

**Atmospheric Circulation and Sea Surface
Temperature Anomalies During the Dry
Summers of 2001/02, 2002/03 and 2003/04
in Southern Africa**

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Contents

<u>Chapters</u>	<u>Pages</u>
Abbreviations	ii
Abstract	1
1. Introduction	2
2. Atmospheric Circulation over Southern Africa	6
2.1. Mean Circulation Patterns	6
2.2. Rainfall Producing Circulation Systems	11
2.3. Circulation Patterns during wet and dry conditions	16
3. Rainfall Variability and Sea surface Temperature (SST)	17
4. Data and Methods	20
5. Rainfall	24
6. Circulation Anomalies	33
7. Sea Surface Temperature	55
8. Discussions and Conclusions	62
Acknowledgement	66
Reference	67

Abbreviations

AVHRR = Advanced Very High Resolution Radiometer

CDC = Climate Diagnostic Center

COADS = Consolidated Ocean Atmospheric Dataset

CRU = Climatic Research Unit

DJF = December to February

ENSO = El Niño/ Southern Oscillation

FAO = Food and Agricultural Organization

GCM = General Circulation Model

GPCP = Global Precipitation Climate Project

IOCZ = Inter Ocean Convergence Zone

IRI = International Research Institute

ITCZ = Inter Tropical Convergence Zone

JFM = January to March

JJA = June to August

NCAR = National Center for Atmospheric Research

NCEP = National Center for Environmental Prediction

NH = Northern Hemisphere

OND = October to December

QBO = Quasi-Biennial Oscillation

SH = Southern Hemisphere

SOI = Southern Oscillation Index

SST = Sea Surface Temperature

ZAB = Zaire Air Boundary

1. Introduction

Drought is a phenomenon associated with the lack or shortage of water. It means less than normal or no water is available. It primarily originates from lack of precipitation. Lack of precipitation leads to depletion of storage of I. soil moisture that results in dry land crop failure and dying-off grazing and other vegetations, II. of ground water, which results in drying up of springs, streams and boreholes and III. of water in man-made reservoirs, which results in stress to households, industry, power stations and irrigation schemes (Davis, 1983). There are three types of drought (Thomas, 1965): meteorological, agricultural and hydrological droughts. Meteorological drought occurs when the rainfall is abnormally low. Agricultural drought exists when the soil is depleted to the extent that crop harvests are reduced significantly (Davis, 1983). Agricultural drought has a common time scale of a season (3 to 6 months) (Harsch E, 1992). Agricultural drought can also be caused by excessive rain or flood leading to a damage of crops. Hydrological drought is associated with scarcity of precipitation on a longer time scale (1- 2 years or more) and its effect is on ground water supply (Meigh et al, 1992). Meteorological drought can be seen as a subset of agricultural drought. If there is agricultural drought then there is also meteorological drought. On the other hand, agricultural and hydrological drought can be out of phase, each having different signatures (Rouault and Richard, 2003).

The impacts of drought in general are social, environmental and economic. Its impacts on society include food insecurity, increased quest for water, reduced sustainability of marginal lands and decreased grazing quality and crop yields. The associated effects of these impacts are famine, malnutrition, illness, migration, conflict between water users, poverty, unemployment, social unrest and distrust. The impact of drought on environment is reflected in reduced forest, diminished crop and range land fertility, reduced water resources and soil productivity, increased soil erosion and sandstorm leading to degradation of landscape quality. The economy of a nation also suffers from drought. Food and energy shortage result in drastic price increase of food items and expensive imports. Farmers tend to sell their livestock at a reduced market price. Drought

impacts depend on their intensity, duration as well as upon once country infrastructure and preparation upon having early warning systems (National Drought Mitigation Center, 2003).

Southern Africa is a predominantly semi-arid region (Tyson, 1986). Drought is a regular and recurrent feature of the South African climate, and it is one of the most important natural disasters in the subcontinent (Unganai LS, 1994)). Extended dry periods look like to be the rule for the region (Rouault and Richard, 2003). The region has experienced meteorological, agricultural and hydrological droughts in the past. Rainfall in the region is the element of climate most critical in its effects on land use and economic development (Zucchini et al., 1992). The economies of most southern African nations are dependent on rain-fed agriculture. The rainfall regime in the subcontinent is of complex type. The main rainy season is the austral summer (October to March), except in the southwestern and southern coastal areas, which receive rain during the Southern Hemisphere (SH) winter and year round respectively. The late summer season (January to March) rainfall accounts for more than 40% of the annual amount for the summer rainfall regions of the subcontinent (Richard et al., 2001). Within the summer rainfall regions, there are temporal and spatial differences of rainfall with different areas having different timing of maximum rainfall (Rouault and Richard, 2003). Though Southern African rainfall does not look to show signs of any trend of aridity or abrupt shift during the 20th Century (Tyson, 1986; Hulme, 1992; Richard et al., 2001) predominantly dry conditions have persisted from early 1980s to the mid 1990s (Mason and Jury, 1997).

Southern Africa was struck by drought, low rainfall, during the summer seasons of 2001/02, 2002/03 and 2003/04. Rainfall during the first three months of the rainy season (October to December 2001) of 2001/02 was within normal ranges through out much of the region. However, during the late summer (January to March, 2002) dry periods extended across large sections of the region, particularly from southern Zimbabwe eastwards into southern Mozambique. These dry periods resulted in crop failures, limited production and an intense famine that killed hundreds of people in Malawi, Zambia and Zimbabwe. The government of Zimbabwe declared a state of

disaster on 3 April 2002 due to drought related food security issues. A report by Southern Africa Development Community (SADC) in June 2002 concluded that 14.4 million people in six countries in southern Africa including Lesotho, Malawi, Mozambique, Swaziland, Zambia and Zimbabwe were threatened by food shortages. The food shortages were partly the result of the drought during the 2001/02 rainy season, and previously diminished food stocks due to flood damage to crops the year before. Heavy rainfall and flooding in early 2001 reduced the food stocks available in 2002 (IRI Climate Information Digest, 2004).

In the summer of 2002/03, much of the region received below normal rainfall for a second year in a row. The amount of October – January accumulated rainfall in Maputo, Mozambique was the lowest since at least 1951/52. The dry conditions killed at least about 35,000 head cattle in the southern Zimbabwe in the first three months of 2003. Heavy rains, produced by remnants of a tropical cyclone Japhet in the early days of March, fell over central and southern Mozambique, parts of Zimbabwe and Zambia. However, they came too late in the season to help crops, which had already been damaged by the dry weather. A FAO report by the beginning of year 2003 indicated that of the approximately 40 million people in need of food, at that time, in sub-Saharan Africa about 16.7 million were from southern Africa (IRI Climate Information Digest, 2004).

The first half of the 2003/04 rainy season produced below normal rainfall through out most of the region except in western areas of Zambia and Zimbabwe, parts of Namibia, Botswana and central south Africa. The poor rainfall either stunted or killed crops normally planted at that time. Because of the dry conditions and low soil moisture early in the growing season, the total corn area planted in South Africa was estimated to be the smallest since the 1942/43 season and the yield estimates were below average. South African President Thabo Mbeki declared six provinces (KwaZulu-Natal, Northern Cape, Free State, Mpumalanga, North West and Eastern Cape) disaster areas on mid of January 2004 due to the dry conditions. Good rainfall in February and March 2004 allowed late planted crops including Maize, the staple crop in the region, to grow

over much of the region, and also permitted some drought resistant crops such as Cassava, sweet potatoes, cowpeas to recover (IRI Climate Information Digest, 2004).

The regional food shortages during these recent droughts were exacerbated by a variety of factors, which differ from country to country, including drought and food damage to crops, foreign exchange shortages, government mismanagement, the impact of HIV/AIDS and deteriorating economic situation in the region (U.S. Agency for International Development, 2002).

The purpose of this study is to identify and describe the atmospheric and sea surface temperature anomalies that are possibly associated with the droughts of summer 2001/02, 2002/03 and 2003/04 in Southern Africa. The hypotheses put forward in this study are: during the dry periods, there were atmospheric circulation and sea surface temperature anomalies (particularly related to ENSO), which, most of them, have been previously identified as unfavorable for rainfall in the subcontinent. The paper has four sections. The first section (Chapter 2 and 3) gives an overview (literature review) of the general pattern of atmospheric and oceanic conditions in relation to precipitation in the summer rainfall region. The data for the rainfall, and atmospheric and oceanic variables and the methods used to analyze them are discussed in Chapter 4. Section three (Chapters 5, 6 and 7) consists the outcome of the analyses with some selected plots of those variables and their discussions. The last section (Chapter 8) summarizes and concludes the results and discussions.

2. Atmospheric Circulation over Southern Africa

2.1. Mean Circulation Patterns

Southern Africa, located in the subtropics, is affected by circulation patterns present in the tropics, subtropics and temperate latitudes. In the tropics, the Inter Tropical Convergence Zone (ITCZ) migrates from Northern Hemisphere (NH) to the Southern Hemisphere (SH) from winter (July) to summer (January). The ITCZ is a planetary scale of pronounced convective activity that arises from convergence of tropical easterly flows (Preston-Whyte, and Tyson, 1987). In the African continent and western Indian Ocean the ITCZ shifts by approximately 30-degree latitude seasonally due to Indian Monsoon wind reversals (Figure 2.1) (Walker, 1989). During the austral summer north of about 25°S three major low-level airstreams are involved along the ITCZ. The northeast monsoon air of east Africa interacts with the deep tropical easterlies from southwest Indian Ocean and with the cyclonically recurved South Atlantic air along the ITCZ. Further west, the tropical easterlies from the Indian Ocean converge with the South Atlantic air along the Zaire Air Boundary (ZAB) sometimes called the Inter Ocean Convergence Zone (IOCZ) (Preston-Whyte, and Tyson, 1987; Walker, 1989; Taljaard, 1996). Closed tropical lows and troughs form within these convergence zones. Their position is a major factor in governing the location of air masses convergence and the resulting precipitation (Taljaard, 1996). They are linked to a weak heat low centered over the central interior of South Africa through a trough across the northern cape. Viewed on annual or seasonal basis the ITCZ/ZAB appear as structures with well-defined regions of steady convergence and ascent. On day-to-day basis, however, the mean convective regions are made up of propagating smaller scale disturbances with lifespan measured in days (Preston-Whyte, and Tyson, 1987). These tropical disturbances interact with the temperate disturbances resulting in important consequences for weather of the subcontinent. During winter the ITCZ migrates to the northern hemisphere and an anticyclone flow prevails over the region.

The subtropical control comes from the South Atlantic Ocean and Indian Ocean anticyclones. These semi-stationary anticyclones undergo latitudinal and longitudinal displacement through out the year. The anticyclone of the Atlantic Ocean makes semi annual oscillations both latitudinally

and longitudinally. The Indian Ocean high undergoes semi annual and annual variations in latitudinal and longitudinal movements respectively. On average the south Atlantic anticyclone is about 3° further north than its Indian counterpart with both cells moving $5-6^{\circ}$ north ward in winter.

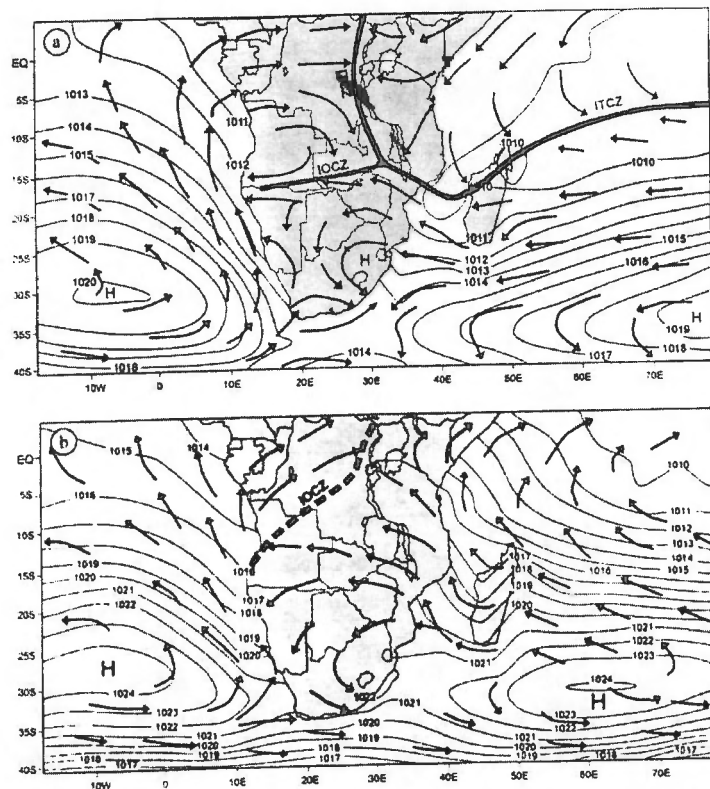


Figure 2.1. Mean sea level pressure (hpa) over the sea and mean flow lines on the sea and land for (a) summer (DJF) and (b) winter (JJA). The thick (broken) lines in summer show the ITCZ and ZAB/IOCZ (after Heerden and Taljaard, 1998).

The annual longitudinal swing of the Atlantic high is of the order of 7 to 13° and don't essentially affect the weather of the subcontinent. On the scale of days, however, the Atlantic high may ridge eastwards and to the south of the subcontinent. Extended ridging leads to a break off a separate high-pressure cell that moves eastward to finally merge with the Indian high and it affects the weather of South Africa and southern Mozambique through its passage. The seasonal east-west shifts of the high in the Indian Ocean (up to 24°) have important effects on summer and winter

weather of the eastern parts of Southern Africa (Preston-Whyte, and Tyson, 1987). The atmospheric variability over the subtropics of the Indian Ocean is higher than over similar latitudes of the South Atlantic both intra-seasonally (McGee and Hatsenrath, 1966) and interannually (Dyer, 1981). The subtropical highs are highly influenced by the positions, intensities and speeds of the middle latitude cyclones, as well as by the behavior of the middle and upper tropospheric westerly waves at the subtropical latitudes (Taljaard, 1996).

The control from the south of the subcontinent comes from the wave perturbations in the circumpolar westerly airflows. The large tropospheric circumpolar vortex of the westerly winds is the dominant feature of the general circulation in the middle latitudes in all seasons. It reaches its maximum at the upper troposphere. The wave disturbances in the westerlies include barotropic, lower number, large-scale, semi stationary, forced waves and the baroclinic, higher number, short wave length, transient, free Rossby Waves (Preston-Whyte, and Tyson, 1987). On a day-to-day basis, from four to eight traveling waves may occur in the westerlies controlling daily weather in the middle latitudes. These high frequency transient eddies with periods of less than two weeks govern at large the total variance and covariance field of geopotential height, kinetic energy and mean eddy momentum flux. Much of the low frequency atmospheric variability in mid latitudes is accredited to changes in either the frequency or the location of these transient disturbances (Preston-Whyte, and Tyson, 1987). They shift further towards the pole in the summer in association with the pole ward displacement of the subtropical anticyclones and subtropical jet streams. (Look at Figures 2.2 and 2.3 for the mean circulation patterns in the lower (850hpa), middle (500hpa) and upper (200hpa) troposphere over the region during summer).

The mean upper tropospheric circulation of the atmosphere over the subcontinent is anticyclonic through out the year. In winter the mean anticyclone intensifies and moves northward and upper level circumpolar westerlies spread out and displace the upper tropical easterlies equator ward (Preston-Whyte, and Tyson, 1987). At 500hpa the subtropical high-pressure belts encircle the SH along about 20°S , and at 200hpa they appear at 15°S over southern Africa.

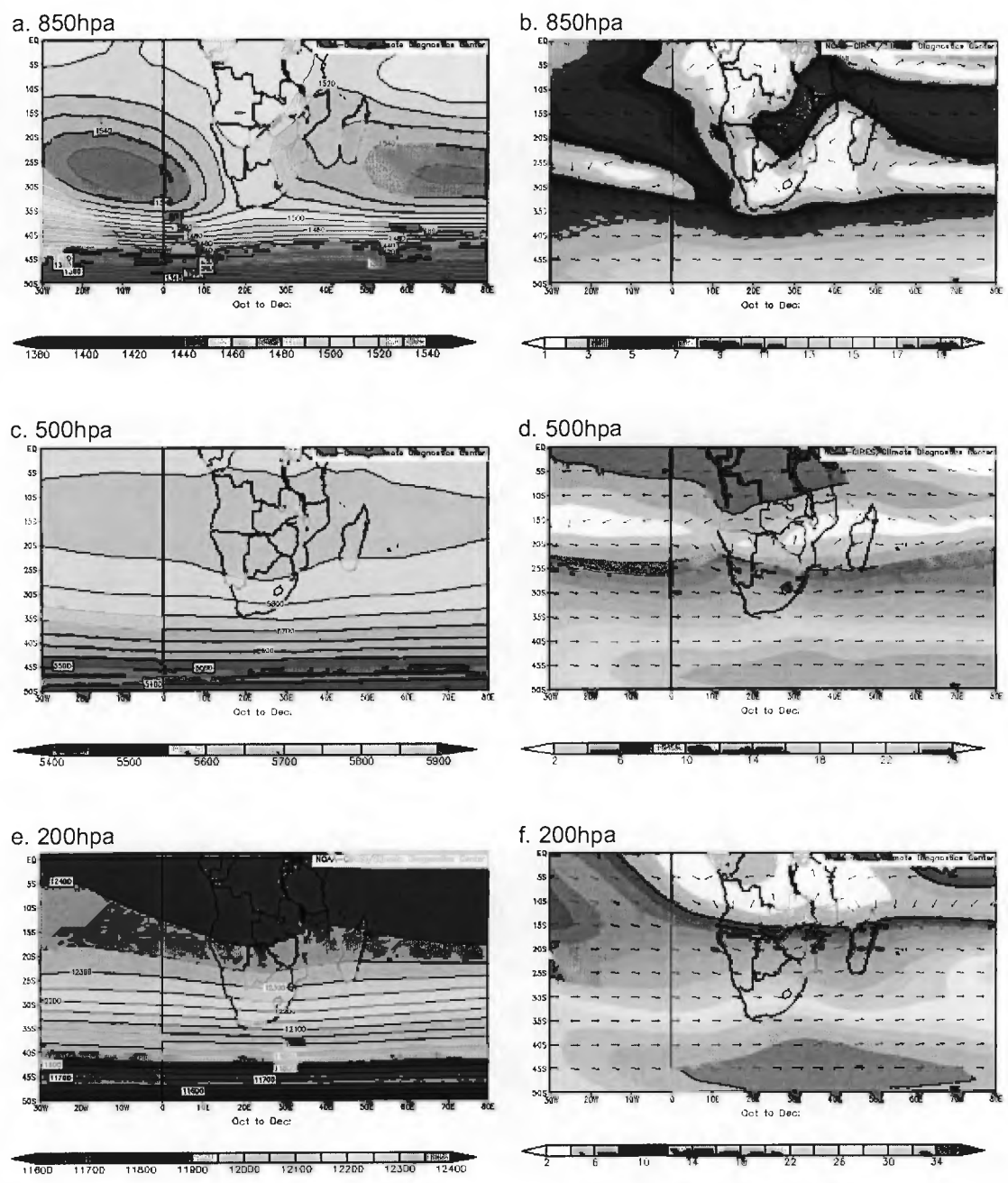
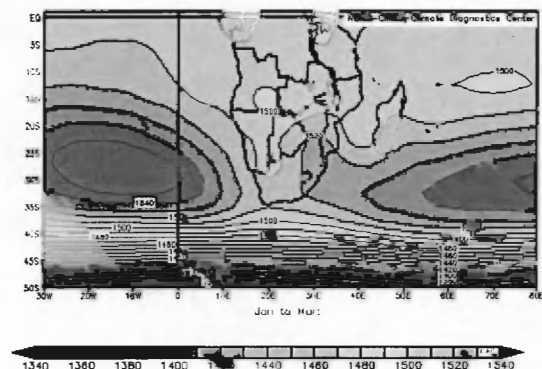


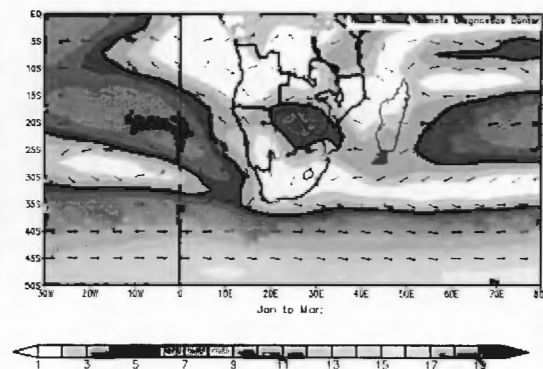
Figure 2.2 Mean geopotential heights (left; interval = 10gpm at the 850hpa and 50gpm at the 500 and 200hpa) and vector winds (right; interval = 1ms⁻¹ at the 850hpa and 2ms⁻¹ at the 500 and 200hpa) for the early summer (OND), plotted from the NCEP/NCAR Reanalysis data (1968-1996) using the CDC website¹.

¹ Note: Refer to the chapter 4 for the description of the NCEP/NCAR Reanalysis data and the CDC website¹.

