars (2003) NCEP Reanalysis and ECMWF operational model underestimation of latent and sensible heat fluxes above the Agulhas Current, Journal of Climate, 16, 776-782.

Rouault, M, P. Florenchie, N. Fauchereau, C. J. C. Reason (2003) South East Atlantic Warm Events And Southern African Rainfall. Geophysical Research Letter, 29, 13, 10.1029/2002GL014663.

Van Aken, H. M., A. K. van Veldhoven, C. Veth, W. P. M. de Ruijter, P. J. van Leeuwen, S. S. Drijfhout, C. P. Whittle and M. Rouault (2003) Observations of a young Agulhas ring, Astrid, during MARE in March 2000, Deep-Sea Research, 50, pp 167-195.

Majodina, M, M R Jury and M Rouault (2002) Ocean-Atmosphere Structure In the tropical Indian Ocean during a ship cruise 1995/1996. The Global Atmosphere and Ocean System, 8, 1-17.

Reason, C.J.C. and M. Rouault (2002) ENSO-like decadal variability and South African rainfall, Geophysical Research Letter, 29, 13, 10.1029/2002GL014663.

Reason, C.J.C. M. Rouault, J-L. Melice and D. Jagadheesha (2002) Interannual winter rainfall variability in SW South Africa and large scale ocean- atmosphere interactions. Meteorol. Atmos. Phys, 80, pp 19-29.

Rouault, M., S. A. White, C. J. C. Reason J. R. E. Lutjeharms and I. Jobard (2002) Influence of the Agulhas Current on a South African extreme weather event. Weather and Forecasting, 17, 655-669.

Roy, C., S. Weeks, M. Rouault, G. Nelson, R. Barlow and C. van der Lingen (2001) Extreme oceanographic events recorded in the Southern Benguela during the 1999–2000 summer season. South African Journal of Science, 97, 455-460.

Rouault, M., I. Jobard, S. A. White and J. R. E. Lutjeharms (2001). Studying rainfall events over South Africa and adjacent oceans using the TRMM satellite. South African Journal of Science, 97, 455-460.

Richard Y., Fauchereau, N, Poccard, I , Rouault, M. and Traska S (2001) XXth Century Droughts in Southern Africa Spatial and temporal variability, teleconnections with oceanic and atmospheric conditions. International Journal of Climatology. 21, 873-885.

Jury, M., H. Mulenga and H. Rautenbach (2000). Tropical Atlantic variability and Indo-Pacific ENSO: Statistical analysis and numerical simulation. The Global Atmosphere and Ocean System, 7(2):107-124

Richard Y., Trzaska S., Roucou P., Rouault M., (2000) : Modification of the Southern African rainfall variability /El Niño Southern Oscillation relationship. Climate Dynamics, 16, 886-895.

Rouault, M., A.M. Lee-Thorp and J.R.E. Lutjeharms (2000) Observations of the atmospheric boundary layer above the Agulhas Current during alongcurrent winds. Journal of Physical Oceanography, 30, 70-85

Rouault, M. and J.R.E. Lutjeharms (2000) Air-sea exchange over an Agulhas eddy at the Subtropical Convergence. The Global Atmosphere and Ocean System. 7, 125-150.

Reason, C. J. C. and H. M. Mulenga, (1999): Relationships between South African rainfall and SST anomalies in the South West Indian Ocean. Interml J. Climatol., 19, 1651-1673.

Lee-Thorp, A, M. Rouault, J.R.E. Lutjeharms (1999) Moisture uptake in the boundary layer above the Agulhas Current: a case study. Journal of Geophysical Research, 104, 1423-1430.

Jury, M., H. Mulenga and S. Mason (1999). Exploratory long-range models to estimate summer climate variability over Southern Africa. Journal of Climate, 12, 1892-1899

Lee-Thorp, A., M. Rouault and J.R.E. Lutjeharms (1998) Cumulus cloud formation above the Agulhas Current. South African Journal of Science, 94, 351-354.

8.2 Oral presentations

49 oral presentations in international or national workshops, conferences, symposium or seminars.

