WIND VARIABILITY OVER THE SOUTHEAST ATLANTIC OCEAN

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I declare that this thesis is my own, unaided work. It is being submitted for the degree of Master of Science in the University of Cape Town, Cape Town. It has not been submitted before for any degree or examination in any other university.

ABSTRACT

The intraseasonal variability of low-level winds over the southeast Atlantic Ocean is investigated using high-resolution satellite derived QuikSCAT wind data spanning a 5-year period from August 1999 to July 2004. Wavelet analysis is applied to 20-70 day bandpass filtered zonal and meridional wind time series over six tropical and subtropical southeast Atlantic Ocean regions identified in previous research as being distinct. The influence of the winds over the tropical southeast Atlantic on southern African rainfall during late austral summer to early autumn (January – April) is studied. Composite analysis of QuikSCAT winds and National Center for Environmental Prediction (NCEP) re-analyses atmospheric circulation variables is performed to investigate the potential mechanisms influencing rainfall.

It is found that intraseasonal wind variability over the six regions is characterised by dominant frequencies ranging between 20 and 40 days. A single spectral peak with a period that shifts from 32 days in the tropical regions (10-18.5°S) to a slightly shorter 26-28 day period over the subtropical zones (19-35°S) is evident in the meridional wind spectra. The zonal wind spectra contain two main frequency peaks at 24-28 and 36-40 days. The 36-40 day frequency peak is somewhat less pronounced between 10° and 23.5°S, becoming more defined towards the south (24-35°S). The intraseasonal wind oscillations in the tropical southeast Atlantic seem to be related to convective activity over the Angola low and the West African monsoon region during late austral summer and winter, respectively. In the subtropical regions, the intraseasonal wind oscillations appear to be associated with eastward propagating midlatitude waves. Significant year-to-year variability in the intraseasonal oscillations is revealed, particularly in the timing and magnitude of dominant oscillations. Enhanced wavelet power is apparent during the 1999-2001 and 2002-2003 La Niña and El Niño events, respectively. This confirms the impact of ENSO signals over the southeast Atlantic Ocean.

Westerly winds over the tropical southeast Atlantic seem to have an important influence on southern African rainfall. Generally, significantly enhanced westerly flow over the

tropical southeast Atlantic coincides with increased moisture flux that feeds into the Angola low and enhanced rainfall over parts of southern Africa. The occurrence, magnitude and spatial extent of the rainfall activity seem to depend primarily on the amount of moisture inflow from the southwest Indian and tropical southeast Atlantic oceans, atmospheric circulation anomalies over southern Africa as well as the intensity of the Angola low. While the enhanced westerly winds over the tropical southeast Atlantic seem to have an influence on southern African rainfall, they do not appear by themselves to lead to above-average rainfall over the region, nor are all periods of above-average rainfall associated with enhanced westerly winds over the tropical southeast Atlantic.

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CHAPTER 1
INTRODUCTION

The southeast Atlantic Ocean encompasses the Benguela Current ecosystem, which is one of the four major coastal upwelling ecosystems in the world. The enhanced productivity that characterises the Benguela upwelling region supports large fisheries within the ecosystem. Other than the highly productive Benguela ecosystem, the southeast Atlantic Ocean also plays an important role in the modulation of rainfall over southern Africa, with major implications for agricultural production.

The fisheries sector is one of the important contributors to the socio-economic development of western southern African countries i.e. Angola, Namibia and South Africa. For instance, the sector accounted for 10% of Gross Domestic Product (GDP) in Namibia, 4% in Angola and 0.37% in South Africa in 2000 (Benguela Current Large Marine Ecosystem Programme, 2003). Agriculture, whose importance to the socio-economic development in the southern African region is perhaps more extensive than the fishing industry, depends on rainfall. Consequently, variability in rainfall has important implications for agricultural production and food security in the region. The significance of the fishing industry and agriculture to the economic growth in southern Africa as a whole, and the need to manage living resources in a sustainable manner has brought about the establishment of initiatives such as the Benguela Current Large Marine Ecosystem (BCLME) programme. Among other activities, the BCLME is involved in research intended to reinforce knowledge and understanding of variability in the Benguela upwelling region.

The upwelling of cold, nutrient-rich waters over the Benguela Current region is essentially wind driven. The winds over the southeast Atlantic are predominantly southerly to southeasterly and these are primarily controlled by the semi-permanent South Atlantic anticyclone. This anticyclone undergoes variations in its intensity and position on a range of timescales but with significant northward and southward displacements in winter and summer, respectively (Tyson and Preston-Whyte, 2000).

Together with the summer heating and winter cooling of the neighbouring landmass, these fluctuations in the anticyclone influence changes in the wind field. Besides the variations in the anticyclone, the winds over subtropical southeast Atlantic are modulated at synoptic timescales by the eastward passage of frontal systems and migratory anticyclones to the south of southern Africa (Shannon et al., 1990). Over the tropical region of the ocean, the synoptic wind variations are influenced by easterly waves and convective activity inland (Risien et al., 2004). Anomalous convection over tropical southern Africa, shifts in westerly wave activity, pressure fluctuations over southern Africa and South Atlantic Ocean related to El Niño Southern Oscillation (ENSO), and other climate modes are some of the mechanisms that modulate the winds at intraseasonal to interannual scales. These wind variations modulate the intensity and spatial distribution of the upwelling in the Benguela ecosystem, which is considered to be highly variable (Shannon and O'Toole, 2003). The consequent oscillations of the upwelling have important implication for fisheries.

There are a few studies (e.g. Shannon et al., 1990; Risien et al., 2004) which focus specifically on wind variability over the southeast Atlantic. Risien et al. (2004) analysed synoptic to intraseasonal variability in the meridional wind-stress over the Benguela upwelling system using 16 month (August 1999- November 2000) satellite-derived QuikSCAT data. It should be mentioned that the period of Risien et al.'s (2004) analysis coincided with a strong La Niña event.

Previous studies (Hirst and Hastenrath, 1983; Nicholson and Entekhabi, 1987; Rouault et al,. 2003) have demonstrated the influence that anomalous South Atlantic sea surface temperature (SST) has on rainfall variability over Southern Africa. The presence of warm SST over the tropical southeast Atlantic during austral summer, in particular, favours enhanced evaporation, low-level atmospheric instability and moisture flux into the heat low that develops over southern Angola and northern Namibia during summer, which has a significant impact on rainfall (Rouault et al., 2003). The moisture inflow into the region partly depends on the direction and magnitude of the prevailing wind over the tropical southeast Atlantic.

In view of the vital role played by the low-level winds in the modulation of upwelling over the Benguela ecosystem, it is essential to better understand wind variability over the southeast Atlantic at different timescales. It is against this background that this study sets out to investigate intra-seasonal variability of low-level winds over the southeast Atlantic. Further, the study explores the influence of low-level winds in the modulation of summer rainfall over southern Africa through its role in the advection of moisture into the region. This study builds on Risien et al.'s (2004) study on intraseasonal wind variability of low-level winds over the southeast Atlantic by looking at an extended QuikSCAT dataset which includes data for 1999-2004. This period was characterised by part of a strong protracted La Niña event (1998-2001), an El Niño event (2002-2003) and two neutral years (2001-2002 and 2003-2004). The data, which consist of both zonal and meridional (u and v) components, were smoothed to a spatial resolution of half a degree and a 2-day temporal resolution over the domain bounded by 10° and 35°S latitude, and 0°E and the southern African coast. Wavelet analysis is applied to the u and v wind time series that have been filtered using a 20-70 day bandpass filter to isolate intraseasonal oscillations.

To establish the role played by the low-level winds in the modulation of rainfall over southern Africa, periods for which there is enhanced westerly flow over the southeast Atlantic are determined. Atmospheric circulation anomalies during these anomalous westerly wind events are then analysed using composite analysis as rainfall activity is largely dependent on these.

The thesis layout is as follows; **Chapter 1** has presented an introduction and objectives of the study. **Chapter 2** provides a literature review. The mean atmospheric circulation over the South Atlantic is discussed. Variability at synoptic to decadal timescales is also considered. An overview of the influence of the southeast Atlantic Ocean on rainfall over Southern Africa is included in this chapter. **Chapter 3** discusses the data and analysis methods used. It briefly describes the QuikSCAT wind data, NCEP and CMAP rainfall datasets used. Wavelet, correlation and composite analyses applied in the study are also described. **Chapter 4** presents results on the intraseasonal variability of wind over the southeast Atlantic. Interpretation of the results in terms of atmospheric features and phenomena that exert some forcing on the wind is given. **Chapter 5** demonstrates the importance of low level winds over the tropical southeast Atlantic in the advection of moisture and modulation of rainfall over southern Africa. Finally the summary and conclusion are presented in **Chapter 6**.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Research on South Atlantic Ocean variability has received attention in recent years (e.g. Venegas et al., 1997; Colberg et al., 2004) in an attempt to better understand the underlying modes of variability and how these impact on the climate of the neighbouring southern African region. Presented in this chapter is a review of literature on the major modes of variability in the South Atlantic Ocean at intraseasonal to decadal timescales. Also discussed is the importance of the tropical southeast Atlantic in the modulation of rainfall over southern Africa. Some features of the mean atmospheric circulation over the South Atlantic based on previous studies are discussed in the following section so that the variations presented later can be put into context.

2.2 Atmospheric circulation

The dominant atmospheric features of the South Atlantic Ocean are the marine inter-tropical convergence zone (ITCZ) in the equatorial region, the subtropical anticyclone and the circumpolar trough in the mid to high latitudes (Tyson and Preston-Whyte, 2000). There are relatively less seasonal differences in the pressure fields and flow patterns over the South Atlantic, particularly in the subtropics, compared to the North Atlantic and Indian Oceans where the change of pressure and wind fields from summer to winter is remarkable (Van Heerden and Taljaard, 1998). However, there is a 3° or 4° northward shift and about 5° westward shift in the centre of the South Atlantic anticyclone from 30° S, 5° W in summer to around 26° S, 10° W in winter (Tyson and Preston-Whyte, 2000). Due to the semi-permanent anticyclone, southerly to southeasterly winds prevail over the southeast Atlantic. These re-curve to become the southwesterlies and westerlies that enter tropical Africa between 12° S and 5° N.

The intensity of winds along the southern African coast is controlled by the pressure gradient between the interior and the South Atlantic anticyclone (Tyson and Preston-

Whyte, 2000). Strong upwelling favourable southerly to southeasterly winds are typically observed in summer due to strong heating of the continent which leads to the formation of the heat low inland. This low contrasts sharply with the anticyclone over the southeast Atlantic which results in a steep pressure gradient along the coast. In winter, the 10hPa and 5hPa increase in pressure along the southwestern coast and at the core of the anticyclone, respectively (Van Heerden and Taljaard, 1998), as well as the presence of a weak high inland weaken the zonal pressure gradient considerably such that the southerly flow diminishes. The northward shift of the South Atlantic anticyclone in winter gives way to the transient disturbances in the south while the flow onto tropical Africa attains an increased southerly component north of 10° S.

The modulation of the mean low-level circulation at synoptic timescales in the southern part of the southeast Atlantic (south of about 30° S) is mainly through the eastward passage of migratory anticyclones, midlatitude westerly troughs and associated frontal systems (Shannon et al., 1990) and west-coast troughs. Cut-off lows are also important in the south and tend to be most frequent in spring and autumn (Singleton and Reason, 2005). Coastal lows and berg winds are features which also influence the circulation south of 25°S but their impact is mainly confined to the coastal area (Reason and Jury, 1990). Most of these transient systems occur throughout the year with varying seasonal frequency and intensity.

The passage of frontal systems which are common in winter or midlatitude westerly troughs throughout the year normally results in significant changes in wind speed and reversal of direction from southeasterly to northwesterly and then southwesterly behind the trough. The midlatitude disturbances occur more frequently in winter and penetrate farther northward. They tend to occur in cycles of 2 to 8 days (Tyson and Preston-Whyte, 2000). Migratory anticyclones usually pass in the wake of frontal troughs. West-coast troughs develop over the western coast of southern Africa particularly in summer.

Coastal lows are closely related to berg winds but they occur throughout the year unlike the berg winds which are active from late March to September (Taljaard, 1995). Tyson and Preston-Whyte (2000) conversely suggested that the winds are most common in late winter and spring. Usually, the coastal lows are initiated on the southwest coast (South Africa and Namibia) of the region and move southward and then eastward and northeastward along the South African coast with offshore flow ahead of them (Reason and Jury 1990). Although coastal lows are typically preceded by berg winds the latter can also occur without a coastal low following them. Berg winds are offshore winds from the plateau to sea level (Taljaard, 1995). These wind events occur when there are strong seaward pressure gradients between the plateau and sea level. This normally happens when a strong anticyclone is present over land or a frontal trough is approaching. High temperatures over coastal areas normally accompany the events due to the adiabatic warming and subsidence that take place.

Over the tropical southeast Atlantic, convective activity inland, particularly over the Angola low in austral summer and West African monsoon region in austral winter, plays a major role in the modulation of the wind flow at both synoptic and intraseasonal scales. Risien et al. (2004) found a correlation in the wavelet spectra of zonal wind-stress over northern Benguela and outgoing longwave radiation (OLR) over Angola and West Africa, which suggests this link between convection and the winds. The synoptic and intraseasonal wind variations over the tropical southeast Atlantic are also forced by easterly waves, which are the main driver of convective oscillations over the Angola low (Mulenga, 1998).

2.3 Variability in the South Atlantic

2.3.1 Intraseasonal variability

Some of the mechanisms or systems influencing variability in the southeast Atlantic at synoptic timescales mentioned above are also important at longer intraseasonal timescales. Besides the forcing exerted by convective activity over tropical Africa on the tropical southeast Atlantic as suggested by Risien et al. (2004), Foltz and McPhaden (2004) presented evidence of a significant correlation between 30-70 day intraseasonal wind fluctuations in the tropical Atlantic and the broadband Madden-Julian Oscillation

(MJO). The MJO signal originates from the equatorial Indian Ocean (Madden and Julian, 1971) and is transmitted through Kelvin waves which propagate eastwards to reach tropical Africa in about 20 days. In the subtropical South Atlantic, Risien et al. (2004) identified the existence of eastward propagating periodic wind events that originate over eastern South America which seem to contribute to the forcing of wind-stress over the southern Benguela at intraseasonal scales. On a broader Southern Hemisphere domain which includes the South Atlantic, Ghil and Mo (1991) found that intraseasonal variability is dominated by midlatitude westerly waves.

2.3.2 Interannual variability

Studies on interannual to interdecadal variability in the South Atlantic have mainly focused on sea surface temperature (SST) variations and the coupled sea level pressure (SLP) and SST variability (e.g. Venegas et al., 1997; Sterl and Hazeleger, 2003; Colberg et al., 2004). This is because the SST is the main parameter linking the ocean and the atmosphere (Tomczak and Godfrey, 1994) and also due to the importance of the ocean-atmosphere interaction which influences the overall climate variability on longer than annual timescales. The crucial role played by the winds in forcing SST variability in the South Atlantic has been demonstrated in previous studies (e.g. Sterl and Hazeleger, 2003; Colberg et al., 2004). The processes by which the winds influence these fluctuations include latent heat flux changes, Ekman pumping, mixing and advection (Tomczak and Godfrey, 1994).

Investigation of atmosphere-ocean variability by Venegas et al. (1997) revealed three dominant South Atlantic modes of variability. They suggested that the first mode represents a 14 – 16 year oscillation in the strength of the subtropical anticyclone accompanied by a north-south SST dipole structure which seems to be forced locally by anomalous winds. The second mode portrays east-west shifts in the position of the anticyclone centre with associated 6 – 7 year SST oscillation off the southern African coast. The SST appears not to be forced locally as enhanced trade winds are observed over the warm SST anomaly in the tropical southeast Atlantic. The spatial characteristic of this mode is similar to that of the first SST mode revealed by Mason (1995). Although Venegas et al. (1997) suggested that the mode depicts a response of the atmospheric circulation to changes in the ocean, it seems to describe warming and cooling of the Benguela upwelling system (Mason 1995).

Benguela Niños

Shannon et al. (1986) termed the extreme warm events over the Benguela region 'Benguela Niños' due to their resemblance to the warming in the Peruvian coastal upwelling during El Niño events. Unlike their Pacific counterparts, Benguela Niños are less frequent and less intense with a periodicity of about 10 years (Shannon et al., 1986). While the Benguela Niños occur less frequently, minor warm and cold surface events develop regularly along the coast of Angola and Namibia (Florenchie et al., 2004). Benguela events have been shown to have negative impacts on fish resources along the Namibian and Angolan coasts (Gammelsrød et al., 1998). During the 1995 event, for instance, high starvation-induced mortalities as well as a southward displacement of sardine stocks from Angola were observed (Gammelsrød et al., 1998).

Jury (1996) suggested that the southeast Atlantic warm events seem to be locally generated following a reduction in trade winds a year prior to an event. In contrast with these findings, Florenchie et al. (2003, 2004) provided evidence from an ocean general circulation model and satellite-derived observations that Benguela Niños as well as minor southeast Atlantic warm events are remotely generated by wind anomalies in the western and central equatorial Atlantic. The temperature anomalies created beneath the surface propagate eastwards in the equatorial wave guide and then along the coast to eventually outcrop at the southern Angola/ northern Namibia coast. On reaching the surface, the anomalies may then start interacting with the atmosphere. This implies that even though the warm episodes are not caused by local atmospheric disturbances, local wind fluctuations may partly modify their expression at the surface as suggested by Florenchie et al (2004). These results are consistent with findings from earlier work by Carton and Huang (1994), and Hirst and Hastenrath (1983).

Carton and Huang's (1994) analysis of the origin of the 1984 and 1988 warm events also revealed that the major cause of anomalous warming in the tropical eastern Atlantic is a response to changes in the wind field over the western and central equatorial Atlantic. They found that the 1984 event was preceded by intense trade winds in the western Atlantic during the summer and autumn of 1983. The relaxation of the wind stress later that year led to a surge of warm water eastward along the equator and on arrival along the southeastern coast deepened the thermocline. The 1988 event, on the other hand seems to have originated in the central equatorial Atlantic due to relaxation of trade winds and, as in the case of 1984, the anomalous warm water traveled southward along the southeastern coast and also deepened the thermocline. The deepening of the thermocline reduced the vertical flux of heat out of the near-surface layer leading to a strengthening of the SST anomaly. It also had the effect of upwelling of relatively water in the Benguela system. Although the surface expression of warm events or Benguela Niños in the southeast Atlantic appears to be limited to the Angola-Namibia coast, they are large scale events extending from the equatorial Atlantic (Florenchie et al., 2004).

ENSO signal in the South Atlantic

Previous studies have revealed that significant interannual variability in the South Atlantic is associated with the El-Niño Southern Oscillation phenomenon (e.g. Nicholson, 1997; Venegas et al., 1997; Reason et al., 2000; Colberg et al., 2004). Venegas et al. (1997) found the third coupled SST and SLP mode of variability to be highly correlated with ENSO. This mode, which has a periodicity of about 4 years, is characterized by the north-south displacement of the South Atlantic anticyclone with SST fluctuations in the central South Atlantic lagging by 1 – 2 months (Venegas et al., 1997). Sterl and Hazeleger (2003) found a largely similar 5-year mode in their analysis of coupled variability in the South Atlantic although they found the mode to be weakly related with ENSO. Enfield and Mayer (1997), and Saravanan and Chang (2000) also suggested that the ENSO signal is rather weak in this region compared to the North Atlantic.

Colberg et al. (2004) studied the response of the South Atlantic Ocean to ENSO using an ocean general circulation model and established that ENSO-induced wind anomalies play a major role in forcing the SST by altering the net surface heat fluxes, the meridional Ekman heat transport and Ekman pumping. They showed that during the April – June (AMJ) and July – September (JAS) seasons of the El Niño onset year, negative sea level pressure anomalies are observed in the subtropics and midlatitudes, which implies the weakening of the subtropical anticyclone. The negative SLP anomaly leads to the weakening of the southeasterly trades and strengthening of the midlatitude westerlies. Warming in the tropics/subtropics and cooling in the midlatitudes follow one season later. A weak positive SLP anomaly develops in the central to eastern South Atlantic during the subsequent January-March period leading to enhanced trade winds and cold SST anomalies, except over the southern Benguela where winds tend to be weaker. The opposite of these conditions observed during El Niño occur during La Niña events. These findings made by Colberg et al. (2004) are generally consistent with Nicholson's (1997) results from an observational study.

While both ENSO and Benguela Niños are associated with SST fluctuations in the southeast Atlantic Ocean, they seem not to occur in unison (Florenchie et al., 2003). Very few Benguela events have occurred in close conjunction with El Niño episodes (Mason, 1995). The recent 2001 Benguela event was preceded by the 1999/2000 La Niña event, which further suggest that Benguela Niños are not necessarily related to El Niño.

Although the influence of ENSO in the South Atlantic has been studied on a broad basin-scale using relatively coarse resolution data, its influence in the southeast Atlantic particularly over the Benguela upwelling region is still not yet clearly understood. Roy and Reason (2001) also noted this in their study on ENSO related modulation of coastal upwelling in the northeastern Atlantic. This study revealed the important contribution of the coastal upwelling to the basin-scale connection between ENSO and North Atlantic, a process which was not considered to be significant in prior studies. They suggested that the resulting weakening (strengthening) of northeast trade winds in the boreal spring associated with El Niño (La Niña) reduces (enhances) the onshore upwelling-favorable wind component. As a result, the intensity of the wind induced coastal divergence that brings cold subsurface water over the shelf is reduced (enhanced) during El Niño (La Niña). Offshore spreading of coastal water contributes to SST anomaly of a scale much larger than the continental shelf. Given these findings, the changes in wind-driven Benguela upwelling could also be important in the modulation of SST in the Southeast Atlantic during ENSO events. The present study thus attempts to investigate the influence of ENSO in the southeast Atlantic, particularly over the upwelling region, by looking at its effect on intraseasonal variability in the surface wind field using high-resolution satellite data. The period covered in this study, which is from 1999 to 2004, consists of one El Niño event, most of a protracted La Niña episode and two neutral years.

2.3.3 Decadal to multidecadal variability

The first coupled ocean-atmosphere mode of variability which has a 14 – 16 year period found by Venegas et al. (1997) indicates the importance of interdecadal variability in the South Atlantic Ocean climate. This mode represents interdecadal oscillation in the strength of the subtropical anticyclone accompanied by a north-south SST dipole which seems to be forced locally by anomalous winds (Venegas et al., 1997). At multidecadal timescales, Wainer and Venegas (2001) established the existence of a 25 – 30 year oscillation in the SST, sea level pressure and barotropic transport fields over the South Atlantic region. They suggested this multidecadal oscillation is forced by changes in the intensity of midlatitude westerlies associated with variability in southward extension of the South Atlantic anticyclone. Reason (2000) proposed that over most of the subtropics to midlatitudes of the Southern Hemisphere oceans, changes in the latent heat driven by moderations to the subtropical anticyclones seem to be more important for SST multidecadal variability than dynamical wind effects.

2.4 The influence of the southeast Atlantic variability on southern African rainfall

The influence of the surrounding oceans, particularly the Indian Ocean, on southern African rainfall has been documented in several studies (e.g. Goddard and Graham, 1999;

Reason and Mulenga, 1999). Relatively less attention has been given specifically to the role played by the tropical southeast Atlantic Ocean with only a few studies (Hirst and Hastenrath, 1983; Nicholson and Entekhabi, 1987; Rouault et al., 2003) dedicated to this area.

The southwest Indian Ocean has been described as the main source of moisture for southern African summer rainfall (Walker, 1990; Mason, 1995; Reason and Mulenga, 1999). Mason (1995) found significant correlations between summer rainfall over South Africa and the SST in the Agulhas current region such that warm anomalies are associated with above-normal rainfall over the country. Reason and Mulenga (1999) also demonstrated this rainfall-SST link using an atmospheric general circulation model. They suggested that the anomalous SST forces changes in the convergence of moist airstreams that originate mainly from the tropical and subtropical South Indian Ocean.

Although the southwest Indian Ocean is the primary moisture source for rainfall over southern Africa, the role played by the tropical southeast Atlantic is not negligible, as recently demonstrated by Rouault et al. (2003). Rouault et al. (2003) studied the influence of the tropical southeast Atlantic extreme warm events on late summer rainfall over southern Africa and observed that above-normal rainfall seems to occur consistently over the Angola/Namibia coast during all events. On the other hand, the magnitude and spatial distribution of the rainfall anomalies further inland varies between events. These appear not to depend on the magnitude of the SST anomaly but on the moisture inflow from the SE Atlantic and most importantly from the western Indian Ocean, coupled with favourable large-scale atmosphere circulation. Earlier studies by Hirst and Hastenrath (1983), and Nicholson and Entekhabi (1987) also revealed the association between southern African rainfall and the SST off the Angola-Namibian coast.

A feature of importance in the rainfall-SST link is the Angola low. The low acts as the tropical source for tropical temperate troughs, which have been described as the most important rain-producing systems for much of southern Africa (Walker, 1990; Todd and Washington, 1998). Moisture flux from the secondary tropical southeast Atlantic source and the primary southwest Indian Ocean source tends to converge over southern Angola and northern Namibia (Cook et al., 2004; Rouault et al., 2003). The moisture convergence is controlled by the intensity of the low (Mulenga, 1998). Enhancement of the Angola low is associated with an increase in the amount of moisture from the tropical South Atlantic while weakening of the low results in a decrease in the flux.

