

The El Niño – Southern Oscillation, Rainfall and Wheat Yields in South Africa

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Abstract

This thesis assesses the relationships between the El Niño–Southern Oscillation (ENSO), rainfall and South African commercial winter wheat yields from 1974 – 2000. The analysis is through a combination of the Pearson’s product moment correlation coefficient and an assessment of the magnitude and consistency of rainfall and wheat anomalies in the year of, and the year following warm (El Niño) and cold (La Niña) ENSO events. The ENSO – rainfall relationship is analysed on timescales from 1 – 24 months and this study finds that there are more unusually dry and unusually wet months during El Niño events than during La Niña episodes (where dry and wet months are <75% and over 25% more than the 1921 – 2000 mean, respectively) and these conditions are consistently found in some rainfall areas during each El Niño or La Niña event; there is marked inter – El Niño and inter La Niña variation in late summer and annual rainfall; and that there has been a significant shift in the timings of maximum rainfall anomalies during El Niño episodes from an earlier investigation. The effects of rainfall on the wheat yield vary spatially, but are most apparent in the Free State where severe droughts have resulted in reduced yields. In the Northern Cape and Western Cape anomalously wet conditions, especially in late summer, coincide with reduced wheat yields. The ENSO – wheat yield relationship is not a simple linear one, and despite yields in the Northern Cape and Western Cape tracking Pacific sea surface temperatures by nearly a year, El Niño and La Niña years are not synonymous with increased or decreased yields in any province. In fact, maximum and minimum yields in the Free State and Northern Cape are found in the year of, or year following a La Niña event, and consequently the present predictability of wheat yields by ENSO is limited. The relationships between ENSO, rainfall and wheat yield in South Africa is not readily apparent, which may be due to the short (<30 years) data set or mediating factors outside this study such as farm – management strategies or hemispheric variation in the evolution of El Niño and La Niña events.

Including 10 Figures and 5 Tables.

Introduction

The El Niño – Southern Oscillation (ENSO) is a quasi – periodic warming of the tropical Pacific Ocean that shifts atmospheric circulation and adjusts climates around the world. In southern Africa, a relationship has been established between the ENSO and maize yields (Cane et al, 1994), brown locust outbreaks (Todd et al, 2002), sugar production (Singels and Bezuidenhout, 1999), horse sickness (Baylis et al, 1999) and breeding failures and mass mortalities in two seabird populations (la Cock, 1986). In Australia, wheat yields have been shown to shift from 1130 kg ha⁻¹ to 2100 kg ha⁻¹ between El Niño (warm ENSO) and La Niña (cold ENSO) phases in Emerald, Northeast Queensland, and such events have been used to forecast wheat yields (Howden et al, 2001).

Precipitation over South Africa is highly seasonal with most of the country receiving over 80% of the mean annual rainfall during the austral summer (October to March) whereas the southwest region has winter rainfall (Tyson, 1986). Rainfall in the summer rainfall region is often related to tropical temperate troughs and their associated cloud bands (Mason and Jury, 1997; Washington and Todd, 1999; Todd et al, 2004). With the exception of February, tropical – temperate links from November to March have a dipole structure that enhances (suppresses) convection in a north – west to south – east band from Zambia (Namibia) to the southwest Indian Ocean (Southern Ocean) near 40°S and 50°E (near 35°S and 30°E) (Todd and Washington, 1998, 1999). The characteristics of a trough event depend on the availability of atmospheric moisture, atmospheric stability, the strength of upper – level divergence and the speed of movement of the trough (Harrison, 1988; Mason and Jury, 1997). Although tropical temperate troughs have been associated with rainfall anomalies > 25 mm day⁻¹ (Washington and Todd, 1999) and late summer flooding events (Walker and Lindesay, 1989), heavier rainfalls are usually associated with cut – off lows or deep west – coast troughs (Mason and Jury, 1997). Furthermore, during the transition seasons, rainfall is directly influenced by the number of cut – off lows (Taljaard, 1985), and the frequency of these lows accounts for most of the interannual rainfall variations in these seasons (Mason and Jury, 1997). The heaviest rainfalls in South Africa however, occur along the eastern seaboard with the passage of tropical cyclones, but these are infrequent and account for little of the annual rainfall (Mason and Jury, 1997).

Rainfall in the southwest of the country is mainly from cold fronts (Reason and Rouault, 2002) although cut – off lows may also provide rain (Mason and Jury, 1997). These frontal systems are affected by the location and intensity of the midlatitude storm tracks in the South Atlantic and Indian Oceans which are affected by the meridional temperature gradient (Reason and Rouault, 2002; Reason et al, 2002). Wet winters are associated with an increase in sea ice in the South Atlantic sector of the Southern Ocean, warm sea surface temperatures (SSTs) in the southwest Atlantic and southeast Atlantic and an equatorial movement of the storm track, whereas these patterns are roughly reversed in dry years (see Reason et al, 2002).