Rouault, M.: Why and where extend the Pilot Research Moored Array in the Tropical South East Atlantic. LEGI seminar, Grenoble, France, 16 April 2003.

Rouault, M.: Scientific rational for the South East extension of the Pilot Research Moored Array in the Tropical Atlantic. EGS Conference, Nice, France, 7/11 April 2003.

Rouault, M.: Scientific rational for the South East extension of the Pilot Research Moored Array in the Tropical Atlantic. LODYC seminar, Paris, France, 1 April 2003.

Rouault, M.: Deploying and recovering Atlas mooring, Report on participation to PIRATA FR-11 cruise (Dakar to Lome) 14 March 2003, SANCOR seminar, UCT, Cape Town.

Rouault, M.: Scientific rational for the South East extension of the Pilot Research Moored Array in the Tropical Atlantic. FUNCEME seminar, Fortaleza, Brazil, 15 February 2003.

Rouault, M.: Status of the South East extension of the Pilot Research Moored Array in the Tropical Atlantic. PIRATA 9 and South Atlantic CLIVAR workshops, 3/8 February 2003, Agra, Brazil.

Rouault, M., P. Florenchie, N. Fauchereau, C. J. C. Reason: South East Atlantic Warm Events And Southern African Rainfall. PIRATA 9 and South Atlantic CLIVAR workshops, 3/8 February 2003, Agra, Brazil.

Rouault, M.: Impact of cold and warm Atlantic Ocean events on Southern African Rainfall, a focus on 1997-2001, CLIVAR AFRICA workshop, 14-18 January 2003, Cape Town.

Rouault, M.: Status of the South East extension of the Pilot Research Moored Array in the Tropical Atlantic. January 2003, Cape Town.

Rouault, M, P. Florenchie, N. Fauchereau, C. J. C. Reason. 2002. South East Atlantic Warm Events And Southern African Rainfall, CRC seminar, Dijon, 20 November.

Rouault, M, P. Florenchie, N. Fauchereau, C. J. C. Reason. 2002. South East Atlantic Warm Events And Southern African Rainfall, LEGOS seminar, Toulouse, 6 November.

Rouault, M, P. Florenchie, N. Fauchereau, C. J. C. Reason. 2002. South East Atlantic Warm Events And Southern African Rainfall, Southern African Symposium of Atmospheric Sciences, Pretoria, 28-29 August 2002.

Rouault, M, Sea Surface Temperature measurement with TRMM satellite. Cape Town, Sancor Seminar, August 2002.

Rouault, M, P. Florenchie, N. Fauchereau, C. J. C. Reason. 2002. South East Atlantic Warm Events And Southern African Rainfall. Southern African Marine Science Symposium 2002, Swakopmund, Namibia, 1-5 July 2002.

Rouault, M and J. Servain. 2002. The PIRATA program and its potential southeast extension. Southern African Marine Science Symposium 2002, Swakopmund, Namibia, 1-5 July 2002.

Rouault, M. C.J.C. Reason. I. Jobard C.J. Reason. 2002. The Influence of the Agulhas Current On South African floods and tornadoes. Southern African Marine Science Symposium 2002, Swakopmund, Namibia, 1-5 July 2002.

Whittle, C. M. Rouault, A. van Veldhoven and J.R.E. Lutjeharms. 2002. A Study Of The Relationship Between Surface Cooling Of Agulhas Rings and the rate heat Loss to the overlying Atmosphere. Southern African Marine Science Symposium 2002, Swakopmund, Namibia, 1-5 July 2002.

Florenchie P, M. Rouault, J.R.E. Lutjeharms and C. Reason. 2002. Origin of warm events in the South East Atlantic ocean. Southern African Marine Science Symposium 2002, Swakopmund, Namibia, 1-5 July 2002.

Eric Machu, Mathieu Rouault and Véronique Garçon, 2002. Impact of the climatic variability on the Benguela ecosystem. Southern African Marine Science Symposium 2002, Swakopmund, Namibia, 1-5 July 2002.