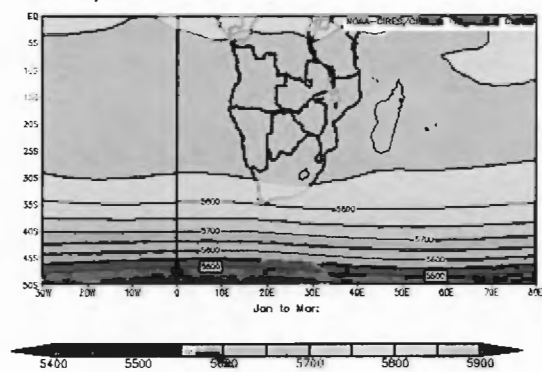
a. 850hpa



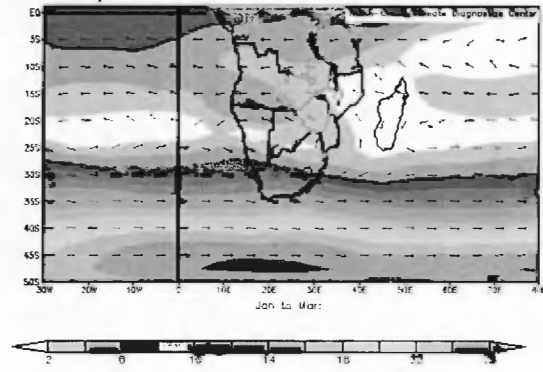
b. 850hpa



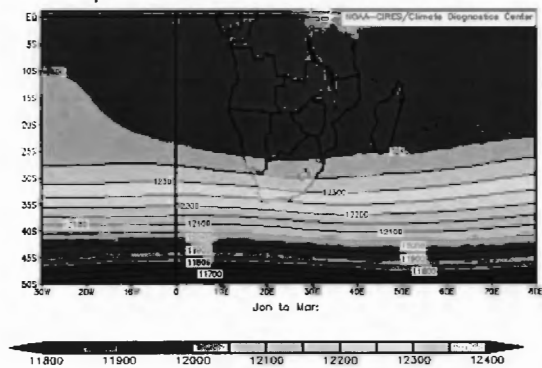
c. 500hpa



d. 500hpa



e. 200hpa



f. 200hpa

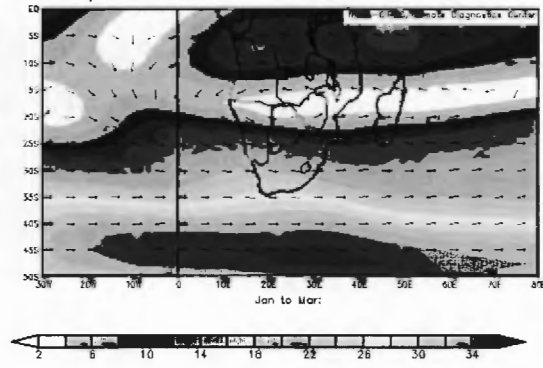


Figure 2.3 Mean geopotential heights (left; interval = 10gpm at the 850hpa and 50gpm at the 500 and 200hpa) and vector winds (right; interval = 1ms^{-1} at the 850hpa and 2ms^{-1} at the 500 and 200hpa) for the late summer (JFM), plotted from the NCEP/NCAR Reanalysis data (1968-1996) using the CDC website.

2.2. Rainfall Producing Circulation Systems

Tropical southern Africa gets its rain in summer from three types of low-pressure systems. These are: the tropical cyclones, heat lows and tropical lows (Van Heerden and Taljaard, 1998). Tropical cyclones develop along or close south of the ITCZ in the Indian Ocean in summer. They migrate westwards and finally southwards, mostly east of Madagascar and about a third cross the Island. Very few develop on the Mozambique Channel. When they seldom approach the land (region) on shore southeasterly winds produce cloud and variable amounts of rain. Whenever they reach the coast or move inland across Mozambique, North East South Africa, Malawi, Zimbabwe, Zambia and Botswana, they produce torrential rain, but they rapidly weaken and become tropical lows or easterly waves. The heat lows are generally shallow systems caused by relatively high temperatures in the lowest few kilometers. They are common in the meeting ground of the northeast and southwest monsoon over Southern Angola and Northern Botswana. Tropical lows or easterly troughs move at variable speeds mostly westward, along the ITCZ/ZAB trough at 15°S. The slow moving weak troughs associated with convergence and deeper than normal cloud masses evidently produce most of the rain. Weak to moderate tropical lows occur much more frequently in the Mozambique Channel and to the east of Madagascar along the ITCZ. Occasionally the ITCZ/ZAB is displaced southwards by the northerly flow east of the tropical lows which normally travel westward and from which troughs extend southward across Zimbabwe and Botswana towards South Africa (Van Heerden and Taljaard, 1998). It appears like there is no clear-cut distinction among the three low-pressure systems. They are interlinked, and one system can develop (or supply energy) to the other system.

The 15° to 20°S belt can be taken as the dividing zone between the tropical and subtropical southern Africa (Van Heerden and Taljaard, 1998). Several classification schemes have been developed for the systems that produce rain over the subtropical southern Africa, especially for South Africa (Harrison, 1986; Tyson, 1986; Diab et. al., 1991; Taljaard, 1996) based on surface and upper tropospheric pressure and circulation systems. The circulation patterns that produce rain during summer are the southward extending tropical easterly troughs mentioned above,

westerly troughs, cold fronts, ridging highs, cut-off lows, blocking highs and tropical cyclones cited previously (Taljaard, 1996). These individual systems vary in intensity and details of the pressure distribution as well as in the humidity and stability of the air masses involved. Therefore the associated rainfall varies appreciably in amount and distribution.

1. The Southward extending Tropical Easterly Troughs or Lows (V-shaped trough or Angola-Botswana low)

The tropical easterly troughs or lows are usually associated with ITCZ/ZAB and the warm humid easterly winds between the zones and the subtropical high-pressure belts (Preston-Whyte, and Tyson, 1987). They are either V or U shaped usually centered over Botswana between the well-defined anticyclones on their eastern and western sides (Van Heerden and Taljaard, 1998). They have a characteristics structure consisting of relatively cool but very humid air in the surface to 700hpa (Taljaard, 1996). Their temperature increases starting from 600hpa. They are weakly developed at 500hpa and are generally absent in the upper troposphere, where high pressure develops due to the their increased and as a result higher temperature than the temperature of their surroundings. Thus low-level convergence occurs to the east of the trough while at 500hpa or above the flow is divergent. The consequence is strong uplift that may sustain rainfall in the absence of pronounced instability. With the presence of unstable air good rains may occur over a wide areas to the east of the trough (Preston-Whyte, and Tyson, 1987). These tropical disturbances are almost exclusively a summer phenomenon and with high frequency between December and February. Their annual cycle does much to control the summer rainfall over the interior parts of southern Africa.

2. The Westerly Troughs

The westerly troughs are part of the baroclinic westerly waves of the circumpolar vortex previously reviewed. They reach down to the plateau level south of about 28°S in summer. The amplitudes of the westerly waves decrease northwards, so that at 20°S and more so at 15°S they hardly exist any more, and at progressively greater heights at 15° to 25°S they are replaced by

the tropical easterlies (Taljaard, 1996). They are tilted westward with height. Conservation of absolute vorticity and changing radius of curvature in the wave produce convergence to the rear of the troughs and divergence ahead of the troughs. Hence the westward slopes of the westerly wave with height creates coincident surface convergence and upper air divergence providing ideal conditions for sustained and gentle uplift of air resulting in formation of clouds and precipitation (Preston-Whyte, and Tyson, 1987).

3. The Cold Fronts

Cold fronts occur together with westerly waves, depressions and cut off lows. Many cold fronts brush past the land. They are associated with distinctive bands of clouds that may stretch far in land. Most of the precipitation along the south coast in post trough and postfrontal southwesterlies are only light to moderate showers. They occur most frequently in winter when the amplitude of westerly disturbance is greatest. They are accordingly much less effective in producing precipitation over the land in summer than in winter (Preston-Whyte, and Tyson, 1987; Taljaard, 1996). There is difference between the waves of the subtropical latitudes (westerly troughs) and those associated with cold fronts of the middle and high latitudes. The later normally move at greater speeds so that they often overtake and merge with the westerly troughs mentioned above. There are suggestions that cold fronts induce the subtropical troughs to intensify and accelerate eastwards (Van Heerden and Taljaard, 1998).

Tropical-Temperate Troughs

Tropical-temperate troughs develop when a temperate westerly wave trough or the cold front is coupled to the tropical U or V shaped low through the subtropical trough creating the well-known northwest to southeast extending cloud bands (Mason and Jury, 1997; Todd and Washington, 1999; Todd, Washington and Palmer, 2004). These cloud bands form hundred kilometers ahead of the upper westerly trough and along the western boundaries of the upper anticyclone. The upper anticyclone is formed as discussed previously due to a latent heat release in the convective cloud towers in the middle and upper troposphere associated with the surface tropical low along

the ITCZ/ZAB (Van Heerden and Taljaard, 1998). The elongated cloud bands are the major source of rainfall for the subcontinent having more incidences in the late summer (Mason and Jury, 1997; Todd and Washington, 1999; Todd, Washington and Palmer, 2004). Truncated troughs, which are possibly more common than the elongated troughs, develop when the temperate link is absent (Mason and Jury, 1997).

4. The Cut-Off Lows

Cut-off lows are cold-cored depressions, which start as a trough in the upper westerlies, and deepen into a closed circulation extending downwards to the surface (Preston-Whyte, and Tyson, 1987, Taljaard, 1996). They are displaced equator ward out of the basic westerly flow and they affect rainfall as far as 15°S. They are baroclinic systems sloping to the west with height and are associated with strong convergence and vertical motion, particularly while they are deepening. They produce rain all year round with peak frequencies during the transition seasons (Taljaard, 1996). They commonly form in conjunction with a ridging high to the south of the subcontinent and provide an onshore flow of warm and humid air from Agulhas Current to the eastern escarpment (Triegaardt et al., 1988).

5. The Ridging Highs

Ridging highs develop from the south Atlantic subtropical anticyclone extending to the south of the subcontinent, where they then separate and form closed anticyclones in the western Indian Ocean and extend to the northeastern part of the subcontinent before they join the Indian Ocean anticyclone (Taljaard, 1996). They are preceded by a coastal pressure minimum and this creates a steep pressure gradient between the Indian Ocean and adjacent inland areas promoting strong advection of moist, unstable air over the land. When they are associated with upper divergence due to the westerly wave at 500hpa produce widespread general rainfall over the eastern parts of Southern Africa.

6. The Blocking Highs or Long Wave Ridges

Blocking highs are occasional strong warm cored high-pressure systems that develop 10 to 15 degrees pole ward of the axis of the subtropical high-pressure belt and they tend to become stationary or slow moving. Above normal pressure and temperature south of the land due to the existence of the blocking highs and at the same time below normal pressure and temperature over the southern part of the west coast is favorable for rain over the South Africa and its northern neighbors (Taljaard, 1996).

7. Tropical cyclones

Tropical cyclones produce rain as discussed in previously. However, there is contrasting effect of these cyclones on rainfall of the region. When they are slow moving and centered on Madagascar or eastern Mozambique Channel, deep southerly flow with associated subsidence sets in over the subcontinent causing dry hot conditions (Taljaard, 1996). They also tend to be more frequent during El Nino - Southern Oscillation (ENSO) years.

2.3. Circulation Patterns during wet and dry conditions

Rainfall variability in southern Africa is caused by changes in the position, frequency, duration, speed and intensity of those rain-producing systems (Harrison, 1983; Taljaard, 1989). Moreover, total rainfall volume from those individual systems depend upon the availability of the atmospheric moisture, atmospheric stability and the strength of the upper level divergence (Harrison, 1988).

When tropical convergence zones lie further north and weaken rainfall over much of the subcontinent decreases and are often offset by increased rainfall over east Africa (Ogallo, 1988). Over the east coast and southwestern Indian Ocean there is evidence for a reversal of a Walker cell between wet and dry years, which would indicate the presence of a convective 'dipole' (Jury, 1992; Jury et al., 1994). A deep anticyclone cell with subsiding air over southern Madagascar is associated with wet summers in southern Africa (Materira, 1990; Jury and Pathack, 1993). Dry summers are dominated by a decrease of convection over the subcontinent compensated by increase to the east of Madagascar (Jury and Pathack, 1993; Jury et al., 1992). During the dry years the Indian Ocean anticyclone is typically weaker than normal so that the northeasterly inflow, which is important source of atmospheric moisture, over the east coast diminishes (Mason and Jury, 1997). Higher geopotential heights over the subcontinent indicate weaker tropical and subtropical troughs during dry years and allow the prevalence of the temperate circulations through out the summer season (Taljaard, 1989; Mulenga et al, 2003), which move anomalously further north (Tyson, 1986). The westerlies in the upper troposphere at 30° – 40°S decreases markedly during wet conditions, while they are anomalously stronger during dry conditions (Triegaardt and Landman, 1995). Increased westerly flow in the mid latitudes favors more frontal systems over southwestern South Africa and advection of cool and dry air from the south or southwest over the northern of South Africa, during dry periods. The weakening of upper level easterlies over tropical southern Africa reduces the frequency and growth rate of tropical disturbances that are needed to promote the source of the cloud bands over the region (Mulenga et al., 2003).

3. Rainfall Variability and Sea surface Temperature (SST)

The control of the ocean on atmospheric (rainfall) variability mainly comes from the ocean's high heat capacity, hence, its ability to store and gradually redistribute heat; and through fluxes of moisture and momentum. The link of the ocean and the atmosphere has many feedback mechanisms, as a result the surface of the ocean exhibits warm and cold temperatures anomalies that are superimposed on observed climatologically SST. The SST fluctuations are usually random and small in scale, but occasionally show considerable order, where vast areas exhibit prolonged SST anomalies (Tennant, 1996). SST anomalies notably in tropical areas can force adjustments in atmospheric circulation leading to changes in balance of continental and marine rainfall. A number of researches have identified the relationship between global and regional SSTs and southern Africa rainfall through statistical and numerical general circulation model (GCM) simulations (Jury, 1995).

Southern Africa rainfall variability is linked with ENSO. ENSO driven warm SST in the Pacific Ocean is connected to drought over southern Africa through atmospheric teleconnections via the propagation of Rossby wave like features. These Rossby wave like features originate from the upper level convergence over the tropical eastern Indian Ocean – Indonesia and propagate ENSO signals southwestwards across the Indian Ocean to impact on Southern Africa (Cook, 2000). During warm ENSO events dry conditions generally occur over much of the region, with strong influence in the southeastern part of the subcontinent and north east of South Africa. ENSO influence has preferred location of the tropical temperate troughs, which is indicated by the sizeable correlation of the Southern Oscillation Index (SOI) and rainfall in the northwest to southeast band across South Africa (Mason and Jury, 1997). However, above average rains are some times experienced during warm ENSO events (Mulenga et al., 2003). Different hypothesis attribute the high rainfall during El Nino events to the Quasi-Biennial Oscillation (QBO), the 18-20 years Quasi Periodic Rainfall Oscillation and SST conditions in the Agulhas Current system (Mason and Tyson, 1992; Jury et al., 1994). SSTs of the Agulhas system have negative

association with ENSO. During warm (cold) ENSO, when rainfall over southern Africa is anomalously low (high), warmer SSTs in the Agulhas region tend to enhance (diminish) rainfall over the subcontinent (Jury and Pathack, 1991; Jury, Valentine and Lutjeharms, 1993; Mason, 1995).

Interannual rainfall variability over subcontinent is not only linked to SST patterns in the remote eastern Pacific Ocean, but it is also associated to the SSTs of the surrounding Indian and Atlantic Oceans. High SSTs in the Mozambique Channel, Agulhas Current and Agulhas retroflection region (Agulhas System) are linked to above average precipitation over the summer rainfall region by strengthening the tropical- temperate troughs, as result of anomalous high sensible and latent heat fluxes into both the tropical easterly inflow and temperate systems forming to the south of the country. Higher SST anomalies to the north of Madagascar and in the central equatorial Indian Ocean are frequently associated with dry conditions in the region (Walker, 1989; Mason 1995, Reason and Mulenga, 1999). They encourage the development of tropical easterly disturbances over the western equatorial Indian Ocean than over the sub-continental interior resulting in dry conditions over the land (Jury et al., 1992). They have strongest correlation with the spring rainfall of the region (Jury, 1995).

Mason (1995) studied in detail the relationship of the SSTs in the South Atlantic and Indian Ocean with the rainfall of the region using principal component analysis. He found 8 principal components, which together explain 75% of the SST variability over the period 1910 – 1989. These areas (principal components) in the order of decreasing variability are the Benguela system, Agulhas system, north-east Brazil coast, western Equatorial Indian Ocean, Central South Atlantic Ocean, south-east Brazil Coast (Brazil Current system), Indian Ocean south east of South Africa, and South Atlantic subtropical convergence region. However, only the SST variability in some of these areas has significant effect on the rainfall of the region. Regions of SST variability that have statistically significant effect on the summer rainfall areas are the central south Atlantic Ocean, South Atlantic subtropical convergence region, western equatorial Indian

Ocean, Agulhas system and the Indian Ocean to the south east of south Africa (Mason, 1995). Atmospheric response to changes in SST in these regions is not always consistent possibly due to the modulating effect exerted by the QBO (Mason et al, 1994). Landman and Mason (1999) have pointed out the instabilities in the association between the SSTs and southern African Rainfall. The remaining principal components or regions have no significant correlation with the rainfall of the region. Anomalous warming in the Indian Ocean to the south east of South Africa is linked with an eastward shift of the locus of the most frequent upper level wave troughs such that the summer rainfall region becomes drier to the west of the upper trough, consequent upon enhanced divergence and subsidence of air on the trailing flank of the trough. Warming of the central South Atlantic Ocean changes the pattern of South Atlantic anticyclone or the baroclinic westerly wave configurations to produce drought conditions in the subcontinent. High SST in the South Atlantic convergence region is associated with enhanced rainfall over the summer rainfall region through structuring and modification of baroclinic westerly waves (Mason et al, 1994).

4. Data and Methods

Rainfall

In this study the focus was on the summer rainfall areas of the subcontinent, struck by drought on the summers of 2001/02, 2002/03 and 2003/04. A rainfall index for the region was computed from the Global Precipitation Climate Project (GPCP) (Huffman et al., 1997) and Climatic Research Unit (CRU) datasets (New et al., 2000). The GPCP dataset provides estimates of gridded monthly mean precipitation data on $2.5^\circ \times 2.5^\circ$ latitude and longitude. The dataset is a multiple analysis incorporating precipitation estimates from low-orbit satellite microwave data, geosynchronous-orbit satellite infrared data and rain gauge observations from more than 6000 stations. The combination method was designed to use the strengths of each data type objectively to produce merged global monthly precipitation fields that are superior to any of the individual datasets (Huffman et al., 1997). The dataset coverage spans from 1979 till the present and it is planned to continue until the year 2005. The GPCP dataset has limitations due to a) its coarse spatial resolution that can not resolve the topographic details of areas in the region b) its short period coverage making it difficult to compare the droughts of the years of interest with the pre 1979 droughts and c) New et al., (2000) has noted some problems in the GPCP interpolation techniques. Hence, in order to see its reliability for the region, the GPCP dataset was compared with the high spatial resolution CRU New monthly precipitation dataset. The CRU New dataset consists of $0.5^\circ \times 0.5^\circ$ latitude-longitude gridded monthly precipitation data entirely derived from observed station data for the period of 1901 to 1998 (New et al., 2000). Comparisons of the two datasets for the domain were made for their joint periods (1979/80-1997/98). Whole summer season's (October to March) rainfall averages and normalized anomalies were used for contrasting the two datasets. It is less important which division of summer (early, late or whole summer seasons) one chooses to compare the two datasets, since the purpose is to look at the closeness of the rainfall values, for the same geographic areas, from the two methods.

The rainfall index was calculated for the rectangular box shown in Figure 4.1. The box was chosen after that of Richard et al. (2000; 2001). Richard et al. (2000) had put forward a synthetic Southern African Rainfall Index based on the interannual rainfall variability, which was achieved through principal component analysis of monthly rainfall data. However, few changes were made to their index. This study unlike Richard et al.'s (2000; 2001) it included the Southern Interior and KwaZulu-Natal of South Africa defined as homogenous rainfall Areas 4 and 7 respectively, based on a cluster analysis of South African rainfall (South African Weather Bureau, 1972). In doing so it also included a small portion of the western Indian Ocean. The geographic regions determined by the box were delimited by 15° to 33° S latitudes and 20° to 35° E longitudes. The box included districts from southern Zambia, Zimbabwe, southern half of Mozambique, extreme areas of southeastern Angola and northeastern Namibia, Botswana, Lesotho and South Africa excluding the winter and all year round rainfall regimes (Figure 4.1).

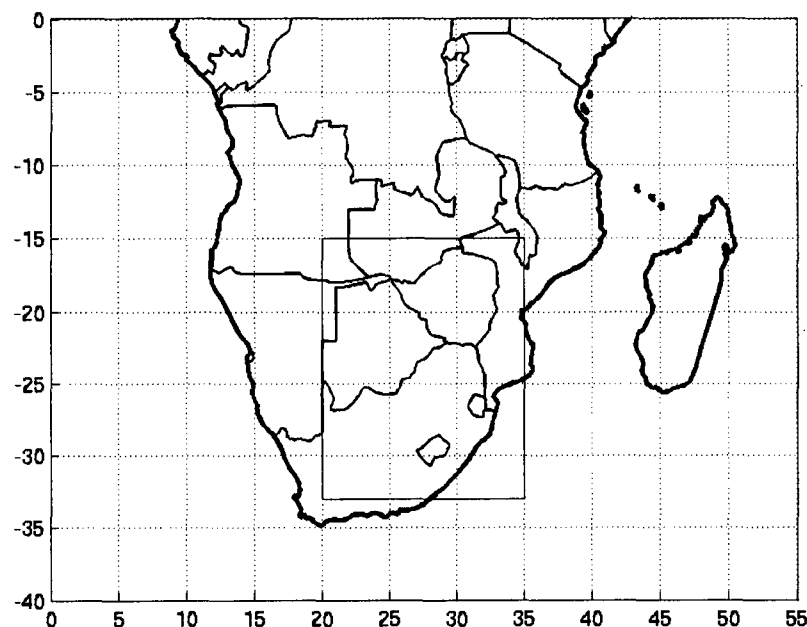


Figure 4.1 Map of southern Africa with the rectangular box indicated.