Rainfall patterns are associated with SSTs in the oceans adjacent to southern Africa (Landman and Klopper, 1998). Unusually warm (cold) water in the Agulhas retroflexion area is associated with increased (decreased) rainfall over the eastern and southern seaboard of South Africa (Rouault et al, 2002) and annual rainfall totals for the summer rainfall region are in phase with the intensity of the SST gradient in the south – eastern Atlantic (Mason, 1990). Dry (wet) conditions are found across much of the country when the south – western Indian Ocean is anomalously warm (cold) (Reason and Mulenga, 1999; Preston et al, 2000; Lizcano and Todd, 2005) Warm SSTs in the northern and central equatorial Indian Ocean are associated with dry conditions over much of southern Africa (Jury, 1996a, 1996b), but the relationship with the equatorial Indian Ocean is not symmetrical and cold SSTs are not necessarily associated with increased rainfall (Mason and Jury, 1997). Whilst the regional forcing of the Atlantic Ocean and the Indian Ocean have important influences on the rainfall variability over southern Africa, these local SST conditions are modulated by ENSO (Landman and Mason, 1999a; Swann et al, 2003). ENSO events lead SST anomalies in the central Indian Ocean and western Atlantic by 1 – 3 months (Fauchereau et al, 2003) and the El Niño events of 1982/83 and 1986/87 led warming in the Atlantic by 6 – 9 months (Nicholson, 1997).

El Niño events are associated with anomalously dry conditions over South Africa (e.g. Jury, 1996b; Nicholson and Kim, 1997; Landman and Mason, 1999b; Rouault and Richard, 2003). During El Niño episodes, the ascending branch of the local Walker Circulation is shifted offshore to the western Indian Ocean (Preston et al, 2000; Mulenga et al, 2003) which encourages an eastward shift in the cloudbands associated with tropical temperate troughs (Washington and Todd, 1998). Composites of mean sea – level pressure and 500hPa

geopotential heights (Reason et al, 2000) show the development of large – scale positive pressure anomalies over the Indian Ocean and southern Africa region which are unfavourable conditions for cloudband development and tropical convection (Mulenga, et al 2003). El Niño years typically have anticyclonic conditions over southern Angola and Namibia and a shift in the jet core (Reason and Rouault, 2002, Mulenga et al, 2003) that result in dry conditions. Furthermore, there is increased advection of drier South Atlantic air over northern South Africa (Tyson, 1986, Mulenga et al, 2003) and decreased advection of moist air from the Southern Indian Ocean in northern and eastern South Africa (Reason and Rouault, 2002). During La Niña years, these atmospheric conditions are roughly reversed which leads to increased rainfall over the country (Jury, 1996b; Mason and Jury, 1997, Reason and Rouault, 2002) although there is a marked asymmetry in the rainfall patterns (Mason and Goddard, 2001) and evolution of SSTs across the Indian Ocean (Reason et al, 2000) between El Niño and La Niña events.

The effects of the El Niño are most pronounced in late summer (Dec – Mar; Mason and Jury, 1997, Richard et al, 2000), and the effects are strongest in the North East of the country (Richard et al, 2001). Across South Africa, five regions have a consistent response (14 out of 20) to the El Niño episodes since 1901 (Nicholson and Kim, 1997). However, since the 1970s the ENSO signal in the tropical western Indian Ocean SSTs has weakened (Landman and Mason, 1999b) and the relationships between ENSO and southern Africa rainfall has been modified (Richard et al, 2000). Prior to 1970, the late summer (Jan – Mar) was typically wet in the year following the low – index year of the Southern Oscillation Index, whereas between 1970 and 1994 these months were generally anomalously dry (5 out of 6 events; Richard et al, 2000). Additionally, it appears that across southern Africa the rainfall response has been more spatially coherent since 1970 (Richard et al, 2000).

The severity of ENSO events have been classified into 3 phases (warm, neutral and cold) depending on Pacific SSTs (Hill et al, 1998). Strong warm (cold) events are generally associated with reduced (increased) crop productivity in Australia (Howden et al, 2001), Mexico (Adams et al, 1999) and across North America (Izaurrealde et al, 1998; Hill et al, 1998; Legler et al, 1999). These relationships are often not linear (Legler et al, 1999) as they are modified and mediated through the spatial and temporal variability of precipitation, evaporation, the amount of weeds, insects and disease, as well as management strategies including planting drought resistant varieties and planting times (Doerge, 1997; Izaurrealde et

al, 1998; Adams et al, 1999). In South Africa, the effects of “weak” and “moderate – strong” El Niño events on a 120 day maize crop have been modelled (SST anomalies in the Niño 3.4 region of 0.6–0.8°C and 1.1 – 3.3°C respectively; United States Geological Survey (USGS), 2002; Funk et al, 2003). Ignoring potentially important controls in the Atlantic and Indian Oceans, the USGS (2002) identified that during weak years the water requirement saturation index (WRSI) to yield ratio is almost normal. The WRSI to yield ratio however, is reduced by 10 – 20% in the Free State during moderate – strong El Niño years (USGS, 2002; Funk et al, 2003), with the effects being even more pronounced in the North East of South Africa at the end of 1983 and 1992 (21 – 30%; USGS, 2002).