2.5 Summary

Intraseasonal to multidecadal variability is important in the South Atlantic Ocean climate as established in previous studies (e.g. Venegas et al., 1997; Reason, 2000; Wainer and Venegas, 2001; Colberg et al., 2004). Low-level winds play a crucial role in the coupled ocean-atmosphere system by forcing SST either locally or remotely at intraseasonal to decadal timescales. The main mechanisms by which the wind influences the SST may include surface-heat flux changes, Ekman pumping, mixing and advection. Convective activity over tropical Africa, particularly over the Angola low region, appears to have a significant influence on low-level winds in the tropical southeast Atlantic at intraseasonal timescales. The impact of ENSO on the South Atlantic winds and SST has been established (Colberg et al., 2004). The relationship is such that El Niño (La Niña) leads to the weakening (strengthening) of the South Atlantic anticyclone which results in reduced (enhanced) southeasterly trade winds and associated SST anomalies. The tropical southeast Atlantic acts as a secondary source of moisture for southern African summer rainfall, particularly over Angola and Namibia. Extreme warm SST events over the northern Benguela region (off the Angola-Namibia coast) are linked with above average rainfall over the neighbouring coastal areas with the inland extension of these rainfall anomalies apparently depending on the prevailing large scale atmospheric circulation as well as moisture flux from the southwest Indian Ocean and the tropical southeast Atlantic Ocean (Rouault et al., 2003).

As already mentioned, while the ENSO influence in the South Atlantic has been studied on a basin scale using relatively coarse resolution data, its effect on intraseasonal wind oscillations, particularly in the tropical southeast Atlantic, needs to be further explored.

Also much still remains to be done to thoroughly understand the mechanisms responsible for the association between SST over the tropical southeast Atlantic and rainfall over southern Africa (Rouault et al., 2003). The role played by the low-level winds over the tropical southeast Atlantic in the advection of moisture that feeds into the Angola low during austral summer region has not been explored in previous studies.

The present study builds on Risien et al.'s (2004) work, which looked at wind-stress variability across the Benguela Upwelling System at synoptic and intraseasonal time scales during 1999-2000 using QuikSCAT winds over the Benguela upwelling region. This thesis utilises 5 years of high-resolution QuikSCAT wind data from 1999-2004 in an effort to further investigate the intraseasonal and interannual variability of the wind field over the southeast Atlantic Ocean during a recent period characterised by both La Niña and El Niño events, and a neutral years. In addition, the thesis explores the influence of low-level winds over the tropical southeast Atlantic on summer rainfall over southern Africa through its role in the advection of moisture over the Angola low region. The work is intended to contribute towards improving knowledge on the southeast Atlantic Ocean variability and the role it plays in the modulation of rainfall across Southern Africa.

CHAPTER 3
DATA AND METHODOLOGY

3.1 Introduction

This chapter gives an account of the data and analysis techniques used in the study. Prior knowledge of the characteristics of the data being utilised in a study is advantageous as it makes interpretation of results easier. The challenge lies in selecting appropriate techniques to use to obtain maximum information contained in the data. Here the main datasets and analysis methods used to study the temporal variability of winds over the southeast Atlantic Ocean and the influence of enhanced winds over the tropical southeast Atlantic on southern African rainfall include QuikSCAT wind, NCEP reanalysis and CMAP rainfall datasets, and wavelet, composite and correlation analyses.

3.2 Data

3.2.1 QuikSCAT Wind Data

The vital role played by the wind field in driving variability in the South Atlantic Ocean has been demonstrated in several studies (e.g. Venegas et al., 1997; Colberg et al., 2004). Understanding the spatial and temporal variability of the low-level winds over the southeast Atlantic Ocean is needed to assess the variability of this region of the ocean which has important implications for fisheries and southern African climate.

The low-spatial resolution and coverage of observational data over the oceans, particularly the South Atlantic Ocean, has been one of the factors hindering research in the past. In recent times, high-resolution satellite data has helped in improving the situation. The availability of high-spatial resolution data makes it possible to detect and study the evolution of mesoscale features that have not been evident in previous research.

QuikSCAT wind data at 0.5° resolution spanning a five-year period from August 1999 to July 2004 in the domain extending from -40°S to 0°S and 0°E to the southern African coast (southeast Atlantic Ocean) were employed in this study. These data were derived from the SeaWinds Scatterometer onboard the NASA QuikSCAT satellite which was launched in June 1999. The SeaWinds on QuikSCAT mission was a "quick recovery" mission to fill the gap created by the loss of data from the NASA Scatterometer (NSCAT), when the satellite it was flying on lost power in 1997. The SeaWinds instrument is a specialised microwave radar that obtains wind speed and direction over the oceans at 10 m above the surface of the water by analyzing the backscatter from the small wind-caused ripples at different azimuth angles. When the microwave pulses strike the ocean surface, it causes a scattering affect referred to as backscatter. A rough ocean surface corresponding to stronger winds returns a stronger signal because the waves reflect more of the radar energy back toward the scatterometer antenna. A smooth ocean surface with weak winds returns a weaker signal because less of the energy is reflected.

In the present work, the original QuikSCAT data of 0.25° and two passes per day were smoothed temporally to 2-day composites and spatially to half a degree resolution with half-power filter cutoffs of 4 degrees of longitude by 2 degrees of latitude by 8 days (4x2x8) . The smoothing technique is applied to fill spatial/temporal gaps as the satellite swath sometimes misses a region of interest and to reduce sampling errors within the data set. Retrieval and processing of these data are discussed at length on the NASA website http://winds.jpl.nasa.gov/missions/quikscat/. Although more accurate than most data sets, the QuikSCAT data also have some errors that are associated with rain-contamination (Weissman et al., 2002). In the presence of rain, some of the energy transmitted does not reach the ocean surface but is backscattered towards the scatterometer. Also, the rain roughens the ocean surface and changes its radar cross section. These introduce errors into the process of estimating surface winds (Weissman et al., 2002). Rain flags are used in the processing of the data to eliminate these errors by identifying and separating contaminated data from the usable or non-contaminated data.

3.2.2 CMAP Rainfall

Climate Prediction Centre Merged Analysis of Precipitation (CMAP) data were utilized for rainfall analysis over the southern African domain to see whether there are any relationships between enhanced westerly winds over the tropical southeast Atlantic and rainfall over the neighbouring countries. These data are derived by merging observations from raingauges with satellite and model-based precipitation estimates and are available as monthly and pentad means over a grid of 2.5° lat x 2.5° lon. A thorough explanation of the derivation of the dataset is provided in Xie and Arkin (1997). The dataset extends back to 1979 and has been used widely in previous studies investigating rainfall variability over southern Africa (e.g. Usman and Reason, 2004; Cook et al., 2004). One of the limitations of CMAP data noted by Usman and Reason (2004) is the relatively coarse spatial resolution which may not capture local topographic effects efficiently.

3.2.3 NCEP Data

The 2.5° x 2.5° grid National Centre for Environmental Prediction (NCEP) reanalysis datasets were used to analyse atmospheric circulation variables over southern Africa, the adjacent oceans and the Southern Hemisphere. The data set comprises a global circulation model (GCM) assimilation of observed values from land stations, ship rawinsonde, pibal aircraft and satellite. The variables utilised include geopotential height, MSLP, wind, specific humidity, velocity potential, omega (vertical motion) and outgoing longwave radiation (OLR). A detailed description of NCEP datasets can be found in Kalnay et al. (1996). Caution must be applied when using the NCEP data as errors due to poor coverage of observational data over the southern hemisphere (Tennant, 2004), particularly over Africa, may arise (. Like the CMAP data, the NCEP data set does not resolve the topographic details well because of the relatively coarse spatial resolution. However, since large-scale circulation anomalies over southern Africa and the adjacent ocean regions are considered in this study, the NCEP resolution is fairly adequate.

The NCEP wind and specific humidity were used to derive low-level moisture flux and moisture divergence at 850hPa level over southern Africa and adjacent oceans. The focus was on the 850hPa level rather than sea-level because that level is close to the surface over much of southern Africa. Moisture flux is calculated as the product of specific humidity (q) and winds (u, v), giving a vector (qu, qv). Moisture divergence is derived by calculating the divergence of qu and qv moisture flux values.

3.2.4 Sea Surface Temperature

Monthly SST data from the 1° resolution 1982 – 2001 Optimal Interpolation SST (OI SST) of Reynolds and Smith (1994) were also used. Monthly composite plots were directly obtained from Mathieu Rouault's website (www.egs.uct.ac.za/~rouault). A number of studies have used this SST dataset to examine variability over the oceans and how it relates to southern African climate (e.g. Rouault et al., 2002; Florenchie et al., 2003; Rouault et al., 2003).

3.3 Methodology

3.3.1 Filtering

Bandpass filters are widely used in climate variability studies (e.g. Foltz and McPhaden, 2004; Matthews, 2004). They are useful tools for removing or isolating fluctuations in selected frequency bands (Emery and Thomson, 1998). In this thesis, a 20-70 day bandpass filter that uses a Dolph-Chebyshev convergence window (Doblas-Reyes and Deque 1998) is used to isolate the intraseasonal signal in the u and v wind anomaly time series over the southeast Atlantic Ocean. The wind anomaly time series were constructed by area-averaging both u and v components and subtracting respective monthly means, calculated for the period 1999-2004, from each average (2-day average) over six regions in the southeast Atlantic. The six regions are identical to the zones derived by Risien et al. (2004) from a self-organizing map (SOM) analysis. These regions are 10-15°S, 15.5-18.5°S, 19-23.5°S, 24-28.5°S, 29-32.5°S and 33-35°S (regions 1 to 6, respectively). They are bounded longitudinally by 0° longitude and the southern African coast.

The bandpass filter (20-70 day) was also applied to Angola low and West Africa outgoing longwave radiation (OLR) indices. Similar to the wind time series, these indices were derived by averaging NCEP/NOAA OLR over 12.5-17.5° S, 17.5-22.5°E, and 5-10°N, 0-10°E, then subtracting respective monthly means to obtain the Angola low and West Africa indices, respectively. OLR is often used as a proxy for deep convection and rainfall in the tropics (Wang and Rui, 1990; Vincent et al., 1998).

One limitation of bandpass filters is the loss of information from the ends of the output time series linked to ringing (spurious oscillations) effects associated with discontinuities at the ends of the input data (Emery and Thomson, 1998). Thus caution must be used in interpreting signals at periods near the margins of the band.

3.3.2 Wavelet Analysis

To study intraseasonal wind variability and interannual variations in these intraseasonal oscillations, wavelet analysis of the 20-70 day filtered wind time series was performed. Presented in this section is a theoretical description of wavelet analysis. A more detailed account of the technique can be found in Daubechies (1992), Weng and Lau (1994), Torrence and Compo (1998) and other wavelet textbooks.

Wavelet analysis is a helpful analysis technique for a detailed study of non-stationary signal characteristics. The tool dissects data into different frequency components, and looks at each component with a resolution matched to its scale (Daubechies, 1992). It has application in several fields such as medical research, optics as well as climate studies. Weng and Lau (1994) demonstrated the usefulness of wavelet analysis in detecting signals in non-stationary time series in a study in which they applied the technique to tropical convection over the Western Pacific. Risien et al, (2004) have also recently used it to study synoptic and intra-seasonal wind-stress variability over the Benguela Upwelling system.

A climate signal consists of various frequency components that may be localized in time relative to the entire data period (Weng and Lau, 1994). The use of standard Fourier transform analysis is not well suited for this kind of non-stationary signal as it only reveals the frequencies present and does not provide information about the time evolution of these frequency components throughout the data record. One method that was introduced as a solution for extracting the local-frequency information is the windowed Fourier transform which slides a fixed-size analysis window with constant intervals in the time and frequency domains. However, because of a wide range of frequency components present in climate data, the fixed window restricts proper detection of longer wavelengths (low frequencies) and over-represents short wavelengths (high frequencies) and therefore also has significant limitations (Weng and Lau, 1994).

Unlike Fourier and windowed Fourier transforms, a wavelet transform is most suitable as a time-frequency localization method as it uses a flexible scale that narrows to fit high-frequency signals and widens when dealing with low-frequency components. One of the main advantages of the tool is the ability to detect weak localized signals in the data that may be important, which would not be identified when using other techniques.

As already mentioned, wavelet analysis decomposes a signal represented by a function $f(t)$ with a set of basic functions $\psi_{b,a}(t)$ called wavelets. The wavelets are derived from dilations and translations of the analyzing wavelet or 'mother wavelet' $\psi(t)$, where

$$\psi_{b,a}(t) = \frac{1}{a}\psi\left(\frac{t-b}{a}\right) \tag{1}$$

b denotes position or time while $a(>0)$ represents scale length or temporal period. An energy normalization factor $1/a$ is used instead of the usual $1/(a)^{1/2}$. Normalization keeps the energy of the wavelets the same as the mother wavelet. With the normalization factor as $1/a$, the components of the continuous wavelet transform (CWT) may be directly compared to each other (Mélice et al., 2001).

The CWT of a real signal *f(t)* is then defined as a convolution of *f(t)* with respect to the analyzing wavelet $\psi(t)$:

$$W(b,a)=\frac{1}{a}\int \psi^{*}\left(\frac{t-b}{a}\right)f(t)dt \qquad (2)$$

where ψ^* indicates the complex conjugate of ψ. By varying the scale *a* and translating along the time index *b*, a picture showing the amplitude of any feature versus the scale and how the amplitude evolves in time can be constructed (Torrence and Compo, 1998).

The choice of the analyzing wavelet is done arbitrarily although it must satisfy the admissibility condition which requires the function to have zero mean and be localized in time and frequency domains. This makes it possible for the original signal *f(t)* to be reconstructed from the wavelet coefficients using the inversion formula

$$f(t)=\frac{1}{C_{\psi}}\int\frac{da}{a^{2}}\int\frac{1}{a}\psi\left(\frac{t-b}{a}\right)W_{b,a}db \qquad (3)$$

where

$$C_{\psi}=\int_{0}^{+\infty}\frac{\left|\hat{\psi}(\omega)\right|^{2}}{\omega}d\omega<+\infty \qquad (4)$$

and $\hat{\psi}$ is the Fourier transform of ψ

In this study, the one dimensional complex Morlet wavelet, which is commonly used in geophysical studies (Weng and Lau ,1994), is utilized. The wavelet is a complex cosine wave modulated by a Gaussian function

$$\psi(t)=\prod^{-1/4}e^{i\omega_0 t}e^{-t^{2}/2} \qquad (5)$$

where $i = (-1)^{1/2}$ and $\omega_0 = (2/\ln 2)^{1/2}$

The advantage of this type of wavelet is that its complex nature allows for detection of both time-dependent amplitude and phase for different frequencies present in the signal or time series.

Before performing the wavelet transform, the time series has to be padded with zeros on either ends (Torrence and Compo, 1998). This is done to offset errors that occur at the beginning and end of the wavelet power spectrum due to the finite-length nature of the time series. The zeroes have to be removed afterward. However, padding with zeroes introduces discontinuities at the endpoints. This region of the wavelet spectrum where the edge effects become important is the cone-of-influence (COI). In cases where the end-points are unimportant, COI can be disregarded (Meyers et al., 1993).

3.3.3 Correlation Analysis

Correlation analysis is often utilized to determine statistical relationships between variables with the correlation coefficient r representing how strongly the variables co-vary in time or space (Emery and Thomson, 1998). It is worth noting that a high correlation coefficient does not necessarily imply cause-and-effect relationships between variables and therefore correlation results should be interpreted cautiously (Emery and Thomson, 1998).

Correlation analysis was used to explore possible links between convection over the Angola low region and West Africa, and QuikSCAT winds over the tropical southeast Atlantic. The correlation was carried out using standardised Angola low and West Africa OLR indices, and u and v wind time series over regions 1 and 2 during the period from August 1999 to July 2004. The time series were standardised by subtracting the monthly climatological mean based on the August 1999 – July 2004 period from each record and dividing by the corresponding standard deviation.

3.3.4 Composite Analysis

Composite analysis helps in identifying the most important or strongest common features in individual events that are composited together. The advantage of using composite fields is that they are easily interpreted and they tend to reduce noise or extraneous influences.

In this study, monthly and pentad (5-day) QuikSCAT wind anomaly composites were used to determine events for which there was enhanced westerly flow over the tropical southeast Atlantic Ocean into southern Africa. CMAP rainfall and atmospheric circulation anomaly composites during the enhanced westerly wind events were also analysed. The focus was particularly on late austral summer to early autumn (January – April) during the period from August 1999 to July 2004. The JFMA period not only corresponds to the second half of the main rainy season over southern Africa but is also the time when it is most likely for the tropical southeast Atlantic to have a significant impact on rainfall due to enhanced evaporation and moisture transport from the ocean owing to SST reaching its annual maxima at this time of year (Rouault et al., 2003).

3.4 Summary

Data and analysis methods used to investigate wind variability over the southeast Atlantic Ocean and to explore the influence of enhanced low-level winds over the tropical part of the ocean on summer rainfall over southern Africa have been discussed in this chapter. Results of the analyses are presented in the next two chapters which deal with wind variability and the tropical southeast Atlantic influence on southern African rainfall, respectively.

CHAPTER 4
WIND VARIABILITY OVER THE SOUTHEAST ATLANTIC

4.1 Introduction

In this chapter, results from wavelet analyses of QuikSCAT winds over the southeast Atlantic are presented. Wavelet analysis is very useful in depicting temporal characteristics of climate signals. Here wavelet plots of 20-70 day bandpass filtered wind data are used to describe intraseasonal wind oscillations and how these vary from year-to-year.

At synoptic and intraseasonal timescales, wind variability in the tropical southeast Atlantic is mainly forced by easterly waves and inland convection. Recently, Risien et al. (2004) suggested that wind-stress variability over the northern Benguela is linked with convective activity over equatorial West Africa in austral winter and the Angola low in austral summer. The broadband Madden-Julian Oscillation (MJO), which originates from the central equatorial Indian Ocean (Madden and Julian, 1971) and is one of the major modes of intraseasonal variability in the tropics, also plays a crucial role in exerting a remote influence on the winds and convection over tropical Africa. Previous studies (e.g. Park and Schubert, 1992; Matthews, 2004; Foltz and McPhaden, 2004) have demonstrated the influence of this MJO signal in the tropical Atlantic. The signal is transmitted through equatorial Kelvin waves which propagate eastward from the equatorial Indian Ocean, reaching tropical Africa in about 20 days (Matthews, 2004). Foltz and McPhaden (2004) revealed evidence of significant positive correlations between the MJO and winds throughout the tropical Atlantic when the MJO leads by about 10-14 days.

Due to its significant effect on tropical convection and circulation, the MJO influence may extend into the extra-tropics (Madden and Julian, 1994). Levey and Jury (1996) suggested that interaction of the tropical MJO and the Rossby wave trains of the extra-tropics modulates intra-seasonal oscillation of convection over subtropical southern

Africa. However, Madden and Julian (1994) pointed out that the MJO response in the extra-tropics might not be as robust as in the tropics.

Ghil and Mo (1991) and Kiladis and Mo (1998) suggested that intraseasonal variability in the extra-tropics of the Southern Hemisphere is mainly dominated by eastward propagating Rossby wave trains. These waves which are mainly characterised by wavenumbers three and four are dominant during austral winter although they still have considerable amplitude in summer (Kiladis and Mo, 1998). In addition to these wave trains, intraseasonal variability in the subtropical southeast Atlantic may arise partly from eastward propagating quasi-periodic wind events which originate from eastern South America (Risien et al., 2004).

4.2 Meridional Wind (v wind)

4.2.1 Intraseasonal Signals During 1999-2004

The wavelet spectra of 20-70 day bandpass filtered v wind over the six regions in the southeast Atlantic show a dominant frequency band with periods ranging between 20 and 40 days. A single spectral peak with a period that shifts from 32 days in the tropical regions 1 and 2 (Figures 4.1c and 4.2c) to a slightly shorter 26-28 day period in the subtropical regions 3 to 6 (Figures 4.3c to 4.6c) is evident. This dominant 26-28 day peak is somewhat narrower in regions 3 to 5. The intraseasonal oscillations appear to be more enhanced over regions 3 and 4, where southeasterly winds are strongest on average relative to the other regions.

Risien et al. (2004) examined wind data for August 1999- November 2000 and found intraseasonal variability in the meridional wind-stress that was centred around 40 days. They found the intraseasonal oscillation to be more apparent in the subtropical regions than over the tropics. Differences in the dominant intraseasonal peaks found between Risien et al.'s (2004) findings and the results in the present study arise mainly due to the fact that here data for 1999-2004 are considered and also because a 20-70 day bandpass filter has been applied to isolate the intraseasonal wind variability. Risien et al. (2004) on the other hand looked at both synoptic and intraseasonal variability. It should also be noted that the August 1999 to November 2000 period considered by Risien et al. (2004) corresponds to a strong protracted La Niña event (1998-2001) whereas the 1999-2004 period examined here also includes neutral seasons (2001-2002, 2003-2004) and an El Niño event (2002-2003). El Niño and La Niña exert a strong but not entirely opposite impact on the winds and SST over the southeast Atlantic (Reason et al., 2000; Colberg et al., 2004).

As mentioned earlier, the observed intraseasonal wind variability over the tropical southeast Atlantic could be partly influenced by convective activity over the Angola low region during austral summer and tropical West Africa in austral winter (Risien et al., 2004). To see whether this link might exist for the 1999-2004 period, correlation analyses between 20-70 day filtered meridional and zonal wind components, and Angola low and West Africa OLR indices are carried out. The Angola low and West Africa OLR indices are standardized time series of area-averaged OLR over the Angola low and West African monsoon regions. The analyses reveal a significant correlation between these parameters. The meridional wind over both regions 1 and 2 is correlated with the Angola low OLR index during late austral summer to early autumn (February - April) with positive correlation coefficients r = 0.47 and 0.45 (both significant at 99%), respectively. Negative correlation (r = -0.45 and -0.33 significant at 99% for regions 1 and 2, respectively), is obtained between the zonal wind component and the Angola low index for February – April period.

A wavelet analysis of the 20-70 day filtered Angola low index (Figure 4.7c) reveals a dominant spectral peak at approximately 24-36 days, which is essentially contained in the dominant frequency band for both the meridional and zonal wind components. The negative (positive) correlation between the zonal (meridional) wind and the Angola low index may suggest that enhanced convection over the Angola low region induces anomalously strong westerly flow from the tropical southeast Atlantic and weakens the southerly wind component. The increased westerly wind flow may strengthen advection of moisture over the neighbouring land leading to increased instability in the lower atmosphere that could fuel the enhanced convection further. Matthews (2004) suggested the existence of this feedback mechanism between circulation in the tropical north Atlantic and convection over the West African monsoon region. The correlation coefficients for region 2 (r = 0.45 and -0.33) are less than those obtained for region 1 (r = 0.47 and -0.45), which suggests that the influence of the Angola low on the winds diminishes southward. This is supported by the weak and insignificant correlation (r = 0.18 and 0.12, for v and u wind respectively) between the Angola low index and the winds over region 3.

A relatively weak negative correlation (r = -0.17 and -0.28 for regions 1 and 2, respectively) exists between the West Africa OLR index and the meridional wind during austral winter (June to August 1999-2004), the period which coincides with the West African monsoon season. On the other hand, the zonal wind over both regions 1 and 2 is positively correlated with the West African index (r = 0.33 and 0.22 significant at 95%, respectively) during the same period. The wavelet analysis of 20-70 day filtered West African index (Figure 4.8c) shows a spectral peak at 32 days, which somewhat resembles the one evident in the meridional wind plots for regions 1 and 2 (Figures 4.1c and 4.2c). The correlation between the West Africa OLR index and zonal winds over regions 1 and 2, though rather weak, may indicate that enhanced convection over tropical West Africa enhances the easterly component of the flow from the tropical southeast Atlantic towards the monsoon region.

Using pentad OLR data for the period 1982-1994, Mulenga (1998) found a primary cycle between 20 and 30 days in convective activity over the Angola low region. Secondary cycles with frequencies as high as 10-days were also evident in some years in Mulenga's (1998) results. Again the slight differences in the dominant period of convective oscillations over the Angola low between Mulenga's (1998) findings and the results of this thesis could be due to the 20-70 day bandpass filtering applied in this study and the different temporal domains used. Easterly waves, which are important at low latitudes, are possibly the main driver of the intraseasonal convective oscillations over the Angola low (Mulenga, 1998).

In addition to the potential link with the tropical southeast Atlantic winds, intraseasonal convective oscillations over the West African monsoon region are modulated by mesoscale convective systems at 10-25 days and by the MJO at 25-60 days (Sultan and Janicot, 2003). The 25-60 day frequency contains the dominant periods evident in the meridional and zonal wind spectra over regions 1 and 2.

The associations between tropical convection and intraseasonal wind variability over the southeast Atlantic shown here could suggest that the MJO exerts an indirect forcing on the winds through its influence on the convective activity. By correlating 30-70 day bandpass filtered winds over the tropical Atlantic with a MJO index, Foltz and McPhaden (2004) found significant positive correlations throughout the tropical Atlantic when the MJO leads by 10-14 days. The correlation is strongest near the equator, diminishing poleward. These findings are consistent with Kiladis and Mo's (1998) suggestion that intraseasonal variability at lower Southern Hemisphere latitudes is dominated by the MJO on the 30-60 day timescale.

Intraseasonal wind variability over the subtropical southeast Atlantic is mainly forced by shifts in the position of the South Atlantic anticyclone (Risien et al 2004) and westerly waves (Ghil and Mo, 1991; Kiladis and Mo, 1998). Ghil and Mo (1991) found the first dominant mode of intraseasonal variability to have a period of 21-26 days in their analysis of 500mb geopotential heights over the Southern Hemisphere. The mode is dominated by eastward-traveling waves with a wavenumber four (Ghil and Mo, 1991). The period for this leading mode is fairly consistent with the meridional wind spectral results obtained for the subtropical regions 3-6 (Figures 4.3c to 4.6c) which show a dominant peak at 26-28 days.

4.2.2 Interannual Variability in the Meridional Wind Oscillations

There are significant year-to-year variations in the intensity and timing of major intraseasonal wind oscillations over both the tropical and subtropical regions (Figures 4.1b to 4.6b). Generally there is significantly enhanced activity in the 20-40 day oscillations during the periods of December 1999 - June 2001, October 2002 – January 2003 and October 2003 – January 2004. The enhanced power is particularly pronounced over regions 3 and 4 (Figures 4.3b and 4.4b) where the meridional wind component is relatively stronger than that over the northern and southernmost regions. Note that 1999/2001 and 2002/2003 coincided with a prolonged La Niña episode and an El Niño event, respectively.