Rouault, M, P. Florenchie, N. Fauchereau, C. J. C. Reason. 2002. South East Atlantic Warm Events And Southern African Rainfall. April 2002. SANCOR seminar Cape Town. SASAS Conference Cape Town.

Rouault, M., H. Mulenga and P Florenchie. 2001: Reasons for the extension of the Pilot Research Moored Array in the Tropical Atlantic Scientific to the South East. CLIVAR Meeting. 24-28 August Paris.

Rouault, M, 2001: Status of East Extension of the Pilot Research Moored Array in the Tropical Atlantic. PIRATA 8 Meeting. 24-28 August Paris.

Florenchie, M, P. Rouault, J.R.E Lutjeharms, C. J. C. Reason, 2001. Origin of Sea Surface Anomalies off South Western Africa, South African Society for Atmospheric Sciences, Cape Town, 6^{th}- 7^{th} September,

Mulenga, H.M (2001), Coupled Modes of Climate Variability over Southern Africa, South African Society for Atmospheric Sciences, Cape Town, 6^{th}- 7^{th} September, 2001.

Rouault, M., I. Jobard C.J. Reason and J.R.E. Lutjeharms. 2001. Influence Of Agulhas Current high latent heat fluxes on South African Weather. South African Society for Atmospheric Sciences, Cape Town, 6^{th}- 7^{th} September, 2001.

Rouault, M., I. Jobard C.J. Reason and J.R.E. Lutjeharms. 2001. Influence Of Agulhas Current high latent heat fluxes on South African Weather. GEWEX Conference. Paris 11-14 September 2001.

Rouault, M., I. Jobard C.J. Reason and J.R.E. Lutjeharms. 2001. Influence Of Agulhas Current high latent heat fluxes on South African Weather. Pre-print P. 2001 Climate Conference. Utrecht 20-24 September 2001

Van Veldhoven A.K., C. Veth, H. van Aken, C.P. Whittle and M. Rouault. 2001. Hydrographic observations during MARE, the Mixing of Agulhas Rings Experiment. Climate Conference. Utrecht 20-24 September 2001

Rouault, M., I. Jobard C.J. Reason and J.R.E. Lutjeharms. September 2001. Influence Of Agulhas Current high latent heat fluxes on South African Weather. LODYC seminar. Jussieu. Paris.

Rouault, M., C.J. Reason and J.R.E. Lutjeharms. 2001. Influence Of Agulhas Current high latent heat fluxes on South African Weather. Pre-print WCRP/SCOR Workshop on Intercomparison and Validation of Ocean-Atmosphere Flux Fields, May 21-24 2001, Potomac, MD. USA.

Mulenga, H and Rouault, M., Impact of ENSO on Southern Africa Tropospheric circulation. SASAS 2000 Conference, University of Pretoria, Pretoria, October 2000.

Rouault, M.: South East Extension of the Pilot Research Moored Array in the Tropical Atlantic. SASAS Conference, Pretoria, October 2000.

Rouault, M.: The Role Of The Agulhas Current on South African Weather. Workshop on African Climate Variability, Dijon, France, October 2000.

Mulenga, H, Modes of summer rainfall over southern Africa and the role of sea surface temperature and tropical circulation. Workshop on African Climate Variability, Dijon, France, October 2000.

White, S, Comparing the Agulhas Current Influence on two storms events. POADS Seminar, University of Cape Town, October, 2000.

Rouault, M., I. Jobard C.J. Reason and J.R.E. Lutjeharms. September 2000. Influence Of Agulhas Current high latent heat fluxes on South African Weather. LMD seminar. Ecole Polytechnique. Palaiseau.

Rouault, M.: South East Extension of the Pilot Research Moored Array in the Tropical Atlantic, SANCOR seminar, Cape Town, September 2000.

Rouault, M. 2000: South East Extension of the Pilot Research Moored Array in the Tropical Atlantic. PIRATA 7 Meeting and CLIVAR Atlantic meeting, Natal, Brazil, May 2000.