The impact of drought on agriculture is particularly strong when annual rainfall varies between 300 – 500 mm (Richard and Pocard, 1998) and therefore periods of water deficit are more pronounced in South Africa (Richard and Rouault, 2003). Wheat is grown on 28% of the total cropland area of South Africa (Arbuthnot, 1996) and common or bread – wheat (*Triticum aestivum*) is the most widespread crop. The three main wheat growing provinces are the Free State, Northern Cape and the Western Cape that together produced over 82% of the national yield in 2000 (Department of Agriculture, 2003). In the Free State, wheat is grown on the plains in the north and north – east as well as along the boarder with Lesotho (van Riet, 1997, USDA, 1999) and the success of the yield depends on the soil moisture storage from the summer rains (Peter Johnston, pers. comn, 2003). Biological productivity is very low in the Northern Cape (0.5–1.75 tonne ha⁻¹; Department of Agricultural Engineering, 1997), and the amount of irrigation is the highest in South Africa (32%). In the Western Cape, wheat is grown along the South Coast (or Rûens area) and in the Swartland region.

The growth cycle of wheat has 10 major stages (germination, seedling, tillering, stem elongation, booting, heading, flowering, milk, dough and ripening; Fowler, 2002). Environmental conditions, particularly moisture availability, are important through the whole growing cycle but especially during germination and tillering and as the kernel develops. Moisture availability during germination allows complete imbibition (Fowler, 2002) and leads to the development of more embryos, while good conditions during the tillering stage encourages more tillers, which, if they produce more than 3 leaves initiate their own root system and are more likely to survive (Simmons et al, 1995). As the kernel develops, adverse weather can reduce the rate of dry matter accumulation and hence the kernel weight (Simmons et al, 1995) while warm, damp weather can result in rapid deterioration of a

ripened crop (Fowler, 2002). In South Africa, the winter wheat is planted between May and July and then harvested between October and December, although these times may be slightly earlier in the Western Cape (United States Department of Agriculture (USDA), 1999).

Drought is the main factor affecting wheat production (Peterson, 1969), although disease, insects, wind, low – temperatures and hail are all detrimental to the crop. The most significant crop damage from wheat diseases was caused by noxious wheat aphids in the Free State 1978 – 1982 (Annecke and Moran, 1982) and bacterial blight (*Xanthomonas campestris* pv. *translucens*) in the Orange River basin during 1988 (Scott, 1990). Winds and temperature relate to the altitude and local land configurations (Tyson, 1986), although El Niño years are generally warmer across the country (Mason and Jury, 1997). Typically, there are 3 – 5 hail occurrences in the Free State (Le Roux and Olivier, 1996), but during an El Niño episode the frequency of these events increase (Olivier and van Rensburg, 1995). The El Niño is associated with dry conditions, increases in temperature and hail frequency in South Africa, all of which can be detrimental to the production of wheat (Peterson, 1969; CIMMYT, 2000; Fowler, 2002).

In recent years, South African agriculture has been characterised by two contrasting trends. Mining, urbanisation and industrial expansion have led to a reduction in the area available for agricultural production (Arbuthnot, 1996), soil quality has reduced through wind erosion, acidification, crusting, compaction and pollution (Koch, 1996), areas have been waterlogged due to poor drainage and over – irrigation (Arbuthnot, 1996), which all may lead to reduced yields, especially if water is limited (de Jager et al, 1987). Conversely, there has been a widespread adoption of hybrid varieties of crops, an improved resilience of cultivars to environmental stresses (particularly after 1994; Dilley, 2000) and the incorporation of climatic information into planting strategies (Callihan et al, 1994; Rook, 1996) which have improved agricultural productivity.

The effect of the El Niño on the yield of wheat in South Africa has not been investigated. The connections between the ENSO and rainfall variability have been well established (e.g. Nicholson and Kim, 1997; Mason and Jury, 1997; Richards et al, 2000) and as it is estimated that 25% of the national wheat crop is irrigated (Purchase et al, 1998), variations in the wheat yield are likely to reflect changes in rainfall. This investigation aims

to assess the effects of ENSO on these overall production trends through the adjustments in rainfall associated with El Niño and La Niña years.

Methods

This thesis assesses the relationship between ENSO, rainfall and commercial winter wheat yields (tonnes ha⁻¹) for 1974 to 2000. The study period is characterised by a warmer global ocean base state than earlier in the century (Graham, 1994), an increased frequency and amplitude of El Niño events (Dai and Trenberth, 1998), a weakened ENSO signal in the western Indian Ocean (Landman and Mason, 1999b) and southern African rainfall (Richard, et al, 2000), and more widespread and intense droughts across southern Africa (Richard et al, 2001). The Climate Prediction Centre (CPC) identify six (five) El Niño (La Niña) events between 1974 and 2000 (Table 1) which are based on a 3 – month running mean of SST anomalies for the Niño 3.4 region. The choice of ENSO years is important (Rouault and Richard, 2003) but definitions, and hence years, vary between investigations.

Within the studied period, three El Niño events evolve in the Pacific with distinct characteristics. The 1977 event was considered the most unusual since 1945 (Harrison and Larkin, 1998) as warming began before the strong decline in the Southern Oscillation Index (SOI) and there was anomalously warm water throughout most of the Atlantic (Nicholson, 1997). The 1982 episode was particularly intense as the SSTs first peaked in December of 1982 and then, after a period of cooling, peaking again in June 1983 (Nicholson, 1997). Additionally, the 1987 episode was atypical in timing and duration, with warm water remaining in the Pacific from mid 1986 and throughout 1987 (Nicholson, 1997).