Over region 1 (Figure 4.1b) enhanced power is also evident during April 2001 - February 2002 and March - June 2004. Enhanced activity, but to a lesser extent, is also apparent during June 2000 and the October 2002 – June 2003 El Niño period. There is markedly diminished power in the period between August 2000 and January 2001. The wavelet pattern for region 2 (Figure 4.2b) strongly resembles the one for region 1 (Figure 4.1b) which implies similar intraseasonal variability over these tropical regions. However, there is a noticeable difference in the intensities of oscillations with relatively more power in the wind oscillations over region 2. This may be partly due to the fact that the meridional wind component over region 2 is climatologically stronger than over region 1. In addition to enhanced power observed during April 2001 - February 2002, March - June 2004, June 2000 and October 2002 – June 2003 there is also increased activity during the austral summer of 1999/2000 (October 1999 – February 2000) over region 2.

For much of the analysis period, there is enhanced power at 20-40 day periods over regions 3 and 4 (Figures 4.3b and 4.4b). However, significantly reduced activity is apparent during July – December 2001. The wavelet spectra for the southernmost regions (Figures 4.5b and 4.6b) show maximum activity in the 20-40 day frequency band from October 1999 to June 2001 and October 2002 to January 2003, periods which respectively coincide with the prolonged La Niña event and an El Niño episode. Enhanced power is visible in July 2003 - February 2004 as well. There is noticeably reduced activity during the period between August 2001 and September 2002.

The enhanced power observed in the wavelet spectra essentially represents increased magnitude in the intraseasonal oscillations, signifying large departures from the mean meridional wind. These departures result from fluctuations in the pressure gradient between the South Atlantic anticyclone and the southern African interior (Tyson and Preston-Whyte, 2000). From the wavelet results presented there is year-to-year variability in the intensity or magnitude of intraseasonal oscillations due to interannual variability in the pressure over both the South Atlantic and the southern African region. Ghil and Mo (1991) also found considerable year-to-year variability in the dominant intraseasonal oscillations in the Southern Hemisphere. This variation is evident in Kamstra's (1987) findings on the interannual variability in the spectra of surface pressure over 2 stations on the west coast of South Africa (Alexander Bay at 29°S and Cape Town at 34°S) as well.

Previous studies (e.g. Lindesay, 1988; Reason et al., 2000; Mulenga et al., 2003; Colberg et al., 2004) have demonstrated that some of the interannual variability over the South Atlantic and southern Africa is associated with ENSO. Colberg et al. (2004) showed that during El Niño (La Niña), negative (positive) sea level pressure anomalies are observed over the subtropical and midlatitude South Atlantic, indicating the weakening (strengthening) of the South Atlantic anticyclone. Indeed pressure anomalies are evident over southern Africa and South Atlantic Ocean during the ENSO events (1999-2001 La Niña and 2002-2003 El Niño) with negative pressure anomalies over the interior of southern Africa and positive anomalies over the subtropical South Atlantic visible during December 1999 – February 2000 and February – March 2001 (Figures 4.15a and 4.15b). Positive pressure anomalies are apparent over much of southern Africa during October – December 2002 (Figure 4.15c). As mentioned earlier, these pressure changes create fluctuations in the pressure gradient between the interior and the South Atlantic anticyclone hence the winds over the southeast Atlantic which explain the enhanced power observed during the protracted 1999-2001 La Niña and 2002-2003 El Niño events. These ENSO signals are somewhat more pronounced over the northern (regions 1 and 2) and southernmost regions (regions 4 and 5). It is not easy to distinguish any interannual signals on the meridional winds over regions 3 and 4 as significant power is apparent during much of the analysis period. It must be stated however, that increased activity is not confined to periods associated with ENSO over the other regions (1-2 and 4-5). For instance, there is enhanced power during March – June 2004 in the wavelet spectrum for region 2 (Figure 4.2b). This is because interannual pressure variations over southern Africa as well as over the South Atlantic occur even during non-ENSO (neutral) years (Mulenga et al., 2003).

The interannual pressure fluctuations over the interior of southern Africa also have an influence on variability in the intensity of the Angola low and consequently convective activity there. Since it has been revealed that both the meridional and zonal winds over tropical regions 1 and 2 are significantly correlated with convection over the Angola low particularly during austral summer, these interannual variations in the convective activity may also partly account for the year-to-year variability in the intensity of wind oscillations over those regions.

4.3 Zonal Wind (u wind)

4.3.1 Intraseasonal Signals During 1999-2004

Wavelet analysis of 20-70 day filtered zonal wind (u wind) timeseries over the six regions show a dominant 20-40 day frequency band with spectral peaks at approximately 24-28 and 36-40 days (Figures 4.9c to 4.14c). The 36-40 day peak is somewhat less distinct in the tropical regions 1 to 3, becoming more pronounced towards the subtropical regions 4 to 6. This secondary peak was not evident in the meridional wind. Another significant difference is the relatively diminished activity in the zonal wind oscillations compared to the meridional wind over region 3 (Figures 4.3b and 4.11b). This weaker activity over region 3 may be because there is less zonal influence from the tropical easterly waves that impact the wind over tropical regions 1 and 2 (Figures 4.9b and 4.10b), and from the midlatitude systems which are more common over regions 5 and 6 (Figures 4.13b and 4.14b).

As discussed earlier, convective activity over the Angola low region and the West African monsoon region may partly explain the intraseasonal wind variability in the tropical regions 1 and 2 during austral summer and winter, respectively (Risien et al., 2004). Correlation analysis has revealed significant negative correlations (r = -0.45 and -

0.33, significant at 99% for regions 1 and 2, respectively) between the zonal wind and the Angola low OLR index during late austral summer/early autumn (February – April). On the other hand, positive correlations (r = 0.33 and r = 0.21 significant at 95% for regions 1 and 2, respectively) are obtained between the zonal wind and West Africa OLR index during austral winter (July - August).

The dominant 24-28 and 36-40 day peak oscillations are consistent with the first and second leading modes of variability in the Southern Hemisphere found by Ghil and Mo (1991). These modes which have periods of 21-26 and 36-40 days are dominated by eastward propagating waves with zonal wavenumbers four, and three and four, respectively (Ghil and Mo, 1991). The influence of these waves on wind variability in the southeast Atlantic appears to be more apparent in the zonal wind than the meridional wind possibly due to the direction in which the disturbances propagate. In addition to westerly waves, Risien et al. (2004) suggested the existence of eastward propagating periodic wind events that originate over eastern South America which may also contribute to the intraseasonal variability in winds over the southern Benguela.

4.3.2 Interannual Variability in the Zonal Wind Oscillations

Similar to the meridional wind, year-to-year variability in the zonal wind intraseasonal oscillations (Figures 4.9b to 4.14b) is apparent. The zonal wind wavelet spectra for regions 1 and 2 (Figures 4.9b and 4.10b) show strong resemblance in their wavelet patterns. The strong similarity in the intraseasonal variability patterns over these tropical regions is also evident in the meridional wind spectra (Figures 4.1b and 4.2b). Again, this suggests comparable variability in the wind over these regions. Markedly enhanced power in the dominant 20-40 day frequency band is visible over both regions from October 1999 to July 2000, diminishing between August 2000 and January 2001. Increased power becomes apparent again in February - August 2001. Intense activity is evident during much of the period from April 2002 to March 2003 and also from April to June 2004 while relatively suppressed activity is visible during July 2003 – January 2004.

There is relatively weaker wavelet power over region 3 (Figure 4.11b) compared to the tropical regions with diminished activity evident in the 20-40 day oscillations during much of the analysis period. However, enhanced power is visible during the austral summer of 1999/2000 (November 1999 – February 2000), the period from February to May 2001, April – June 2002 as well as during April – June 2004. Over region 4 (Figure 4.12b), the intraseasonal wind oscillations seem to have significantly enhanced intensity during the austral summer and autumn months somewhat consistently throughout the analysis period. Relative maxima in the ~20-36 day frequency band are observed during November 1999 – January 2000, April - May 2000, October – November 2000, February – March 2001, December 2001 – February 2002, April – June 2002, November 2002 – January 2003 and October 2003 – January 2004. These show that although the intraseasonal oscillations seem to be consistently enhanced during austral summer and autumn during the analysis period, there are year-to-year variations in the period of increased activity.

Over region 5 (Figure 4.13b), significantly enhanced power in the ~20-40 day frequency band is apparent during August – December 2000 and October 2003 – May 2004. Enhanced activity but to a lesser extent is also evident from October 1999 to August 2000, June 2001 to February 2002 and August 2002 to January 2003. The interannual variability in the oscillations over region 6 (Figure 4.14b) appears to be similar to that over region 5. However, the intensity of oscillations is relatively stronger over region 6 than over region 5. this strengthening over the southernmost region may be due to the midlatitude eastward propagating waves having more influence there than over region 5. Intraseasonal oscillations in the 20-40 day frequency band are visibly enhanced from December 1999 to November 2000, becoming significantly diminished from January – April 2001 but then strengthen again during June – December 2001, July – September 2002 and December 2003 - June 2004.

Like in the meridional wind component, the ENSO influence on the zonal winds over the southeast Atlantic appears to be relatively pronounced over the northernmost tropical regions 1 and 2 (Figures 4.9b and 4.10b) with significantly enhanced power in the intraseasonal oscillations during the La Niña summer of 1999/2000 and the 2002/2003 El Niño period. Over the subtropical regions 4 – 6 (Figures 4.12b to 4.14b), the intraseasonal oscillations seem to be generally active during much of the period including ENSO and neutral years. As stated earlier, ENSO events are associated with significant pressure fluctuations over southern Africa and the South Atlantic with consequent variations in the pressure gradient and winds over the southeast Atlantic (e.g. Lindesay, 1988; Reason et al., 2000; Colberg et al., 2004; Reason and Jagadheesha, 2005). This is also portrayed by Figures 4.15a to 4.15c which show significant pressure anomalies over southern Africa and the South Atlantic Ocean during periods which coincided with the ENSO events. The pressure variations over southern Africa modulate the intensity of the Angola low and the convective activity which is significantly correlated with the zonal winds over the tropical regions 1 and 2. Again, the presence of enhanced activity during non-ENSO periods suggests that interannual wind variability over the southeast Atlantic is not entirely explained by ENSO.

4.4 Summary

Intraseasonal wind variability in the southeast Atlantic is characterised by dominant frequencies ranging between 20 and 40 days with spectral peaks generally found at 24-28 days for both zonal and meridional winds with an additional peak at 36-40 days evident in the zonal wind spectra. Wind oscillations in the tropical southeast Atlantic seem to be partly related to convective activity over the Angola low and the West African monsoon region during late austral summer/early autumn and winter, respectively, with significant correlations between the wind and OLR over these regions. In the subtropical regions, the intraseasonal wind oscillations seem to be related to eastward propagating (westerly) waves. The influence of these waves on the subtropical winds is more distinct in the zonal wind component than in the meridional wind which is possibly due to the zonal direction in which the disturbances propagate.

The timing and magnitude of major oscillations vary from year-to-year as portrayed by the wavelet spectral plots. ENSO might partly account for this interannual variability in the intraseasonal wind patterns, particularly in the tropical regions, as the results show enhanced wavelet power indicating significantly increased magnitude of oscillations during the 1999/2001 and 2002/2003 La Niña and El Niño events, respectively. These results are consistent with previous work (e.g. Lindesay, 1988; Reason et al., 2000; Colberg et al., 2004) which has established that there are significant pressure anomalies over southern Africa and the South Atlantic during ENSO events. These pressure changes modulate the pressure gradient between the interior of southern Africa and the South Atlantic anticyclone (Tyson and Preston-Whyte, 2000) leading to large wind fluctuations over the southeast Atlantic. The interannual pressure variations over the interior also modulate the intensity of the Angola low and associated convective activity and hence the winds over the tropical southeast Atlantic regions (regions 1 and 2).

It should be mentioned that enhanced magnitude in the intraseasonal wind oscillations is also observed during some non-ENSO (neutral) periods as significant pressure variations can also occur over southern Africa and the South Atlantic region during some neutral years (Mulenga et al., 2003).

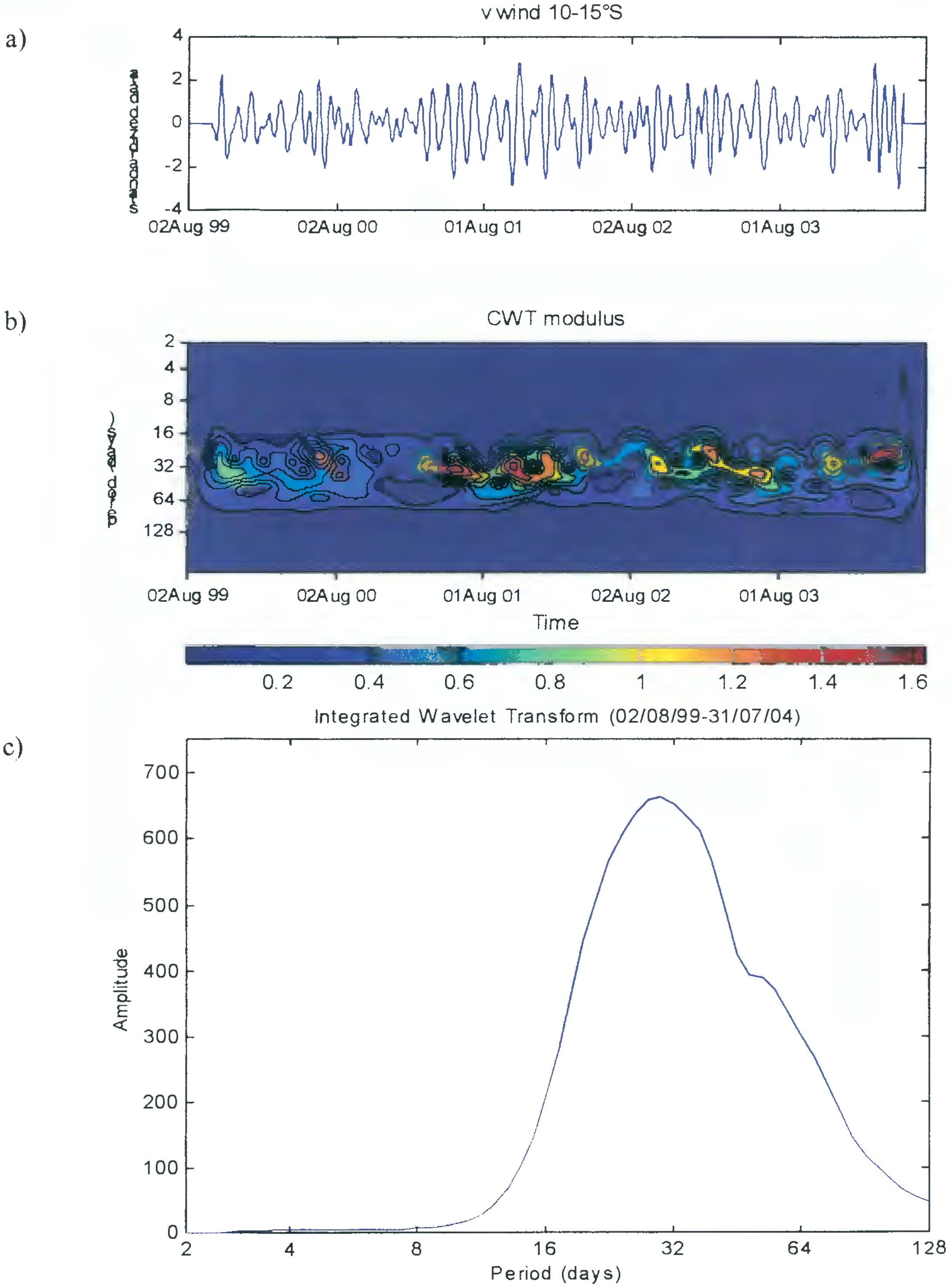


Figure 4.1 Region 1 (10-15°S). (a) The standardised time series of the meridional (v) wind component (02 August 1999 to 31 July 2004), (b) the modulus of the continuous wavelet transform (CWT), and (c) the integrated wavelet transform for the same period.

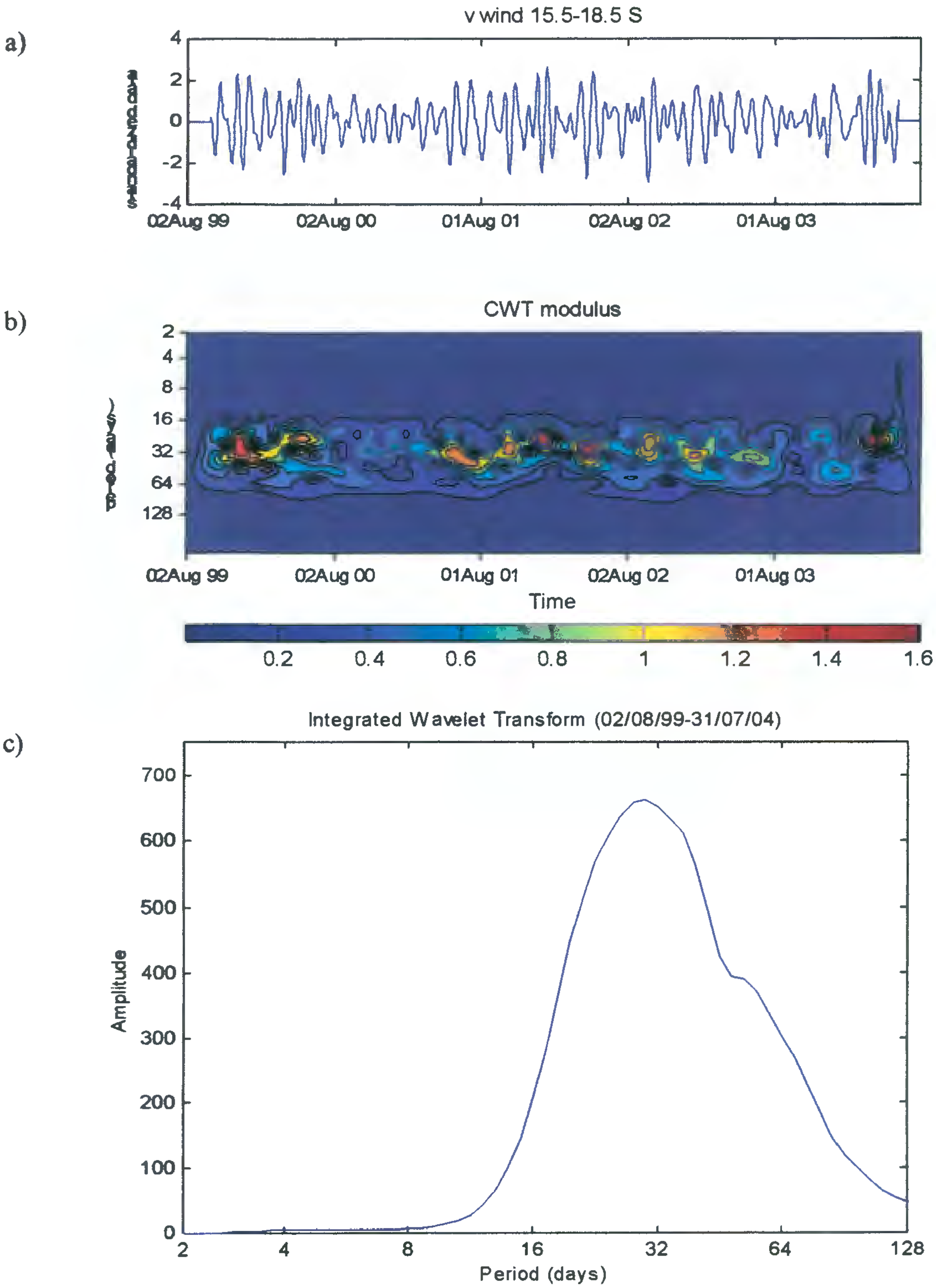


Figure 4.2 Region 2 (15.5-18.5°S). (a) The standardised time series of the meridional (v) wind component (02 August 1999 to 31 July 2004), (b) the modulus of the continuous wavelet transform (CWT), and (c) the integrated wavelet transform for the same period.

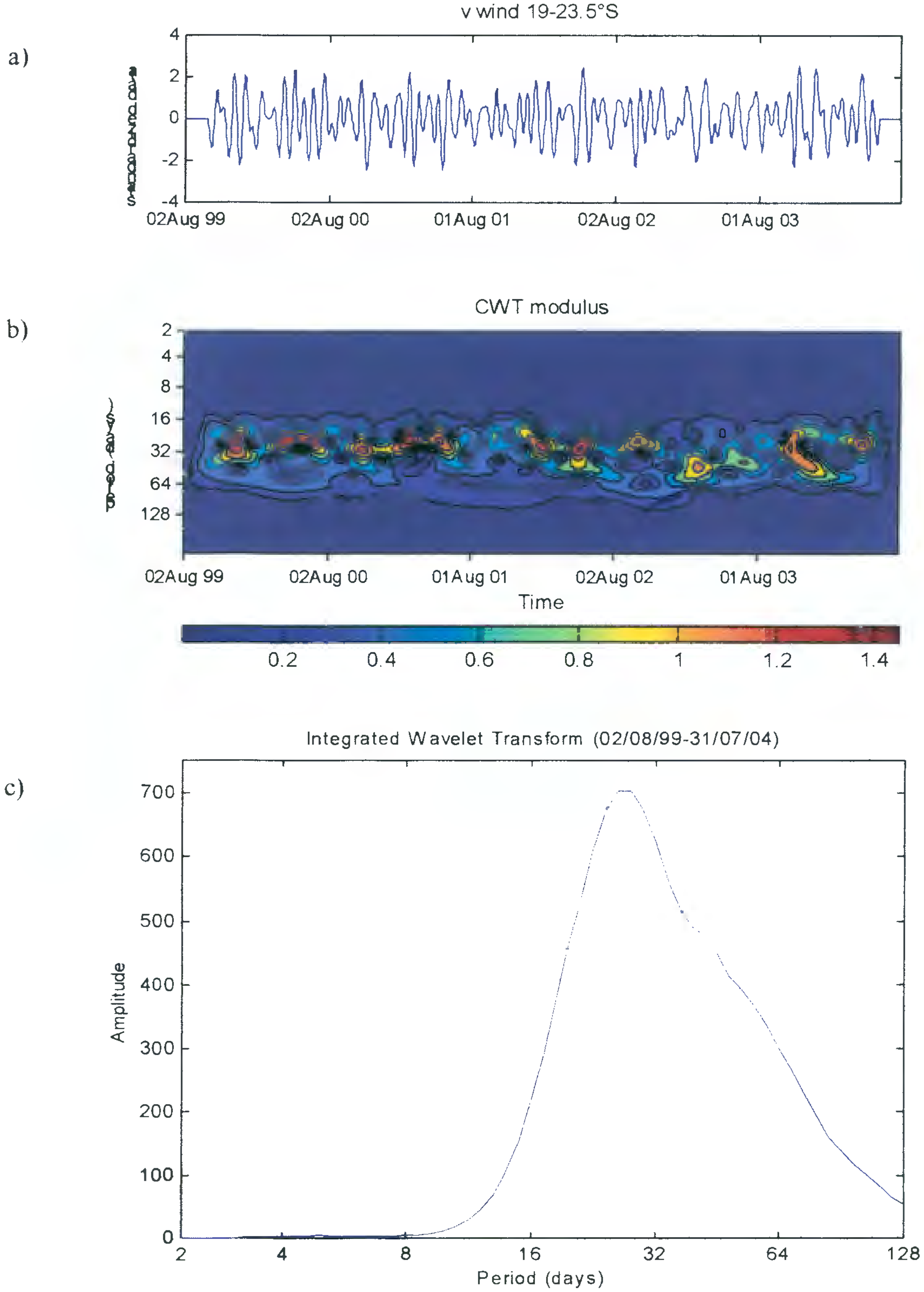


Figure 4.3 Region 3 (19-23.5°S). (a) The standardised time series of the meridional (v) wind component (02 August 1999 to 31 July 2004), (b) the modulus of the continuous wavelet transform (CWT), and (c) the integrated wavelet transform for the same period.