Mean monthly rainfall data from 1979 to the year 2004 (until March) were extracted for the box (the region) from the GPCP dataset. The data were then area averaged to form the box rainfall

index for the early (October to December, OND), late (January to March, JFM) and whole (October to March) summer season, and a normalized rainfall anomaly of each division of the summer was plotted. The normalized rainfall anomaly was computed by dividing the difference of the rainfall value from the climatology (mean) of 1979-2004 by a standard deviation. The summer rainfall season of the subcontinent is divided into early and late summer according to the major atmospheric circulation patterns. There is more control from the mid-latitude circulation during the early summer, while during the late summer the circulation is of more tropical nature (D'aberton and Lindesay, 1993). The areas within the box receive their maximum rainfall during the late summer sub season. In order to look at the spatial distribution of the rainfall over the region, GPCP precipitation anomaly for each month was plotted using the Climate Diagnostic Center (CDC) Monthly/Seasonal Climate Composites website (<http://www.cdc.noaa.gov/cgi-bin/Composites/printpage.pl>). The area covered, by each plot, is Greenwich Meridian to 80°E between the equator and 40°S. All these plots were based on the 1979-2000 climatology.

Atmospheric Circulation Patterns

The circulation anomalies possibly associated with the droughts were examined using the National Center for Environmental Prediction - National Center for Atmospheric Research (NCEP-NCAR) Reanalysis Project dataset (Kalnay et al., 1996). The NCEP-NCAR Reanalysis dataset consists of daily and monthly gridded data of many atmospheric parameters on 2.5° latitude by 2.5° longitude of horizontal resolution with around 28 vertical levels. The dataset is derived by merging observations and model results based on the NCEP global operation model. The observational data comprises of global rawinsonde data, the Consolidated Ocean Atmospheric Dataset (COADS) surface marine data, aircraft data, surface land synoptic data, special sounding microwave/imager surface wind speeds, satellite cloud drift winds and satellite sounder data. The dataset is available from 1948 till the present. In this study, monthly anomalies of pressure (geopotential heights) and wind have been chosen at lower (850hpa), middle (500hpa) and upper (200hpa) levels based on the 1968-1998 climatology. Plots of these atmospheric variables were made using the CDC Monthly/Seasonal Climate Composites website (<http://www.cdc.noaa.gov/cgi->

[bin/Composites/printpage.pl](#)). Each plot covers 30^oW to 80^oE between the equator and 50^oS. Although all plots of the pressure and wind anomalies for the three levels and for each month have been presented, only selected plots, which possibly show the main causes of the observed weather for each month, have been described and discussed in the result section.

Sea Surface Temperature (SST)

In this study, monthly 1^o latitude-longitude grid spatial resolution Reynolds Optimum Interpolation (OI) version (v)-2 sea surface temperature (SST) analysis dataset was used to look at the SST anomalies in the world oceans with possible linkage to the droughts. This dataset is constructed from observations from ships, moored and drifted buoys, and from the Advanced Very High Resolution Radiometer (AVHRR) satellite data (Reynolds et al., 2002). The Reynolds OI v2 SST dataset is consistent with other SST products, though they exhibit monthly differences of greater than 5^oC in the mid and high latitude Southern Oceans as well as in the very dynamic western boundary currents. These areas exhibit very high gradient to be properly resolved on a 1^o grid, and, hence, the SST conditions in these areas should be looked at with caution. The KNMI Climate Explore website (<http://www.knmi.nl/~oldenbor>) was used to plot the SST anomalies. This site gives the opportunity to explore different oceanographic and climatic datasets and the relationship among them. In addition to looking at the SST, the Southern Oscillation Index (SOI) is used to see the development of ENSO. The SOI is a sea level pressure difference between Tahiti and Darwin found in the Pacific Ocean. Positive (high phase) SOI denotes cold ENSO (La Niña) while negative (low phase) SOI indicates warm ENSO (El Niño) conditions. The link between the SST anomalies in the oceans surrounding the subcontinent and the rainfall of the region has been discussed in the light of the findings from previous studies of the association between the two. The relationships between the rainfall of the region and SSTs of adjacent and remote oceans have been reviewed in the previous chapter.

5. Rainfall

The GPCP and CRU datasets had similar average summer rainfall estimates for the region (Figure 5.1). The GPCP values were higher than the CRU values for all summer years except for 1996/97 and 1997/8. The mean difference between the rainfall estimates of the two datasets was 0.271 mm/day. This deviation between the rainfall values of the two datasets was statistically insignificant at the 95% confidence level (students t-test for independent sample means of GPCP = 2.94 and CRU = 2.68, t-value = -1.62, $p = 0.11 > 0.05$, degree of freedom = 36). The corresponding normalized rainfall anomalies of both datasets also had comparable estimates (Figure 5.2).

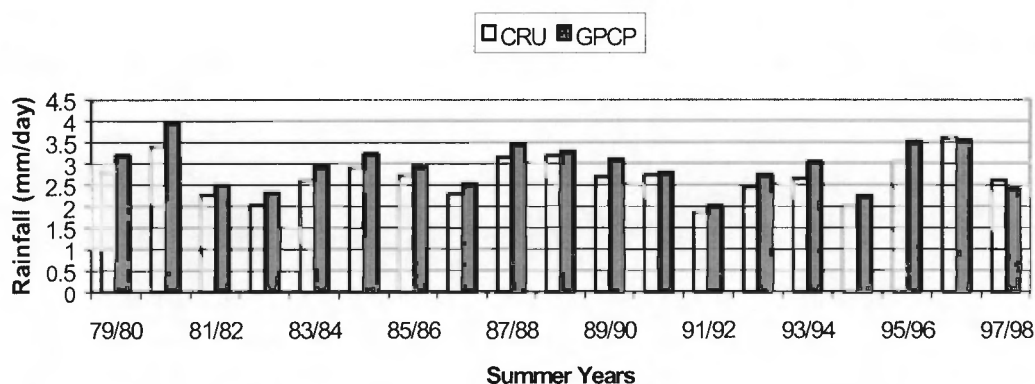


Figure 5.1 Time series of CRU (white) and GPCP (dark) average summer (October – March) rainfall for the region (box).

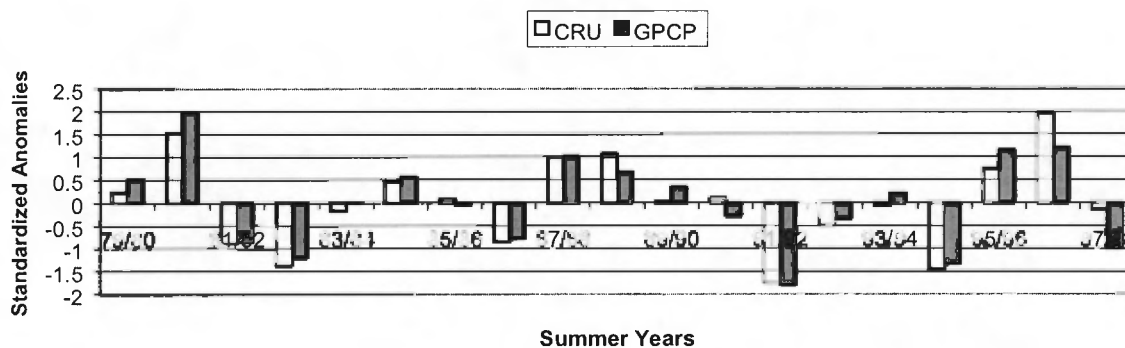


Figure 5.2 Time series of normalized CRU (white) and GPCP (dark) summer (October to March) rainfall anomaly for the region.

This close match between the datasets made the usage of GPCP data reliable in describing the rainfall patterns in the region. Figures 5.2 and 5.3, of the normalized rainfall anomalies using the GPCP data, precisely denote the dry and wet years experienced in the region in the past 25 years. It needs to be noted, however, that the box of the geographical areas covers a small portion of the western Indian Ocean, which the CRU data has no values for. This little discrepancy might partly explain the difference between the values of the two data sets.

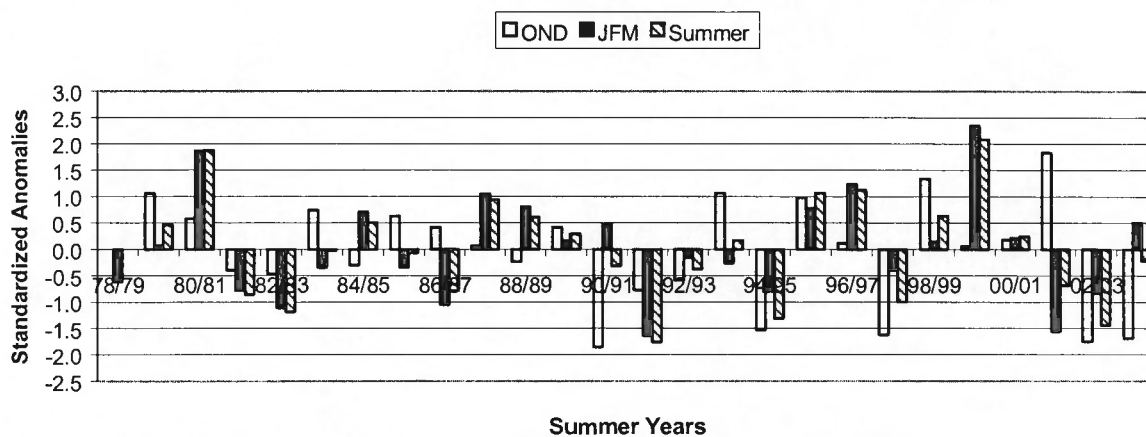


Figure 5.3 Time series of normalized GPCP rainfall anomaly for the region for the early (OND, white), late (JFM, dark) and entire (October – March, striped) summer.

As in Mulenga et al. (2003) the dry years were defined as significantly dry for those for which the normalized rainfall anomaly was less than or equal to -0.5 and greater than -1 ; and as extremely dry for those for which the rainfall was equal to or below 1 standard deviation from the mean. According to these definitions the region had experienced extreme drought in the following summer (October to March) years: 1982/83, 1991/92, 1994/95, 1997/98, and 2002/03; and in 1981/82, 1986/87, and 2001/02 it had significantly dry rainy seasons (Figure 5.3). The summers of 1982/83, 1986/87, 1991/92, 1994/95, 1997/98, and 2002/03 were together with ENSO years. The region had extremely dry early summer (OND) seasons in the following years: 1990, 1994, 1997, 2002 and 2003, and in the late summer (JFM) seasons of 1983, 1987, 1992 and 2002 (Figure 5.3). When one looks further at figure 5.3, there were contrasting rainfall patterns between the early and late summer seasons during certain years. As in the 2001/02 summer

there was above average rainfall during early summer followed by dry late summer in 1983/84, 1985/86, 1986/87, and 1993/94. And as in the summer of 2003/04, there was below average rainfall in the early summer followed by enhanced rainfall during the late summer in 1984/85, 1990/91, and 1988/89.

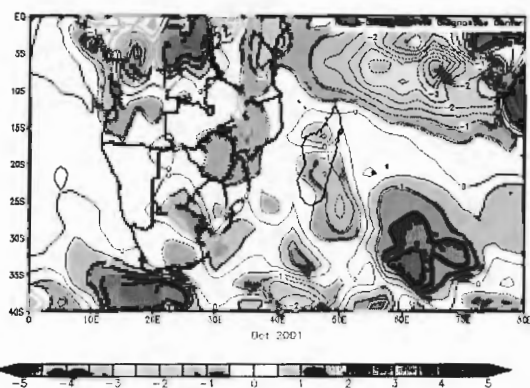
Having seen the recent droughts in relation to previous ones, the focus in the next part will be on the spatial extent and distribution of these droughts over the region. GPCP precipitation plots of each month have been shown and described. This approach would show areas that were most affected by the drought.

2001/02-Summer

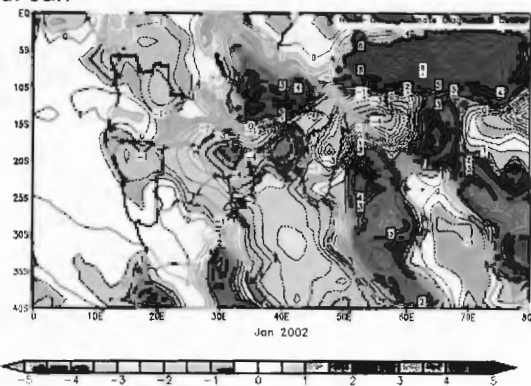
Early summer (October to December, 2001)

During the beginning of this summer season (Figure 5.4a) the southern African region received close to normal rainfall except Central Interior and KwaZulu-Natal of South Africa and southern Botswana, which received above average rainfall. October, as the start of the rainy season for the subcontinent has little impact as a rainy month for some areas especially for the northern section of the region (Taljaard, 1989). In November (Figure 5.4b) much of the subcontinent experienced very wet conditions. The region had witnessed the biggest precipitation for November in this year of all other years beginning from 1979. This very high rainfall however didn't continue accordingly in December (Figure 5.4c), it rather shifted into the western Indian Ocean. Throughout December the rainfall was normal on most parts of the subcontinent with only western Zimbabwe, southern Mozambique and small parts of the Central Interior of South Africa receiving above average rainfall. When the precipitation is combined for the early summer months, the subcontinent had a wet sub season (Figures 5.3). The region had the wettest early summer season of all the years for which the GPCP data applies. Meanwhile, the southeastern of the African continent was hit by drought. Previous studies have found out that the region on one hand and southeastern Africa (Ogallo, 1988) and equatorial Indian Ocean (Jury et al., 1992) on the other hand have opposite rainfall trends.

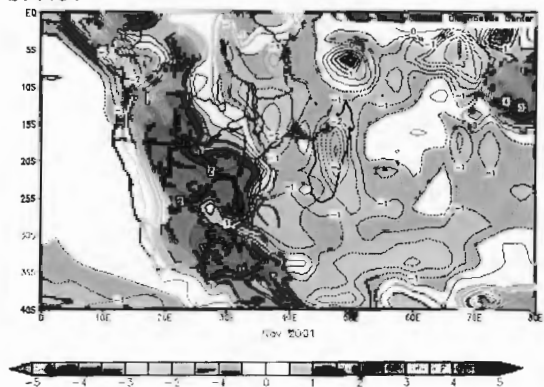
a. Oct



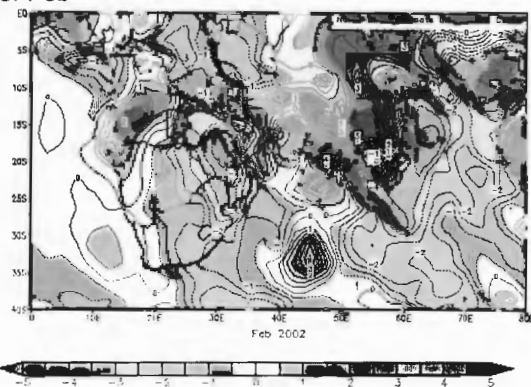
d. Jan



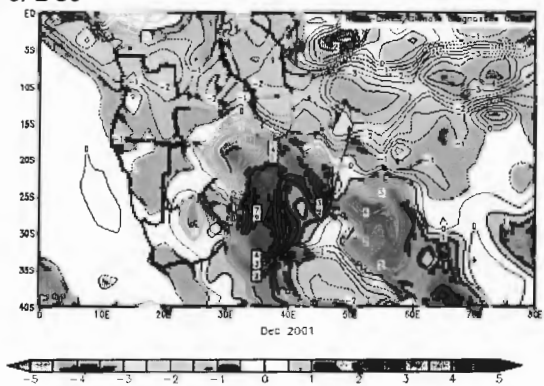
b. Nov



e. Feb



c. Dec



f. Mar

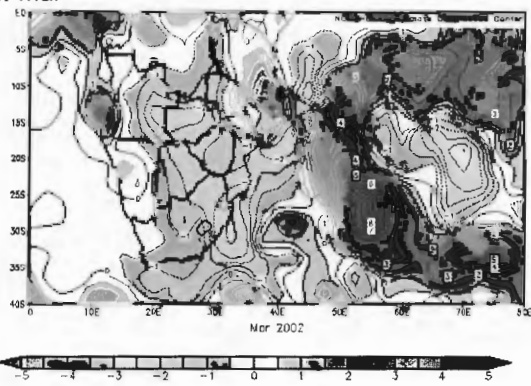


Figure 5.4 GPCP composite precipitation (mm/day) anomaly for early (left) and late (right) summer months of 2001/02¹.

¹ **Note:** All plots of GPCP precipitation (mm/day) were based on 1979-2000 climatology and plotted using the CDC website.

Late summer (January to March, 2002)

In January (Figure 5.4d), conditions started to change that the region experienced below average rainfall, with the exception of normal conditions over the southwestern part of Botswana, parts of South Africa (Western Interior, Central Interior and KwaZulu-Natal), and Lesotho. The negative rainfall anomalies were particularly very high in Zimbabwe and the southern half of Mozambique. Meanwhile, there was above average rainfall to the east of Madagascar over the Indian Ocean as well as in the equatorial Indian Ocean, extending into tropical southeastern Africa, into the northern parts of Malawi and Mozambique. In February (Figure 5.4e) and March (Figure 5.4f) the drought extended into the whole subtropical southern Africa. The region had experienced the driest March and second driest JFM (the driest JFM being that of 1992) in this year of all the last 25 summer seasons (Figure 5.3). These negative rainfall anomalies in the region were compensated by above average rainfall along the longitudinal axis of the western Indian Ocean.

During the 2001/02 summer as a whole, central Zambia, southern Malawi and Mozambique, Zimbabwe, Swaziland, the eastern half of Botswana, and the North-Eastern Interior of South Africa had dry rainy season, whilst in the western Indian Ocean to the east of Madagascar wet conditions were prevailing.

2002/03 Summer**Early Summer (October to December, 2002)**

In the start of the 2002/03 rainy season (Figure 5.5a), much of South Africa and Swaziland had below average rainfall while there was above normal rainfall across Zimbabwe and Mozambique. In November (Figure 5.5b) the dry conditions stretched towards north over much of Botswana and Mozambique and the southern parts of Zimbabwe, Zambia and Malawi. During December (Figure 5.5c) the unusually dry conditions were further northward over the whole Zimbabwe and Zambia, much of Mozambique and Malawi, southern Angola, Northern Namibia, while the central part of South Africa and southern Botswana experienced slightly above average precipitation. Figure 5.3 indicates that the region had one of the extremely dry early summer seasons during

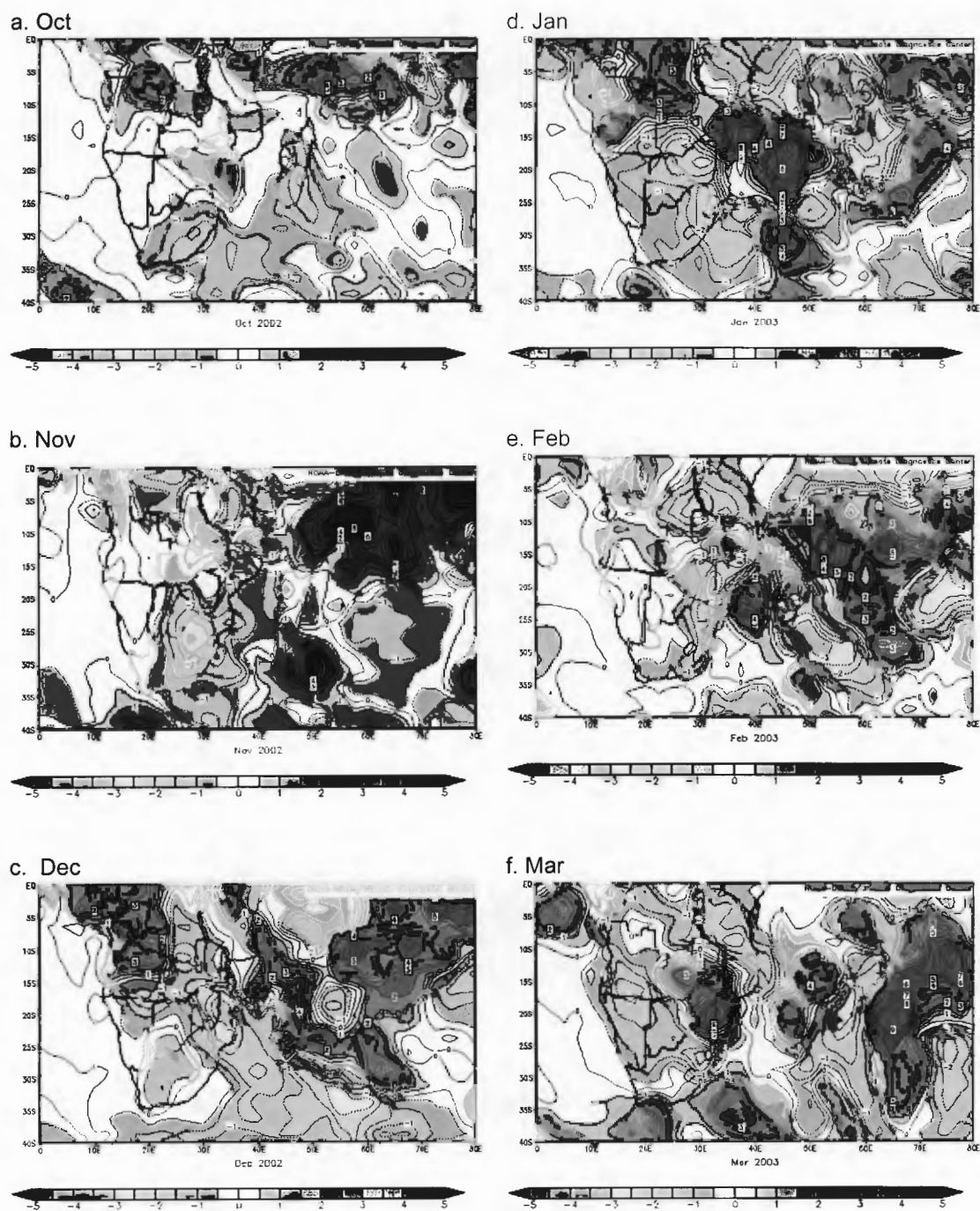


Figure 5.5 GPCP composite precipitation (mm/day) anomaly for early (left) and late (right) summer months of 2002/03.

this period, with KwaZulu-Natal and North-Eastern Interior in South Africa, Lesotho, Swaziland and the southern most of Mozambique being the most affected areas.