Rouault, M, 2000: SouthEast Extension of the Pilot Research Moored Array in the Tropical Atlantic. CLIVAR Meeting, Casablanca, Morocco, April 2000.

White, S, Couvreux, F, Rouault M, 1999: Satellite Remote Sensing of Rainfall over the Ocean South African Marine Science Symposium SAMSS 2000, Wilderness. Nov 22-26,1999.

Rouault, M and Lutjeharms, 1999: Air-sea Interaction above a warm eddy at the Subtropical Convergence. South African Marine Science Symposium SAMSS 2000, Wilderness. Nov 22-26,1999.

Rouault, M, Couvreux, F, White, S, Desbois M, Jobard L., Majodina M, Stuart F 1999 Meteosat and TRMM measurements of extreme weather during the South African 98/99 rainy season: A South African French Cooperative project. 15 Th Annual South African Society for Atmospheric Science Conference, Richards Bay, 18-19 November 1999

Rouault, M, Couvreux F, White, S, Desbois M, Jobard L 1999: TRMM measurements of extreme weather during the South African 98/99 rainy season. TRMM Global Precipitation Mission Meeting. October 25-29, 1999. University of Maryland.

Rouault, M. 1999: The Role Of The Oceans On South African rainfall, Journee Afrique du Sud, Centre de Recherche Climatologique, 16-17 September 1999.Universite de Dijon,

Rouault, M. 1999: The Weather of South African. Journee Afrique du Sud, Centre de recherche Climatologique, 16-17 September 1999, Universite de Dijon.

Rouault, M. 1999: Meteosat and TRMM measurements of extreme weather during the South African 98/99 rainy season: A South African French Cooperative project: Seminar at Laboratoire de Meteorology Dynamique, 24 September 1999, Paris, France.

Rouault, M. 1999: The role Of The Oceans On South African rainfall, Workshop on water issues, 5 - 9 July 1999, Pretoria, CSIR Conference Centre.

Rouault, M, M Desbois and J.R.E. Lutjeharms: 1998, Satellite remote sensing survey of the 98/99-summer rainfall season a French South African co-operative project, SASAS annual meeting Pretoria, October 28-29 1998.

9 Bibliography

Allan RJ, Lindesay JA, Parker D. 1996. *El-Nino Southern Oscillation and Climatic Variability*. CSIRO Publishing.
Bane J M Jr, 1989: Results From the Genesis of Atlantic Lows Experiment, Physical Oceanographic Studies: Introduction, *J. Geophys. Res*, 94, 10685.
Barclay JJ, Jury MR, Landman W.1993. Climatological and structural differences between wet and dry troughs over southern Africa in early summer. *Meteorology. Atmospheric Physcis* 51: 41-54.
Bigot S., Camberlin P., Moron V., Richard Y., Roucou P.: 1995, Modes of rainfall variability in tropical africa and their stability trough times. 21e Conference of the American Meteorological Society " Hurricanes and Tropical Meteorology ", Miami, Florida, 448-449.
Bigot S., Roucou P., Moron V.: 1994, Amélioration des données de précipitation en zone tropicale en vue de la validation des modèles atmosphériques de circulation générale: exemple de l'Amérique du sud et de l'Afrique. *Publications de l'Association Internationale de Climatologie*, 7, 421-431.
Bosart, L. F., and S.C. Lin, 1984: A diagnostic study of the President Day Storm of February 1979. *Mon Wea. Rev*, 112, 2148-2177.
Bouchet, O.: 1997, L'influence Climatique des aerosols (*in french*), *La Météorologie*, 8, 17, 11-22.
Camberlin P, Janicot S, Poccard I 2001. Seasonality and atmospheric dynamics of the teleconnection between African rainfall and tropical sea surface temperature : Atlantic vs. ENSO. *International Journal of Climatology*, 21, 973-1005
Cook K.C. 2000.The South Indian Convergence Zone and Interannual Rainfall Variability over Southern Africa. Journal of Climate , 13 , 3789-3804.
Cook K.C. 2001.A Southern Hemisphere Wave Response to ENSO with Implications for Southern Africa Precipitation., Journal of the Atmospheric Sciences, 58 , 2146-2162.
D'Abreton PC, Lindesay JA.1993. Water vapour transport over southern Africa during wet and dry late summer months. *International Journal of Climatology* 13:151-170.
Déqué M., Dreveton C., Braun A., Cariolle D.: 1994, The ARPEGE/IFS atmosphere model: a contribution to the French community climate modelling. *Clim. Dyn.*, 10, 249-266.
Dyson, L.L. and J. van Heerden : 2001, The heavy rainfall and floods over the northeastern interior of South Africa during February 2000. *South African Journal of Sciences*, 97, 80-86.
Folland C.K., Owen J., Ward N.M., Coleman A. : 1991, Prediction of Seasonal Rainfall in the Sahel Region Using Empirical and Dynamical Methods , *J. of Forecasting*, 10, 21-56.
Folland C.K., Parker D.E., Colman A.W., Washington R.: 1999, Large Scale modes of ocean surface Temperature since the late Ninteenth century, *in Beyond El Nino : Decadal and Interdecadal Climate Variability*, ed. A. Navarra, Springer-Verlag, pp.400
Fowler A.M., Hennessy K.J.: 1995, Potential impacts of global warming on the frequency and magnitude of heavy precipitation. *Natural Hazards*, 11, 283-303.
Friehe, C.A., Shaw, W.J., Rogers, D.P., Davidson, K.L., Large, W.G., Stage, S.A., Crescenti, G.H., Khalsa, S.J.S., Greenhut, G.K., and Li, F.: 1991, Air-sea fluxes and