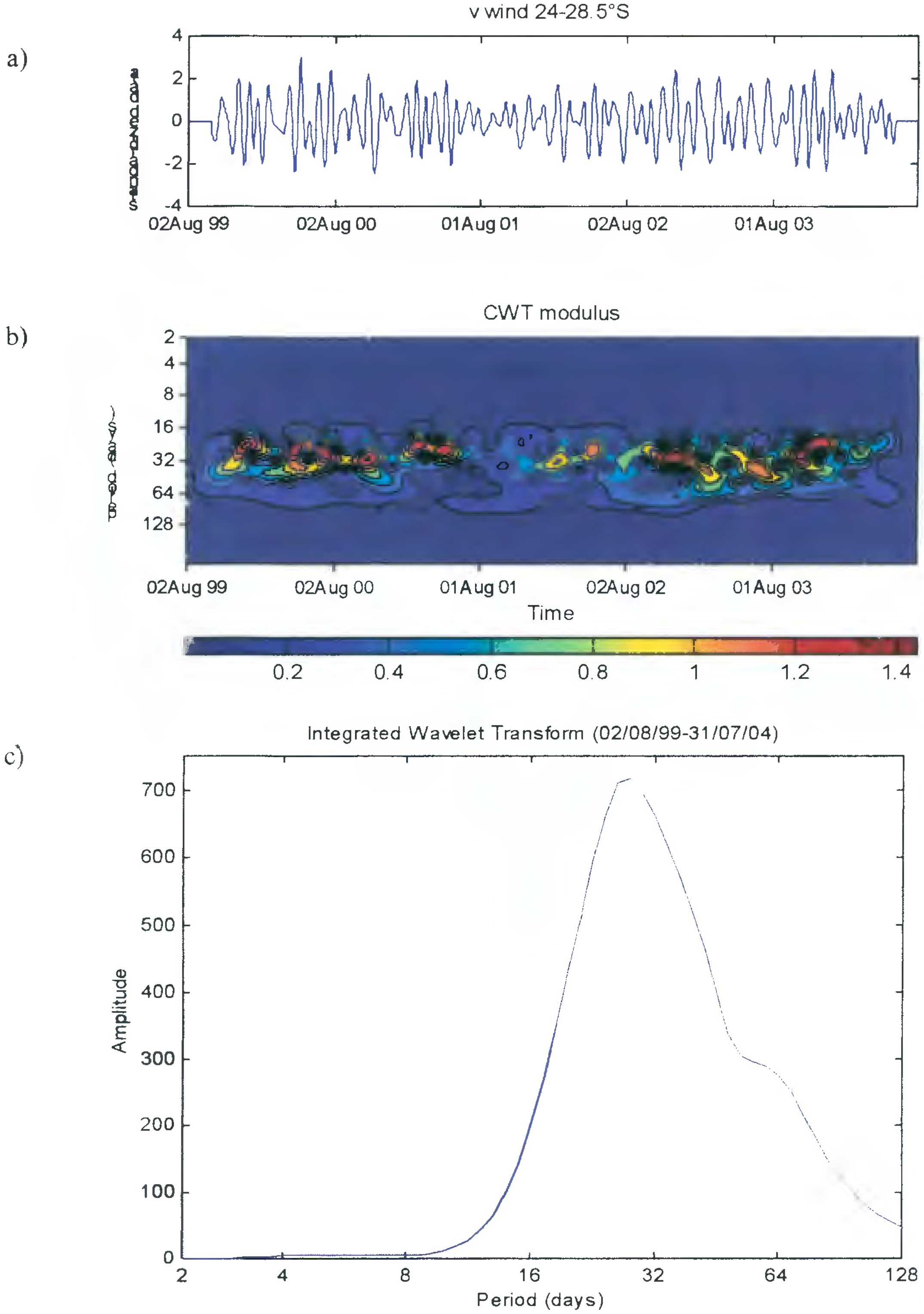


Figure 4.4 Region 4 (24-28.5°S). (a) The standardised time series of the meridional (v) wind component (02 August 1999 to 31 July 2004), (b) the modulus of the continuous wavelet transform (CWT), and (c) the integrated wavelet transform for the same period.

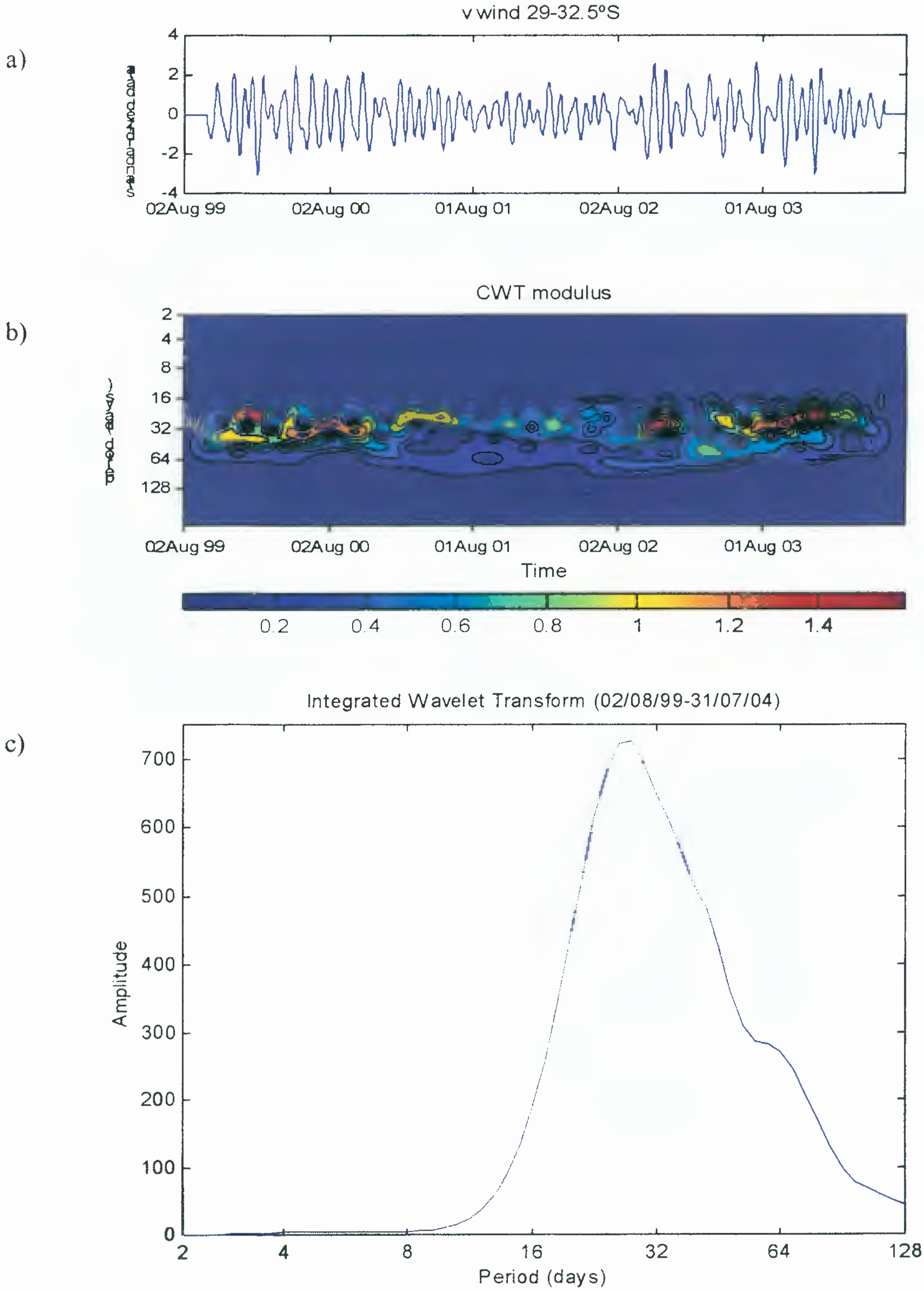


Figure 4.5 Region 5 (29-32.5°S). (a) The standardised time series of the meridional (v) wind component (02 August 1999 to 31 July 2004), (b) the modulus of the continuous wavelet transform (CWT), and (c) the integrated wavelet transform for the same period.

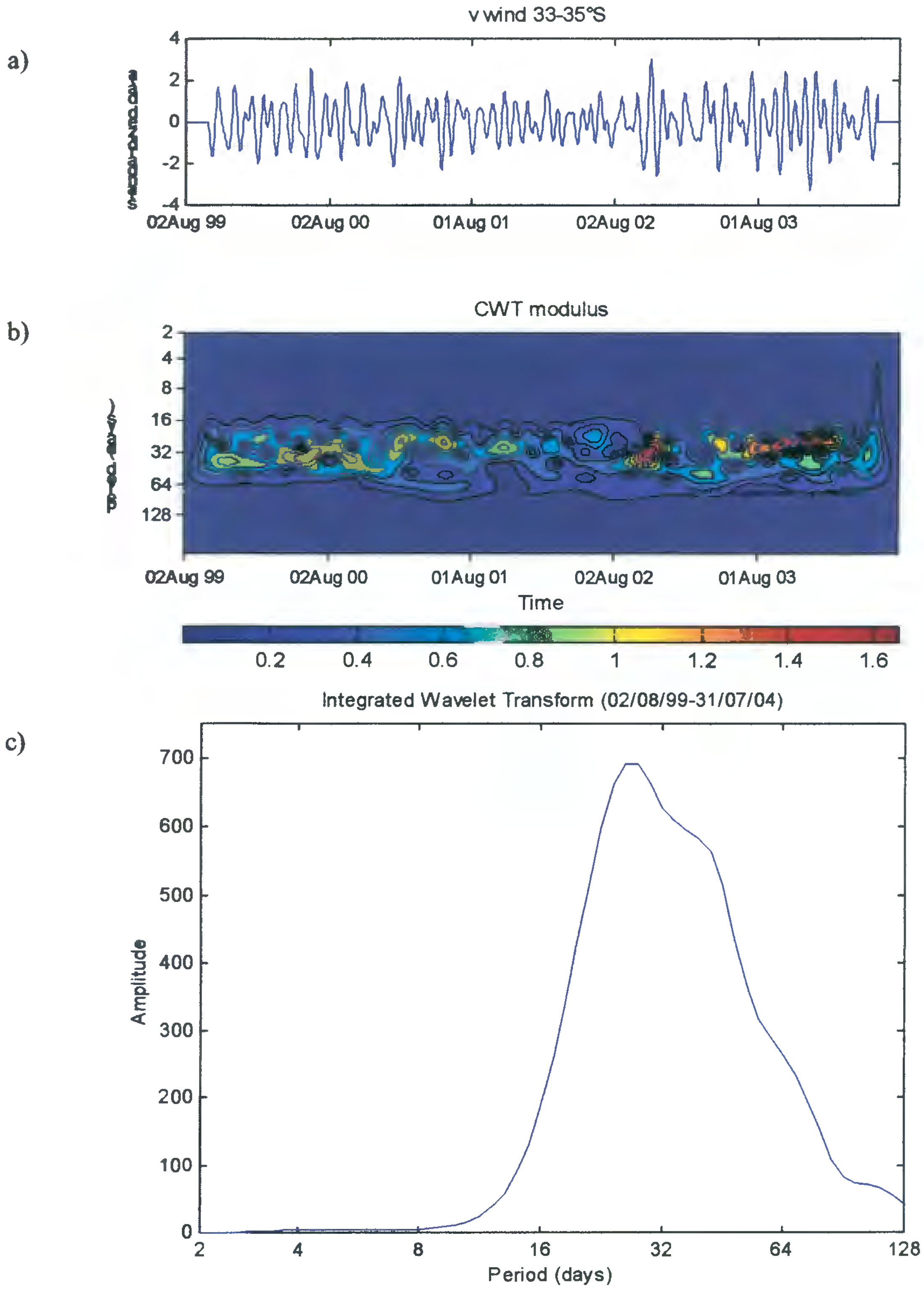


Figure 4.6 Region 6 (33-35°S). (a) The standardised time series of the meridional (v) wind component (02 August 1999 to 31 July 2004), (b) the modulus of the continuous wavelet transform (CWT), and (c) the integrated wavelet transform for the same period.

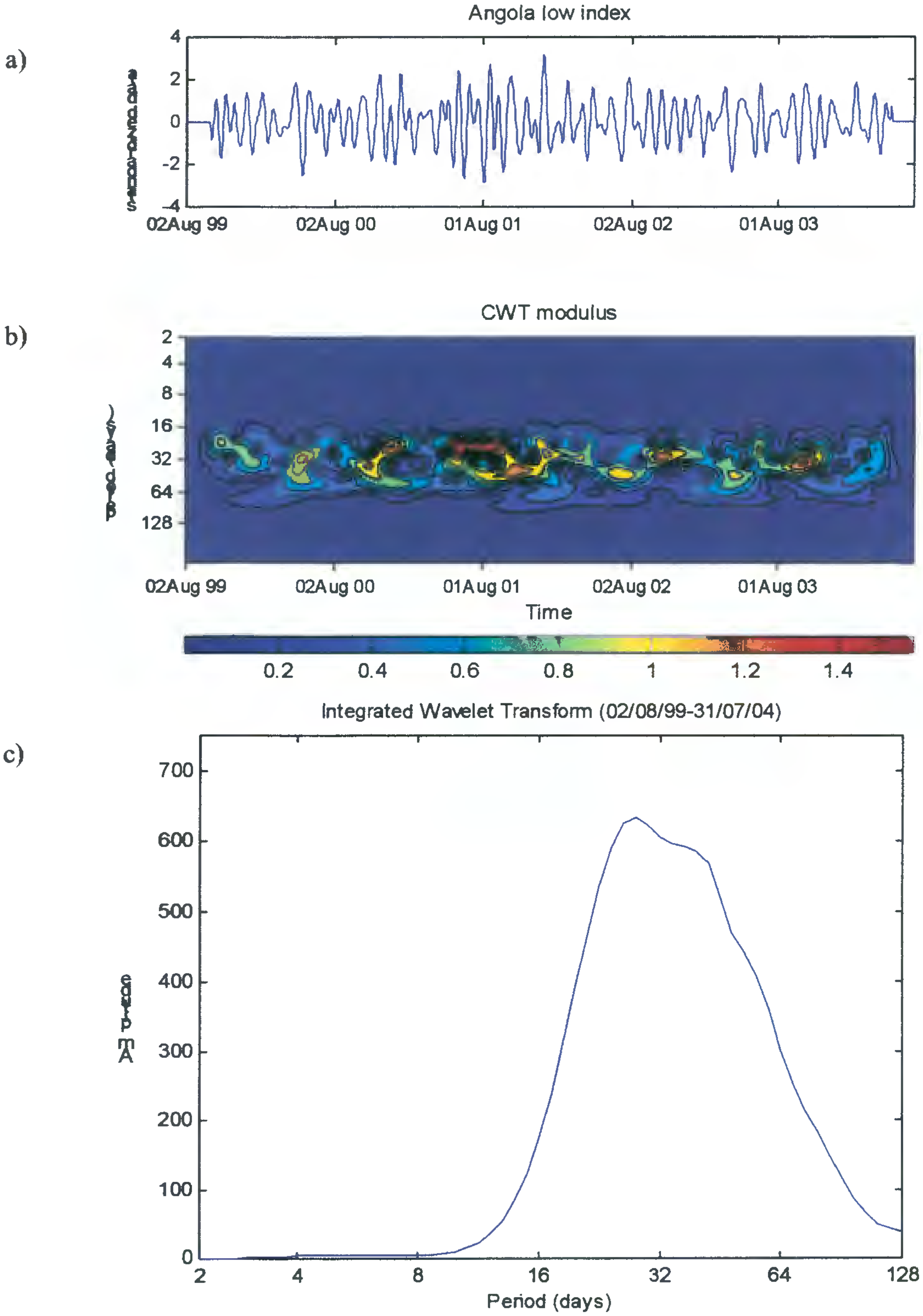


Figure 4.7 (a) The standardized time series of the Angola Low OLR index (02 August 1999 to 31 July 2004), (b) the modulus of the continuous wavelet transform (CWT), and (c) the integrated wavelet transform for the same period.

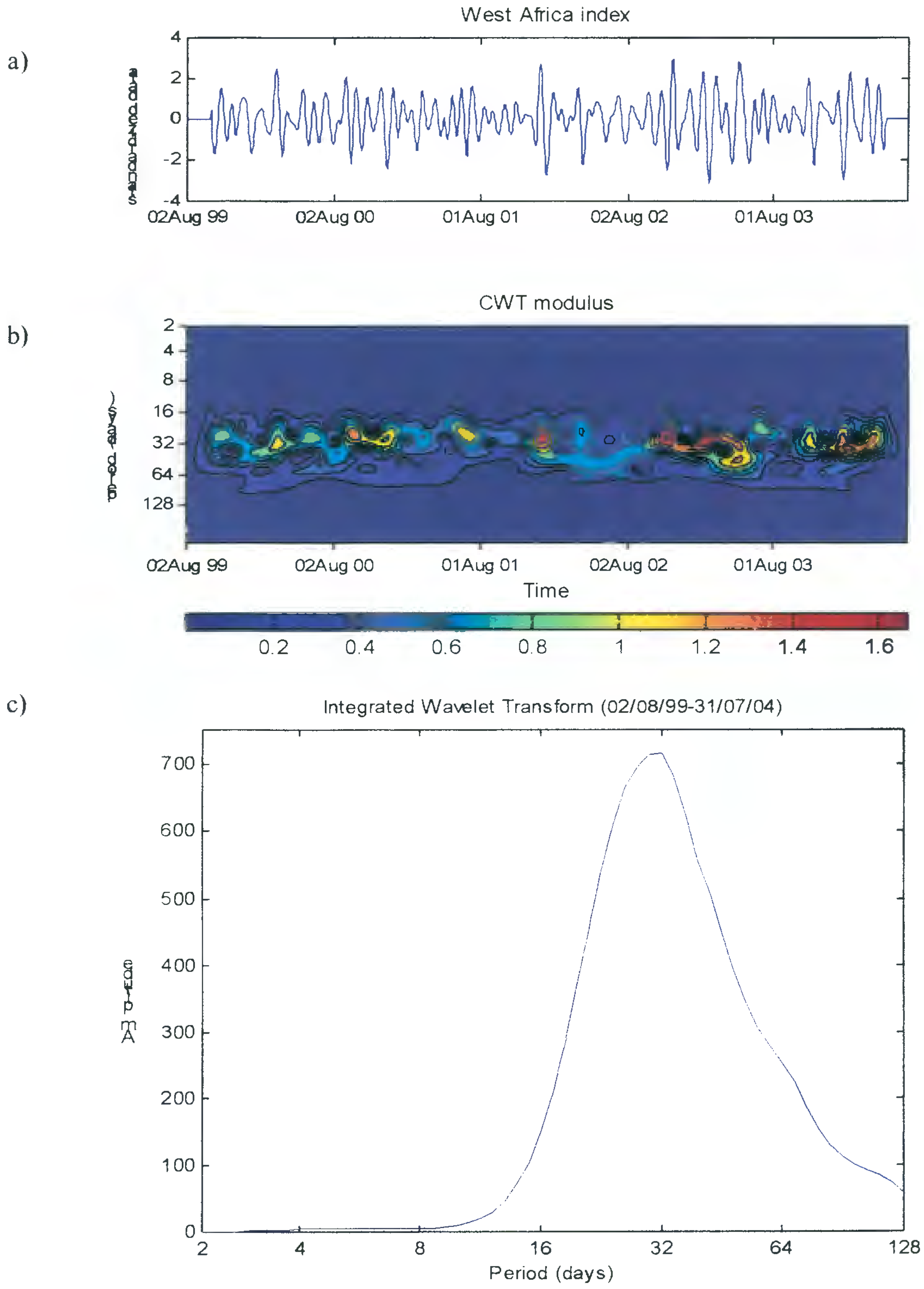


Figure 4.8 (a) The standardized time series of the West Africa OLR index (02 August 1999 to 31 July 2004), (b) the modulus of the continuous wavelet transform (CWT), and (c) the integrated wavelet transform for the same period.

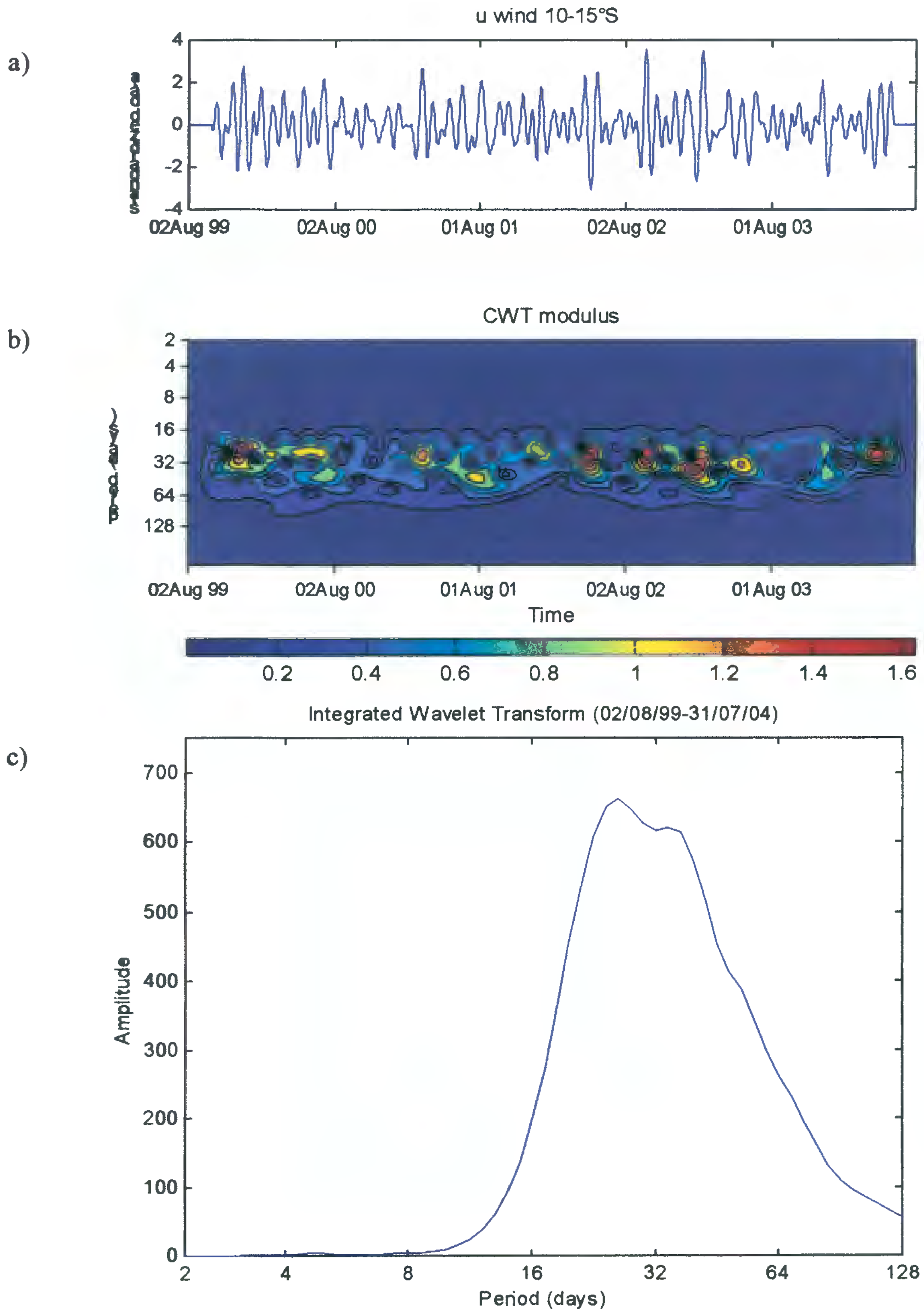


Figure 4.9 Region 1 (10-15°S). (a) The standardised time series of the zonal (u) wind component (02 August 1999 to 31 July 2004), (b) the modulus of the continuous wavelet transform (CWT), and (c) the integrated wavelet transform for the same period.

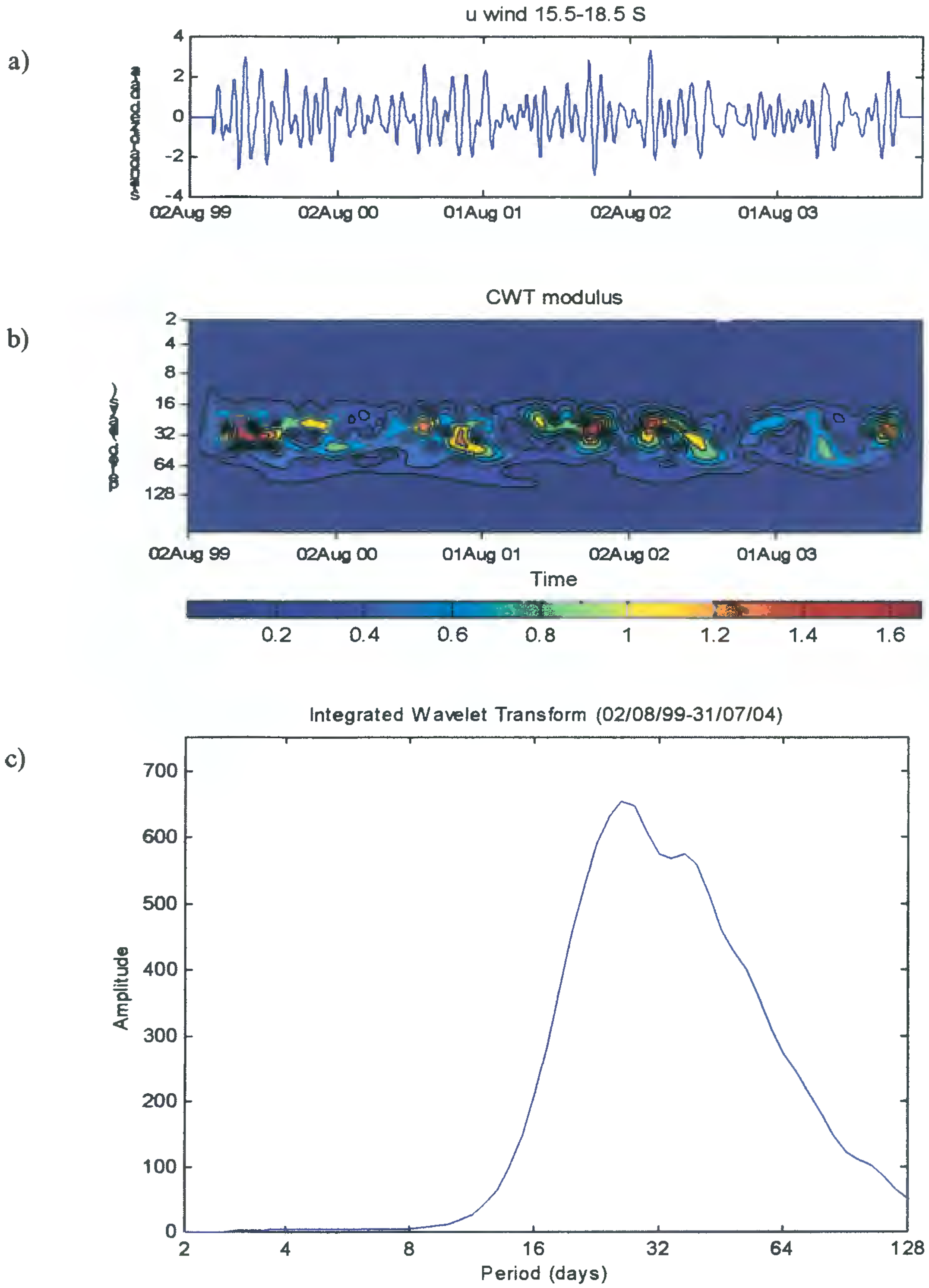


Figure 4.10 Region 2 (15.5-18.5°S). (a) The standardised time series of the zonal (u) wind component (02 August 1999 to 31 July 2004), (b) the modulus of the continuous wavelet transform (CWT), and (c) the integrated wavelet transform for the same period.