Late summer (January to March, 2003)

The unusually dry conditions in the region, observed in the early summer continued to dominate in January (Figure 5.5d) and they were severe in areas along which the tropical temperate-trough often extends. In February (Figure 5.5e) the dry conditions eased on the western side of the region with much of Zambia and Botswana and central South Africa receiving close to normal rainfall. Meanwhile the drought persisted on the eastern section of the region in Zimbabwe, Mozambique, Swaziland and the eastern parts of South Africa. On the other hand, during both January and February there was enhanced rainfall in parts of Malawi, northern Mozambique, Mozambique Channel and parts of the Indian Ocean to the north east of Madagascar. During March (Figure 5.5f), above average rainfall, due to a tropical cyclone JAPHET that occurred in the beginning of the month brought some relief over much of Mozambique, Zambia and the whole of Zimbabwe. The rest of southern Africa, however, largely remained dry and continued to accumulate precipitation deficits. There was below average precipitation during the peak of the wet season (January to March, 2003; Figure 5.3) in general, with Botswana and much of South Africa being the most affected areas. The above average precipitation that occurred in March in some parts of the region had a large contribution to the rainfall total. However, in an agricultural point of view, it didn't save those areas from the effects of the drought they experienced from October to February.

The 2002/03 summer was much drier than the previous one. The region had unusually very low rainfall both in the early and late summer seasons compared to the summer of 2001/02.

2003/04 Summer

Early Summer (October to December, 2003)

In the beginning of the early summer of 2003/04 (Figure 5.6a) there were dry conditions over much of South Africa, Lesotho and Swaziland, while over much of Zimbabwe and small part of Mozambique there were wet conditions. During November (Figure 5.6b) dry conditions were observed over western Zambia, the eastern half of Botswana, and much of Zimbabwe, South Africa, Lesotho and Swaziland. In December the drought persisted and intensified, and covered much of the region (Figure 5.6c). The region did not have a good start of the rainy season with Swaziland, Lesotho, and the Northeastern Interior and KwaZulu-Natal in South Africa collecting more rainfall deficit compared to the remaining parts of the region. Meanwhile, there was excess precipitation along the Mozambique Channel and parts of the Equatorial Indian Ocean. The intensity of the drought was comparable to the drought seen in the early summer of the previous year (Figure 5.3).

Late summer (January to March, 2004)

After two successive years of scarce rainfall, some parts of the subcontinent started to get some relief during January 2004 (Figure 5.6d). The western Interior and eastern part of South Africa, Lesotho, Swaziland and southernmost of Mozambique had above average rainfall while most of the remaining parts of the region, with the exception of much of Botswana, received close to normal precipitation. In February (Figure 5.6e), there were dry conditions over Zimbabwe, Zambia, Malawi and Mozambique, while Botswana, South Africa, Lesotho and Swaziland received from normal to above average precipitation. During March (Figure 5.6f) much of the region had complete relief by getting above average rainfall. When the precipitation is added for the late summer months, the subcontinent had a wet sub season (Figures 5.3). The subcontinent in general had relatively less dry summer (Oct – March) than the previous two summers.

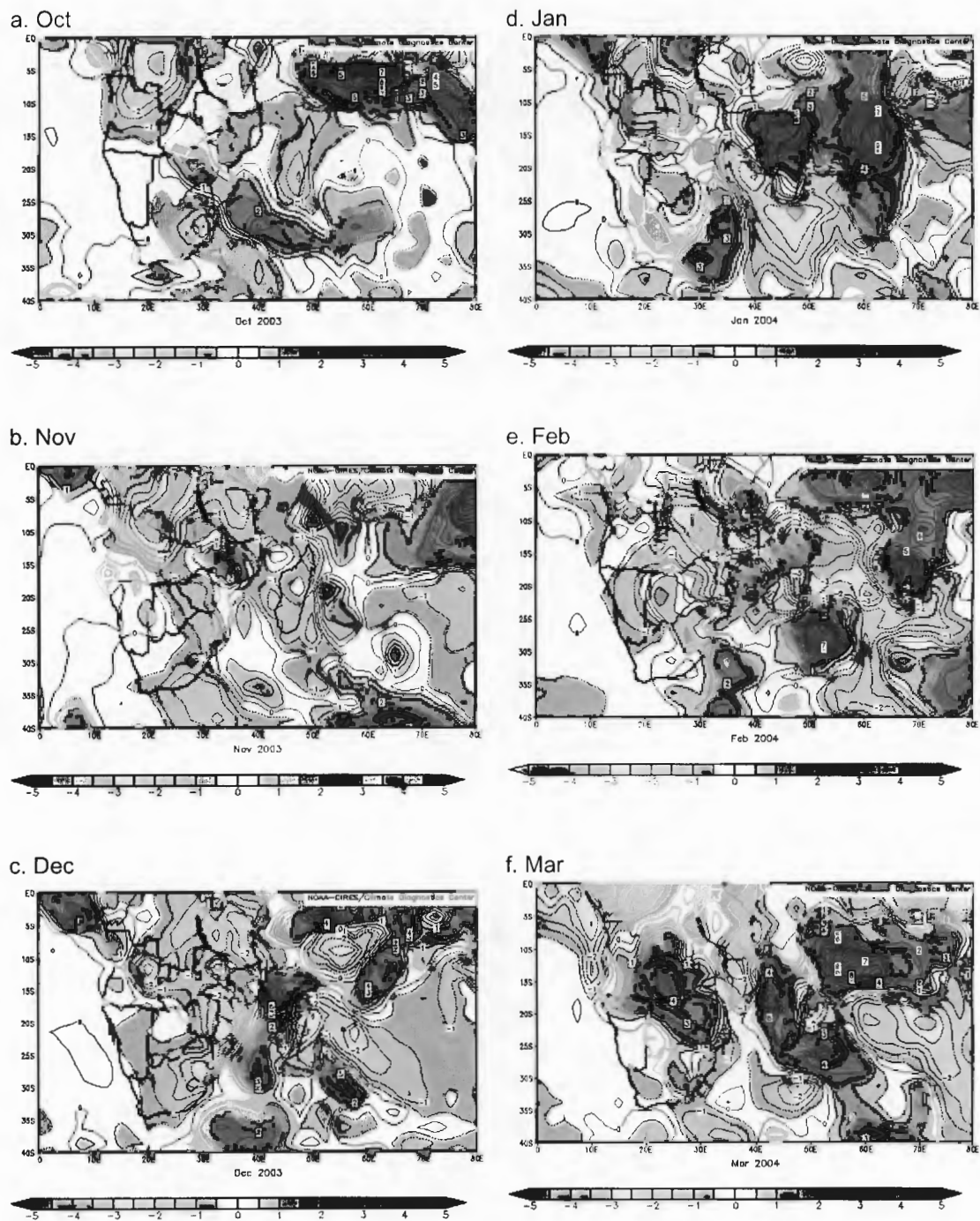


Figure 5.6 GPCP composite precipitation (mm/day) anomaly for early (left) and late (right) summer months of 2003/04.

6. Circulation Anomalies

2001/02 Summer

Early Summer (October to December 2001)

Deviations of the geopotential heights and winds at the 850, 500 and 200hpa isobaric surfaces during the early summer season of 2001/02 from the climatology of 1968-1996 are given in Figures 6.1 and 6.2. During October and November, there was weak low-pressure anomaly (5gpm, not indicated in the scale of the plot) present at the lower levels over the western part of southern Africa, extending from its center over the southeastern Atlantic Ocean. Meanwhile, in the mid latitudes high-pressure anomalies prevailed at all levels with greater intensity at upper heights and were stretched towards the western Indian Ocean to the south of Madagascar. These pressure features, over the region and adjacent oceans, created an ideal condition for the propagation of rain bearing wind systems into the region (Figure 6.1b). The sharp contrast between the enhanced low-pressure and high-pressure systems over parts of southern Africa and the western Indian Ocean, respectively, resulted in a stronger advection of moisture-loaded air from the Indian Ocean into the region. Furthermore, and more importantly, there was increased inflow of air, in a cyclonic fashion, from the tropical South Atlantic Ocean into the subcontinent. Essentially, these circulation patterns indicate the deepening of the Angola and Botswana low, as well as the amplification of the Zaire Air Boundary (ZAB), and were reminiscent of late summer conditions. The increases of the easterly winds that are associated with the formation of the easterly troughs over the low latitudes of southern Africa (10°S to 15°S) at 200hpa were also conducive for above normal rainfall seen in this month. The west wind regime in the middle latitudes, at all levels, was diminished due to the high-pressure anomalies. During December (Figure 6.2) the higher geopotential height anomalies seen in the previous months over the western Indian Ocean to the east of the subcontinent and to the immediate south of South Africa were replaced by slightly negative geopotential height anomalies. These indicate the diminishing of the Indian subtropical anticyclone. Consequently, the speed of the incoming air masses from the weakened subtropical Indian Ocean high-pressure system into the region was lower compared to the previous month (Figures 6.2b). Moreover, the southerly component of the winds

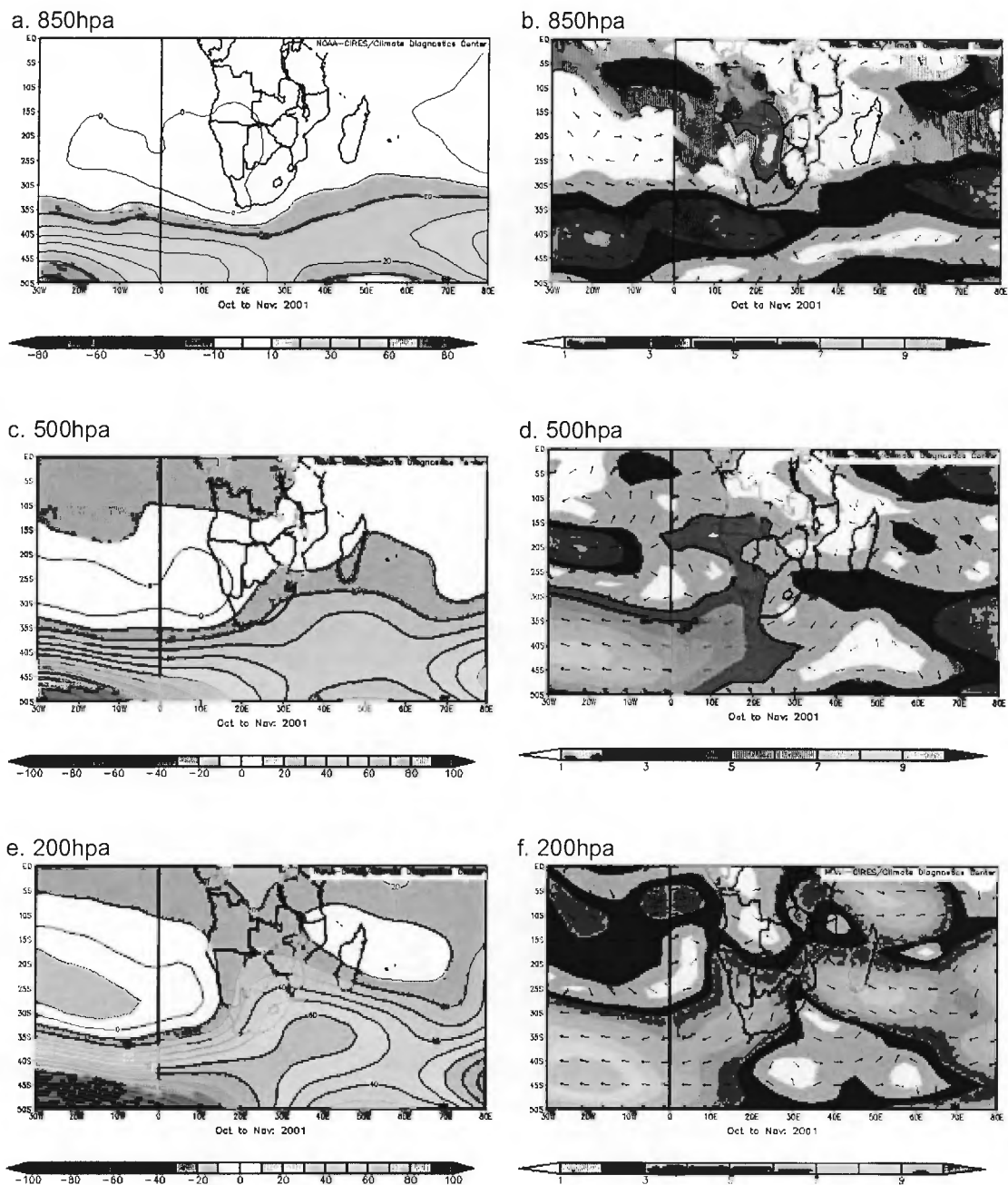
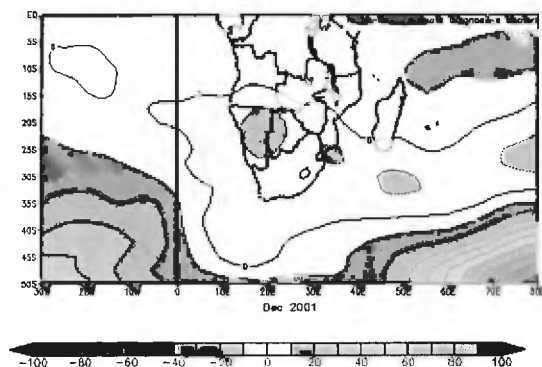


Figure 6.1 Composite geopotential height (left; interval = 10gpm) and wind (right; interval = 1ms^{-1}) anomalies at the indicated isobaric surfaces for October and November 2001².

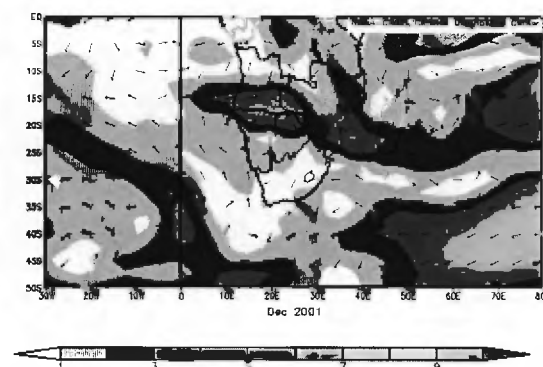
² **Note:** Plots of the entire pressure and wind anomalies in this study were made using the CDC website from the NCEP/NCAR Reanalysis data based on the 1968-1996 climatology.

coming from the tropical South Atlantic Ocean into the region was decreased. These could fairly explain the decreased rainfall in December in comparison to that of November.

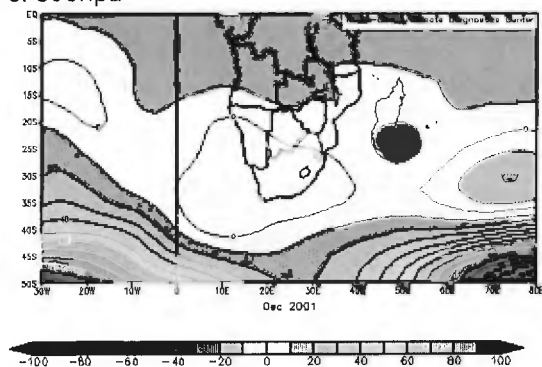
a. 850hpa



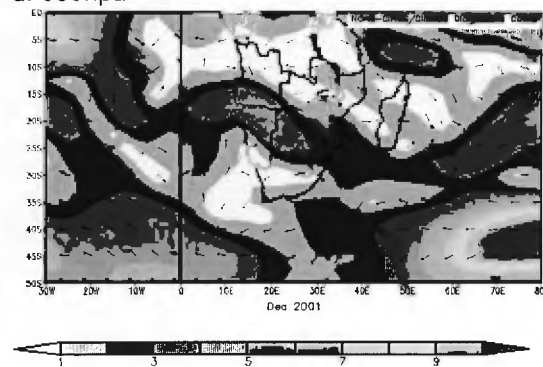
b. 850hpa



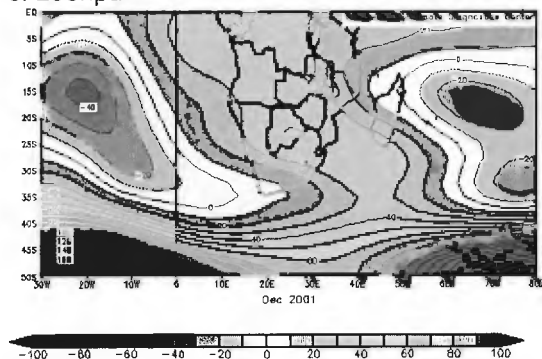
c. 500hpa



d. 500hpa



e. 200hpa



f. 200hpa

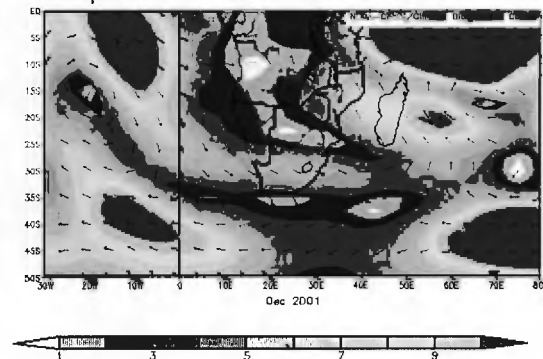


Figure 6.2 Geopotential height (left; interval = 10gpm) and wind (right; interval = 1ms^{-1}) anomalies at the indicated pressure surfaces for December 2001.

Late Summer (January to March, 2002)

Geopotential height and wind anomalies at the 850, 500 and 200hpa isobaric surfaces during the late summer season of 2001/02 are given in Figures 6.3, 6.4 and 6.5. During January (Figure 6.3) the center of the low-pressure anomaly seen in the previous months situated a few 100 kilometers away from Cape Town. It intensified and extended to the western part of subtropical southern Africa with progressive heights away from the surface. It resulted in an influx of dry air masses into the subcontinent (Figure 6.3b) from the subtropical South Atlantic Ocean. The dry air masses were progressing further into the western Indian Ocean. The low-pressure anomaly over the subtropical Indian Ocean indicates the weakening of the subtropical Indian Ocean anticyclonic system. The high-pressure anomaly continued to dominate in the middle latitudes at all levels resulting in the reduction of the west wind regime. The predominantly westerly anomalies at the middle and upper levels over the tropical and subtropical southern Africa were more of winter features than summer and are consistent with findings of previous studies of dry summer circulation patterns for the region (Mulenga et. al 2003) as previously reviewed. They imply the weakening of the easterly winds and their associated tropical easterly troughs or lows over tropical southern Africa. In February (Figure 6.4) different atmospheric conditions developed over and around the region. Pressure was higher than normal over much of southern Africa, south of the equator, which indicates the prevalence of subsidence and decrease of convection systems over these locations. The belt of high-pressure anomaly seen in the preceding months over the temperate latitudes broke off over the southwestern parts of the Indian and Atlantic Oceans (It is not shown on the Atlantic Ocean side due to the small scale of the plots). Thus, there was a low-pressure anomaly to the southeast of southern Africa extending from the middle latitudes across Marion Island, while on the other side a large anticyclonic anomaly, which was well established over Gough Island, approached the subcontinent from the southwest. All these pressure deviations from normal over and around the region stretched from the lower level to higher levels with greater intensification. As a result there were accompanying anomalous air circulations unfavorable to rain over the region. The advance of moist (easterly) winds from the western Indian Ocean onshore into the region was diminished. Instead there were

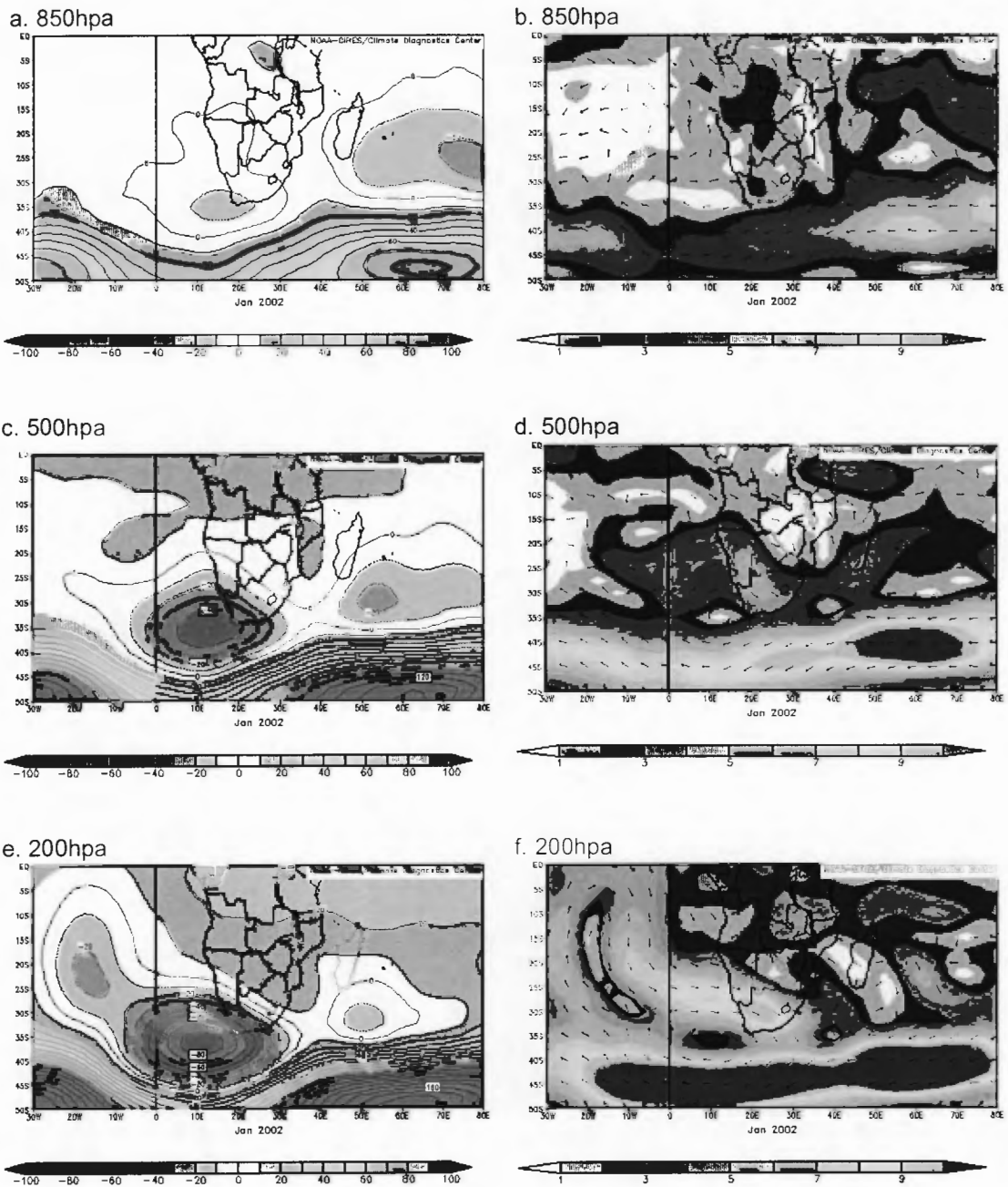


Figure 6.3 Geopotential height (left; interval = 10gpm) and wind (right; interval = 1ms^{-1}) anomalies at the indicated pressure surfaces for January 2002.