Throughout this investigation, four indicators have been used to represent conditions in the Pacific, which, for reasons of conciseness are described in this document as the Pacific Indexes. The SOI, which a measure of sea – level pressure between Tahiti and Darwin, SST anomalies (from the 1971 – 2000 mean SST temperature) for the Niño 3 region in the eastern tropical Pacific (5°N – 5°S, 150°W – 90°W) and the Niño 3.4 area in the eastern central tropical Pacific (5°N – 5°S, 170°W – 120°W) have been taken from the Climate Prediction Centre (CPC). The final index is the Multivariate ENSO Index (MEI) which is derived from

sea – level pressure, zonal and meridional components of the surface wind, SST, surface air temperature and total cloudiness fraction of the sky. Values for the MEI are from the Climate Diagnostics Centre and interpretation of the time series on a monthly time scale follows the guidance of Wolter and Timlin (1993, 1998).

A cluster analysis by the South African Weather Service (1972) was used to divide the country into eight homogenous rainfall zones based on 93 rainfall districts (Figure 1). The spatial variation in rainfall between zones is clear (Figure 2). The North – Western Cape (area 1) and South – Western Cape (area 2) form the winter rainfall region, whereas the South Coast (area 3) receives rainfall at a similar rate throughout the year. The Western interior (area 5), Central Interior (area 6) and the North Eastern Interior (area 8) are in the summer rainfall region, with maximum monthly rainfalls in late summer (Jan – Mar).

Wheat data is from the Abstract of Agricultural Statistics (Department of Agriculture, 2003) and has been supplemented with unpublished provincial data from the same department. While this data is the most reliable available, some problems may exist. Between 1984 and 1996, the old provincial boundaries were used for recording the data and then worked back for the current areas, which may have led to slight inaccuracies (Faith Hawkins, pers comn, 2003). While the area planted and the total production are estimated, to maintain accuracy, production values are verified with the volumes delivered to the South African Grain Institute Service.

The relationships between ENSO, rainfall and wheat yield are explored through a combination of statistics as well as the coherency of response, where the coherency is determined by the consistency and magnitude of an anomaly (Nicholson and Kim, 1997). These relationships are examined on timescales of 1 – 24 months (i.e. the rainfall and wheat anomaly in the El Niño/La Niña year and the following year). However, there are some problems associated with this method due in part to the short time series and high frequency of ENSO events. In the cases where a canonical ENSO occurs (e.g. an El Niño is followed the next year by La Niña conditions as in 1987/88), the rainfall and wheat anomalies in 1988 have been assessed as the year following an El Niño and also the year of a La Niña.

1) El Niño and rainfall

Synoptic (Harrison, 1984), interannual (Jury, 1997; Nicholson and Kim, 1997; Landman and Klopper, 1998; Landman and Mason, 1999a; Goddard and Graham, 1999), decadal (Trzaska et al, 1996; Richard et al, 2001) and multi – decadal to millennial time scales (Tyson, 1986; Tyson et al, 2002) have been used to investigate rainfall variability over South Africa. This investigation focuses on rainfall variability on timescales from 1 – 24 months for the 1974 – 2000 period and also compares general trends in South African rainfall with changes for the subcontinent (Richard et al, 2001).

Connections between rainfall in South Africa and the SOI are well established (Lindesay, 1988) with the relationship being strongest in a band from the northwest to southeast across the country (Jury, 1997). The relationships between SST anomalies in the Niño 3 region (Jury, 1996b; Swann et al, 2003), the Niño 3.4 region (Todd et al, 2002, USGS, 2002) and the MEI (Poccard et al, 2001) with South African rainfall are documented. This investigation explores the ENSO – rainfall connections using the Pearson's product moment correlation coefficients with lag times at 3 – month intervals from 3 – 18 months, and assesses the spatial variability in timing of the strongest relationships.

Monthly rainfall has a high noise to signal ratio (Jury, 1996b), but understanding coherent changes in rainfall associated with ENSO events on this time scale would be beneficial to decision makers. This investigation uses percentages of the “expected” (1921 – 2000 mean) rainfall to assess the monthly rainfall and dry months (<75% of the expected rainfall), wet months (over 25% more than expected) and months with no rainfall were calculated for the whole period and for El Niño and La Niña years. Furthermore, the changes in monthly rainfall characteristics from 1921 – 73 and 1974 – 2000 were assessed using the Mann Whitney *U* test for large samples (Christie, 2004).

The effects of El Niño are most pronounced in late summer rainfall in southern Africa (Lindesay, 1988; Richard et al, 2000). The consistency of late summer (Jan – Mar) and annual rainfall during the year of, and the year following the El Niño (La Niña) have been assessed for each rainfall area using the percentages of the expected rainfall (1921 – 2000 mean).

Nicholson and Kim (1997) used composites of 20 El Niño episodes from 1901 – 1988 and identified the maximum positive (wet) and negative (dry) anomalies for a consecutive 3 – month period. They used a 2 – year El Niño episode that commenced “in July prior to the low – index year of the Southern Oscillation (designated July –1) and continued until June of the year after the low – index year (designated June +1)” (Nicholson and Kim, 1997, page 118). This same 24 – month approach is used to construct maximum precipitation anomalies for the six El Niño events between 1974 and 2000, and the findings are compared with those of Nicholson and Kim (1997) for the same geographical areas.