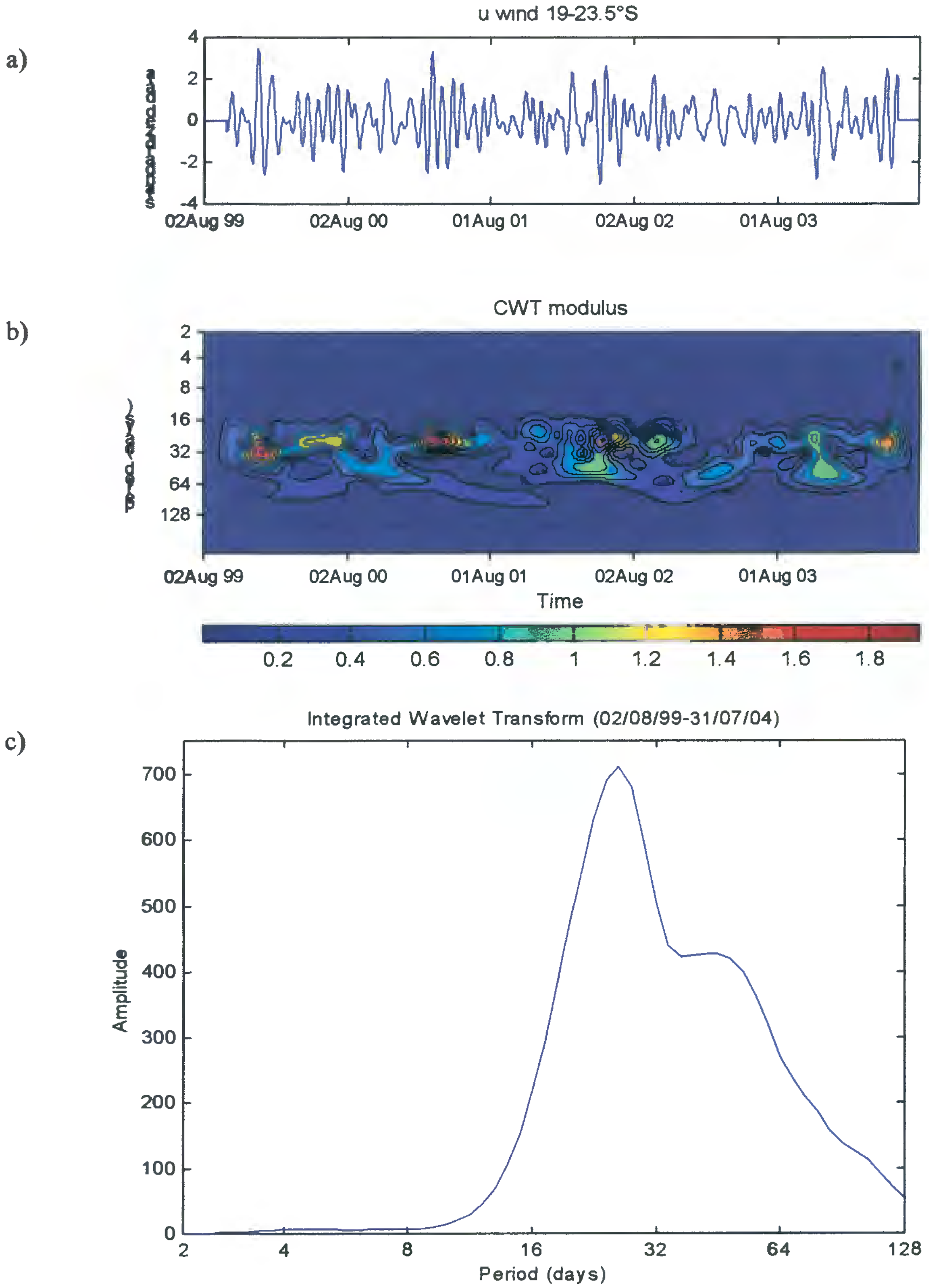


Figure 4.11 Region 3 (19-23.5°S). (a) The standardised time series of the zonal (u) wind component (02 August 1999 to 31 July 2004), (b) the modulus of the continuous wavelet transform (CWT), and (c) the integrated wavelet transform for the same period.

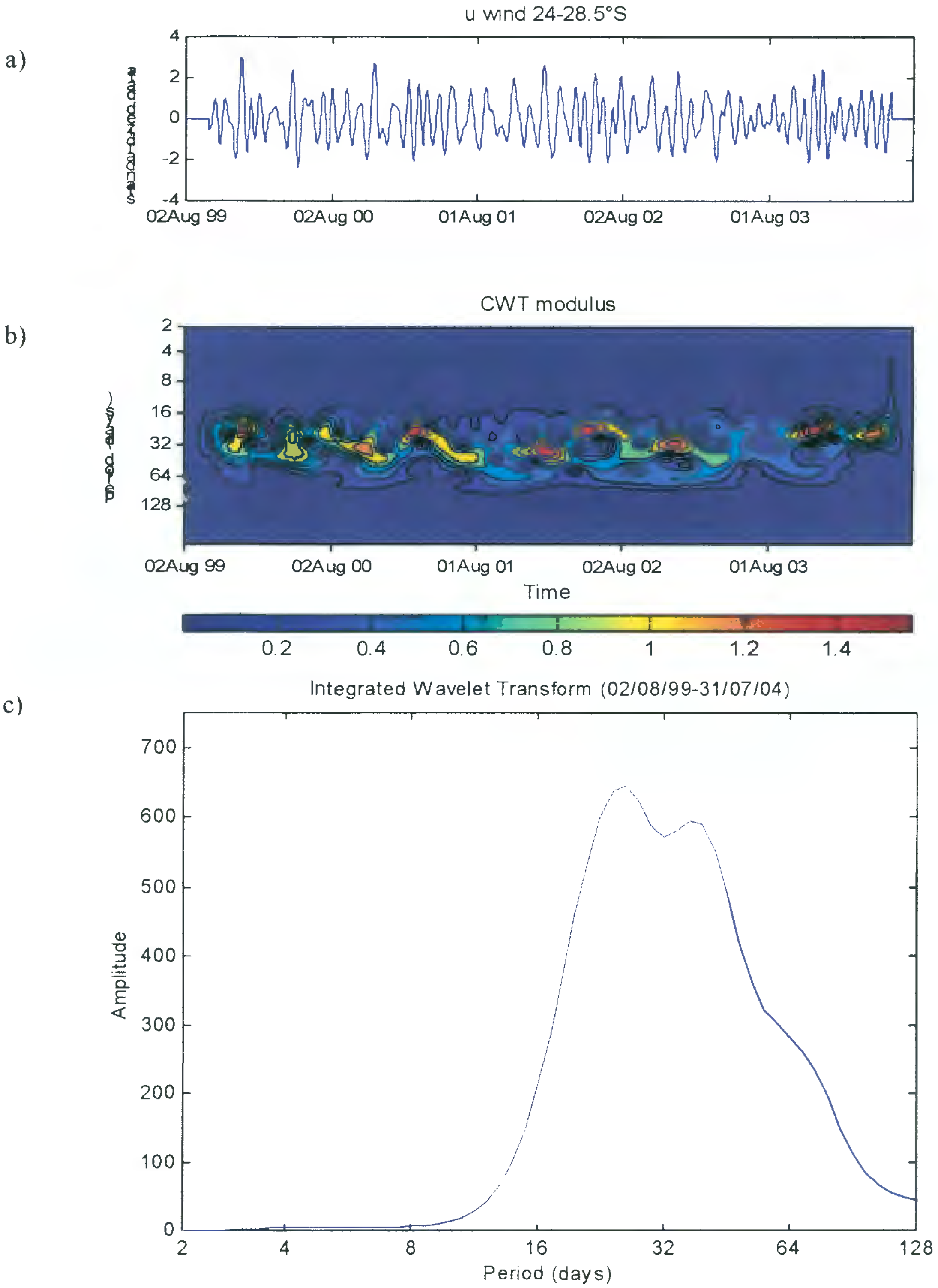


Figure 4.12 Region 4 (24-28.5°S). (a) The standardised time series of the zonal (u) wind component (02 August 1999 to 31 July 2004), (b) the modulus of the continuous wavelet transform (CWT), and (c) the integrated wavelet transform for the same period.

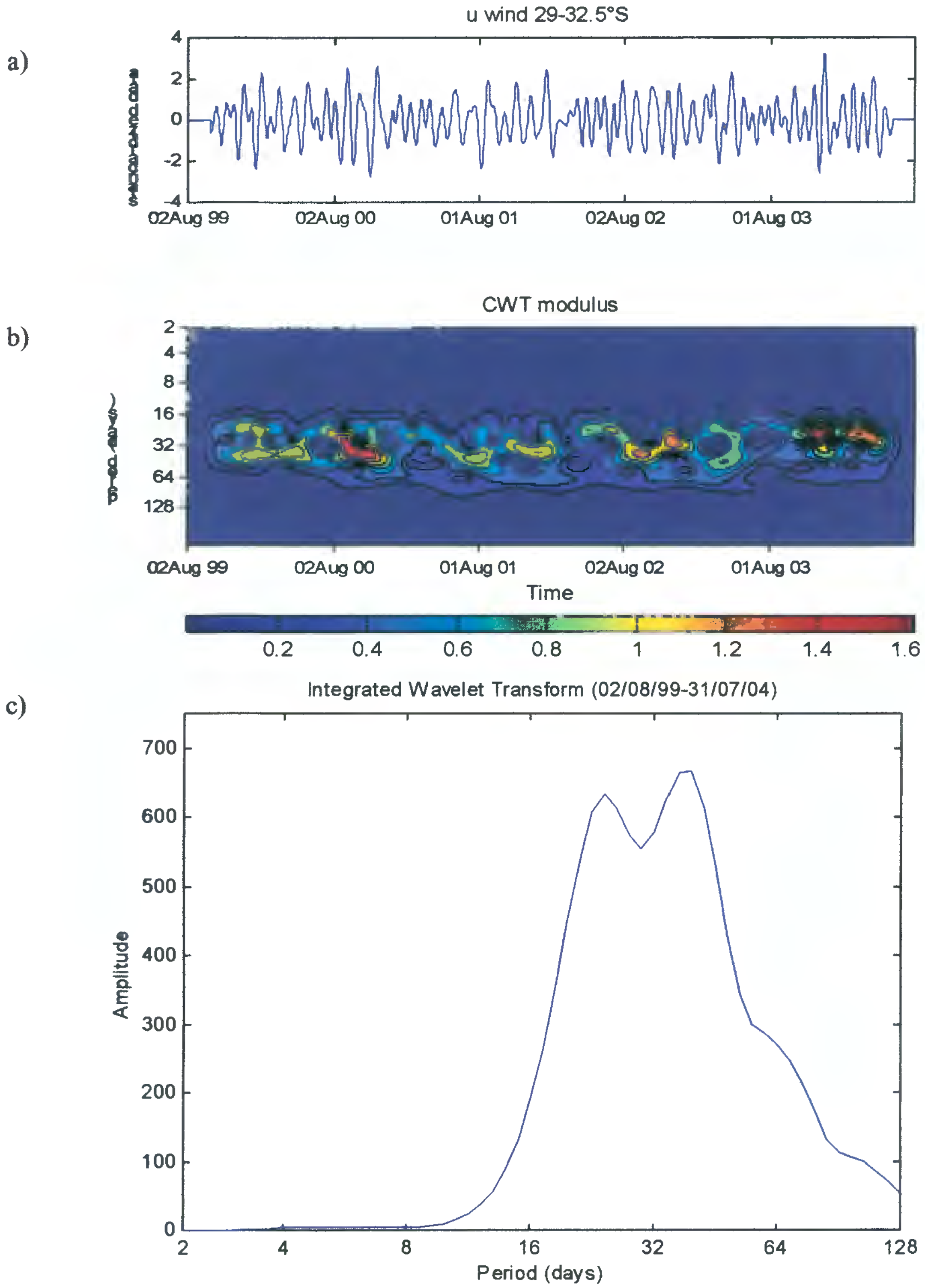


Figure 4.13 Region 5 (29-32.5°S). (a) The standardised time series of the zonal (u) wind component (02 August 1999 to 31 July 2004), (b) the modulus of the continuous wavelet transform (CWT), and (c) the integrated wavelet transform for the same period.

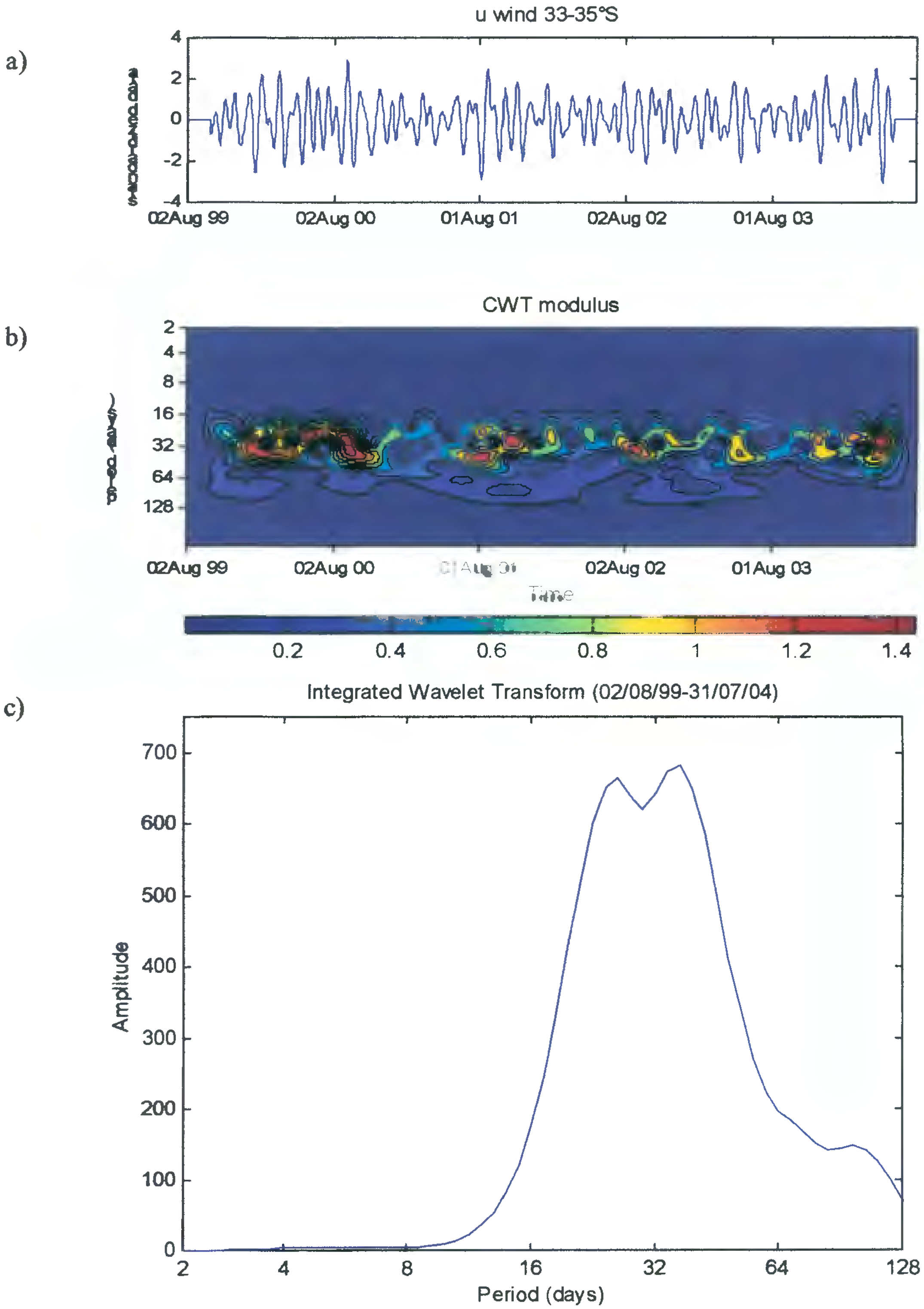


Figure 4.14 Region 6 (33-35°S). (a) The standardised time series of the zonal (u) wind component (02 August 1999 to 31 July 2004), (b) the modulus of the continuous wavelet transform (CWT), and (c) the integrated wavelet transform for the same period.

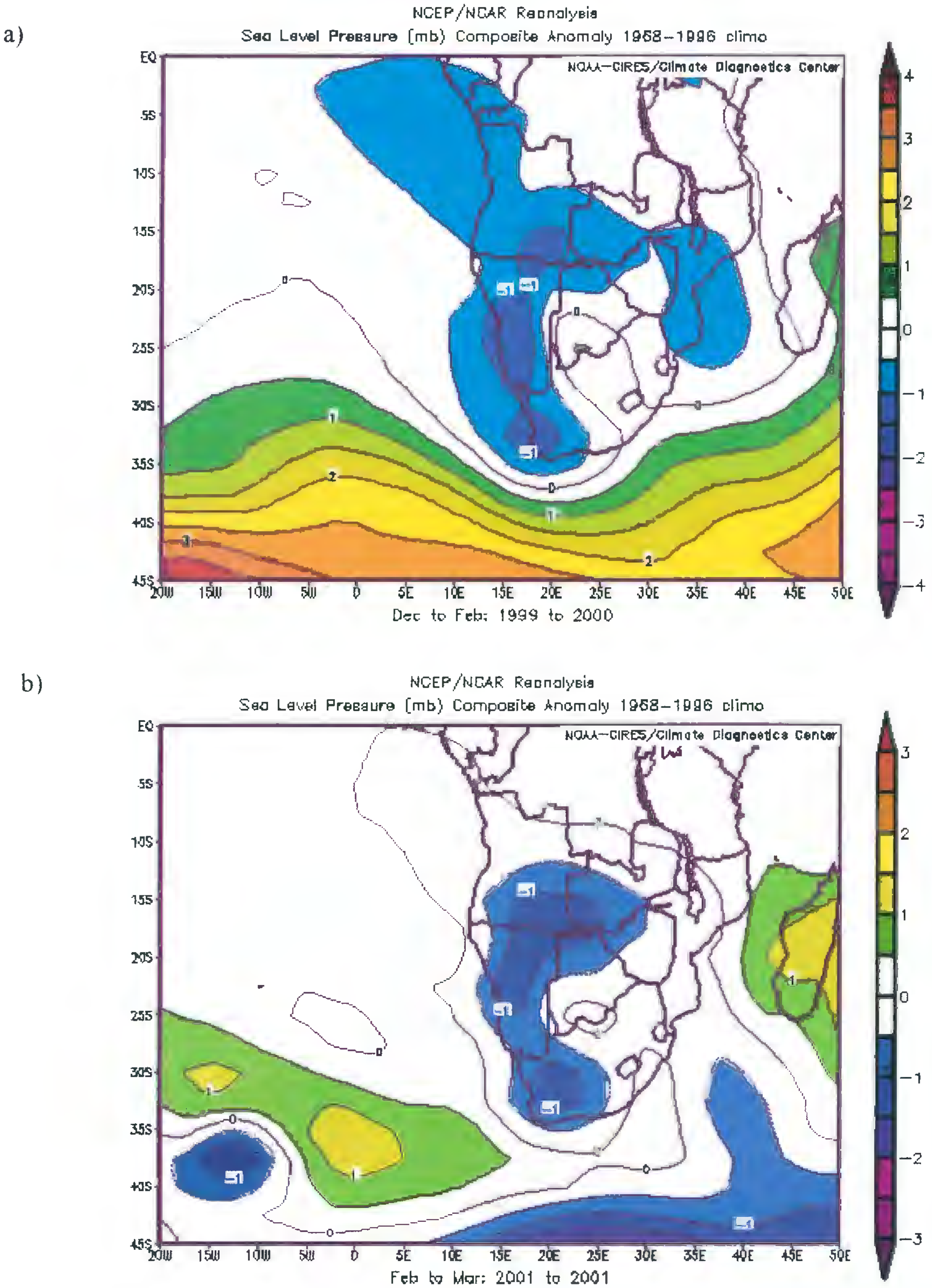


Figure 4.15 Sea-level pressure anomalies for (a) December 1999 – February 2000, and (b) February – March 2001 (contour interval 0.5 mb).

c)

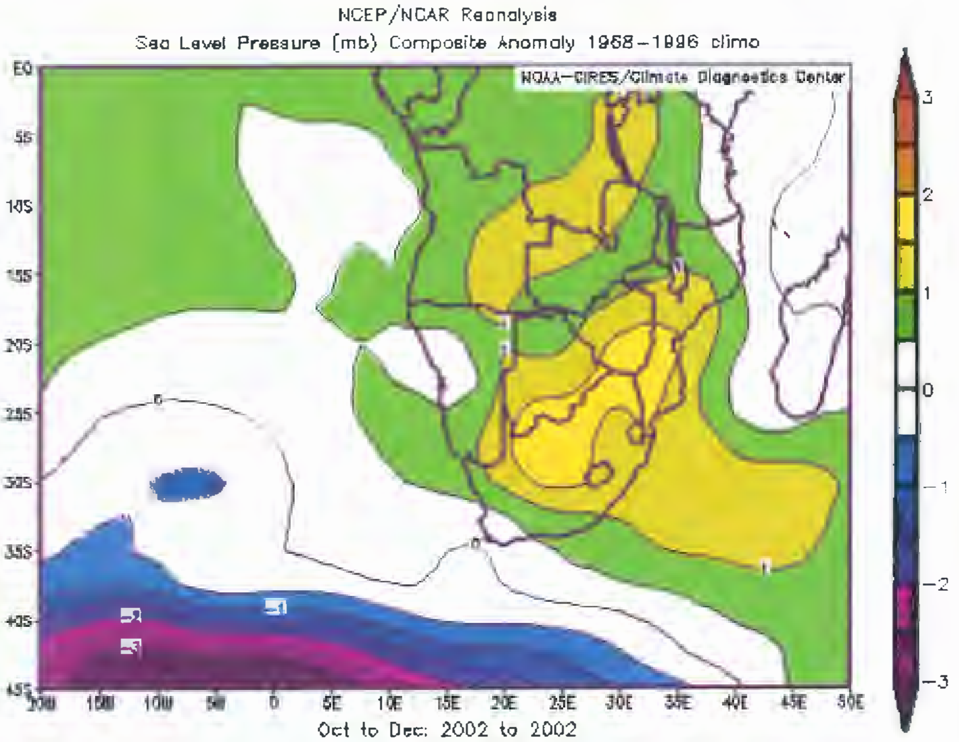


Figure 4.15 (c) Sea-level pressure anomalies for October – December 2002 (contour interval 0.5 mb).

CHAPTER 5
TROPICAL SOUTHEAST ATLANTIC INFLUENCE ON SOUTHERN AFRICAN RAINFALL

5.1 Introduction

Since the socio-economic development of the southern African region depends largely on rain-fed agriculture, it is crucial to understand the characteristics of rainfall variability over the region, as well as how this variability is influenced by the surrounding oceans. This chapter focuses particularly on the importance of low-level wind over the tropical southeast Atlantic in the modulation of summer rainfall over the region through its role in the advection of moisture into the Angola low.

The Angola low is an important feature for summer rainfall over southern Africa (Mulenga, 1998; Cook et al., 2004). It tends to form in September or October in the low latitude near-surface easterly flow over southern Africa as the landmass heats up and is typically strongest in January and February. Generally, it weakens in autumn and is not active after about May. Cook et al. (2004) suggested that this low may act as the tropical source for tropical-temperate troughs which are the major rainfall-bearing systems over the region (Harrison, 1984; Walker, 1990; Todd and Washington, 1998).

It should be noted that the southwest Indian Ocean is the major source of moisture for southern African rainfall with the tropical southeast Atlantic playing a secondary but still significant role (Rouault et al., 2003). During late austral summer (January - March), the Inter-Tropical Convergence Zone (ITCZ) moves to its southernmost position usually over northern Zimbabwe and Mozambique, and the subtropical anticyclones over the South Atlantic and Indian oceans both move further southward and southeastward, respectively (Tyson and Preston-Whyte, 2000). The mean circulation is characterised by strengthened onshore low-level westerly flow over the tropical southeast Atlantic north of about 15°S and easterly flow from the southwest Indian Ocean, with consequently enhanced moisture flux that converge over the Angola low from these sources (Cook et al., 2004). During this period (JFM), the Angola low is significantly stronger encouraging enhanced moisture convergence which is favourable for the formation of tropical-temperate troughs and widespread rains over the region.

Recently, Rouault et al. (2003) studied the influence of southeast tropical Atlantic warm SST events on southern African rainfall and revealed that above-average rainfall occurs along the Angola/Namibia coast during all warm events with the inland extension of these rainfall anomalies dependent on the prevailing atmospheric circulation anomalies. In this chapter, events for which the low-level flow over the tropical southeast Atlantic shows anomalous westerly winds towards tropical southern Africa are analysed to determine the possible influence on summer rainfall over the region during the study period (1999-2004). Prevailing atmospheric circulation anomalies over southern Africa and the adjacent oceans for the individual events are also discussed as rainfall activity is largely dependent on these. The analysis is carried out bearing in mind that the southwest Indian Ocean is the primary source of moisture for summer rainfall over the region (Rouault et al., 2003).