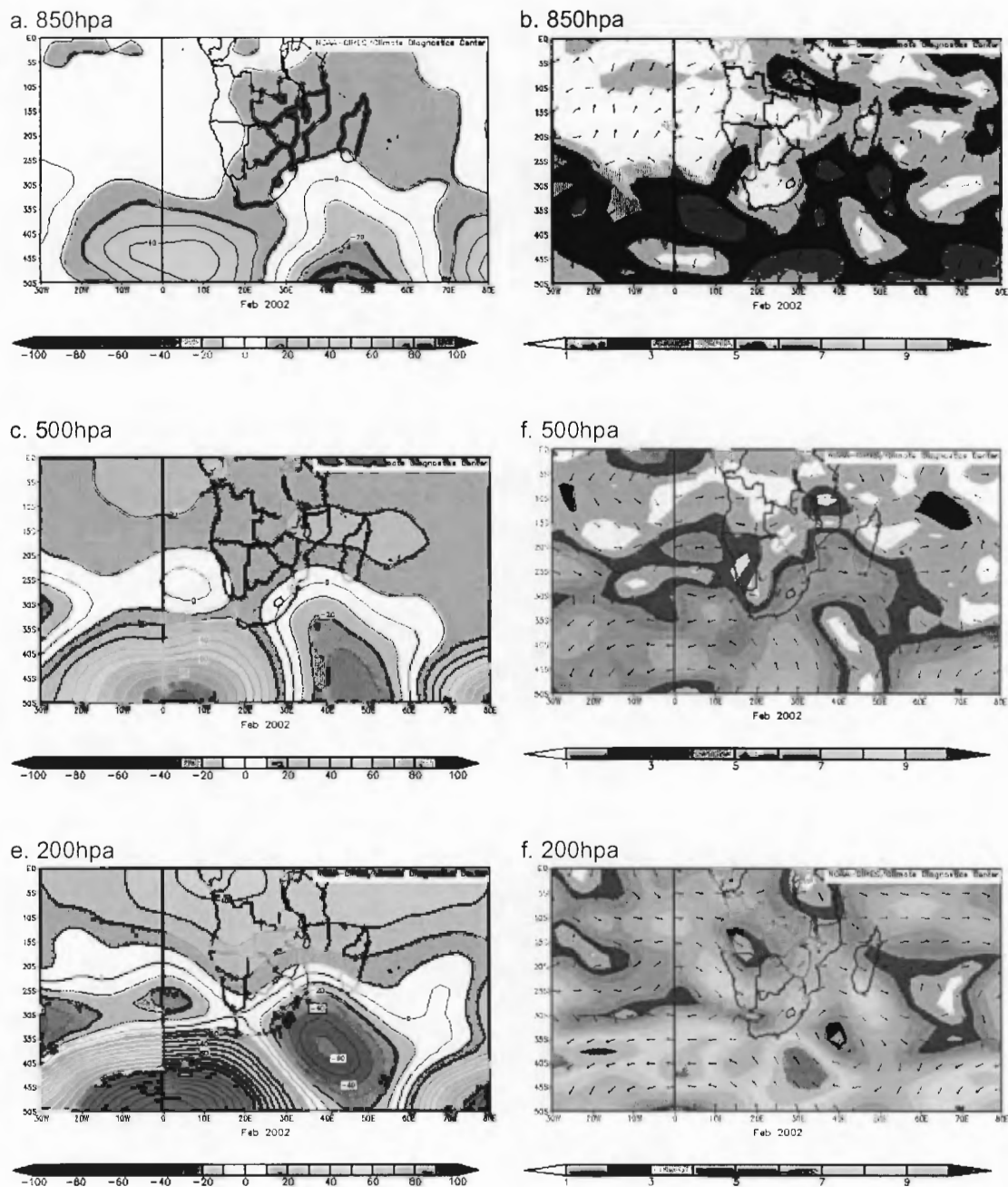
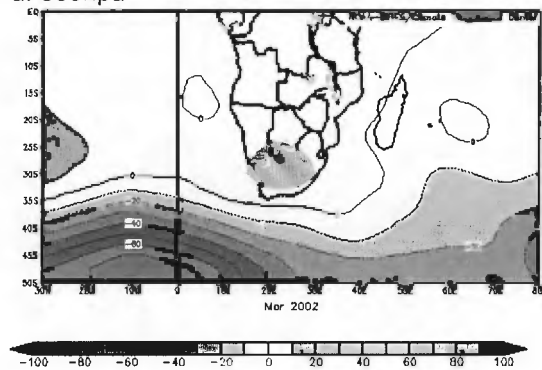
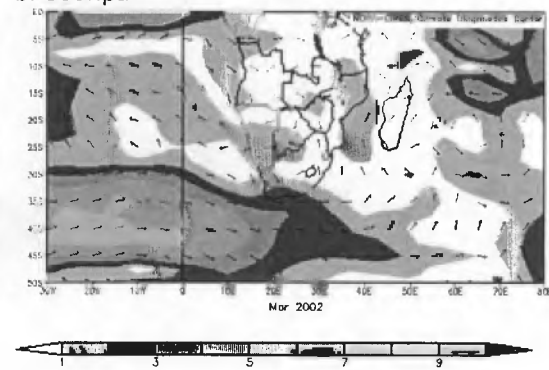


Figure 6.4 Geopotential height (left; interval = 10gpm) and wind (right; interval = 1ms^{-1}) anomalies at the indicated pressure surfaces for February 2002.

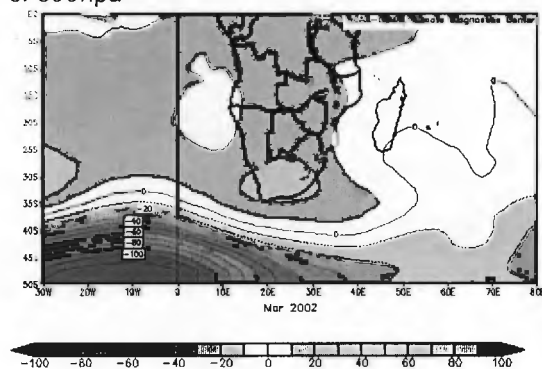
a. 850hpa



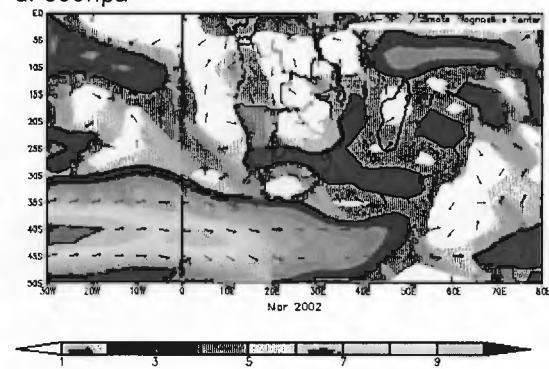
b. 850hpa



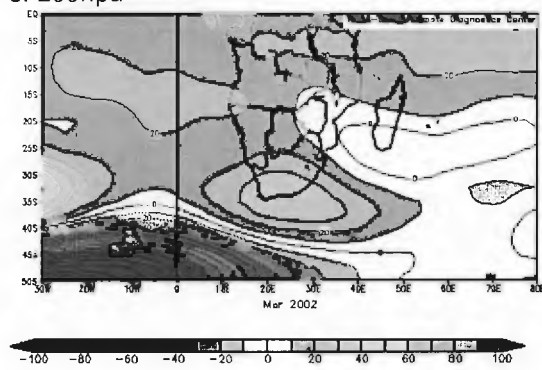
c. 500hpa



d. 500hpa



e. 200hpa



f. 200hpa

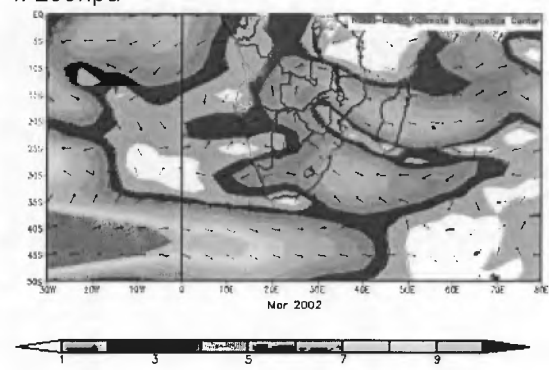


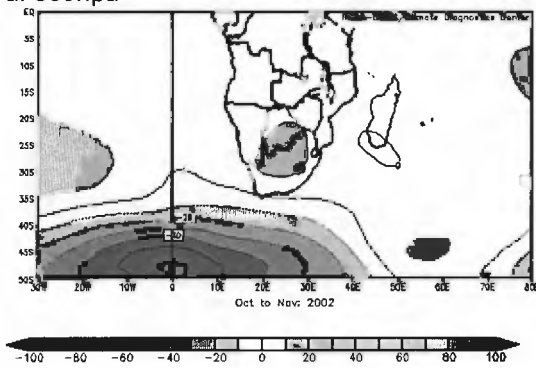
Figure 6.5 Geopotential height (left; interval = 10gpm) and wind (right; interval = 1ms⁻¹) anomalies at the indicated pressure surfaces for March 2002.

2002/03 Summer

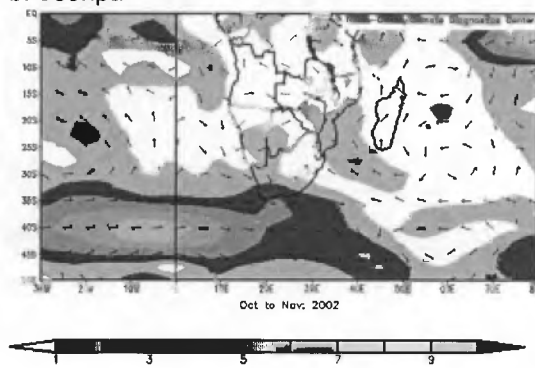
Early Summer (October to December 2002)

Geopotential height and wind anomalies at the 850, 500 and 200hpa isobaric surfaces during the early summer season of 2002/03 are given in Figures 6.6 and 6.7. During October and November (Figure 6.6), over much of South Africa and Botswana, there were positive geopotential height anomalies at the lower levels. Consequently an anticyclonic circulation anomaly with subsiding air dominated the lower levels of the region, preventing the advance of moist airflows into the region from the Indian and tropical south Atlantic Ocean. Dry northwesterly wind anomalies from the subtropical South Atlantic Ocean were observed, at lower levels, over much of South Africa. Pressure to the south of the subcontinent over the middle latitudes was less than average at all isobaric surfaces. As a result the west wind regime was stronger than normal to the south of the subcontinent. During December (Figure 6.7) conditions started to behave differently particularly over the neighboring oceans. There were high-pressure anomalies over most of southern Africa, to the south of the subcontinent, and over tropical latitudes of the surrounding oceans. Meanwhile, the subtropical high-pressure systems over the Indian and South Atlantic Oceans were slightly weaker than normal. Similar situations existed at all levels with slightly greater intensities. The positive geopotential height anomalies over the subcontinent operated to weaken lows and troughs associated with the ITCZ and ZAB. There were also westerly and easterly anomalies over the tropical and subtropical parts of the subcontinent, respectively, which were well defined at the middle and upper levels. These atmospheric features are consistent with the dry summer circulations experienced before (Taljaard and Steyn, 1991; Mulenga et al. 2003).

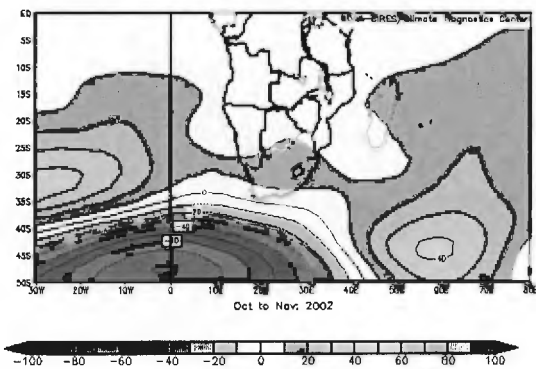
a. 850hpa



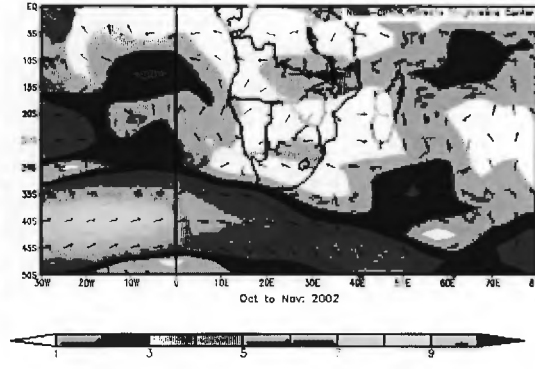
b. 850hpa



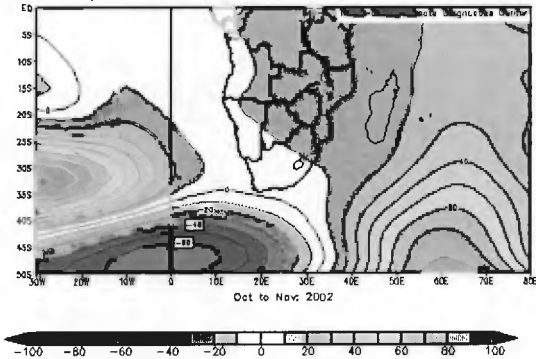
c. 500hpa



d. 500hpa



e. 200hpa



f. 200hpa

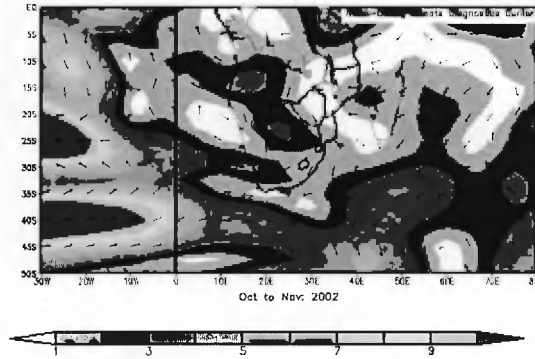


Figure 6.6 Geopotential height (left; interval = 10gpm) and wind (right; interval = 1ms^{-1}) anomalies at the indicated pressure surfaces for October and November 2002.

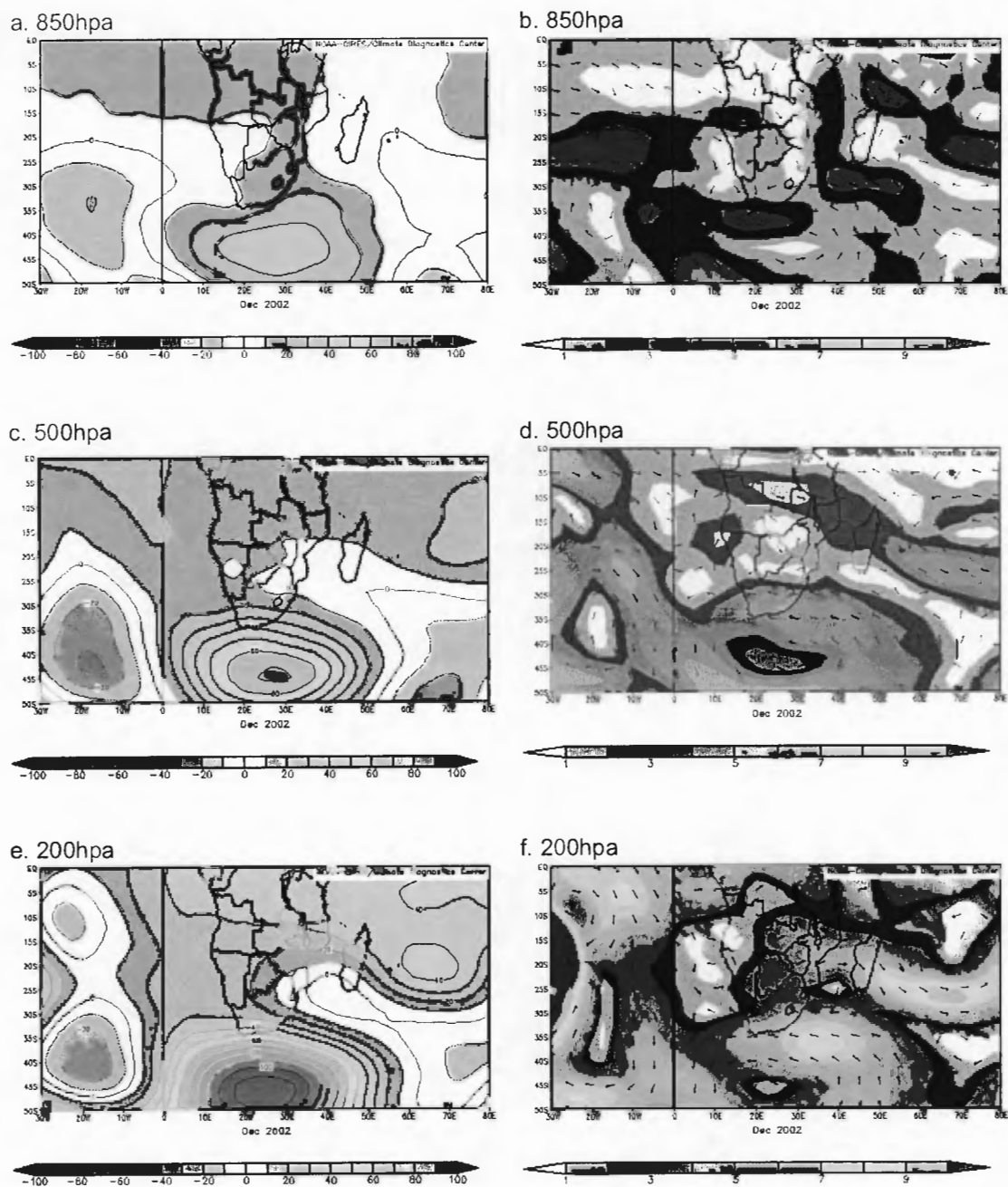


Figure 6.7 Geopotential height (left; interval = 10gpm) and wind (right; interval = 1ms^{-1}) anomalies at the indicated pressure surfaces for December 2002.

Late Summer (January to March, 2003)

During the heart of the rainy season (January and February, Figure 6.8) Pressure was above average over the tropical and subtropical parts of southern Africa and surrounding oceans at the 500 and 200hpa surfaces. These high-pressure anomalies were weakly extending to the lower levels at a scale of 5gpm interval (It is not shown in the plots of 10gpm interval). Meanwhile, pressure over the middle latitudes was less than normal. These anomalies created a strong pressure gradient between the lower and higher latitudes resulting in unusually strong westerlies over the middle latitudes. It is the pressure difference between the tropical (high pressure) and temperate (lower pressure) latitudes that results to the formation of the west wind regime. The higher the pressure gradient between the two zones the stronger the west wind regime. The positive geopotential height anomalies over the subcontinent might have acted to inhibit convection cells over the region by promoting subsidence. The reduced easterlies at the middle and upper levels over the tropical southern Africa indicate the diminishing of the easterly waves, which in turn indicate the weakening or shift of the ITCZ/ZAB and associated tropical lows and barotropic troughs. In March (Figure 6.9) closer to the surface there was low-pressure anomaly over the eastern section of the region, extending from the large low pressure anomaly southwest of Cape Town this time sitting further south; meanwhile there was high pressure anomaly to the southeast of South Africa over southern Indian Ocean. The Angola and Botswana low was well developed during this month. Southwesterly wind anomalies were advancing into South Africa from the subtropical South Atlantic Ocean. There was reduced onshore flow of moist winds from the western Indian Ocean, for the Indian Ocean anticyclonic circulation was sitting further south.

southerly wind anomalies along the eastern coastal areas of the region (Figure 6.4b). At the 200hpa westerly anomalies continued to dominate over southern Africa, except over the southernmost coastal areas. A high-pressure system southwest of the country is associated with good rainy season over the region. However, during this month other important circulation features were suppressed for the precipitation to occur. Taljaard and Steyn (1991) have noted that when the anticyclones advance with their cores south of about 45°S , they have little effect on the rainfall over the subcontinent. They suggest that for the maximum effect on the region's rainfall, the near surface tracks of their center must be restricted roughly to $37 - 42^{\circ}\text{S}$ zone. During March (Figure 6.5) the positive geopotential height anomalies over the whole subcontinent were still lingering at the middle and upper levels, but they were weakly descending to the lower levels to be only localized over much of South Africa at 850hpa surfaces. On the other hand, the high-pressure anomalies, observed in the previous months, in the middle latitudes entirely disappeared and were replaced by negative geopotential heights, at all levels, with larger magnitude over the South Atlantic Ocean side. The Indian subtropical anticyclonic circulation system was pushed to the northeast by the low-pressure anomaly in the middle latitudes. As a result the winds from the western Indian Ocean were brushing the region from south instead of directly onshore into the region from the northeast (Figure 6.5b). The declines of the easterlies and westerlies at upper heights over tropical and subtropical southern Africa respectively indicate the less prevalence of their corresponding easterly and westerly troughs. Moreover, the reduced and intensified westerlies over the subtropical parts of the region and to the south of the continent in the middle and upper levels, in that order, indicate the pole ward shift of the temperate storm tracks. The temperate storm tracks or cold fronts are important for the establishment of the tropical-temperate troughs and their associated cloud bands.