2) Rainfall and wheat yields

Rainfall over southern Africa exhibits a high degree of interannual variability, and severe droughts have led to reduced crop and stock production (Dilley, 2000; Mulenga et al, 2003). In South Africa, the majority of commercial winter wheat is rainfed (Purchase et al, 1998), and yields benefit from the summer soil moisture storage, particularly in the Free State (Peter Johnston, 2003, pers. comm).

The main areas of wheat production have been compared to the rainfall areas (Table 2). Within the studied period, the provincial boundaries have changed and accurate wheat data is only available for the same regions for two sub – periods (1974 – 1983; 1984 – 2000). To extend the time series (1974 – 2000), data for the same geographical area has been added together (i.e. the data for the Northern Cape and Western Cape have been extended to include the Cape Province; and the data for the Free State includes data from the original provincial area). Monthly, seasonal (Jan – Mar; Apr – Jun; Jul – Sept; Oct – Dec) and annual rainfall totals have been correlated with wheat yields for the full period using the Pearson’s product moment correlation coefficient. Furthermore, a lag of 12 months has been used to assess the relationships between rainfall and the wheat yield in the subsequent production year.

Agricultural drought occurs on time scales of 3 – 6 months (Harsch, 1992) but longer periods (12 – 24 months) of reduced rainfall may result in hydrological drought which leads to reductions of groundwater and streamflow (Meigh et al, 1999). The spatial extensions of the 20 worst droughts since 1922 have been documented using the standardised precipitation index (Rouault and Richard, 2003). The events of 1979, 1983, 1987 and 1992 were the most significant in the main areas of wheat production, and the effects of these have been

compared with the wheat anomaly from the provincial mean (for the appropriate sub – period).

3) El Niño and wheat yield

The majority of commercial winter wheat in South Africa is rainfed (Purchase et al, 1998). El Niño (La Niña) years are associated with dry (wet) conditions in South Africa (e.g. Lindsay, 1988; Nicholson and Kim, 1997; Richard et al, 2000; Landman and Mason, 1999b), and modelling studies have shown that during a severe El Niño event there is a reduction in water availability and decreased maize yields in South Africa (USGS, 2002; Funk et al, 2003). Pacific SSTs have been shown to lead maize yields in Zimbabwe by over 12 months (Cane et al, 1994). To investigate if changes in the Pacific affect South Africa wheat on a similar timescale, monthly Pacific Indexes (MEI, SOI, SSTs in the Niño 3 and 3.4 index) for the year before the production year and in juxtaposition to the growing season have been correlated with the area planted and yields (1974 – 2000) using the Pearson's product moment correlation coefficient. These correlations have also been calculated for the 1984 – 2000 period to eliminate any errors associated with adjustments in the provincial boundaries and to provide an indication of any changes in the industry since the mid 1980s.

Wheat yield anomalies are calculated with respect to the mean yield for the two sub – periods (1974 – 1983 and 1984 – 2000). The consistency and magnitude of the wheat yield anomaly is assessed in the year of El Niño or La Niña and the following year, with specific attention to severe El Niño and La Niña years (1982, 1991, 1997 and 1975, 1988, respectively) as defined by the CPC.

Results

1) Rainfall and ENSO

Mean annual rainfall has been higher across most of South Africa during 1974 – 2000 than the 1921 – 2000 period (Table 3), and late summer precipitation (Jan – Mar) has increased in all areas. The interannual and late summer rainfall variability has increased since the late 1960s, and rainfall anomalies are stronger (more than 2 S.D) since that time (Figures

3 and 4). Rainfall varies spatially and although each area has significantly reduced rainfall for prolonged periods (where at least four out of five years have anomalies more than 0.5 S.D), generally these droughts are spatially limited, and only the drought of the early 1980s has three rainfall areas (South Coast, Western Interior and Central Interior) that receive this level of prolonged water deficit.

Monthly rainfall has been correlated with the SOI, MEI and the SST anomalies for the Niño 3 and 3.4 regions on different timescales. Correlations between at least one of Pacific Index and rainfall were statistically significant (at the 95% level), on timescales from 3 – 15 months. All relationships are positive (negative) with the MEI and SST anomalies for the Niño 3 and 3.4 regions (SOI). Rainfall correlates with each Pacific Index after 3 months in the South Coast, Western Interior, Central Interior and North – Eastern Interior and 6 months in certain areas (North – Western Cape, South Coast, Western Interior and the North – Eastern Interior). Highest correlations were observed with the SOI (significant at the 99% level) in the South Coast, Western Interior, Central Interior and North – Eastern Interior after 3 months, and in the North – Western Cape and South – Western Cape after 9 months.

The monthly rainfall condition for each rainfall area (1974 – 2000) is shown in Figure 5. Months where rainfall is <75% of the long – term mean occur more frequently than unusually wet months (over 25% more than the long term mean). In the summer rainfall area, particularly dry months are found in the driest months, whereas these dry conditions occur throughout the year in the North Western Cape, South Western Cape and South Coast. The timings of unusually wet (over 25% more than the mean) conditions are fairly well distributed throughout the year in all areas. However, the Mann – Whitney *U* test for large samples (Christie, 2004) shows that there has been no significant change in the monthly rainfall between 1921 – 73 and 1974 – 2000 (all values rejected at the 95% confidence level). During El Niño years, the frequency of unusually dry and unusually wet months is higher than during La Niña years (Figure 6), and some months consistently have the same magnitude of signal in El Niño years (August in the Western Interior) and La Niña years (July, North Western Cape; February, South West Cape).