5.2 Enhanced Westerly Wind Events

Pentad QuikSCAT wind and CMAP rainfall anomaly plots for the rainfall seasons (December – April) of 1999/2000 to 2003/2004 show that in 2000/01 there are several pentads during which enhanced westerly winds over the tropical southeast Atlantic occurred simultaneously with above-normal rainfall over much of southern Africa. The 2000/2001 late summer/autumn rainfall season (February – April) as a whole (Figure 5.1a) shows above-average rainfall over a region extending from southern Angola/ northern Namibia eastwards to the Mozambique Channel. Some parts of southern Africa experienced floods which led to loss of property and life (Rouault et al. 2003). The bulk of the rains seem to have occurred during February and April (Figures 5.1b and 5.1d). Rainfall and atmospheric circulation patterns during selected enhanced westerly wind events are described below.

Firstly, it should be noted that the 2000/2001 rainfall season occurred towards the end of the prolonged 1998-2001 La Niña event. Above-average rainfall is usually observed over much of southern Africa during these events due to circulation changes that occur over the region and adjacent oceans. Low pressure anomalies and uplift are typically observed inland while over the Indian and South Atlantic Oceans positive pressure anomalies and associated subsidence prevail (Lindesay, 1988; Reason et al., 2000). As expected, Figure 5.3 shows low pressure anomalies with an enhanced Angola low evident over the interior of southern Africa during February-April (FMA) 2001. In addition, a trough extends southwards over Namibia and western South Africa. High pressure anomalies are evident south of the region and over the southwest Indian Ocean. The trough is favourable for the development of convection over the western interior. The high pressure anomalies over the southwest Indian Ocean suggest that there could be increased advection of low-level marine air over South Africa.

On a hemispheric scale (Figure 5.4), there are some similarities with the typical anomalous 500hPa geopotential height pattern observed during La Niña events (Kiladis and Mo, 1998). Figure 5.4 somewhat shows the reverse phase of the Pacific South American pattern (Mo and Peagle, 2001; Colberg et al., 2004) with high pressure anomalies apparent over midlatitude South Atlantic and South Indian Oceans and wave trains extending from the South Pacific into the mid-to-high latitude South Atlantic.

The velocity potential anomalies for FMA 2001 (Figure 5.5) suggest the presence of the ascending branch of the local Walker circulation over southern Africa which promotes convection, in agreement with the strong relative ascent observed over much of the region (Figure 5.6). This scenario where the local Walker circulation ascends over southern Africa is typically associated with La Niña, whereas El Niño is usually characterised by an offshore shift of the ascending branch so that it lies over the western Indian Ocean rather than over the southern Africa (Lindesay, 1988; Reason et al., 2000). Figure 5.6 shows a strengthened rising branch of the Walker circulation over the Indonesian region consistent with La Niña conditions.

QuikSCAT wind and low-level NCEP-derived moisture flux anomaly plots for FMA 2001 (Figures 5.7 and 5.8) show moderately enhanced westerly flow over the tropical southeast Atlantic into Angola, with a distinct cyclonic anomaly evident over southern Angola/ northeastern Namibia indicating an intensification of the Angola low. On the other hand, the easterly moisture inflow from the tropical southwest Indian Ocean was weaker than average with northeasterly moisture flux anomalies visible over Mozambique and the Channel area. There is a strong relative moisture convergence at 850hPa that is centred over southeastern Angola (Figure 5.9) corresponding to the cyclonic anomaly present in the moisture flux anomaly plot (Figure 5.8), again portraying the strengthened Angola low. The region of relative convergence over Angola extends eastward over Zambia, Zimbabwe and Mozambique. Cook et al. (2004) suggested that this indicates that the ITCZ over tropical southeastern Africa is enhanced and shifted southwards. Consistent with the suggestion, the CMAP rainfall anomaly plot (Figure 5.1) actually shows above-average rainfall over the aforementioned countries where the ITCZ and associated convection appear to be enhanced. Relative moisture convergence is also visible over central South Africa while anomalous divergence is present over the southeastern coast. The OLR anomaly plot (Figure 5.2) also confirms the enhanced convection over much of the region with a band of strong negative anomalies stretching eastward from Angola to the Mozambique Channel and southwest of Madagascar.

Furthermore, persistent warm SST anomalies were in existence over the tropical southeast Atlantic Ocean and along the Angolan and Namibian coasts as well as over the Agulhas Current region during the period from February to April 2001 (Figure 5.10 (a)-(c)). The anomalies over the tropical southeast Atlantic Ocean correspond to a moderate Benguela Niño event (Rouault et al., 2003; Florenchie et al., 2004). Enhanced evaporation of moisture off the warm SST anomalies may have resulted in increased low-level instability and moisture inflow inland towards the Angola low (Rouault et al., 2003). Warm SST anomalies were also present in the southwest Indian Ocean off the southeastern coast of southern Africa. Previous work (Walker, 1990; Reason, 1998; Rouault et al., 2002) has shown that the presence of warm SST over the Agulhas Current region may lead to increased low-level advection and convergence of moisture over the region. However, the moisture anomaly plot for FMA 2001 (Figure 5.8) does not indicate a significant increase in the easterly moisture inflow from the southwest Indian Ocean but rather shows a near to slightly above-average easterly flow over southern Mozambique and the eastern coast of South Africa, respectively. This can be explained by the close to average low-level easterly winds over the eastern coast of southern Africa (Figure 5.7) during the FMA 2001 period. Farther north over northern Mozambique and Madagascar, stronger easterly anomalies are evident consistent with the high pressure anomalies over the southwest Indian Ocean shown in Figure 5.3.

Given that intraseasonal wet and dry spells occur throughout the southern African rainy season regardless of whether the season has an overall above or below-normal rainfall, it is important to also look at pentad composites as these may portray the influence of enhanced westerly flow from the tropical southeast Atlantic on rainfall more clearly. Hence composites for specific pentads for which westerly winds over the tropical southeast Atlantic were particularly enhanced are considered below.

9-13 February 2001

The CMAP rainfall anomaly plot for this period (Figure 5.11a) shows above-average rainfall over southern Angola and Namibia, spreading eastward over Zambia, Zimbabwe and Mozambique where strong positive anomalies are observed. Dry conditions are evident over Botswana and eastern South Africa. These rainfall anomalies are reflected in the OLR anomaly plot (Figure 5.12a) which shows a band of strong negative anomalies extending from Angola to the Mozambique Channel indicative of enhanced convection over areas where there is above average rainfall. There is also slightly enhanced convection over Namibia and western South Africa.

Due to the enhanced onshore winds over the Angolan coast (Figure 5.13a), increased moisture advection from the tropical southeast Atlantic could be expected. Indeed a somewhat increased westerly moisture flux into the Angola low is evident (Figure 5.14a), with a distinct cyclonic anomaly feature visible over southern Angola/ northern Namibia.

This feature effectively implies a strengthening of the Angola low. Strong relative low-level moisture convergence (Figure 5.15a) indicated by negative divergence anomalies is present over the Angola low. Also observed is a weakly enhanced easterly moisture inflow from the southwest Indian Ocean into southern Mozambique and Kwa-Zulu Natal. This moisture flow appears to diverge over eastern South Africa where there is a weak high pressure anomaly extending from the southwest Indian Ocean (Figure 5.16a).

Figure 5.17a indicates relative ascent in the middle-levels over much of the region with strong uplift evident over the Angola low region and southeast of Mozambique. The region of uplift over the Angola low extends south as far as western South Africa suggesting favourable conditions for trough formation and convective rainfall over the region. Weak relative subsidence is apparent over eastern South Africa which explains the dry conditions observed there.

As mentioned earlier, this period was characterised by a warm SST anomaly off the Angolan coast which implies more low-level moisture advection over the Angola low region by the enhanced westerlies over the tropical southeast Atlantic (Figure 5.14c). Together with the strong convergence over the Angola low (Figures 5.14a and 5.15a), conditions were favourable for enhanced rainfall over Angola and Namibia as observed.

6-10 March 2001

Figure 5.11b shows positive rainfall anomalies over Angola extending eastward over Zimbabwe and Mozambique. Well above-average rainfall is observed over southern Mozambique and the Channel area while below-average rainfall is apparent over eastern South Africa. These rainfall anomalies are consistent with the OLR pattern (Figure 5.12b) which indicates enhanced convection over tropical southern Africa with intense activity evident over the Mozambique Channel. The rainfall anomaly pattern bears some resemblance to the one for the 9-13 February event (Figure 5.11a) discussed above. One of the noticeable differences though is in the magnitude of the rainfall anomalies over southern Angola/ northern Namibia, with stronger positive anomalies observed during the

9-13 February event. Compared to the February event, the Angola low appears to be less intense and shifted east during the 6-10 March period as this can be deduced from the moisture flux and divergence anomaly plots (Figures 5.14b and 5.15b) discussed below. These differences may have led to the rainfall anomalies being weaker and less spatially extensive during this event compare to the February case.

Relatively stronger westerly flow over the tropical southeast Atlantic (Figure 5.13b) is observed during this 6-10 March 2001 period. The moisture flux anomaly plot (Figure 5.14b) shows significantly enhanced moisture inflow from the tropical southeast Atlantic but located farther north than in February. The cyclonic anomaly observed during the February event is present over southern Angola/northern Namibia during this period as well, although not as well-defined, and is shifted eastward to merge with a second cyclonic anomaly apparent over the Mozambique Channel area. The latter feature signifies the presence of a tropical depression over the Channel area which is also reflected in the 850 hPa geopotential height anomaly (Figure 5.16b) that portrays negative anomalies centred over southern Mozambique coast. Relative low-level convergence (Figure 5.15b) is apparent over tropical southern Africa with an east-west oriented band of negative divergence anomaly stretching from Angola to Mozambique. Again, the relative convergence over Angola is not as strong as in the February event further supporting the suggestion that the Angola low was not as intense during this period.

Intense relative ascent (Figure 5.17b) is apparent over the Mozambique Channel confirming the presence of a deep tropical low there. The existence of a tropical low or cyclone located over the Channel area is often associated with dry conditions over much of subtropical southern Africa (Reason 1998, Reason and Mulenga 1999, Cook et al. 2004) as moisture is drawn away towards the low. This inhibits the formation of tropical-temperate troughs and cloud-bands over subtropical southern Africa, hence the below-normal rainfall conditions observed over southern Namibia, Botswana, South Africa and Lesotho during this period. The relative dominance of the feature over the Mozambique Channel also acts to reduce the influence of the enhanced westerly flow off the tropical southeast Atlantic into the stronger Angola low, thus reinforcing the suggestion that this feature is not by itself able to produce widespread rains if conditions elsewhere over southern Africa are not favourable.

31 March- 04 April 2001

This period is characterised by relatively widespread above-average rainfall over Angola, Namibia and eastern and central South Africa (Figure 5.11c). Enhanced convection (Figure 5.12c) corresponding to the observed rainfall anomalies is apparent, with a northwest-southeast band of strongly negative OLR anomalies found over southern Africa. These rainfall and OLR anomaly patterns strongly resemble conditions typical of cloud-band activity associated with the existence of a tropical-temperate trough located over the central and western parts of region.

The low-level wind anomaly plot (Figure 5.13c) shows anomalous westerly flow over the tropical southeast Atlantic north of about 10°S. The moisture inflow into southern Africa from both the tropical southeast Atlantic and the northerm Mozambique Channel is significantly enhanced as portrayed by the anomalous northeasterly/easterly flow over northeastern South Africa, Zimbabwe and Mozambique, and westerly flow over Angola (Figure 5.14c). The anomalous moisture flux over the latter feeds a considerably stronger and spatially more extensive Angola low that stretches over most of Angola, Namibia, Botswana and western Zambia. Strong relative convergence (Figure 5.15c) is found over southeast Angola and northern Namibia extending southward over western South Africa consistent with the deepened Angola low and enhanced interior trough over the western region of the landmass.

The 850 hPa geopotential height anomaly plot (Figure 5.16c) reflects the presence of an enhanced interior trough during this period with negative pressure anomalies visible over the western part of southern Africa. High pressure anomalies are evident over large areas of midlatitude South Atlantic and Indian Oceans, a pattern that is characteristic of La Niña events (Reason et al., 2000; Colberg et al., 2004). At 500 hPa, there are low pressure anomalies over western South Africa and south of the region. These low-pressure anomalies observed over the western interior of southern Africa in the lower and middle levels are favourable for the formation of tropical-temperate troughs and associated cloud-bands which result in considerable rainfall over subtropical southern Africa (Walker, 1990; Washington and Todd, 1998). Furthermore strong relative ascent in the middle levels (Figure 5.17c) is apparent over much of the region, consistent with the above-average rainfall conditions observed.

5.3 Summary

Previous studies (Hirst and Hastenrath, 1983; Rouault et al., 2003) have demonstrated the existence of a link between SST variability over the tropical southeast Atlantic Ocean and summer rainfall over the western regions of southern Africa particularly Angola and Namibia. The results presented here have confirmed this association where enhanced westerly winds over the tropical southeast Atlantic lead to increased westerly moisture flux and rainfall over parts of the region. When a warm SST anomaly exists off the Angola/Namibia coast the enhanced westerly winds are able to evaporate more moisture and advect this into the Angola low region (Rouault et al., 2003). The enhancement of evaporation and low-level atmospheric instability due to the presence of the warm SST anomaly (Rouault et al., 1998) further contributes to the increased intensity of the Angola low which was indicated by the existence of a distinct anomalous cyclonic moisture feature and enhanced moisture convergence over large areas of tropical southern Africa during the three events discussed.

The intensity and spatial distribution of rainfall anomalies or the extent of the impact of enhanced moisture inflow from the tropical southeast Atlantic on rainfall seems to greatly depend on the moisture inflow from the southwest Indian Ocean and prevailing atmospheric circulation anomalies, consistent with Rouault et al. (2003).

For the 31 March – 4 April 2001 event where, in addition to enhanced westerly moisture flux over the tropical southeast Atlantic Ocean, there was above average inflow of moisture from the southwest Indian Ocean as well as atmospheric circulation anomalies favourable for cloud-band formation, relatively widespread positive rainfall anomalies extended south from Angola to southwestern South Africa were evident. On the other hand, the area of enhanced rainfall was mainly confined to tropical southern Africa during 6-10 March 2001. This particular event was characterised by a weakened easterly moisture inflow from the southwest Indian Ocean due to the presence of a tropical depression over the Mozambique Channel, which drew moisture away from the region. These results support the suggestion that the extent of the tropical southeast Atlantic influence on southern African rainfall depends to some extent on the amount of moisture inflow from the southwest Indian Ocean and atmospheric circulation anomalies over the region as well as over the adjacent oceans. Thus, favourable conditions over the tropical southeast Atlantic Ocean and the Angola low do not appear by themselves to lead to above-average rainfall over southern Africa except perhaps over coastal Angola. Instead, convergence of low-level moisture that originates from both the western Indian and southeast Atlantic oceans over southern Africa seems to be required for widespread good rains.

It must be pointed out that although the results presented here show that enhanced low-level westerly wind events over the tropical southeast Atlantic partly influence rainfall over southern Africa through increased moisture advection, not all events coincide with enhanced rainfall over the region. Also, above-average rainfall is observed during some periods when there is enhanced moisture flux from the southwest Indian Ocean but reduced inflow from the tropical southeast Atlantic as the southwest Indian Ocean is the primary source of moisture for southern African rainfall.

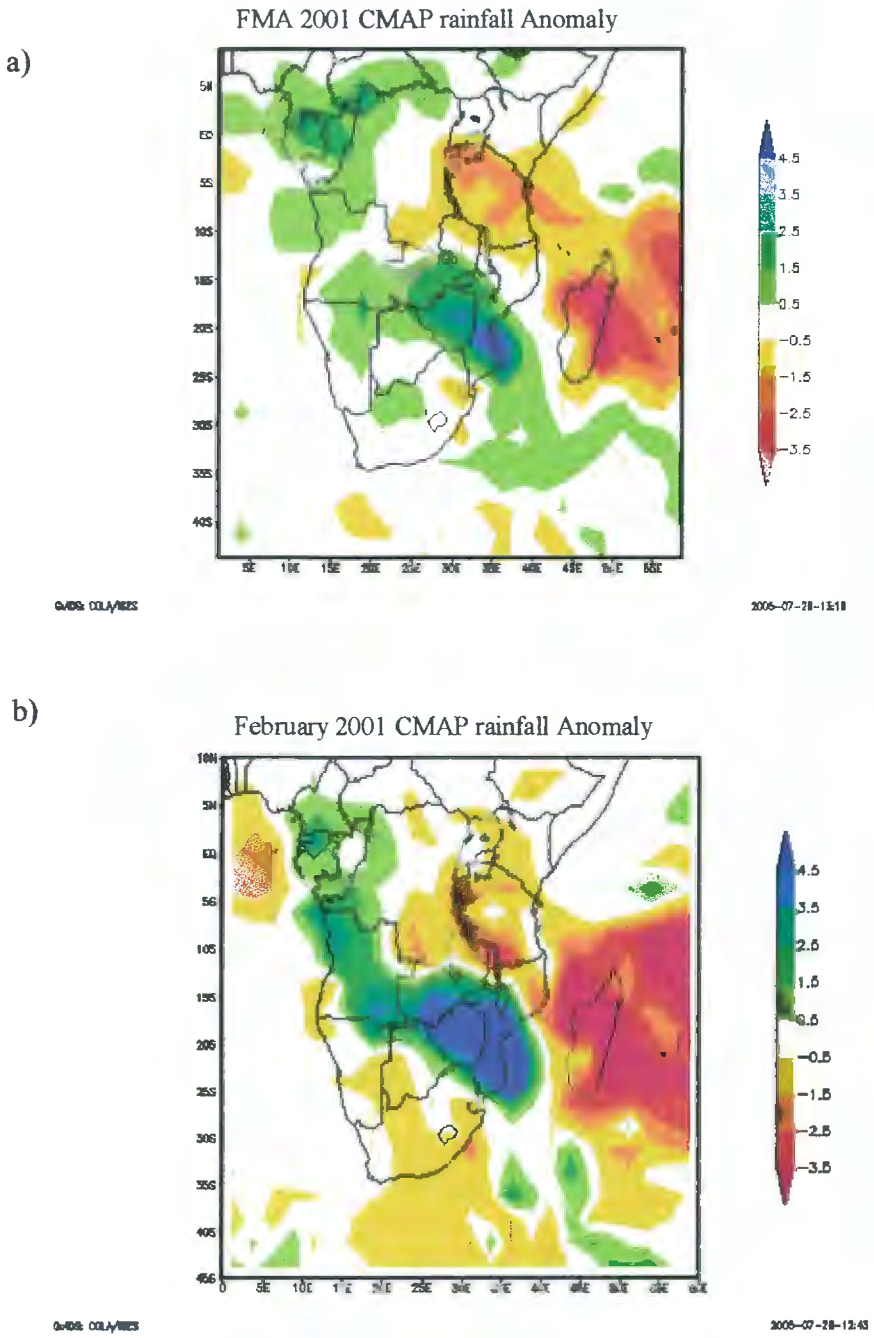
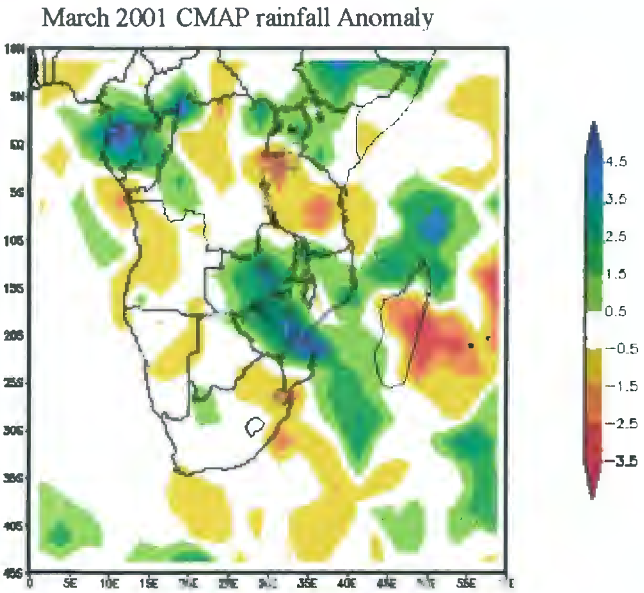


Figure 5.1 CMAP rainfall anomalies (in mm) for (a) FMA 2001 and (b) February 2001.

c)


March 2001 CMAP rainfall Anomaly

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d)

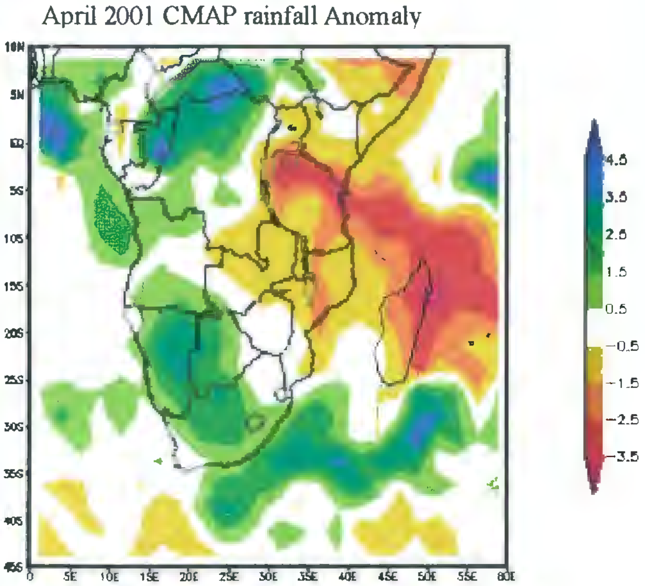
April 2001 CMAP rainfall Anomaly

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Figure 5.1 CMAP rainfall anomalies (in mm) for (c) March 2001 and (d) April 2001.

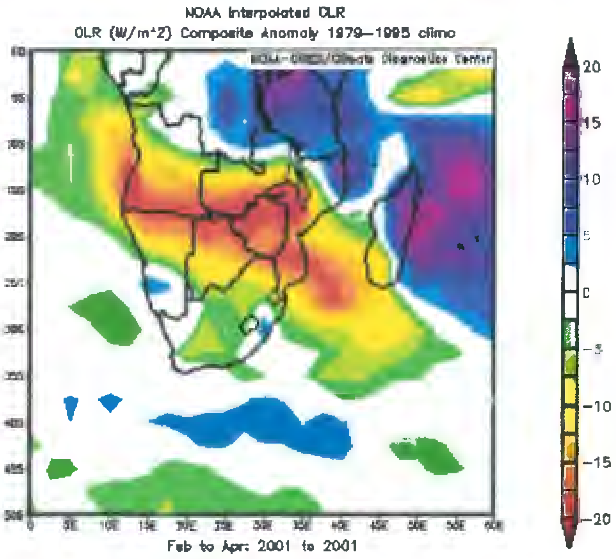


Figure 5.2 OLR anomalies for FMA 2001. Negative values indicate enhanced convection.

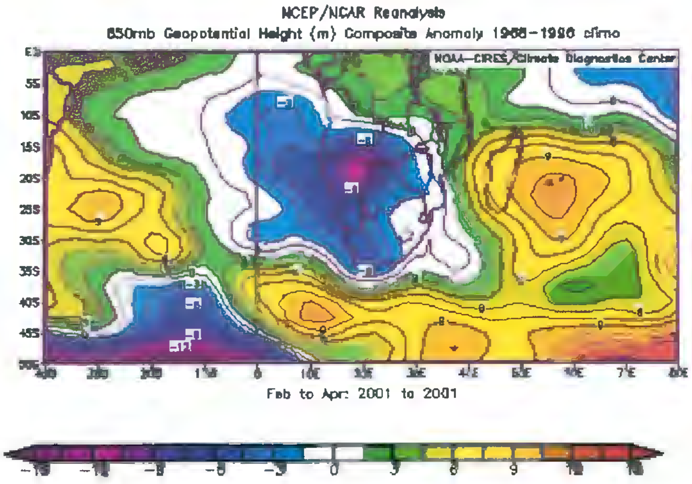


Figure 5.3 850 hPa geopotential height anomalies (contour interval 1.5 m) for FMA 2001.

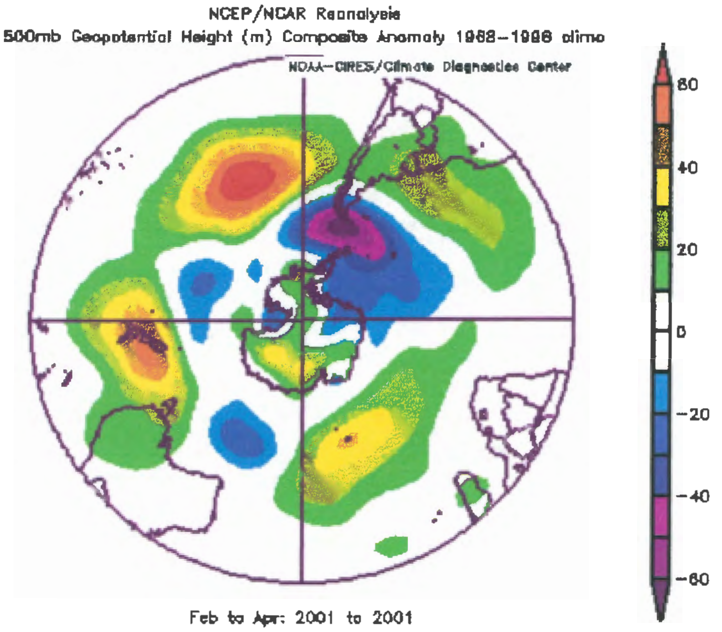


Figure 5.4 500 hPa geopotential height anomalies (contour interval 10 m) for FMA 2001.