surface layer turbulence around a sea surface temperature front, *J. Geophys. Res.* 96, 8593-8609.
Goddard, L. and Graham N.E., 1999. The importance of the Indian Ocean for GCM based climate forecasts over eastern and southern Africa. *Journal of Geophysics Research* 104: 19099-19116.
Harrison MSJ. 1984. A generalised classification of South African Summer rain bearing synoptic systems. *Journal of Climatology* 4: 547-560.
Harsch E.: 1992, Drought devastates Southern Africa. *Drought Network News*, 2, 17-19.
Hasselmann, K.: 1993, Optimal Fingerprints for the Detection of Time-dependent Climate Change, *Journal of Climate*. 6, 1957-1971.
Hegerl G.C., Von Storch H., Hasselmann, K, Santer, B.D., Cubash, U, Jones, P.D.: 1996, Detecting Greenhouse-Gas-Induced Climate Change with an Optimal Fingerprint Method, *Journal of Climate*, 9, 2281-2305.
Hewitson B.C.: 1997, A methodology for developing Regional Climate Change Scenarios from General Circulation Models. *WRC report No 594/1/97. 35p.*
Hulme M.: 1992a, A 1951-80 global land precipitation climatology for the evaluation of General Circulation Models, *Climate Dynamics*, 7, 57-72.
Hulme M.: 1992b, Rainfall changes in Africa: 1931-1960 to 1961-1990. *Int. J. of Climatol.*, 12, 685-699.
Hulme M.: 1996, Recent climatic changes in the World's drylands. *Geophysical Research Letters*, 23, 61-64.
Hulme, M., and co-authors: 1996, *Climate Change and Southern Africa, an exploration of some potential impacts and implications in the SADC region.* CRU/WWF, 104 p.
Janowiak JE. 1988. An investigation of interannual rainfall variability in Africa. *Journal of Climate* 1: 240-255.
Jones, P.D.: 1994, Hemispheric surface air temperature variations: a reanalysis and an update to 1993. *J. Climate*, 7, 1794-1802.
Joubert A.M.: 1997, Simulations by the atmospheric model intercomparison project of atmospheric circulation over Southern Africa. *International Journal of Climatology*, 17, 1129-1154.
Joubert A.M., Mason S.J., Galpin J.S.: 1996, Droughts over Southern Africa in a doubled-CO_2 climate. *International Journal of Climatology*, 16, 1149-1156.
Jury MR, McQueen CA, Levey KM. 1994. SOI and QBO signals in the African region. *Theoretical and Applied Climatology* 50: 103-115.
Jury MR, Mulenga H, Rautenback H. 2000. Tropical Atlantic Variability and Indo Pacific ENSO. Statistical analysis and numerical simulation. *The Global Atmospheric and Ocean system* 7: 107-124.
Kalnay E, and Coauthors. 1996. The NCEP/NCAR Reanalysis 40 year Project. *Bulletin of the American Meteorological Society* 77: 437-471.
Karoly, D.J, Vincent, D.G. 1998. Meteorology of the Southern Hemisphere, *Meteorological Monographs*, Vol 27, Number, 49, 410pp
Kawamura R. : 1994, A Rotated EOF Analysis of Global Sea Surface Temperature Variablity with Interannual and Interdecadal Scales , *J. Phys. Oceanogr.*, 24, 707-715.
Kiladis GN, Diaz HF. 1989. Global Climatic Anomalies Associated with Extremes in Southern Oscillation. *Journal of Climate* 2: 1069-1090.
Kiladis GN, Mo KC. 1998. Interannual and Intraseasonal Variability in Southern Hemisphere. *Meteorology of Southern Hemisphere*. American Meteorological Society. 307-336.