Figure 7 shows how late summer rainfall varies between El Niño episodes in each rainfall area. Across the country, the signal and magnitude of the precipitation anomaly varies greatly between events. No rainfall area has the same annual (not shown) or late summer

rainfall anomaly (e.g. dry conditions) in either the El Niño year or the following year, and only the North – Western Cape (the year after the El Niño) has the same annual reduced rainfall anomaly five times (1983, 1988, 1992, 1995, 1998). Actual precipitation between the year of the El Niño and the following year (+1) vary greatly across the country with the Western Interior receiving 85% more than the average in 1987 and just 44% of the long term mean annual rainfall in 1992. Similarly, the magnitude and signal of the late summer anomaly varies in the year of the La Niña and the following year (not shown). However, the annual anomaly for the North – Western Cape has the same anomaly in each La Niña event (reduced precipitation by 3 – 46% less than the 1921 – 2000 mean; Figure 8).

To assess the timing of the rainfall during an El Niño, a composite for the episodes between 1974 – 2000 has been constructed and the timings of the maximum and minima rainfall anomalies identified using a 3 – month running mean (Figure 9). The composites have been compared against those for El Niño years between 1901 – 1988 (Nicholson and Kim, 1997). While both investigations show that during a typical El Niño event, anomalously wet conditions precede dry conditions, there are some regional variations. Nicholson and Kim (1997) identify that these unusual rainfall conditions occur outside the wet and dry seasons and that only the Central Interior receives anomalously wet conditions during the wettest season. More recently however, the wet season is unusually dry during an El Niño with the Central Interior and North Eastern Interior having reduced rainfall in NDJ (0) and DJF (0) respectively. Conversely, in the North – Western Cape the wet season receives more rain during an El Niño episode. Furthermore, the timing between the maximum and minima rainfall anomaly has reduced and only the North – Western Cape (8 months) has over two months between the ending of unusually wet conditions and the beginning of dry ones. However, whilst there appears to be a significant change in the characteristics of the rainfall between the two investigations, it should be noted that Nicholson and Kim analyse 20 episodes and this investigation is limited to just 6 El Niño events. Furthermore, there is a large amount of variation in rainfall pattern for the 1974 – 2000 episodes which suggests that these results are not very robust (Figure 9).

2) Rainfall and Wheat

Throughout the studied period, South Africa has exported wheat (between 6,000 and 1,249,000 tonnes), reflecting relatively stable economic conditions (Department of

Agriculture, 2003). Nationally, from 1974 and throughout the 1980s, the area planted is fairly constant (1,627,000 – 2,013,000 hectares; Department of Agriculture, 2003). Across the country, there is a significant variation in yields (Figure 10) but the yield variations are fairly spatially coherent with all regions having poor yields in the mid 1980s. Despite a significant reduction in the area planted in the 1990s, this decade has the highest mean yield (1.87 t ha⁻¹; Department of Agriculture, 2003) as a result of improved farming practices and large – scale adoption of more resilient cultivars.

Wheat yields have been correlated with monthly (Table 4), seasonal (JFM, AMJ, JAS, OND) and annual rainfalls for the full period (1974 – 2000). On a 3 – month timescale, yields in the Northern Cape and Western Cape track the changes in late summer (JFM) rainfall (a negative correlation significant at the 95% level) whereas in the Free State good rainfall during JAS coincides with improved yields. The only significant relationship between the total annual rainfall and yield is in the Northern Cape (-0.31) with no time lag. It is noteworthy that the months with the strongest correlations are often outside the seasons with significant relationships.

The standardised precipitation index (SPI) shows the spatial extension (on a 6 – month timescale, ending in April) of the 20 worst droughts since 1922 (Rouault and Richard, 2003). The events of 1979, 1983, 1987 and 1992 were the most significant in areas of wheat production and the 1983, 1987 and 1992 droughts have been associated to El Niño (Rouault and Richard, 2003). These events have been described in the SPI terminology and compared to the yield anomaly for the appropriate provinces. Extremely and severely dry conditions were found in the North – Western Cape and South Coast area (1983) and extended across most of the Free State in 1983 and 1992. Severely dry conditions were found in the south coast area (1987) and moderately dry conditions were found in the North – Western Cape (1979) and Free State (1987). In 1984, the South – Western Cape was actually wetter than normal. The two most severe droughts in the Free State (1983 and 1992) coincide with decreases in the yield (anomalies of -1.13 and -0.47 tonnes ha⁻¹, respectively) whereas in the Western and Northern Cape these dry events cause only a slight reduction (-0.26 tonnes ha⁻¹) in wheat yields. However, Rouault and Richard (2003) identify unusually wet conditions in the south west of the country in 1984, which coincides with the lowest recorded yield for the Northern Cape (1.81 tonnes ha⁻¹ below the mean yield).