The most peculiar feature in the late summer was the different pressure conditions observed particularly in the middle latitudes among the three months. However the total outcome and effect of these variable atmospheric conditions on the subcontinent were the same, less than average precipitation.

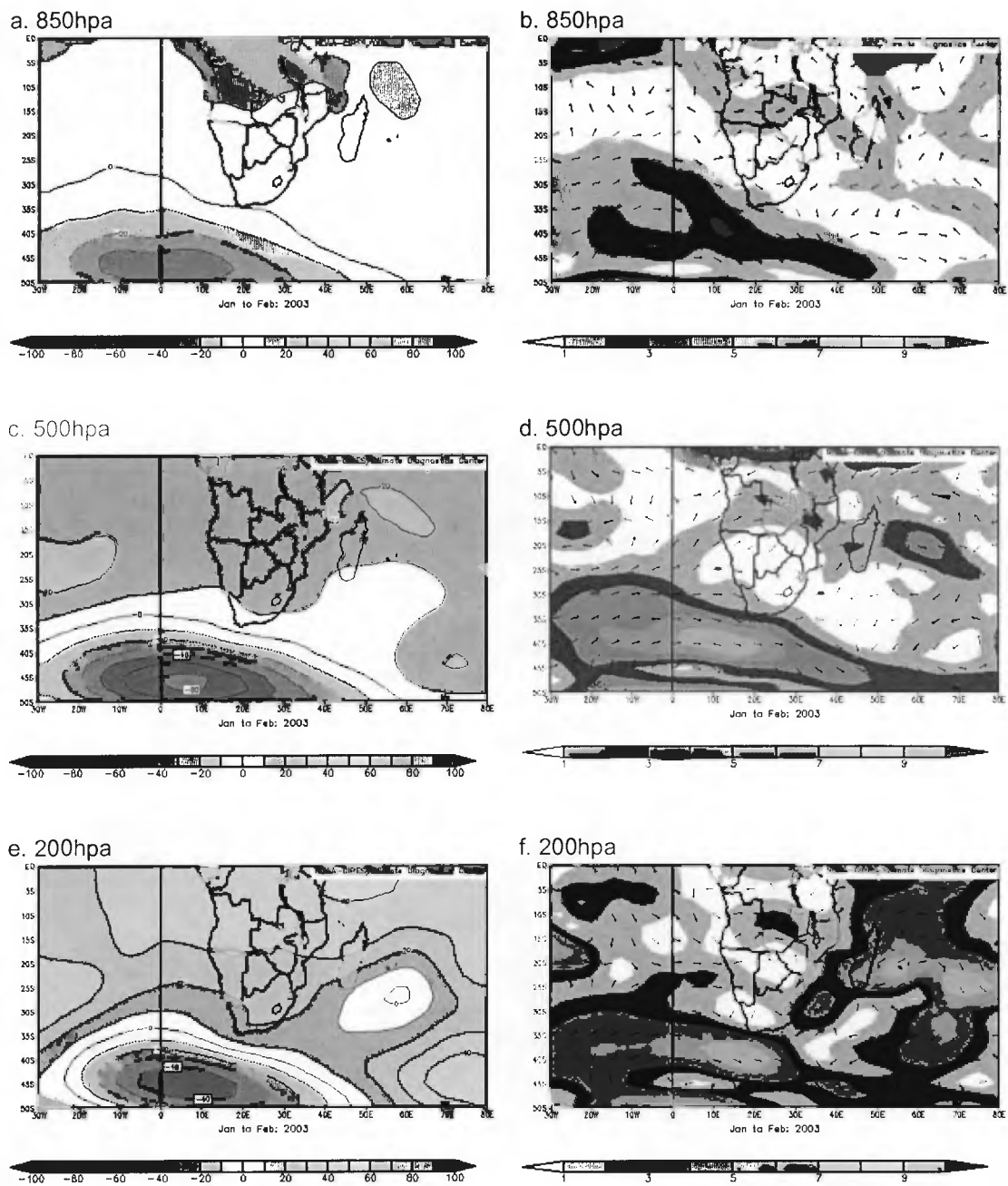


Figure 6.8 Geopotential height (left; interval = 10gpm) and wind (right; interval = 1ms^{-1}) anomalies at the indicated pressure surfaces for January and February 2003.

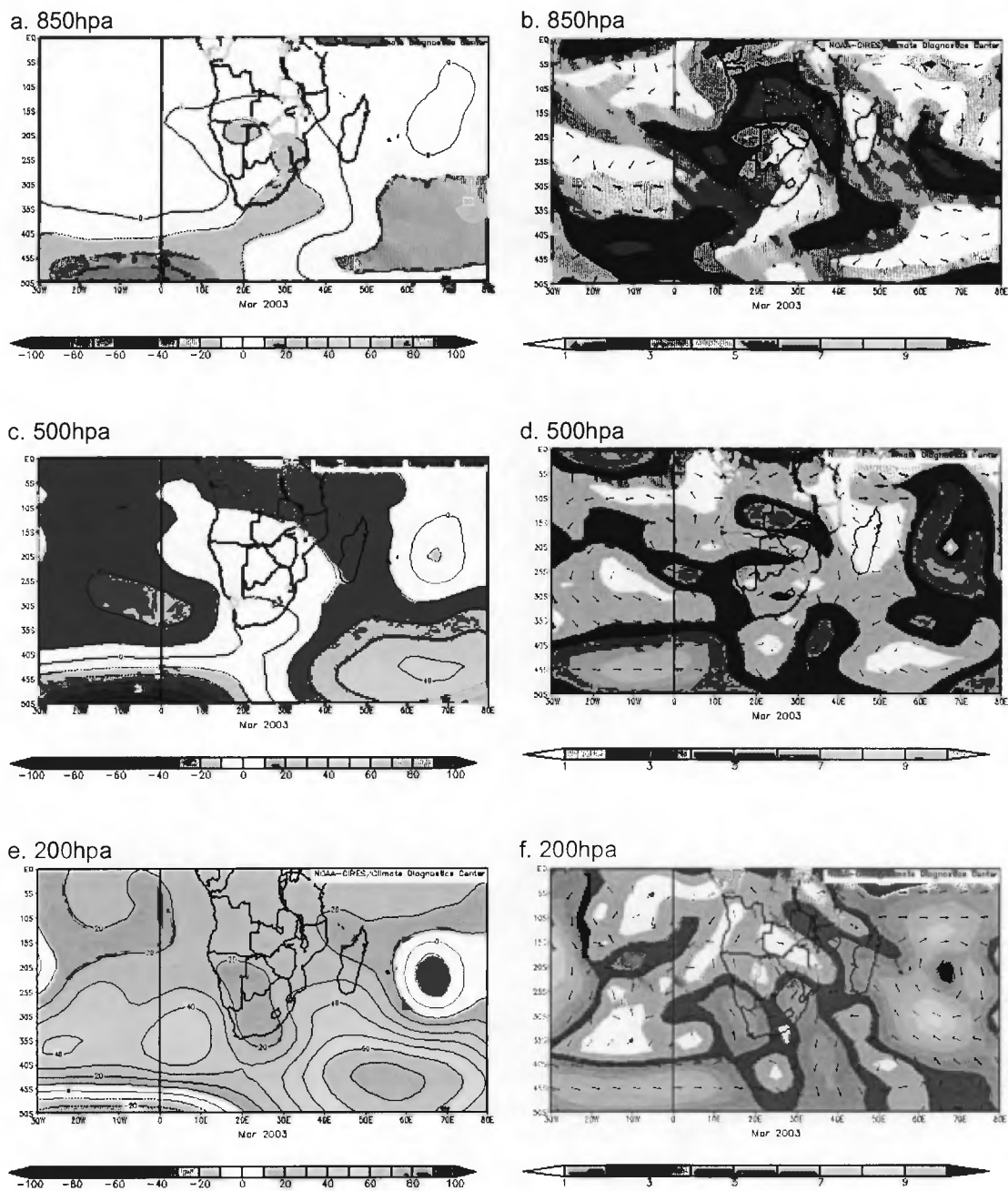


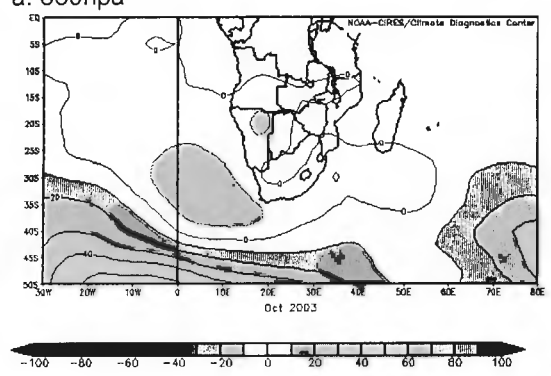
Figure 6.9 Geopotential height (left; interval = 10gpm) and wind (right; interval = 1ms^{-1}) anomalies at the indicated pressure surfaces for March 2003.

2003/04 Summer

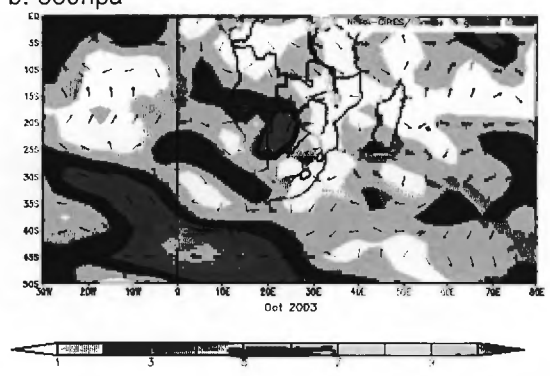
Early Summer (October to December 2003)

In October (Figure 6.10) closer to the surface, negative geopotential height anomalies prevailed over the South Atlantic Ocean, weakly extending to the western part of the region. Meanwhile, pressure was higher than average over the temperate latitudes at all isobaric surfaces. The Indian Ocean anticyclone shifted east, as a result there was limited advection of moist air masses from the western Indian Ocean into the region. Instead dry westerly to northwesterly wind anomalies from the subtropical South Atlantic Ocean were observed over South Africa at the 850hpa isobaric surface, resulting in a poor start to the rainy season. In November (Figure 6.11) conditions over the region and surrounding subtropical oceans were close to normal at the lower level, but at the middle level, there was high-pressure anomaly over much of South Africa and Botswana. In the mid latitudes the high-pressure anomalies seen in the previous month were replaced by low-pressure anomalies. At upper level, a high-pressure anomaly dominated over the whole subcontinent and over much of the adjacent oceans. The westerly anomalies were still lingering closer to the surface over South Africa, limiting the advection of moist air from the Indian Ocean into the region. During December (Figure 6.12), at all levels, there were low-pressure anomalies sitting south of the subcontinent, and were sandwiched from the east and the west by high-pressure anomalies from the Indian and Atlantic Ocean sides. The region experienced normal pressure conditions closer to the surface, but at the middle and upper heights, positive geopotential height anomalies were prevailing. At lower levels, strong dry westerly anomalies from the subtropical South Atlantic Ocean continuously crossed over South Africa and the southern part of Namibia and Botswana into the western Indian Ocean. The Indian anticyclone sat further south and east during this month, thus there was diminished influx of moisture from the western Indian Ocean into the region.

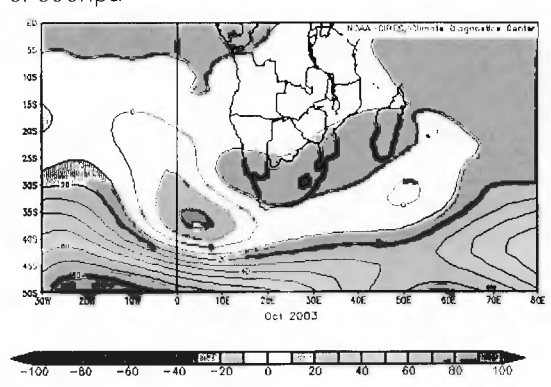
a. 850hpa



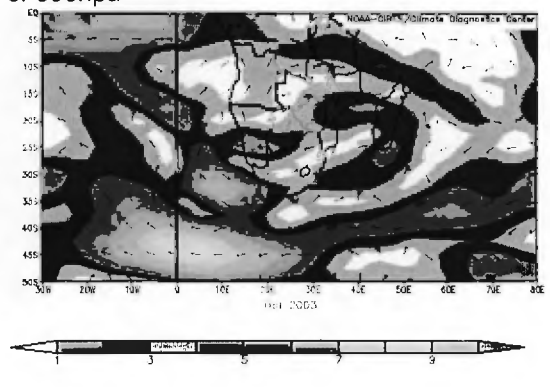
b. 850hpa



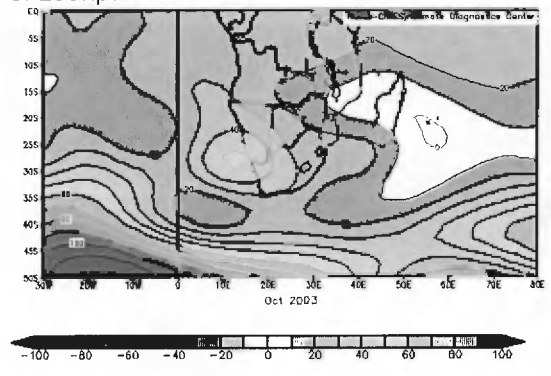
c. 500hpa



c. 500hpa



e. 200hpa



f. 200hpa

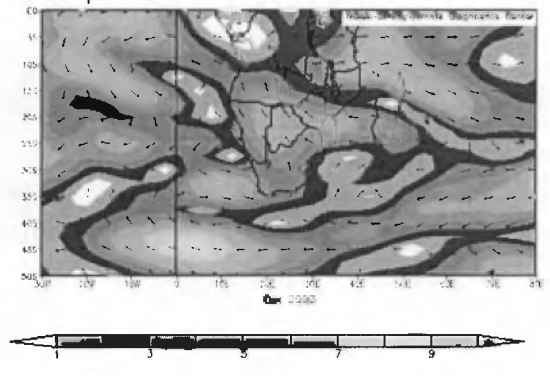


Figure 6.10 Geopotential height (left; interval = 10gpm) and wind (right; interval = $1ms^{-1}$) anomalies at the indicated pressure surfaces for October 2003.

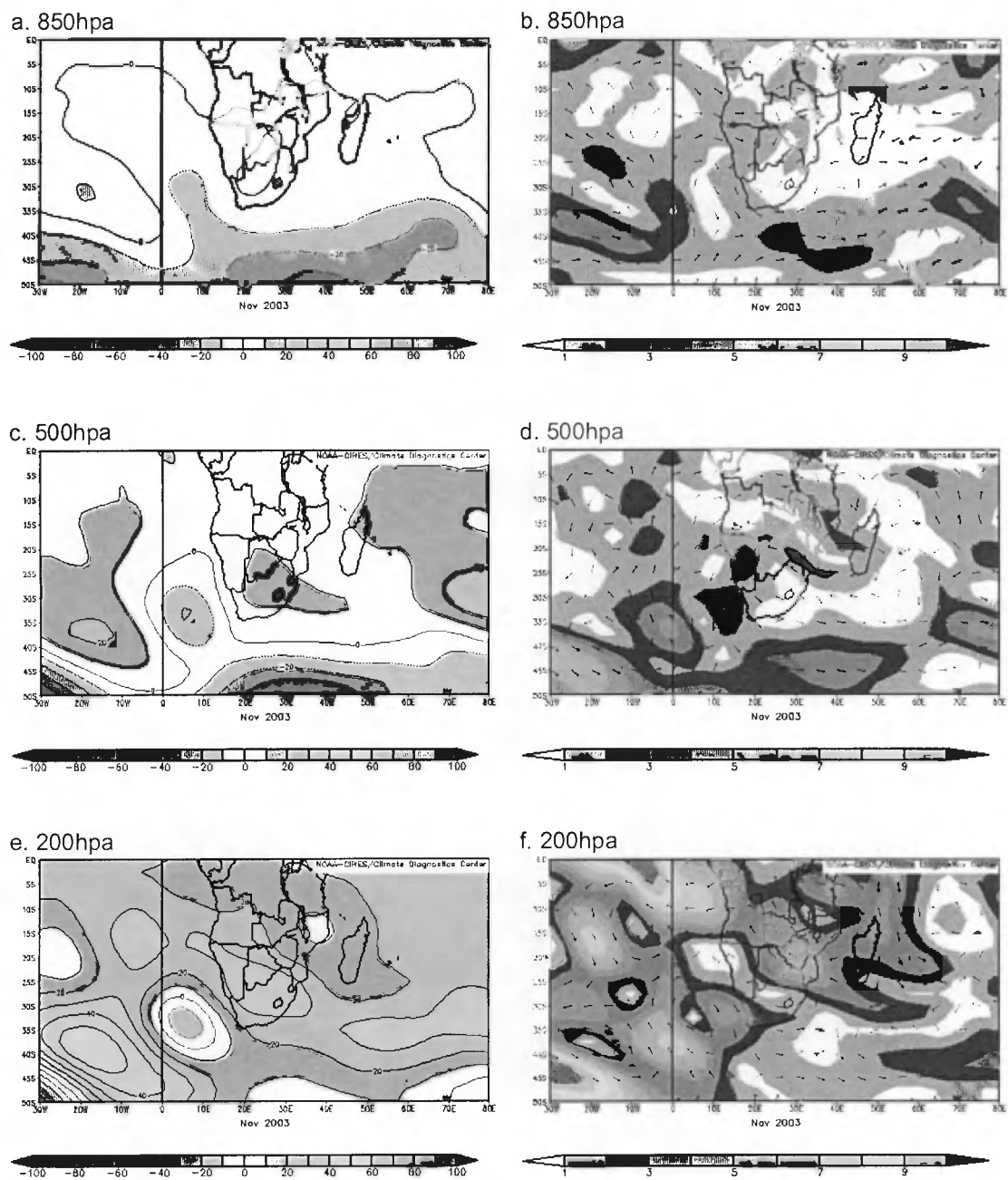


Figure 6.11 Geopotential height (left; interval = 10gpm) and wind (right; interval = 1ms^{-1}) anomalies at the indicated pressure surfaces for November 2003.

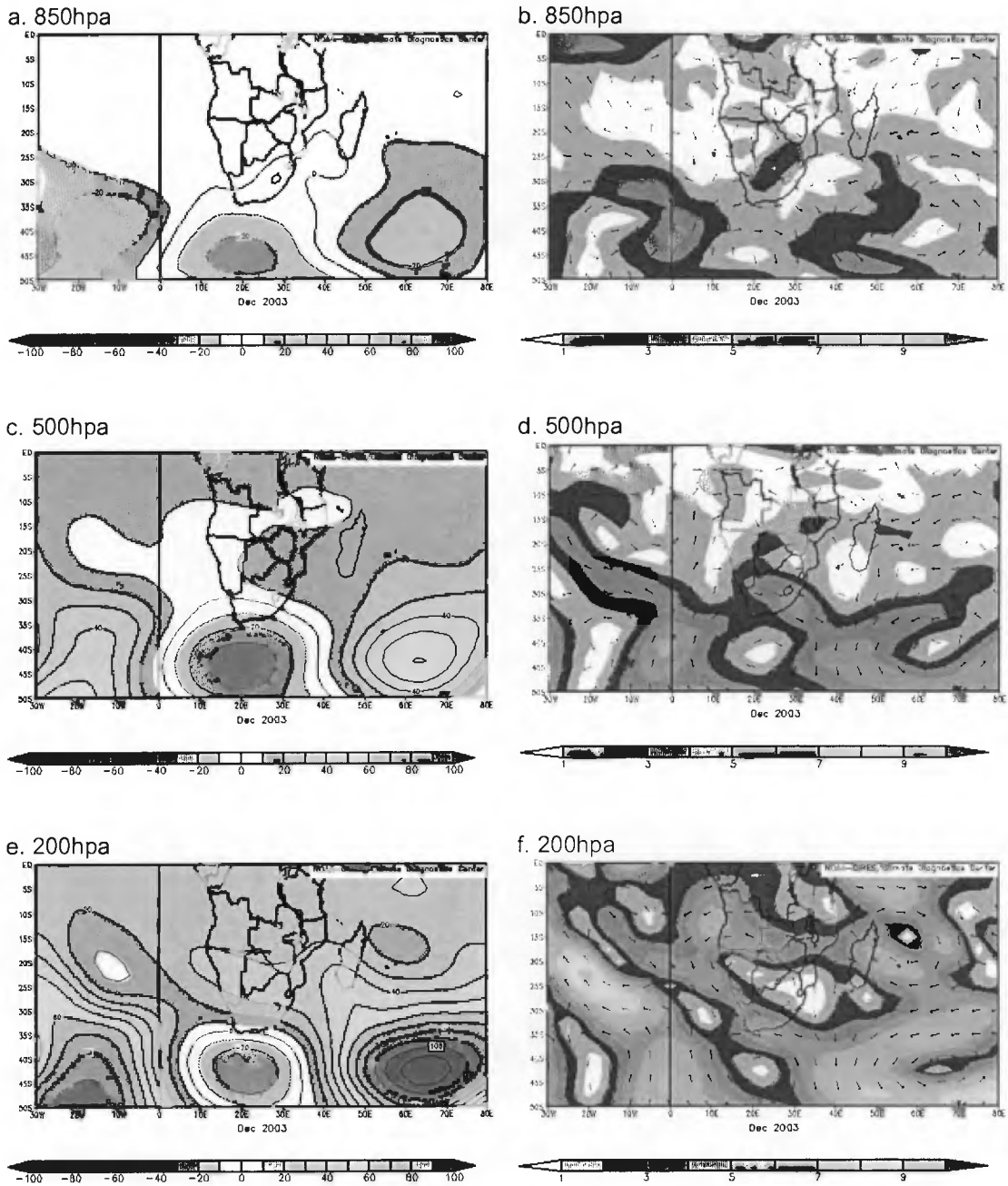
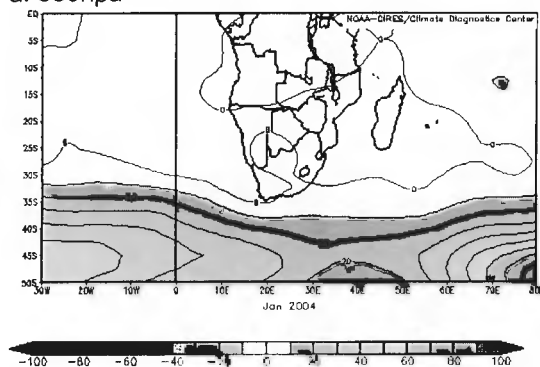


Figure 6.12 Geopotential height (left; interval = 10gpm) and wind (right; interval = 1ms^{-1}) anomalies at the indicated pressure surfaces for December 2003.