Kruger A.C. : 1999, The influence of the decadal-scale variability of summer rainfall on the impact of El-Nino and La Nina events in South Africa. , *International Journal of Climatology* , 19, 59-68

Landman WA, Mason SJ. 1999. Change in the association between Indian Ocean sea surface temperature and summer rainfall over South Africa and Namibia. *International Journal of Climatology* 19: 1477-1492.

Le Treut H., Forichon, M., Boucher, O. and Li, Z. X.: 1995, Equilibrium climate response to CO2 and sulfate aerosol forcings. In *Climate sensitivity to radiative perturbations : physcal mechanisms and their validation* , 267-280. H. Le Treut Ed., NATO ASI Series I, vol. 34.

Lee-Thorp, A.M. Rouault, and J. R. E. Lutjeharms, 1998a: Moisture uptake in the boundary layer above the Agulhas Current: a case study. *J. Geophys. Res.*, 104, 1423-1430.

Lee-Thorp A.M. Rouault, and J. R. E. Lutjeharms, 1998b: Cumulus cloud formation above the Agulhas Current. *S. Afr. J. Sci.*, 94, 351-354.

Lee-Thorp A and M. Rouault, 2000: Observations of cloud formation above Agulhas Current intrusions in the South-east Atlantic. *S. Afr. J. Sci.*

Lindesay JA. 1988. South African rainfall, the Southern Oscillation and a Southern Hemisphere semi-annual cycle, *Journal of Climatology* 8: 17-30.

Manabe S., Wetherald R.T., Stouffer R.J.: 1981, Summer dryness due to an increase of atmospheric CO2 concentration. *Climatic Change*, 3, 247-386.

Manabe S., Stouffer R.J.: 1994, Multiple-Century response of a Coupled Ocean-Atmosphere Model to an Increase of Atmospheric Carbon Dioxyde, *J.Climate*, 7, 5-23.

Mason S.J.: 1996, Climatic change over the Lowveld of South Africa. *Climatic Change*, 32, 35-54.

Mason SJ,Lindesay JA. 1993. A note on the modulation of Southern Oscillation-southern African rainfall associations with Quasi-Biennial Oscillation. *Journal of Geophysical Research* 97: 5847-5856.

Mason S.J., Joubert A.M.: 1997, Simulated changes in extremes rainfall over Southern Africa. *International Journal of Climatology*, 17, 291-301.

Mason S.J., Jury M.: 1997, Climatic variability and change over Southern Africa : a reflection on underlying processes, *Progress in Physical Geography*, 21, 23-50

Mason S.J., Waylen P.R., Mimmack G.M., Rajaratnam B. and Harrison J.M. : 1999, Changes in extreme rainfall events in South Africa. *Climatic Changes*, 41, 249-257.