This investigation presents the relationships between wheat yield and rainfall on timescales of 1 – 24 months. It highlights 5 main points: (a) yields in the Northern Cape and Western Cape appear to be reduced following a wet late summer (JFM); (b) Rainfall may affect the next production year in all areas (i.e. the role of water storage on timescales greater than the growing season appear to be significant); (c) Rainfall simultaneous to the growing season may affect yields in the Western Cape and Free State, particularly rainfall in March, August, September and October; (d) In the Northern Cape, the yield is never improved by unusually wet conditions; (e) Widespread severe drought (on a 6 – month timescale) in the main wheat growing areas consistently reduces the yield.

3) El Niño and Wheat

Wheat yields for the 1974 – 2000 period have been correlated with the monthly anomalies for the Niño 3 and Niño 3.4 regions and the monthly anomaly for the MEI and SOI. Significant (at the 95% level) negative (positive) correlations are found for the SOI (Niño 3 and 3.4 SST anomalies) in April, May and June and yields in the Northern Cape and Western Cape, with a years lag. The only significant relationship in the Free State occurs is with the SOI in the November of the production year (0.36, significant at the 95% level). The strongest correlation is between yield and the MEI (0.45, for the Northern Cape in the May before the production year) and this is the only relationship that is significant at the 99% confidence level.

To eliminate any error associated with the changing of boundaries, the four Pacific Indexes have been correlated for a shortened time series (1984 – 2000). There is a noticeably decrease in the frequency of the relationships between ENSO and yield, and the only significant (at the 95% level) relationships (with SOI) occurs simultaneously to the harvest (November and December) in the Free State. However, there is now evidence of incorporation of ENSO into planting strategies in the Northern Cape, with a reduced area of planting the year after warm SSTs in the Niño 3 region.

The consistency and magnitude of the wheat anomaly in the El Niño and La Niña years and the following year has been assessed for the full time series (1974 – 2000). The yield anomaly is not the same in the year of an El Niño or La Niña event in any province, and the year following these events do not have the same type of anomaly in the Free State and

Western Cape. For the 1984 – 2000 period however, yields in the Northern Cape are consistently improved in the year following El Niño but the magnitude of these is very small (1 – 16% of the 1984 – 2000 mean), whereas in the Free State and Northern Cape the maximum and minimum yields since 1984 are found in either the year of, or following a La Niña (Table 5). The Kruskal Wallis test for independent sample medians show that the yields in El Niño and La Niña years were not found to be significantly different to non – ENSO years (maximum $H = 5.36$, rejected at the 95% confidence level). It is also noteworthy that the minimum and maximum yields are often consecutive (e.g. maximum yields in the Western Cape are 1994 and 1995), which suggests there is a strong influence of non – ENSO factors.

The Climate Prediction Centre (2004) identified three El Niño years that were particularly severe over 1.7°C (1982, 1991, 1997). Wheat yields in 1982 were actually slightly above average in the Free State and Cape areas (1.13 and 1.23 tonnes ha^{-1} , respectively). The 1991 episode coincided with decreased wheat yields across the country especially in the Northern Cape (0.67 tonnes ha^{-1} below average), whereas 1997 was more productive in the Free State (1.47 tonnes ha^{-1}) but the Western Cape and Northern Cape had slightly decreased yields (1.47 and 4.68 tonnes ha^{-1} , respectively). The most severe (over 1.7°C) La Niña episodes (1975 and 1988) coincide with increase yields in the Free State (0.92 and 1.90 tonnes ha^{-1}). The yield was slightly below average in the Cape (1975; 0.87 tonnes ha^{-1}) and the Western Cape (1988; 1.11 tonnes ha^{-1}) but was particularly good in 1988 in the Northern Cape (5.59 tonnes ha^{-1}).

Whilst there appears to be a statistical link between ENSO and the wheat yield for the full period in two provinces (Northern Cape and Western Cape), this connection is not very robust and it is neither apparent in the shortened time series (1984 – 2000) nor is the anomaly consistent in El Niño or La Niña years. The lack of clarity between ENSO and wheat yield may be due to changes in farming practice within the studied period (e.g. increases in the area under irrigation, improved availability of resistant crops; Dilley, 2000), the short (<30 years) time period (Barnston and Ropelewski, 1992), or other factors mediating the wheat yield.

The SOI – rainfall relationship is well established (Lindesay, 1988; Nicholson and Kim, 1997; Richard et al, 2000). This investigation recognises that across South Africa, the SOI relationship is typically stronger than the Niño 3 and 3.4 SST anomalies and the MEI. Across the country, the timing of the strongest ENSO – rainfall relationships vary, with the strongest correlations occurring over the summer rainfall region (after a 3 month lag) and in the south west of the country after 6 – 9 months. The equatorial Pacific Ocean plays an important role in the predictability of South African rainfall (Landman and Klopper, 1998; Landman and Mason, 1999a), but the influences of regional SST forcing are also very important (Fauchereau et al, 2003; Swann et al, 2003). The spatial differences in the ENSO – rainfall relationship may be explained in part through the manifestation of the ENSO signal in the oceans adjacent to South Africa. Rainfall conditions over large areas of the country, especially in late summer, are associated with the SSTs in the equatorial Indian Ocean (near 60°E) (Mason, 1990; Jury, 1996b) and strong relationships in this part of the Indian Ocean follow ENSO events by 1 to 3 months (Fauchereau et al, 2003). Warm SSTs in the South East and South West Atlantic favour cyclogenesis which, in conjunction with other atmospheric changes, enhances rainfall over the South Western Cape (Reason et al, 2002) and during the major El Niño episodes of 1982 and 1987, the maximum warming in the eastern Pacific led warming in these areas by 6 to 9 months (Nicholson, 1997).