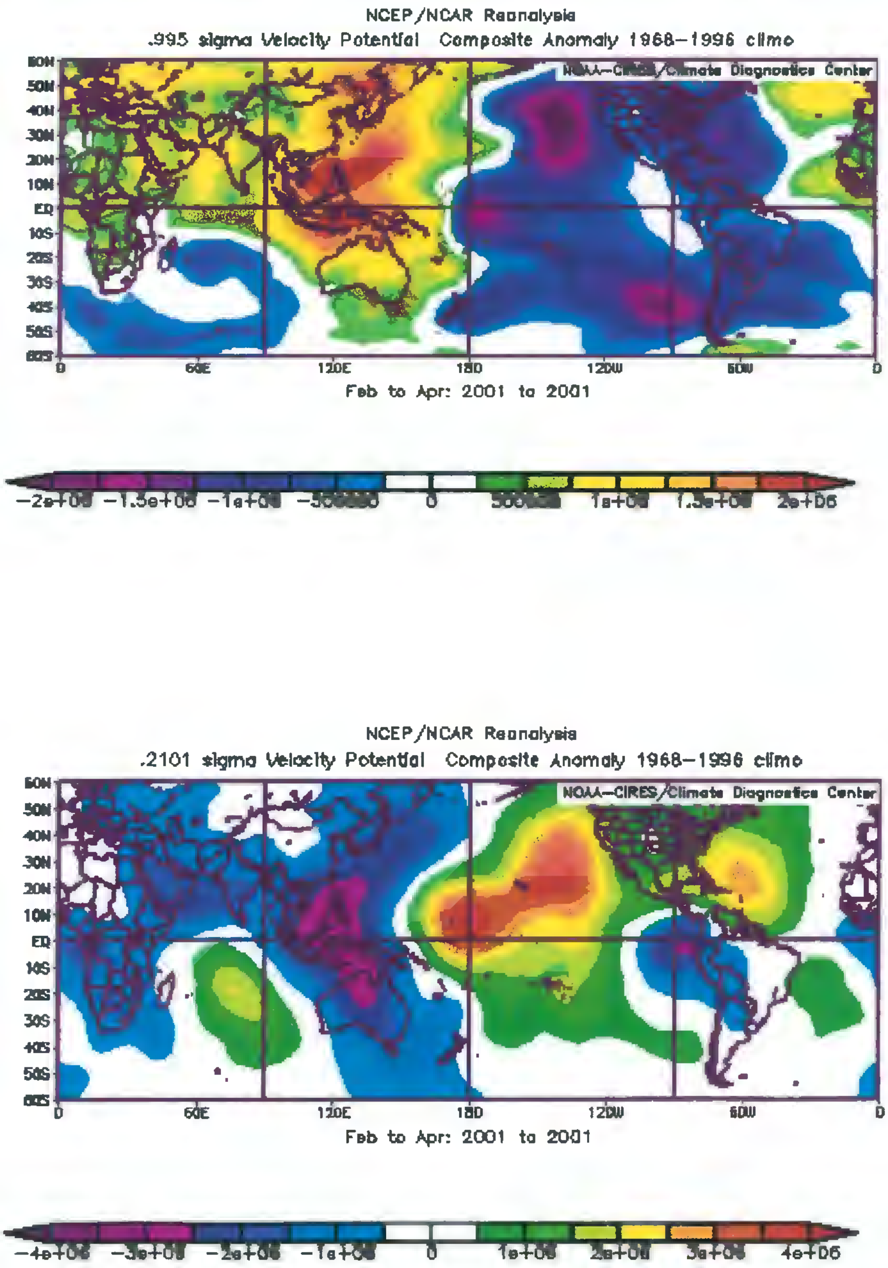


Figure 5.5 Low-level (top) and upper-level (bottom) velocity potential anomalies for FMA 2001.

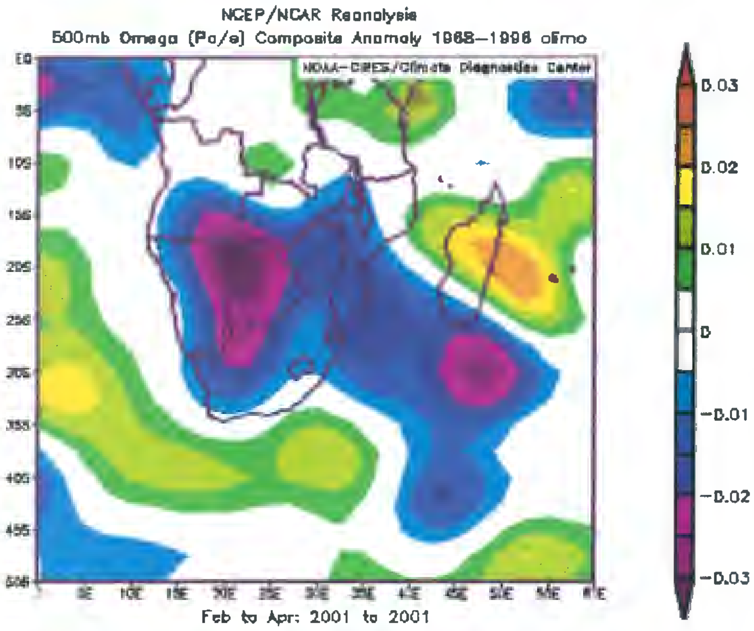


Figure 5.6 Pressure tendency at 500 hPa for FMA 2001. Negative values indicate relative ascent.

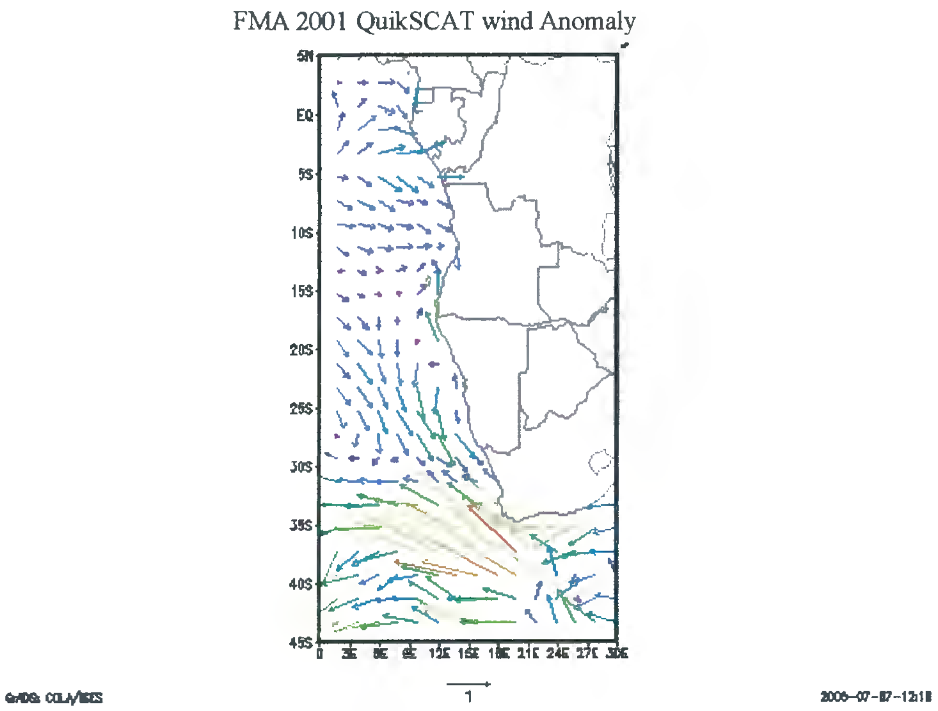


Figure 5.7 QuikSCAT vector wind anomalies for FMA (February-April) 2001.

FMA 2001 850 hPa Moisture Flux Anomaly

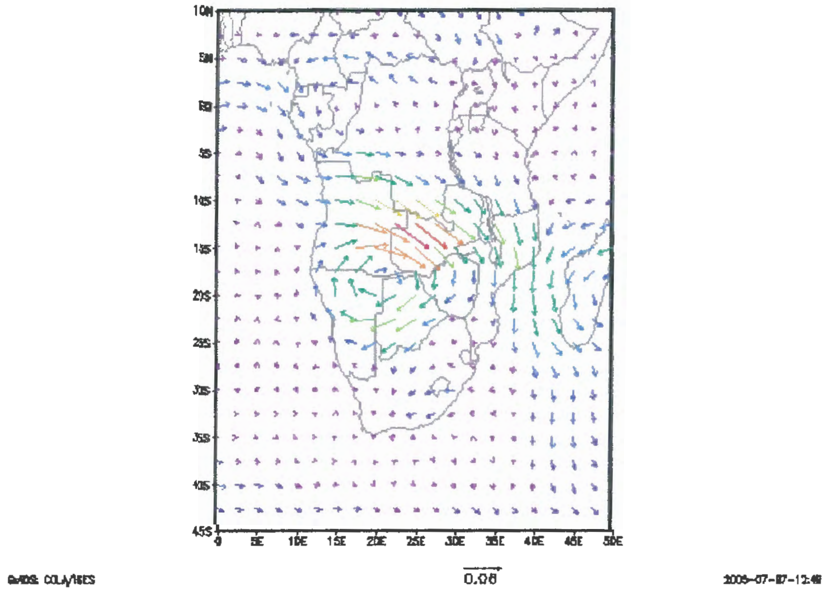


Figure 5.8 850 hPa moisture flux anomaly for FMA 2001.

FMA 2001 850 hPa Moisture Divergence Anomaly

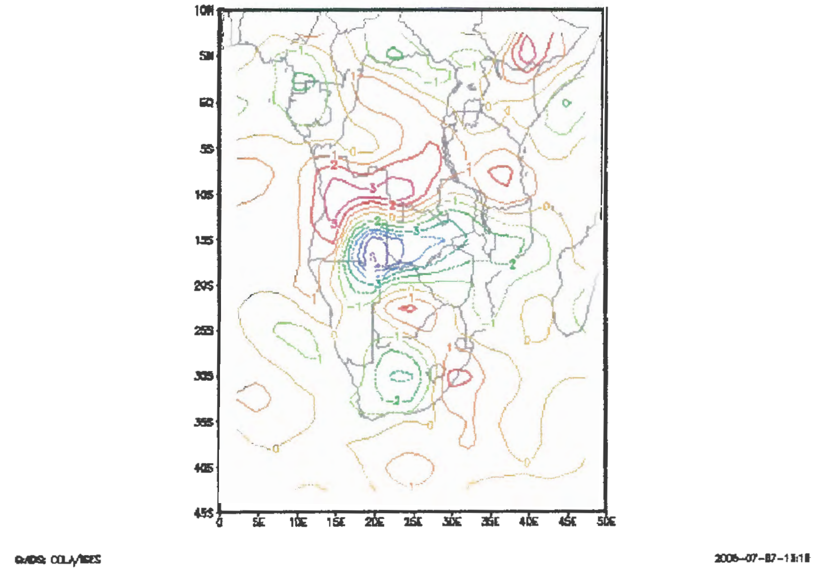


Figure 5.9 850 hPa moisture divergence anomaly (in kg $kg^{-1}s^{-1}$) for FMA 2001.

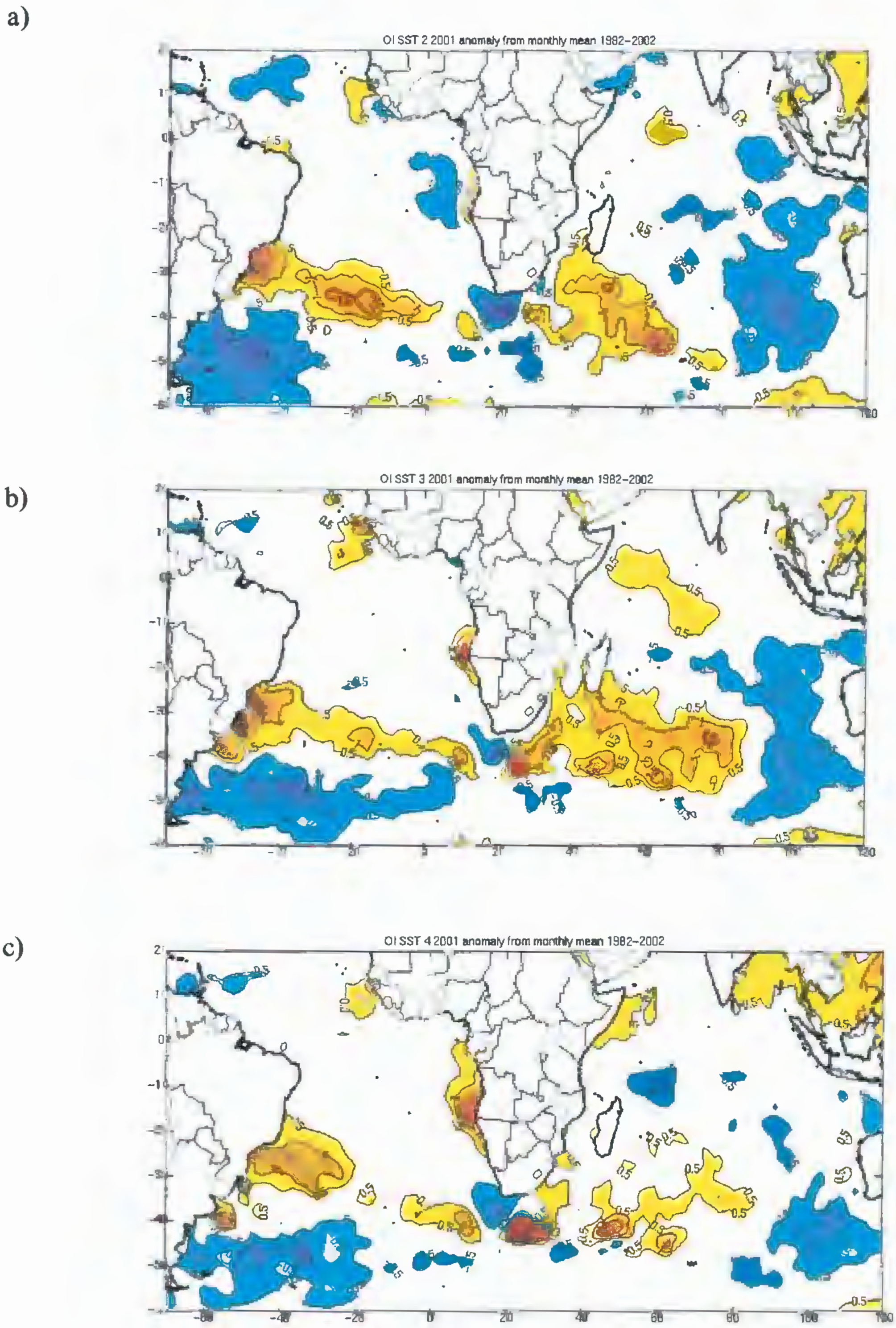
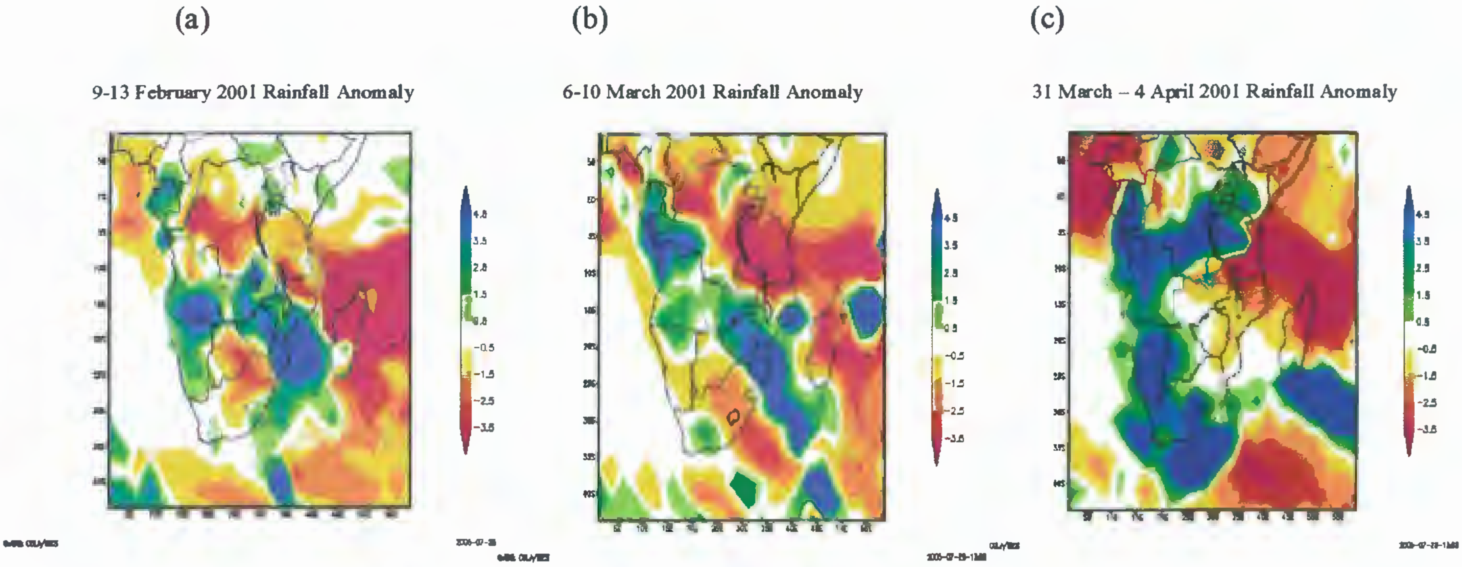


Figure 5.10 Monthly SST anomalies (contour interval 0.5°C) for a) February, b) March and c) April 2001. After www.egs.uct.ac.za/rouault.

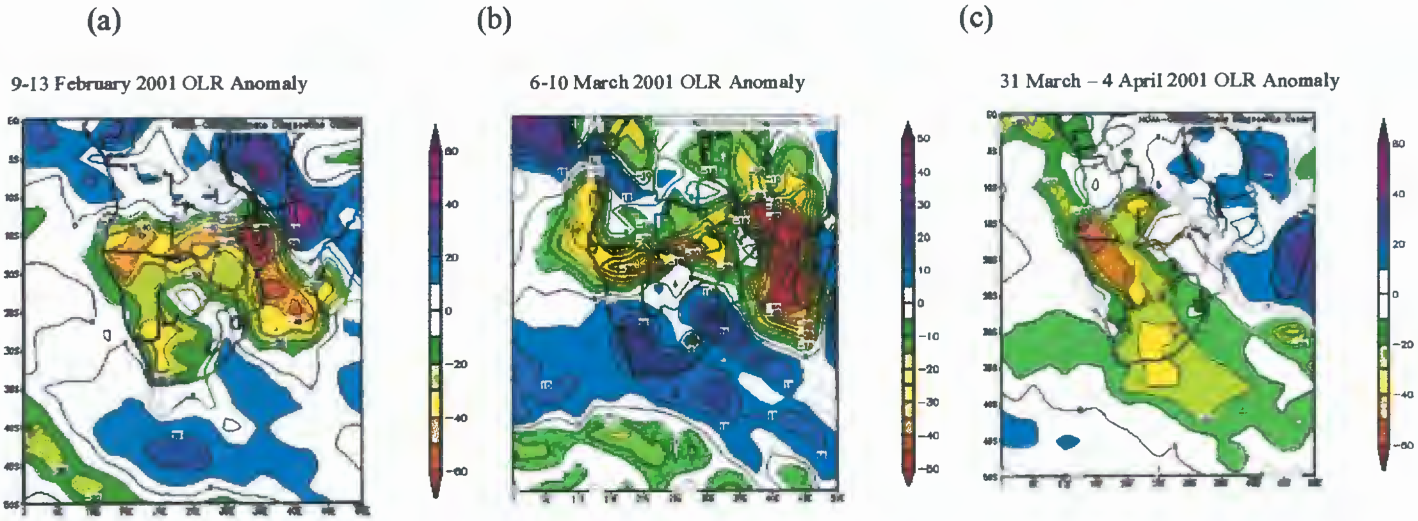


(a) 9-13 February 2001 Rainfall Anomaly

(b) 6-10 March 2001 Rainfall Anomaly

(c) 31 March – 4 April 2001 Rainfall Anomaly

Figure 5.11 CMAP rainfall anomalies (in mm) for (a) 9 - 13 February, (b) 6 - 10 March and (c) 31 March - 4 April 2001.

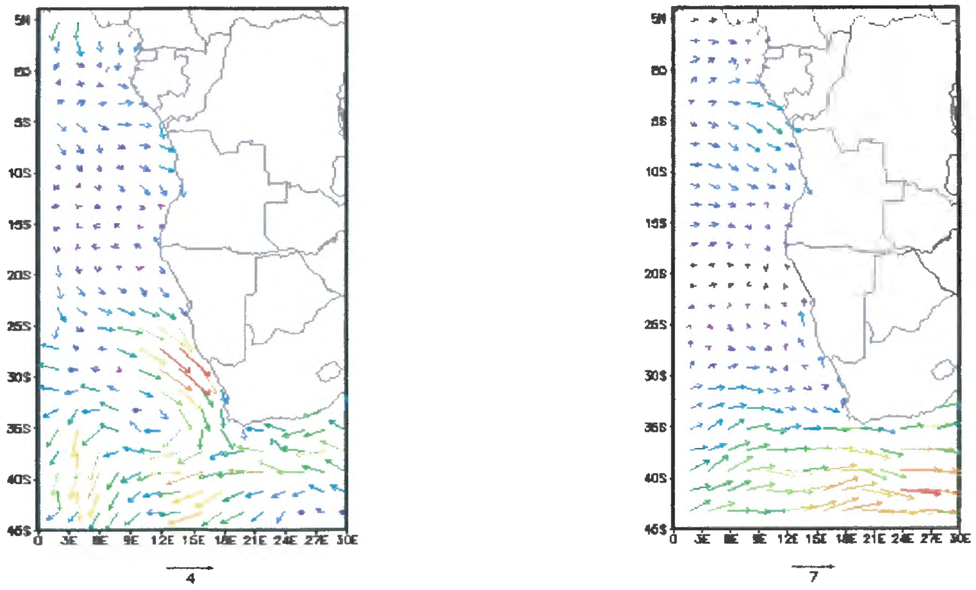


(a) 9-13 February 2001 OLR Anomaly

(b) 6-10 March 2001 OLR Anomaly

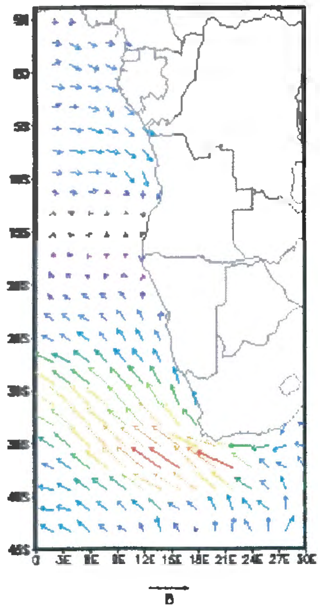
(c) 31 March – 4 April 2001 OLR Anomaly

Figure 5.12 OLR anomalies for (a) 9 - 13 February, (b) 6 - 10 March and (c) 31 March - 4 April 2001. Negative values indicate enhanced convection.



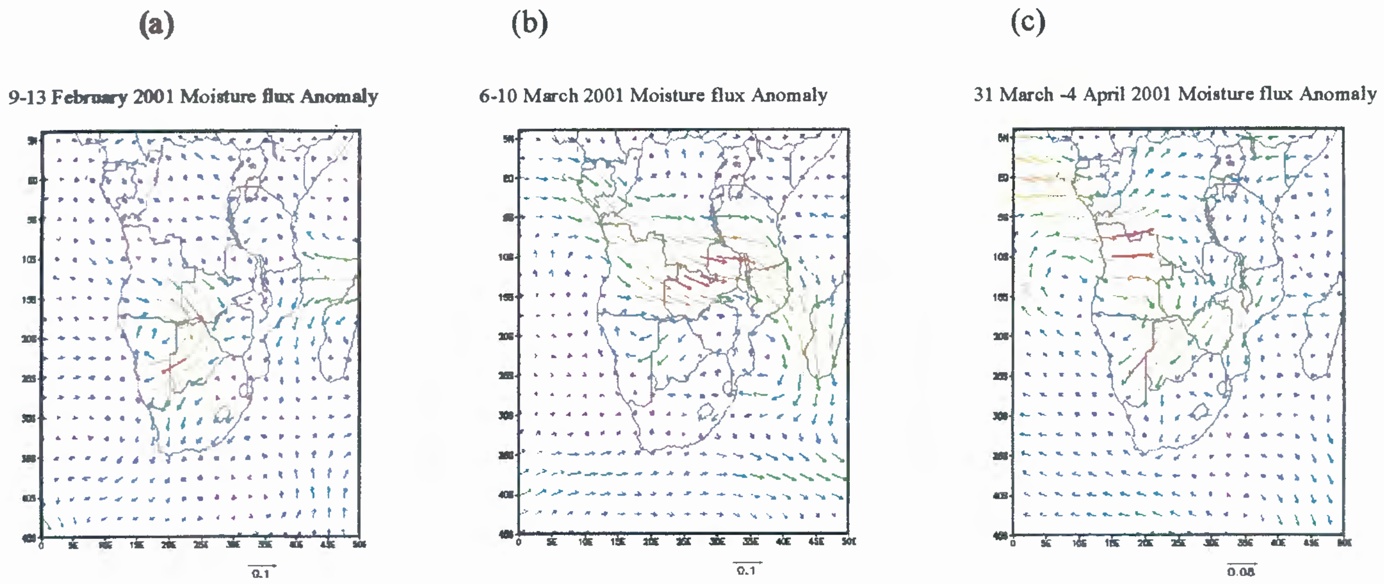
(a) 9-13 February 2001 Wind Anomaly

(b) 6-10 March 2001 Wind Anomaly



(c) 31 March- 04April 2001 Wind Anomaly

Figure 5.13 QuikSCAT vector wind anomalies for (a) 9 - 13 February, (b) 6 - 10 March and (c) 31 March - 4 April 2001.