Mestre, O., 2000: *Méthodes statistiques pour l'homogénéisation de longues séries climatiques*. Ph.D. Thesis (*in French*), Université Paul Sabatier, Toulouse, 225p.

Mitchell J.F.B., Johns T.C., Gregory J.M. and Tett, S.F.B.: 1995, Climate response to increasing levels of greenhouse gazes and sulfate aerosols, *Nature*, 376, 501-504.

Miron O, Tyson PD. 1984. Wet and dry conditions and pressure anomaly fields over outh Africa and adjacent oceans 1963-1979. *Monthly Weather Review* 112: 2127-2132.

Nicholson SE , Kim J. 1997. The relationship of the El-Nino Southern Oscillation to African rainfall. *International Journal of . Climatology* 17: 117-135.

Parker D.E., Jones P.D., Folland C.K., Bevan A.: 1994, Interdecadal changes of surface temperature since the late ninteenth century, *J. Geophys. Res.*, 99, 14,373-14,399.

Pittock A.B.: 1983, Recent climatic change in Australia: Implications for a CO_2-Warmed Earth. *Climatic Change*, 5, 321-340.

Pittock A.B., Salinger M.J.: 1991, Southern hemisphere climate scenarios. *Climatic Change*, 18, 205-222.

Preston-Whyte RA,Tyson PD. 1988. *The atmosphere and weather of Southern Africa*. Oxford University Press: Cape Town.
Rahmstorf S.: 1995, Multiple Convection Patterns and Thermohaline Flow in an Idealized OGCM, *J. Climate*, 8, 3028-3039
Rasmusson EM, Carpenter TH.1982. Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation /El-Nino. *Monthly Weather Review* 110: 354-384.
Reason CJC, Lutjeharms JRE. 1998. Variability of South Indian Ocean and implications for southern African rainfall. *South African Journal of Science* 94:115-123.
Reason CJC. 2001. Subtropical Indian Ocean SST dipole events and southern African rainfall. *Geophysical Research. Letters* 28:327-330.
Reason CJC, Allan RJ, Lindesay JA, Ansell TJ. 2000. ENSO and Climatic signals across the Indian Ocean basin in the global context . Part1 , Interannual Composite patterns. *International Journal of Climatology* 20: 1285-1327.
Reason CJC and Mulenga H. 1999. Relationships between South African rainfall and SST anomalies in the south west Indian ocean. *International Journal of Climatology* 19: 1651-1673.
Renfrew, I.A., G.W.K. Moore, P.S. Guest, and K. Burke, 2001: A comparison of surface-layer and surface turbulent-flux observations over the Labrador Sea with ECMWF analyses and NCEP reanalyses, *J. Phys.Oceanogr.*, in press.
Reynolds, R. W. and T. M. Smith, 1994: Improved global sea surface temperature analyses using optimum interpolation. *J.Climate*, 7, 929-948.
Richard Y, Trzaska S, Roucou P, Rouault M. 2000. Modification of the Southern African rainfall variability/ENSO relationship since late 1960's.*Climate Dynamics* 16: 883-895.
Richard Y., Fauchereau N., Poccard I., Rouault M. and Trzaska S.: 2001, XXth Century Droughts in Southern Africa - Spatial and temporal variability, teleconnections with oceanic and atmospheric conditions. *Int. J. Climatol.*, 21, 873-895
Richman M.B. :1986, « Rotation of Principal Components », J. of Climatol., 6, 293-335
Rocha A, Simmonds I. 1997. Interannual variability of south-eastern African summer rainfall. Part I. Relationships with air-sea interaction processes. *International Journal of Climatology* 17: 235-265.
Ropelewski C.F., Halpert M.S.: 1987, Global and regional scale precipitation and temperature patterns associated with El Niño/Southern Oscillation , *Mon. Wea. Rev.*, 115, 1606-1626
Ropelewski C.F., Halpert M.S.: 1989, Precipitation patterns associated with the high indices phase of the Southern Oscillation , *J. Climate*, 2, 268-284
Ropelewski C.F., Halpert M.S.: 1996, Quantifying Southern Oscillation -Precipitation relationships , *J. Climate*, 9, 1043-1059
Rouault, M., A. M. Lee-Thorp, I. Ansorge, and J. R. E. Lutjeharms, 1995: Agulhas Current air-sea exchange experiment. *S. Afr. J. Sci.*, 91, 493-496.
Rouault, M., A.M. Lee-Thorp. (1997). Fine-Time resolution measurements of atmospheric boundary layer properties between Cape Town and Marion Island. *S. Afr. J. Mar. Sci.*, 17, 281-296.
Rouault.M, A.M. Lee-Thorp, and J. R. E. Lutjeharms, 2000: Observations of the atmospheric boundary layer above the Agulhas Current during along current winds. *J. Phys. Oceanogr.*, 30, 70-85.