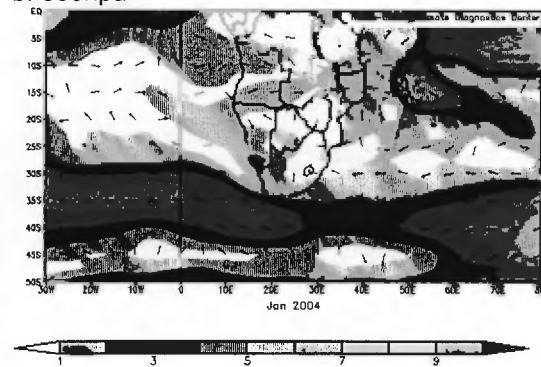
Late Summer (January to March, 2004)

In January (Figure 6.13) conditions over the region and surrounding subtropical oceans were close to normal from lower to middle levels, meanwhile at 200hpa, there were high pressure and low pressure anomalies over the region and the subtropical part of the Indian Ocean respectively. Positive geopotential height anomalies dominated the middle latitudes at all levels, with greater intensity at the upper level. Accordingly, the west wind regime was greatly reduced due to decreased pressure gradient between the tropics and middle latitudes. Previous studies of circulation anomalies during dry and wet years have associated above average rainfall with the diminishing of the west wind regime (Taljaard and Steyn, 1991). In February (Figure 6.14) the South Atlantic subtropical high pressure system was stronger than normal, on the other hand, the Indian Ocean high pressure system was abnormally weaker than normal to the west of Madagascar. Elsewhere over the region conditions were normal at the lower and middle troposphere, but negative pressure anomalies prevailed at the upper level. Over the middle latitudes there were low pressure and high-pressure anomalies to the southwest and southeast of the subcontinent respectively. Closer to the surface at the 850hpa there were dry westerly to southwesterly winds dominating over South Africa and southern Botswana. Stronger westerly wind anomalies prevailed at the middle level and upper levels over whole southern Africa except over South Africa. During March (Figure 6.15) at all levels, there was a low-pressure anomaly sitting south of the subcontinent. Pressure was closer to normal over the subcontinent at the lower and middle levels while at 200hpa the region experienced higher geopotential heights.

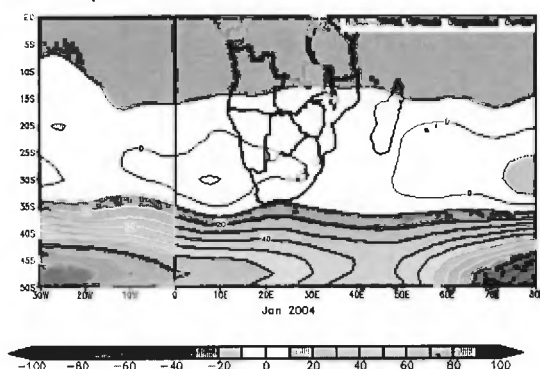
a. 850hpa



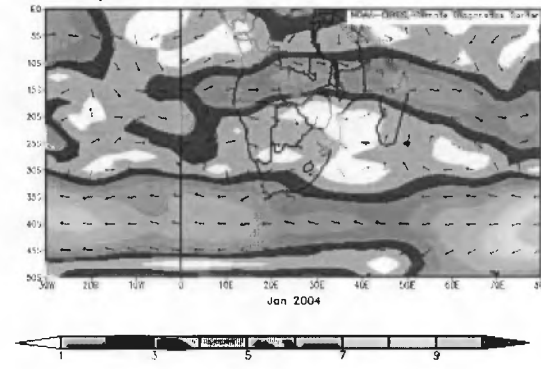
b. 850hpa



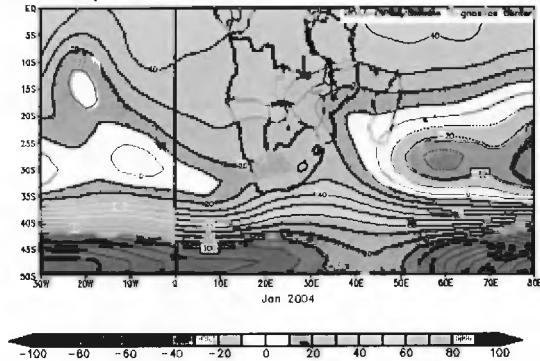
c. 500hpa



d. 500hpa



e. 200hpa



f. 200hpa

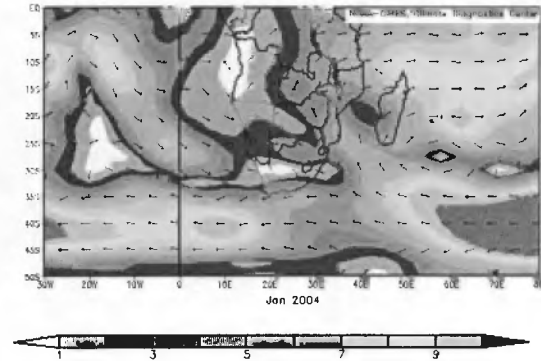
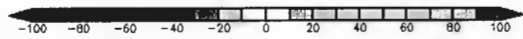
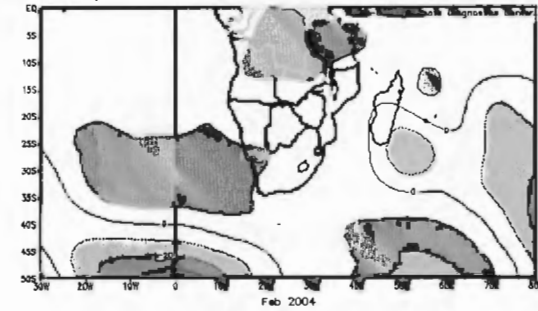
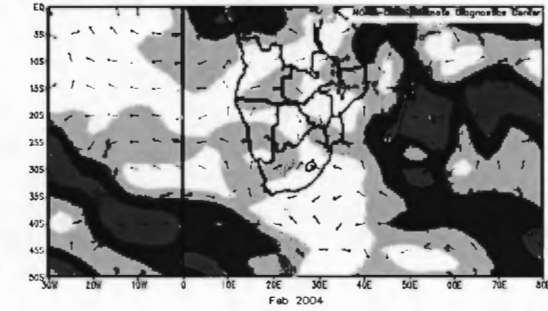


Figure 6.13 Geopotential height (left; interval = 10gpm) and wind (right; interval = 1ms^{-1}) anomalies at the indicated pressure surfaces for January 2004.

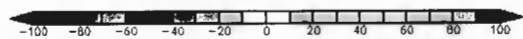
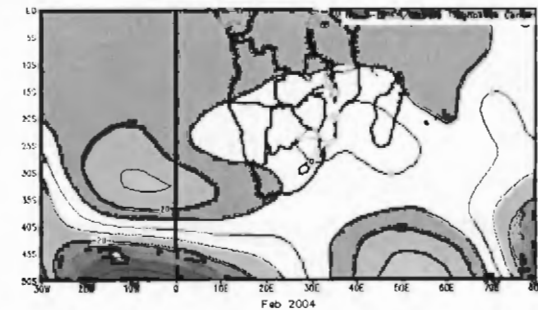
a. 850hpa



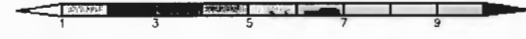
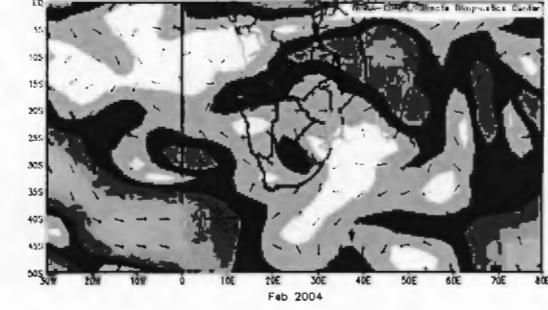
b. 850hpa



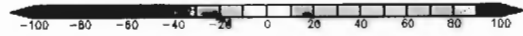
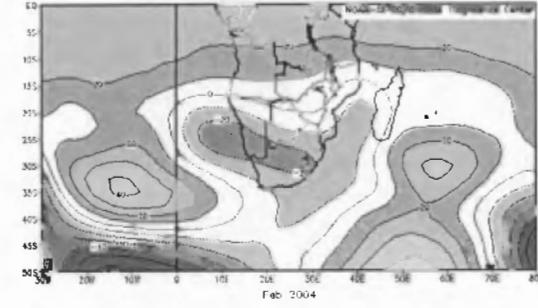
c. 500hpa



d. 500hpa



e. 200hpa



f. 200hpa

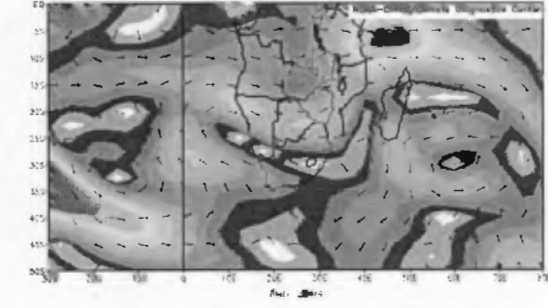


Figure 6.14 Geopotential height (left; interval = 10gpm) and wind (right; interval = 1ms^{-1}) anomalies at the indicated pressure surfaces for February 2004.

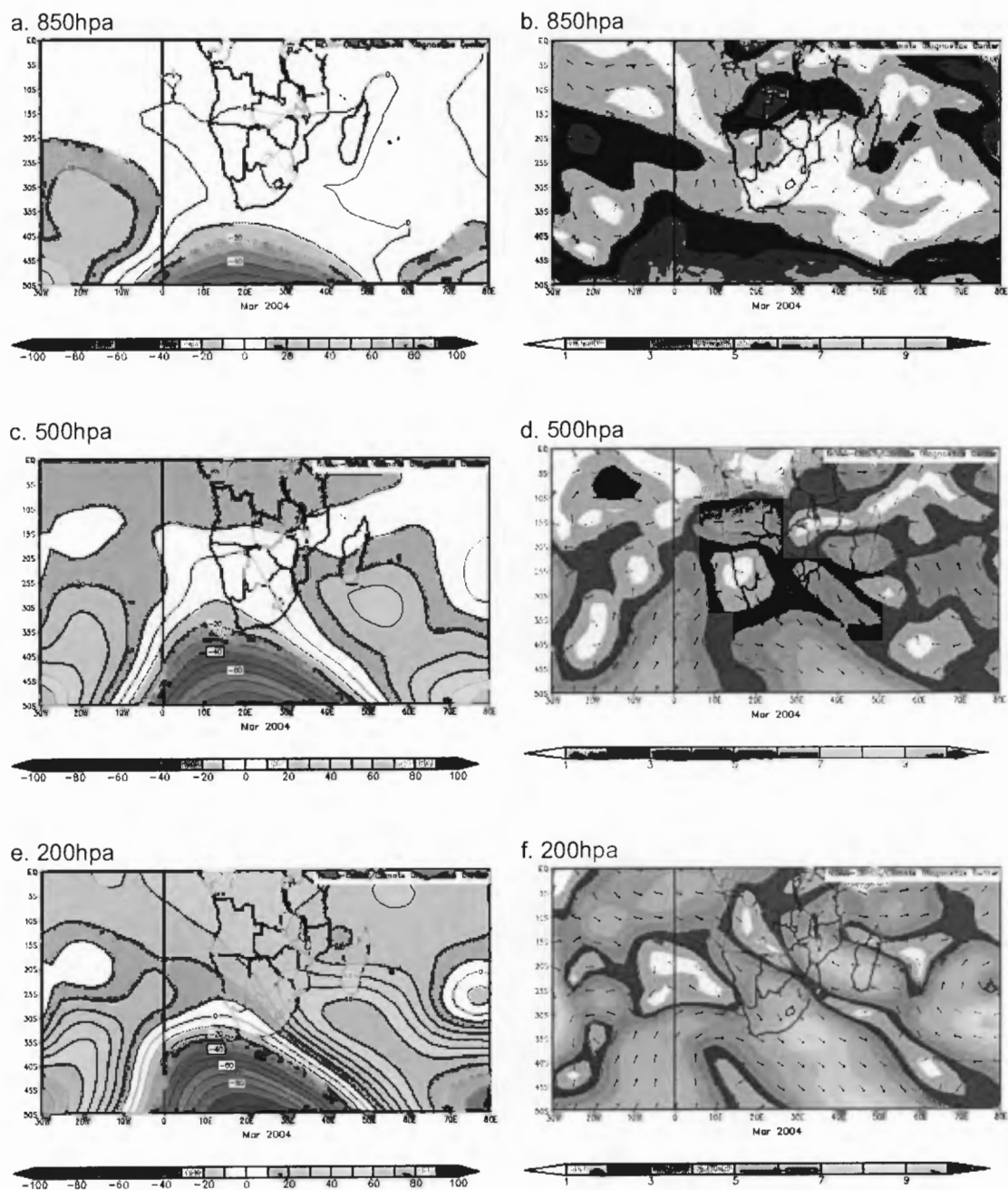


Figure 6.15 Geopotential height (left; interval = 10gpm) and wind (right; interval = 1ms^{-1}) anomalies at the indicated pressure surfaces for March 2004.

7. Sea Surface Temperature

2001/02 Summer

Early Summer (October to December 2001)

In October (Figure 7.1a) the oceanic area surrounding the subcontinent were mostly under normal conditions. Small patches of anomalously high SSTs were present to the south of South Africa and in the central Indian Ocean ($0.5 - 1.0^{\circ}\text{C}$). The Brazil current was warmer than average by $0.5 - 1.5^{\circ}\text{C}$. In the central subtropical South Atlantic Ocean colder ($-1.0 - -0.5^{\circ}\text{C}$) conditions existed. As it has been noted in earlier sections that some studies (Mason et al., 1994; Mason, 1995) have associated anomalously low SSTs in subtropical South Atlantic Ocean region with above normal rainfall in the subcontinent. In November (Figure 7.1b) the anomalously high SSTs in the Brazil Current intensified and covered a large area. Warmer SSTs emerged along the Mozambique Channel ($0.5 - 1.0^{\circ}\text{C}$) and the Benguela system ($0.5 - 2.0^{\circ}\text{C}$). The high SSTs in the Mozambique Channel can be linked with the above normal rainfall, observed in the subcontinent during this month. They possibly had provided extra moisture to the overlying atmosphere that was probably carried away onshore into the region by the surface easterlies. During December (Figure 7.1c) the warming event in the Benguela system persisted while the one in the Mozambique Channel diminished. Anomalously high SSTs occurred in the central equatorial Indian Ocean ($0.5 - 1.0^{\circ}\text{C}$) and in the temperate latitudes (30° to 60°S) of both the central Indian ($0.5 - 2.5^{\circ}\text{C}$) and South Atlantic Oceans ($0.5 - 2.0^{\circ}\text{C}$). The warm anomaly in the central equatorial Indian Ocean was accompanied by higher rainfall over the same area and below normal rainfall over corresponding locations in southern Africa. This, link of the rainfall with the SST with regard to the two areas, could probably indicate the shift of the tropical low-pressure systems from the subcontinent into the Indian Ocean. It is also consistent with the above average rainfall observed in November over the subcontinent, which shifted into the western Indian Ocean during December (as it has been mentioned in chapter 5). The anomalously high SSTs in the temperate latitudes could be linked with the weakening of the west wind regime, which was discussed in the previous chapter. Stronger winds over the sea surface means more evaporation, which in turn means cooler SSTs.

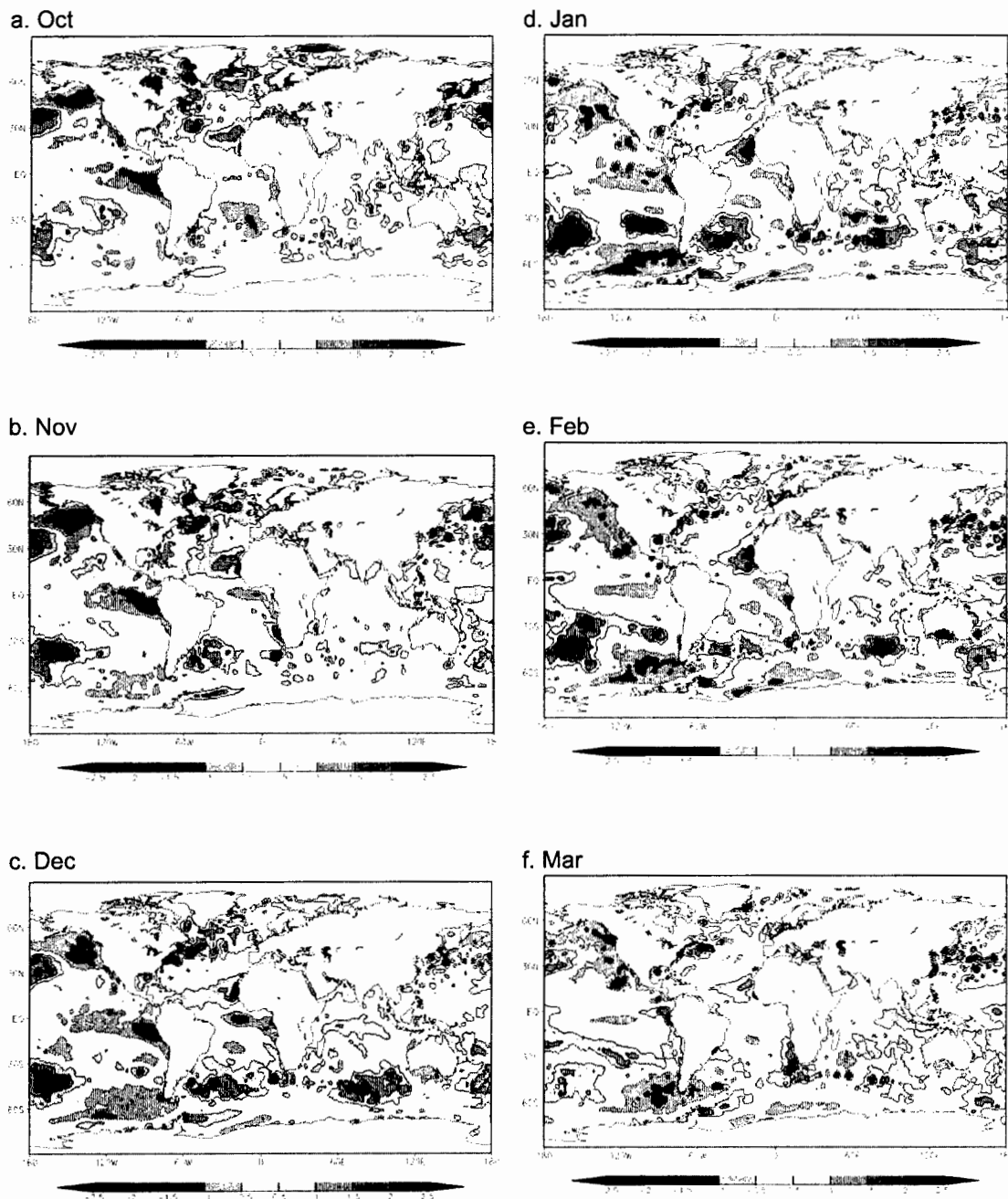


Figure 7.1 SST anomalies in the world Oceans during the early (left) and late (right) summer months of 2001/02³.

³ Note: All plots of SST anomalies in this study were based on 1982 - 2000 climatology.

The SSTs along the Eastern Pacific Ocean were cooler than normal through out the early summer.