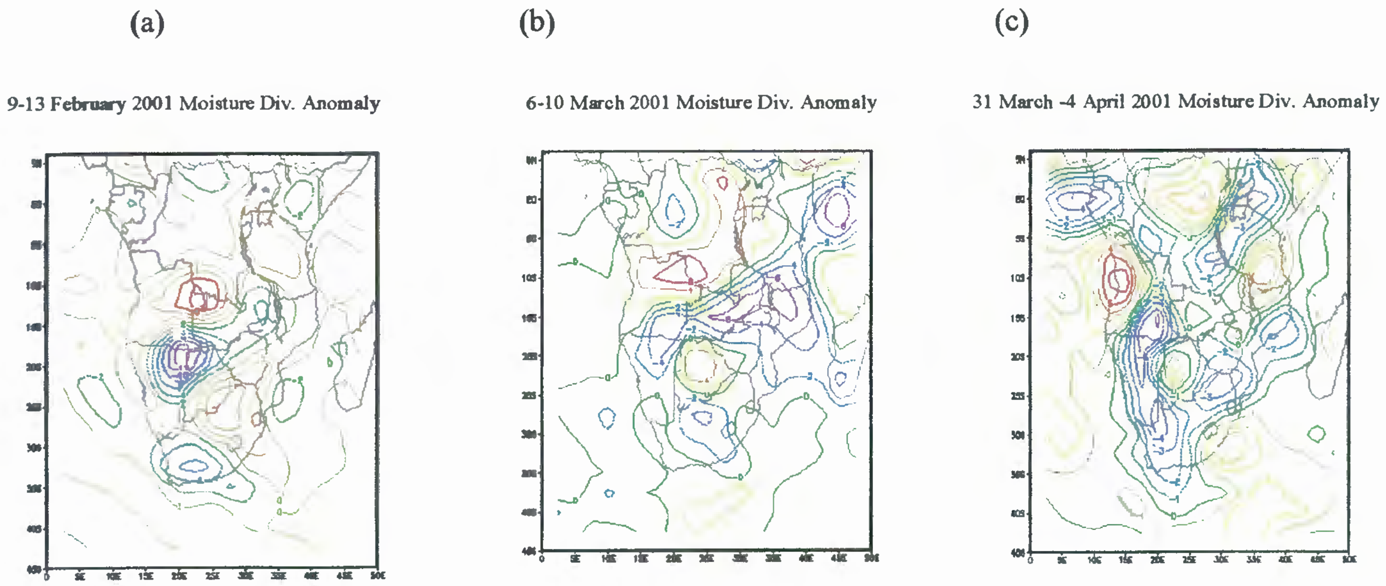


(a) 9-13 February 2001 Moisture flux Anomaly

(b) 6-10 March 2001 Moisture flux Anomaly

(c) 31 March -4 April 2001 Moisture flux Anomaly

Figure 5.14 850 hPa moisture flux anomaly for (a) 9 - 13 February, (b) 6 - 10 March and (c) 31 March - 4 April 2001.



(a) 9-13 February 2001 Moisture Div. Anomaly

(b) 6-10 March 2001 Moisture Div. Anomaly

(c) 31 March -4 April 2001 Moisture Div. Anomaly

Figure 5.15 850 hPa moisture divergence anomaly (in kg kg^{-1}s^{-1}) for (a) 9 - 13 February, (b) 6 - 10 March and (c) 31 March - 4 April 2001. Negative values indicate relative convergence.

(a) 9-13 February 2001 850 hPa Geopotential Height Anomaly

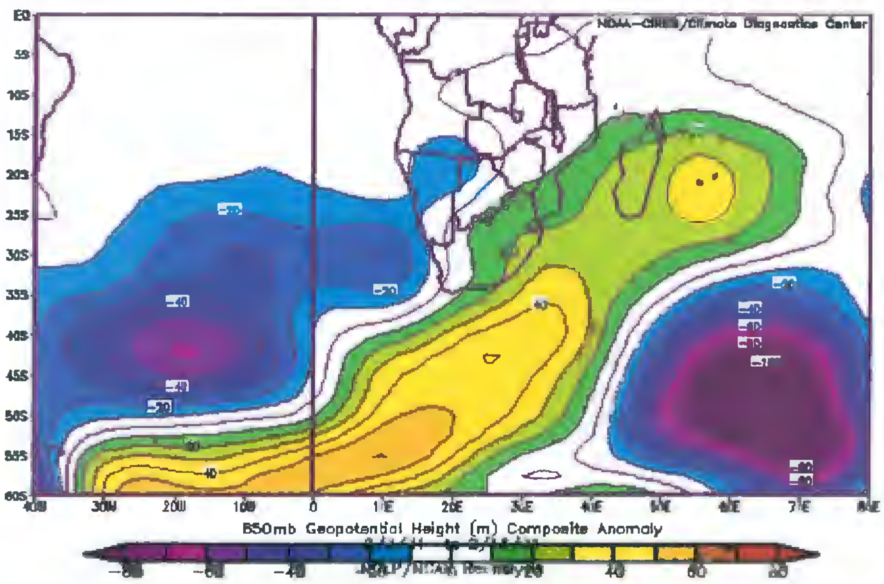


Figure 5.16 (a) 850 hPa geopotential height anomalies (contour interval 10 m) for 9-13 February 2001.

(b) 6-10 March 2001 850 hPa Geopotential Height Anomaly

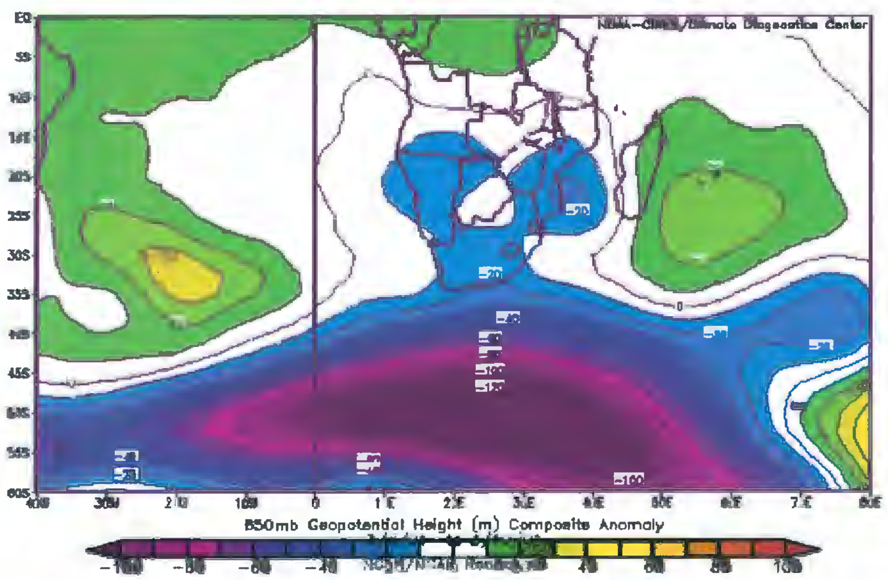


Figure 5.16 (b) 850 hPa geopotential height anomalies (contour interval 10 m) for 6-10 March 2001.

(c) 31 March – 4 April 2001 850 hPa Geopotential Height Anomaly

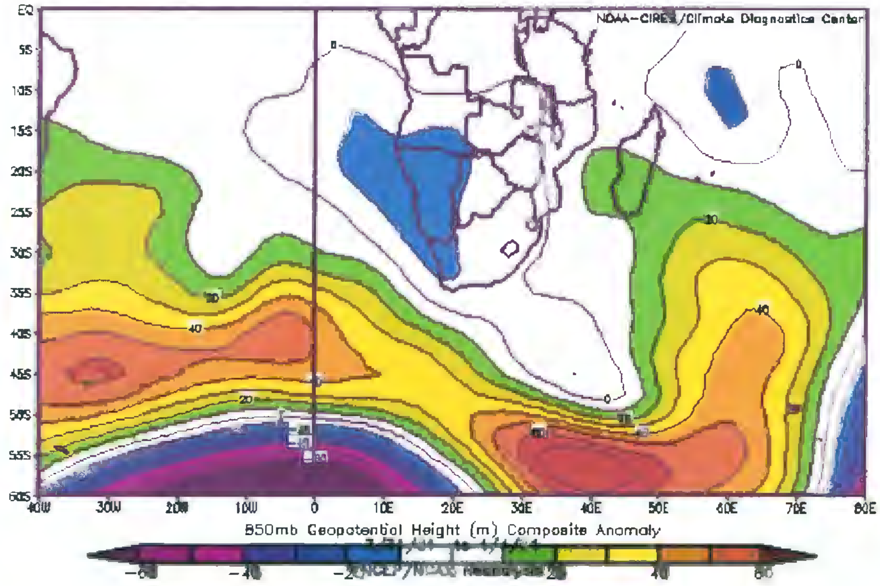


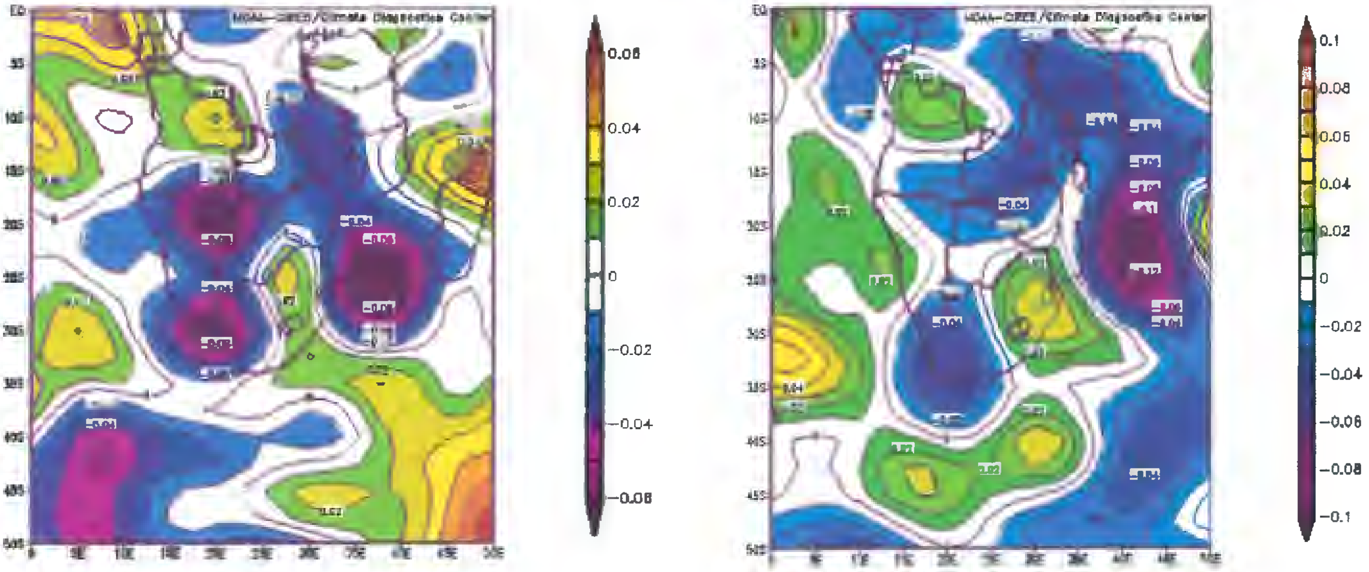
Figure 5.16 (c) 850 hPa geopotential height anomalies (contour interval 10 m) for 31 March – 4 April 2001.

(a)

9-13 February 2001 500 hPa Omega Anomaly

(b)

6-10 March 2001 500 hPa Omega Anomaly



(c)

31 March – 4 April 2001 500 hPa Omega Anomaly

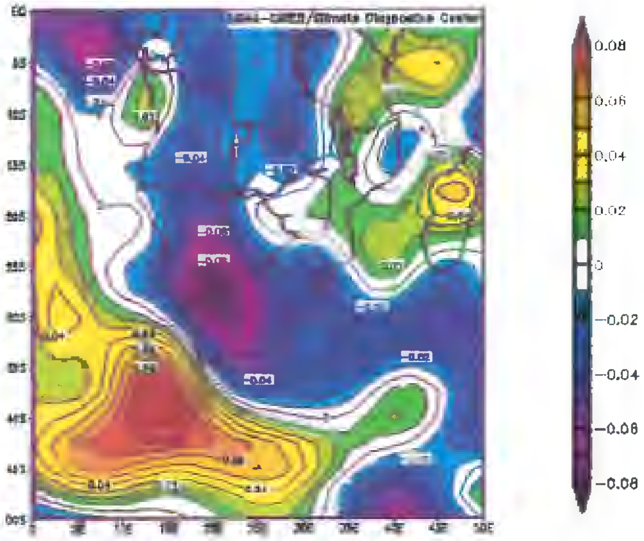


Figure 5.17 Pressure tendency at 500 hPa for (a) 9 - 13 February 2001, (b) 6 - 10 March 2001, and (c) 31 March - 4 April 2001. Negative values indicate relative ascent.

CHAPTER 6
SUMMARY AND CONCLUSIONS

Intraseasonal variability in the low-level winds over the southeast Atlantic Ocean using high-resolution QuikSCAT wind data during the period August 1999 – July 2004 has been investigated in this thesis. Interannual variability in the intraseasonal wind oscillations has been analyzed. The significance of the winds over the tropical southeast Atlantic Ocean in the modulation of summer rainfall over southern Africa has also been explored.

In order to isolate the intraseasonal variability, a 20-70 day bandpass filter was applied to the data. Wavelet analysis, which is more useful in depicting temporal characteristics of climate signals than the traditional Fourier transform technique, was applied to 20-70 day filtered u and v QuikSCAT wind time series over six southeast Atlantic regions identical to the six distinct zones identified by Risien et al. (2004) using SOM analysis. The temporal domain of the data analysed (August 1999 – July 2004) consisted of most of the prolonged La Niña event (1998-2001), an El Niño year (2002-2003) and two neutral years. To investigate the possible forcing exerted by convective activity over tropical Africa on southeast Atlantic tropical winds (Risien et al., 2004), correlation analysis between 20-70 day Angola low and West Africa OLR indices, and u and v winds time series over tropical regions 1 to 2 was carried out for the analysis period (August 1999 – July 2004).

Intraseasonal wind variability over the six regions in the southeast Atlantic was found to be characterised by dominant frequencies ranging between 20 and 40 days. A single spectral peak with a period that shifts from 32 days in the tropical regions (10-18.5°S) to a slightly shorter 26-28 day period over the subtropical zones (19-35°S) was evident in the meridional wind spectra. The zonal wind spectra contain two main frequency peaks at 24-28 and 36-40 days. The 36-40 day frequency peak was somewhat less pronounced between 10° and 23.5°S and became more defined towards the south (24-35°S). The intraseasonal wind oscillations in the tropical southeast Atlantic seemed to be related to convective activity over the Angola low and the West African monsoon region during late austral summer and winter, respectively. Significant correlations were obtained between the wind over the tropical southeast Atlantic and OLR over these regions. In the subtropical regions, the intraseasonal wind oscillations appeared to be related to eastward propagating midlatitude waves with the peak frequency periods consistent with periods of dominant intraseasonal oscillations over the Southern Hemisphere associated with westerly waves (Ghil and Mo, 1991). The influence of these waves on the subtropical winds was more prominent in the zonal wind component than in the meridional wind which is possibly due to the zonal direction in which the disturbances propagate.

Significant year-to-year variability in the intraseasonal oscillations has been revealed, particularly in the timing and magnitude of dominant oscillations. Enhanced wavelet power indicating considerably increased magnitude of the intraseasonal oscillations was generally observed during the 1999 – 2001 and 2002 – 2003 La Niña and El Niño events, respectively. The ENSO signals were somewhat more evident in the meridional wind over the northernmost tropical (10-18.5°S) and the southernmost regions (29-35°S), than over the region between 19°S and 28.5°S where enhanced wavelet power was apparent during much of the analysis period. In the zonal wind spectra, the ENSO signals were prominent over the tropical regions (10-18.5°S). Variations in the strength of the South Atlantic anticyclone and pressure over the interior of southern Africa which typically occur during ENSO (Reason et al., 2000; Colberg et al., 2004) created fluctuations in the pressure gradient which in turn enhanced the magnitude of the oscillations. This suggested the presence of ENSO signals over the southeast Atlantic, consistent with previous studies (e.g. Lindesay 1988, Reason et al. 2000, Colberg et al. 2004). However, it should be stated that enhanced magnitude in the intraseasonal wind oscillations was also observed during some non-ENSO (neutral) periods as significant pressure anomalies occur over southern Africa and the South Atlantic even in some neutral years (Mulenga et al., 2003).

To explore the influence of the low-level winds over the tropical southeast Atlantic Ocean on summer rainfall modulation over southern Africa during the August 1999 –

July 2004 period, composite analysis was utilized. Atmospheric circulation composites anomalies during events for which westerly wind flow into the Angola low region were significantly enhanced were also analysed as rainfall activity is influenced by the circulation anomalies.

Pentad QuikSCAT wind and CMAP rainfall anomaly plots showed that there were several pentads during which enhanced westerly winds over the tropical southeast Atlantic coincided with above-average rainfall over much of southern Africa during the latter part of the 2000/2001 rainfall season (January – April). This period coincided with the end of a protracted La Niña event and showed more westerly wind events that concurred with above-average rainfall over parts of southern Africa than in the other years. The 2000/2001 rainfall season as a whole was characterised by average to above-average rainfall conditions over the region with the bulk of the rains observed between February and April (FMA) 2001. In addition to enhanced westerly winds over the tropical southeast Atlantic during this season, analysis of atmospheric circulation anomalies has revealed that there was enhanced low-level moisture into the deepened Angola low with increased convergence of moisture from the primary southwest Indian source and the tropical southeast Atlantic over tropical southern Africa. These anomalies together with other circulation anomalies including low pressure anomalies and low-level relative ascent over southern Africa created favourable conditions for widespread rains over the region.

Analysis of individual enhanced westerly wind events using pentad composites revealed that enhanced westerly winds over the tropical southeast Atlantic may result in increased westerly moisture flux into the Angola low and rainfall over parts of the region. When a warm SST anomaly exists off the Angola/Namibia coast, the enhanced westerly winds are able to evaporate more moisture and advect it into the Angola low region (Rouault et al. 2003). The enhancement of evaporation and low-level atmospheric instability due to the presence of the warm SST anomaly (Rouault et al., 1998) may further contribute to the increased intensity of the Angola low. In the cases analysed, the latter was indicated by the existence of a well defined anomalous cyclonic feature, and enhanced moisture convergence over large areas of tropical southern Africa.

The intensity and spatial distribution of rainfall anomalies or the extent of the impact of enhanced moisture inflow from the tropical southeast Atlantic on rainfall seemed to largely depend on the moisture inflow from the southwest Indian Ocean and prevailing atmospheric circulation anomalies, consistent with Rouault et al. (2003). For the 31 March – 4 April 2001 enhanced westerly wind event where, in addition to enhanced westerly moisture flux over the tropical southeast Atlantic Ocean, there was above average inflow of moisture from the southwest Indian Ocean as well as atmospheric circulation anomalies favourable for cloud-band formation, widespread above-average rainfall occurred over Angola and extended southward to southwestern South Africa. On the other hand, the area of enhanced rainfall was mainly confined to tropical southern Africa during 6-10 March 2001. This particular event was characterised by a weakened easterly moisture inflow from the southwest Indian Ocean due to the presence of a tropical depression over the Mozambique Channel. Previous studies (e.g. Reason and Mulenga, 1999; Cook et al., 2004) have established that the presence of the low over the Channel area usually results in dry conditions over subtropical southern Africa as the moisture tends to be drawn away from the region. These results support the suggestion that the extent of the tropical southeast Atlantic influence on southern African rainfall depends to a certain degree on the amount of moisture inflow from the southwest Indian Ocean and atmospheric circulation anomalies over the region as well as over the adjacent oceans. Thus, favourable conditions over the tropical southeast Atlantic Ocean and the Angola low do not appear by themselves to lead to above-average rainfall over southern Africa except perhaps over coastal Angola. Instead, convergence of low-level moisture that originates from both the western Indian and southeast Atlantic oceans over southern Africa seems to be required for widespread good rains.

Although enhanced low-level westerly wind events over the tropical southeast Atlantic appear to partly influence rainfall over southern Africa through increased moisture advection, not all events coincided with enhanced rainfall over the region. Also, above-average rainfall was observed during some periods when there was enhanced moisture flux from the southwest Indian Ocean but reduced inflow from the tropical southeast Atlantic as the southwest Indian Ocean is the primary source of moisture for southern African rainfall.

In conclusion, it has been revealed that intraseasonal variability in the low-level winds over the southeast Atlantic is dominated by oscillations with periods ranging between 20 and 40 days. There is significant year-to-year variability in the intensity of the oscillations which seems to be in part influenced by ENSO. These oscillations have important implications for fisheries as they force variability in the upwelling and SST over the Benguela Current ecosystem. Also established is the role the winds over the tropical southeast Atlantic play in the modulation of rainfall over southern Africa. Enhanced westerly winds over the tropical southeast Atlantic are associated with enhanced moisture influx into the Angola low region and rainfall over parts of southern Africa. The occurrence of rainfall activity, its magnitude and spatial extent appear to be primarily determined by the amount of moisture inflow from the southwest Indian and tropical southeast Atlantic oceans into southern Africa, the intensity of the Angola low and atmospheric circulation anomalies over the region.

This study has some limitations associated with the relatively short QuikSCAT wind data period (5 years) and the small spatial domain used. Due to the short data span which consisted of 1999 – 2001 La Niña and 2002-2003 El Niño events, the consistency of the ENSO forcing on the intraseasonal oscillations over the southeast Atlantic could not be captured. Risien et al. (2004) suggested that eastward propagating periodic wind events that originate over eastern South America seem to be important to the wind forcing over the southern Benguela. This implies that it might be advantageous to look at a relatively larger spatial domain (basin-scale) than the one used in this work in order to establish the origin of some of the systems that force winds over the southeast Atlantic.

Further work is required to investigate systems responsible for the observed interannual variability in the wind oscillations using a larger high-resolution wind data set as it is evident from the results that there might be modes other than ENSO which also influence the oscillations. In addition, the modulation of SST and upwelling by these wind oscillations needs to be investigated. Knowledge emanating from this could be useful in impact assessment models on marine resources. Much still remains to be done to understand the role played by the tropical southeast Atlantic in the modulation of rainfall over southern Africa. In particular, the influence of warm SST off the Angola/Namibia coast in the modulation of the Angola low could be explored through dynamical model-based studies.

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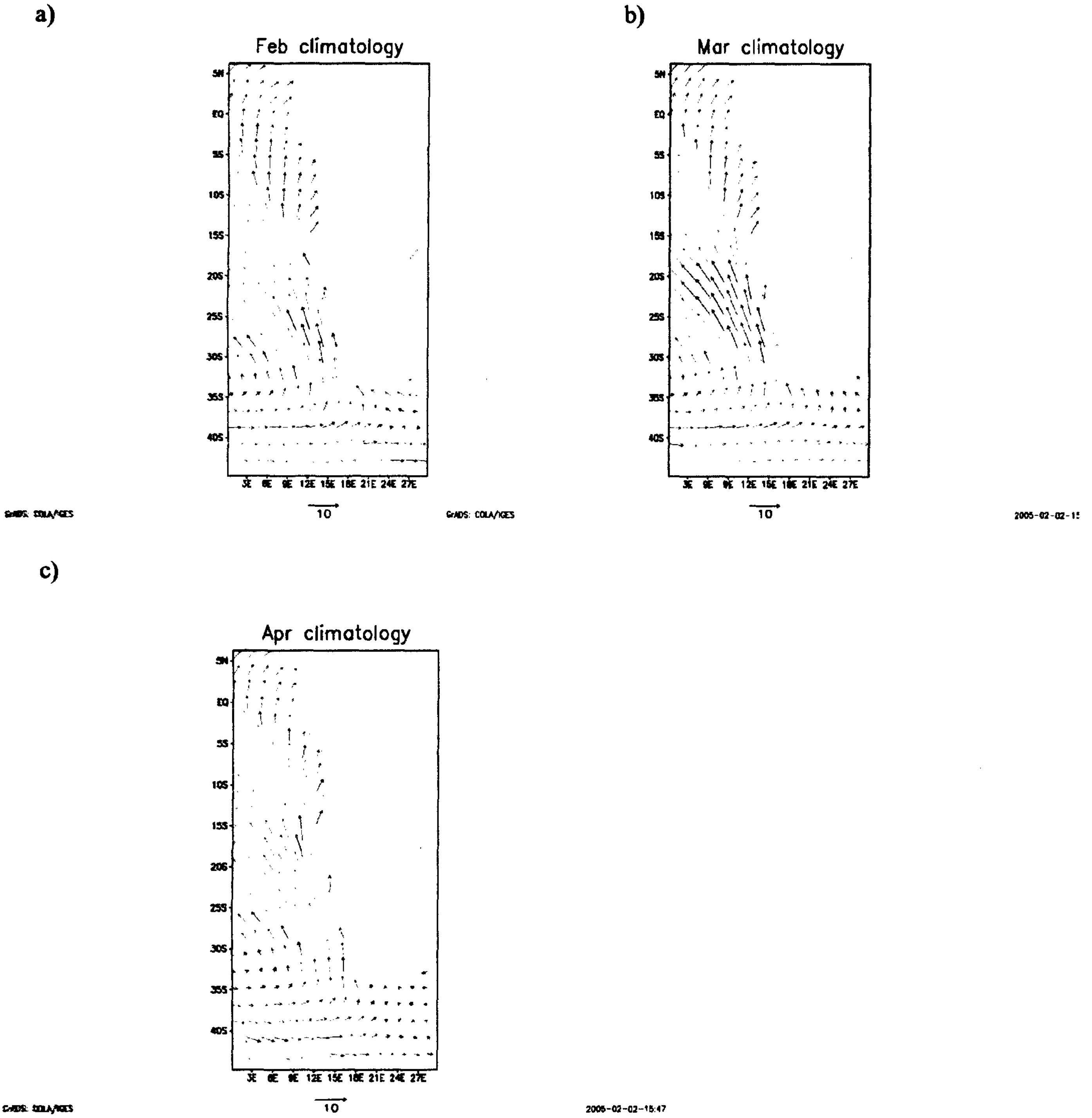
APPENDIX I:



Monthly QuikSCAT wind climatology (1999 – 2004) for (a) February, (b) March and (c) April.