Shulze R., Meigh J. and Horan M.: 2001, Present and potential future vulnerability of eastern and southern Africa hydrology and water resources. *South African Journal of Sciences*, 97, 150-160.

Smakhtina O.: 1998, Historical changes in rainfall pattern in the Eastern Cape Province, South Africa. *Proceedings of the Abidjan'98 Conference held at Abidjan, Côte d'Ivoire, November 1998, IAHS Publ.* No. 252, 135-142.

South African Weather Bureau, 1972. District rainfall for South Africa and the annual march of rainfall over southern Africa. *South African Weather Bureau*, WB35: Pretoria.

Suppiah R., Hennessy K.J.: 1998, Trends in total rainfall, heavy rain events and number of dry days in Australia, 1910-1990. *International Journal of Climatology*, 10, 1141-1164.

Timmermann A., Oberhuber J., Bacher A., Esch M., Latif M., Roeckner E.: 1999, Increased El Niño frequency in a climate forced by future greenhouse warming. *Nature*, 398, 694-697

Trenberth, K.E., Hoar, T.J.: 1996, The 1990-1995 El Niño – Southern Oscillation event : longest on record. *Geophysical Research Letters*, 23,1,57-60.

Trenberth, K.E., Hoar, T.J.: 1997, El Niño and Climate Change. *Geophysical Research Letters*, 24, 23, 3057-3060.

Trenberth KE, Guillemot CJ, 1998. Evaluation of the atmospheric moisture and hydrological cycle in the NCEP/NCAR reanalyses. *Climate Dynamics*, 14, 213-231

Trzaska S., Moron V., Fontaine B.: 1996, Global Atmospheric response to specific linear combinations of the main SST modes. Part 1: numerical experiments and preliminary results. *Ann. Geophysicae*, 14, 1066-1077.

Tyson P.D.: 1981, Atmospheric circulation variations and the occurence of extended wet and dry spells over southern Africa. *J. of Climatol.*, 1, 115-130.

Tyson P.D.: 1991, Climatic change in southern Africa: past and present conditions and possible future scenarios. *Climatic Change*, 18, 241-258.

Vogel CH.: 1994, (Mis)management of droughts in South Africa: past, present, future. *South African Journal of Science*, 90, 4-5.

Walker N.D.: 1990, Links between South African summer rainfall and temperature variability of the Agulhas and Benguela system. *J. Geophys. Res.*, 95 (C3), 3297-3319.

Wang X.L., Ropelewski C.F.: 1995, An assessment of ENSO-Scale secular variability , J. Climate, 8, 1594-1599.

Weaver, A.J, Aura, S.M. and, Myers, P.G.: 1994, Interdecadal Variabilty in an Idealized model of the North Atlantic , *J. Geophys. Res.*, 99, C6, 12423-12441.

Slonosky, V.C., Jones, P.D. and Davies, T.D.: 1999, Homogenization techniques for European monthly mean surface pressure series, *Journal of Climate*, 12, 2658-2672.

Xue, H., J.M. Bane Jr. and L.M. Goodman, 1995: Modification of the Gulf Stream through strong air-sea interaction in winter: Observations and Numerical Simulations. *J. Phys. Oceanogr.*, 25, 533-557.

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