Late Summer (January to March 2002)

In January (Figure 7.1d) there were anomalously high SSTs south of the Subcontinent ($0.5 - 2.5^{\circ}\text{C}$), north of Madagascar, along much of the central longitudinal axis of the southern Indian Ocean (0.5°C) extending further into temperate latitudes ($0.5 - 2.5^{\circ}\text{C}$), and in the Brazil current system ($0.5 - 2.5^{\circ}\text{C}$). A small area to the south east of Madagascar had anomalously low SSTs ($-1.5 - -0.5^{\circ}\text{C}$). During this period most part of the central Indian Ocean had very wet conditions, while the subcontinent was experiencing drought. In February (Figure 7.1e) there were above normal SSTs in the temperate latitudes of both the South Atlantic ($0.5 - 1.5^{\circ}\text{C}$) and southern Indian ($0.5 - 2.5^{\circ}\text{C}$) Oceans as well as in the central subtropical Indian Ocean ($0.5^{\circ}\text{C} - 1.0^{\circ}\text{C}$). During March (Figure 7.1f) anomalously high SSTs ($0.5 - 2.0^{\circ}\text{C}$) existed in the Benguela system and to the south of the subcontinent while the anomalously high SSTs in the temperate latitudes, in the South Atlantic Ocean, disappeared. The disappearance of the anomalously high SSTs from the South Atlantic Ocean could be linked with the increase of the west wind regime. El Nino conditions ($0.5 - 2.0^{\circ}\text{C}$) started to develop along the coasts of Peru and Ecuador.

2002/03 Summer

Early Summer (October to December 2002)

In October (Figure 7.2a) El Niño ($0.5 - 2.5^{\circ}\text{C}$) conditions were still noticeable in the central and eastern Pacific Ocean. There were anomalously high SSTs ($0.5 - 1.5^{\circ}\text{C}$) in the central tropical southern Indian Ocean and in the Brazil current system. During November (Figure 7.2b) and December (Figure 7.2c) approximately similar conditions continued to appear in the SSTs of the oceans, with direct or indirect influence on the rainfall of the subcontinent, except that the temperate latitudes of the South Atlantic Ocean had lower SSTs ($-2.0 - -0.5^{\circ}\text{C}$) than normal.

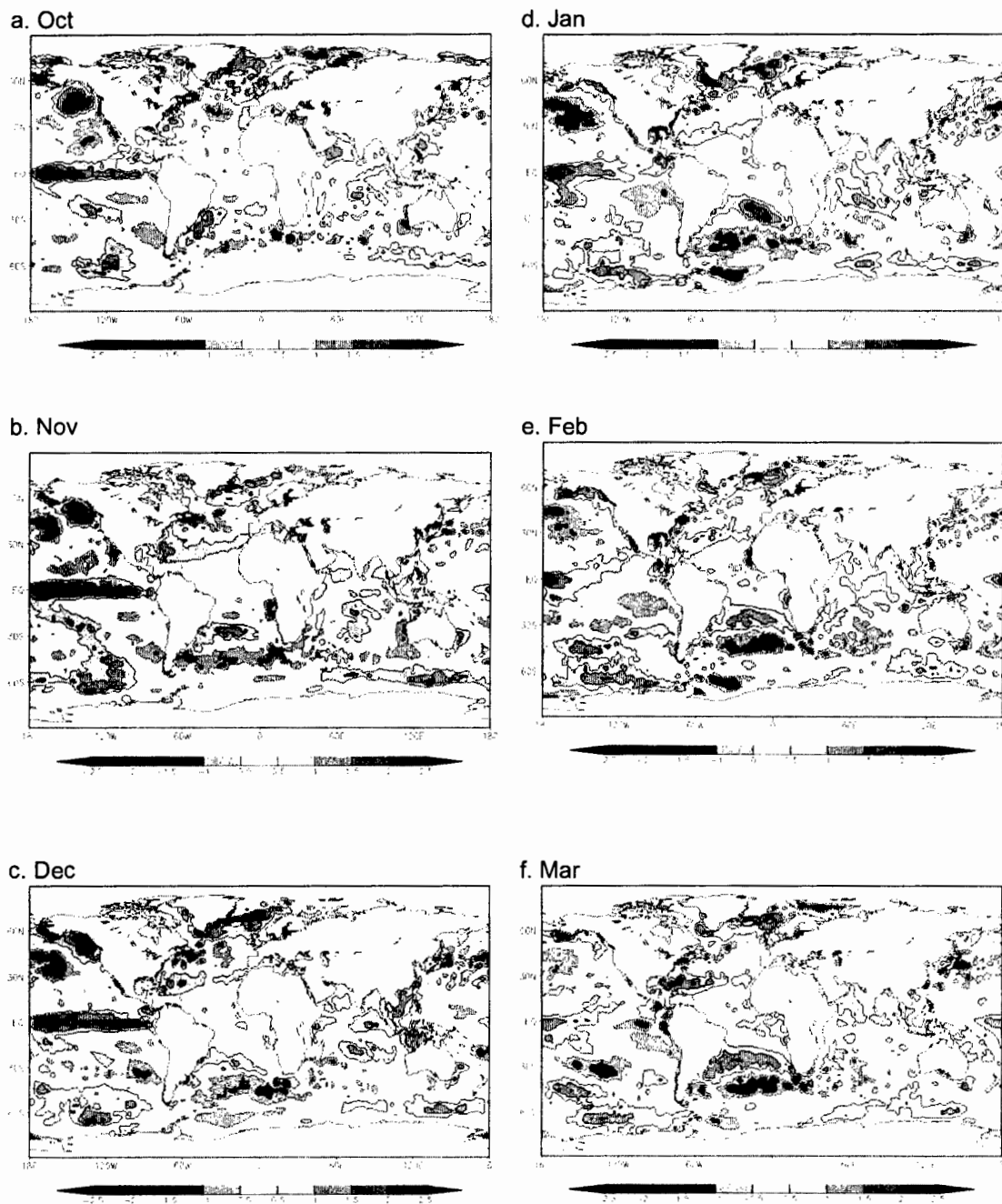


Figure 7.2 SST anomalies in the world Oceans during the early (left) and late (right) summer months of 2002/03.

Late Summer (January to March 2003)

In January (Figure 7.2d) extensive anomalously high SSTs occurred in the tropical and subtropical part of the western Indian Ocean ($0.5 - 1.5^{\circ}\text{C}$) and the subtropical South Atlantic Ocean ($0.5 - 2.0^{\circ}\text{C}$). The warming event in the central and eastern Pacific Ocean started to ebb. The colder ($-2.0 - -0.5^{\circ}\text{C}$) conditions, previously observed, persisted in the temperate zone of South Atlantic Ocean and to the south of the subcontinent, and they were consistent with the stronger west wind regime. Comparable SST conditions continued during February (Figure 7.2e) and March (Figure 7.2f), except that the anomalously high SSTs in the Indian Ocean were only found in the central equatorial part of the ocean, Agulhas Current system ($0.5 - 2.0^{\circ}\text{C}$) and to the east of Madagascar. SSTs in the equatorial Indian Ocean are strongly associated with the southern Oscillation during JFM and OND (Mason, 1995). Hence, the anomalously high SSTs observed in the equatorial Indian Ocean during this summer were in line with El Niño conditions. Warming (cooling) of the Indian Ocean occurs during low (high) phase of the Southern Oscillation.

The summer of 2002/2003 coincided with an El Niño year. In addition to the anomalously high SSTs in the Pacific Ocean, the negative SOI index (Figure 7.5) shows the development of warm ENSO during this year. The association of El Niño events with a drought over southern Africa has been well documented (Mulenga et al., 2003).

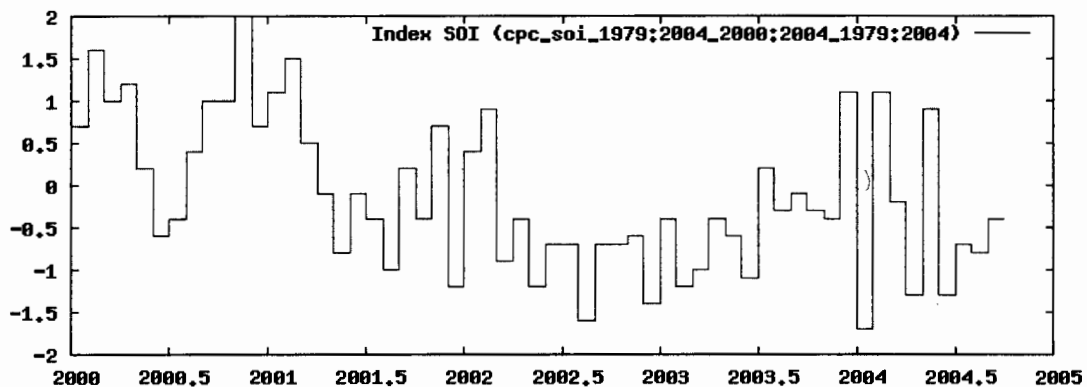


Figure 7.3 SOI index (2002 to mid of 2004) plotted using The KNMI Climate Explore website (<http://www.knmi.nl/~oldenbor>).

2003/04 Summer**Early Summer (October to December 2003)**

In October (Figure 7.4a) there were anomalously high SSTs ($0.5 - 1.5^{\circ}\text{C}$) along the west coast of the entire southern Africa. Separated patches of above normal SSTs ($0.5 - 1.0^{\circ}\text{C}$) were present in the tropical South Atlantic and Indian Oceans; meanwhile there were colder events in areas along the Agulhas Current system. Colder than normal SSTs in the Agulhas Current means reduced moisture flux into, and as a result lower rainfall in, South Africa. During November (Figure 7.4b) and December (Figure 7.4c) there were anomalously high SSTs in the subtropical Indian Ocean ($0.5 - 2.5^{\circ}\text{C}$) and anomalously low SSTs ($-1.0 - -0.5$) to the south of the subcontinent, elsewhere conditions were more or less similar to that of October. The anomalously high SSTs in the subtropical Indian Ocean to the east and south east of South Africa could possibly have shifted the location of the upper trough of the westerly waves eastwards into the Indian Ocean (Mason et al., 1994), in such a way that the region was drier than normal, while the western Indian Ocean had above normal rainfall.

Late Summer (January to March 2004)

During January (Figure 7.4d) the anomalously high SSTs of $0.5 - 1.5^{\circ}\text{C}$ in the subtropical Indian Ocean had much coverage and stretched towards the equator. There were slight warming in the Mozambique Channel ($0.5 - 1.0^{\circ}\text{C}$) and anomalously low SSTs ($-1.5 - -0.5$) in the subtropical South Atlantic Ocean. In February (Figure 7.4e) the colder SSTs in the South Atlantic Ocean expanded to its entire subtropical latitudes, meanwhile there were anomalously high SSTs ($0.5 - 2.5^{\circ}\text{C}$) to the south of South Africa. The anomalously high SSTs in the Indian Ocean were only limited to its subtropical regions. In March (Figure 7.4f) the anomalously high and low SSTs in the subtropical regions of the Indian and South Atlantic Oceans, respectively, were still lingering. During all the three late summer months there were contrasting SST anomalies over the subtropical Indian (warm) and South Atlantic (cold) Oceans both with contrasting influence on the rainfall of the subcontinent (Mason et al., 1994).

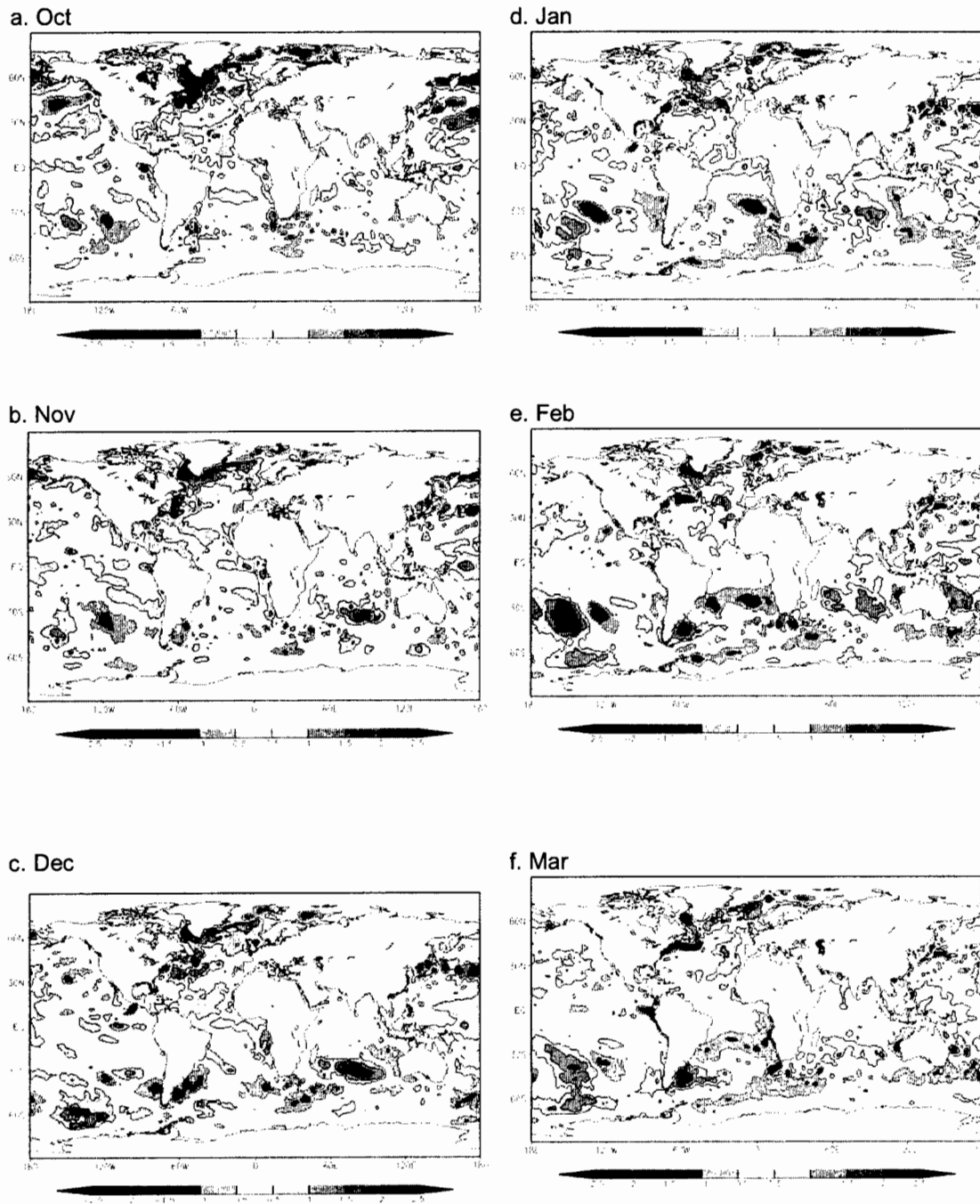


Figure 7.4 SST anomalies in the world Oceans during the early (left) and late (right) summer months of 2003/04.

8. Discussions and Conclusions

Drought is a natural disaster that emanates from the dearth of rainfall. Southern Africa, located in the subtropics is prone to recurrent droughts. Rainfall is the most important climate element in this sub-humid to arid region. During the dry periods the subcontinent experienced, it was subjected to either agricultural or hydrological droughts with many negative implications upon the social, economic and environmental aspects of the individual countries within its domain. Recently the subcontinent was hit by drought for three successive summer seasons of 2001/02, 2002/03 and 2003/04. This study has tried to examine the monthly atmospheric and SST anomalies possibly associated with the droughts during these periods.

Drought can be attributed, firstly, to the high frequency or persistence of atmospheric circulation systems that are decidedly unfavorable for rain and, secondly, to the lack or weakness of systems favorable to rain. Monthly anomalies of geopotential heights and winds, hence rainfall, can be dominated, seldom, by conditions during the prevalence of one or two strong slow moving systems, the effects of which overshadow those of a half a dozen or more weaker systems, even if most of these weaker systems have the effect of opposite sign. For example, the very large positive rainfall anomaly during the OND of 2001 over the whole region was largely due to the above average rainfall in November. Another instance of this is the very wet condition that occurred during the beginning of March 2003 in some areas of the subcontinent due to the cyclone JAPHET, which increased the rainfall total of the JFM of 2003 for the region. Nevertheless, most of the time, similar effects of several systems dominate the signs of monthly anomalies (Taljaard and Steyn, 1991). It was decided to make composite plots of months that had a great deal of similarity between them with regard to pressure and wind anomalies, while months that exhibit different patterns from the rest are treated separately. Therefore, composite plots of October and November both for the years 2001 and 2002 as well as composite plots of January and February for 2003 were made. The GPCP dataset from which the rainfall data for the region was extracted was helpful in describing the rainfall patterns and distributions over the subcontinent. Though it had coarse resolution, it significantly corresponded with the higher

resolution of CRU data. The subcontinent had below average rainfall during the three summer seasons of 2001/02, 2002/03 and 2003/04, except for the first (OND of 2001) and last (JFM of 2004) sub seasons. The extent of the droughts in those summer seasons were comparable to other severe droughts that occurred during other periods for which the GPCP applies. The summer of 2002/03 was the driest with below average rainfall during both early and late summers, in contrast to both the preceding and following summer seasons. During most of these dry periods the rainfall regime appeared to shift into parts of the Indian Ocean, which may indicate the reversal of the Walker Circulation.

In the early summer (OND) of 2001 the above average rainfall in the region was associated with the small drop of pressure over the western part of the subcontinent (centered along the coast of Namibia) and adjacent South Atlantic Ocean, and with the positive geopotential height anomalies over the middle latitudes extending equator-ward into the western Indian Ocean south of Madagascar. Stronger winds than normal were blowing into the region from the western Indian Ocean and tropical South Atlantic Ocean creating ample conditions for convergence and convection and formation of tropical lows with resulting clouds and rainfall. The anomalously high SSTs observed in the Mozambique Channel during this period were possibly feeding moisture into the region via the surface easterlies. Previous studies (Mirron and Tyson, 1984, Taljaard and Steyn, 1991) of pressure and wind patterns during wet and dry periods have noted similar situations during wet periods. During the succeeding dry summer seasons, diverse circulation anomalies occurred over the region and surrounding oceans. When the center of the negative geopotential height anomaly sat south west of Cape Town in January 2002, it allowed dry subsided air of the subtropical South Atlantic Ocean to flow over South Africa swiping away moisture from the region back into the western Indian Ocean. Besides, the anomalously high SSTs in the central Indian Ocean during the same month might have led to the weakening of the Indian subtropical high-pressure system, which in turn might have caused the reversal of the Walker circulation with ascending limb over the Indian Ocean and descending limb over the subcontinent creating wet and dry conditions over the two regions respectively. During February

and March 2002 and October 2002 to February 2003, high-pressure anomalies over the subcontinent with their characteristic anticyclonic circulation, often extending from middle or upper levels down close to the surface, were responsible for the droughts by inhibiting formation of tropical lows and convection cells. The reduction of winds flowing from the Indian Ocean onshore into the region during all the dry months imply how much the inflow of these, moisture loaded, air masses into the subcontinent is important for rainy conditions to occur. The abnormally strong westerly winds over tropical and subtropical parts of the subcontinent are consistent with circulation anomalies of previous studies of dry years (Taljaard, 1989; Mulenga et al, 2003). During JFM and OND of 2002 and January and February of 2003, the strong westerly anomalies over the low latitudes of southern Africa, at upper levels, indicate the reduction and weakening of the easterlies and their associated barotropic disturbances, which are necessary for the formation of the tropical link of the major rain producing system in the region viz. tropical-temperate-trough. On the other hand, the abnormally strong westerlies over the subtropical part of southern Africa, during some dry months, could mean high constancy of westerly winds having few or no meridional (north-south) wind components, hence weakening or less frequency or displacement of the westerly troughs. The westerly (temperate) troughs of the west wind regime, with their associated baroclinic disturbances, are the other extra-tropical link of the tropical-temperate troughs. The westerlies over subtropical southern Africa were not only stronger but they also tended to be weaker during some other dry periods, which might indicate as well the lower prevalence or migration of the temperate troughs over the region. When low-pressure anomalies, closer to the surface over the temperate latitudes particularly over the South Atlantic Ocean side, approached south of the subcontinent, westerly-southwesterly-northwesterly winds brought dry subsided air of the subtropical South Atlantic Ocean into the region. The connection between the low (high) pressure anomaly southwest or south of the subcontinent and dry (wet) summers has long been documented (Taljaard, 1989). Nevertheless, during the dry months of February and December of 2002 there were ridges sitting to the southwest and south of the subcontinent respectively. Likewise, during the wet month of March 2004 there was low-pressure anomaly sitting south of the subcontinent. Taljaard and Steyn (1991), on their reviews of studies

of atmospheric circulation and rainfall over the region, suggested that one has to be very cautious in formulating rules about the anomalies associated with dry and wet conditions.

The year 2002/03 was a moderate ENSO year. Previous studies on the association of ENSO with rainfall over the region have pointed out the bulk connection of drought in the subcontinent with ENSO during the late summer season, since ENSO is a tropical phenomenon. The circulation anomalies that occurred during this period were largely consistent with those of previous ENSO years (Taljaard, 1989; Mulenga et al, 2003). High pressure anomalies dominated over the subcontinent and neighboring tropical and subtropical oceans, while there was low pressure anomalies over the middle latitudes particularly to the south of the subcontinent. As a result the westerlies were exceptionally very strong on the south coast and to the south of the subcontinent.

The droughts of the last three summer seasons were associated with a multitude of geopotential height, wind and sea surface temperature anomalies. Southern Africa, being situated in the subtropical region has weather and climate that appear to be very sensitive to changes of atmospheric and oceanic patterns in the tropics and temperate latitudes. Many factors act together to effect the weather of the subcontinent. These recent droughts were worth studying in that they were associated with most of circulation anomalies identified before to be unfavorable for rainfall in the region. The study was analogous to a criminal investigation in that it tried to discover irregular behaviors of atmospheric circulation and SST patterns over the region and adjacent oceans that are behind the devastating droughts. Similarly, with more witnesses at hand to inquire, more could have been revealed regarding the causes of the droughts. Thus, further studies, which tries to look at the recent droughts through all angles, by incorporating supplementary variables such as moisture flux, divergence anomalies, temperature, and outgoing wave radiation could give more understanding to the causes of the droughts observed in the past three years. Such studies are important in providing information regarding rainfall to policy makers, agriculturists, business people and the general public for decision making and planning.

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