Since the 1980s, across southern Africa there has been a slight decrease in precipitation (Richard et al, 2001). In South Africa however, this study finds that there has been a slight increase in rainfall since the 1970s due to unusually wet conditions and a limited spatially extension of the severe droughts in the 1980s and the beginning of the 1990s. These findings are roughly in agreement with the trends for the southern hemisphere subtropics (20 – 40°) that have exhibited an increasing trend of 3.6 mm decade⁻¹ throughout the 20th Century (New et al, 2001). Furthermore, the three distinct sub – periods (1900 – 1935; 1935 – 1970; 1970 – 1998) of late summer interannual rainfall variability that have been identified for the subcontinent (Richard et al, 2001) cannot be seen in South Africa.

ENSO warm (cold) events are associated with dry (wet) conditions over southern Africa (Jury, 1996b; Nicholson and Kim, 1997), and the effects are more prominent in late summer rainfall (Lindesay, 1988). Over southern Africa since 1970, decaying El Niño (La

Niña) episodes have been associated with unusually dry (wet) conditions during the late summer (Richard, et al, 2000). This investigation recognises marked adjustments in late summer and annual rainfall responses to warm (cold) Pacific events, which may reflect the inter – El Niño variation in the evolution of SSTs in the Pacific (Nicholson, 1997) and circulation patterns across the southern hemisphere (Vera et al, 2004), the manifestation of the ENSO signal in the tropical Indian Ocean (Goddard and Graham, 1999; Reason et al, 2000), the phase of quasi – biennial oscillation (Jury, 1996b; Mason and Jury, 1997) or some other climatic parameters. Alternatively, these differences may partly be explained through the choice of ENSO years and the small areas (and a high noise to signal ratio) used in this investigation (Jury, 1996b).

This investigation recognises an adjustment in the timings of mean rainfall anomalies through a 24 – month El Niño event from those of Nicholson and Kim (1997). Whilst unusually wet conditions precede dry conditions during an event in both investigations, the timing of these maximum anomalies is significantly reduced in this study. It should be noted that this investigation is based on a relatively short time series (just 6 events compared to the 20 used in Nicholson and Kim), and that there is considerable variation in the timings of the maximum anomaly within the studied period. However, this study provides a useful understanding of the rainfall response to El Niño since the late 1960s when there was a modification of SST conditions in the tropical and extratropical Southern and Indian Oceans (Trzaska et al, 1996) and the global ocean (Graham, 1994), and an adjustment in the ENSO – rainfall relationship over southern Africa (Richard et al, 2000).

Dry conditions associated with El Niño have been shown to be detrimental to the maize yield in South Africa (USGS, 2002; Funk et al, 2003). This present investigation assesses the yield – rainfall relationships on timescales from 1 – 24 months, and finds that the months where rainfall correlates with yield are often outside those seasons where the rainfall – yield connections are strongest. These differences in timings may be associated to rainfall during critical times of the growing season or the mediating effects of local soil surface characteristics and moisture storage on precipitation which are particularly important over short time scales (Landman et al, 2001). The soil moisture storage from the late summer rains affects the yield in the Free State (Peter Johnston, pers. comm. 2003), but this study finds rainfall in JAS is more important in this province whereas late summer rainfall is important in the Northern Cape and Western Cape.

Winter wheat is planted between May and July, head in late August and September and is then harvested between October and December across most of South Africa, although these times may be slightly earlier in the south west of the country (USDA, 1999). Environmental conditions are critical to wheat growth, especially during the tillering stage, as the kernel matures (Simmons et al, 1995) and just before harvest where wet conditions increase the head size (Fowler, 2002). This study recognises that a wet summer (especially January and February) before planting is generally detrimental to the yield whereas improved production relates to high rainfall as the wheat heads and matures (July – October). A wet summer may cause reduced yields as fields may be waterlogged, competition with established weeds may be greater and there is more leaching of fertilisers and critical micronutrients from the soil (CIMMYT, 2000). These problems associated with excess water, especially increased waterlogged area and the leaching of nutrients, may partly explain why all relationships with rainfall are negative in the most irrigated province, the Northern Cape.

The major droughts of 1991/92, 1994/94 and 1997/98 have been associated with El Niño conditions in the Pacific, and since the early 1990s there has been increased interest in climate forecast information across southern Africa from farm – level to government decision makers (Callihan et al, 1994; Rook, 1996; Dilley, 2000). This investigation recognises the integration of this forecast information into the planting strategies in the Northern Cape, with the area planted being reduced the year after warm SSTs in the Nino 3 region of the Pacific. However, whereas modelling studies (USGS, 2002; Funk et al, 2003) have identified moderate – strong El Niño years as causing significant drought and decreasing the maize yield by 10 – 20% in the Free State, the effects of the El Niño episodes on South African wheat are less apparent. The 1982 and 1991 El Niño events were associated with severe droughts in the wheat growing areas of the Free State (Rouault and Richard, 2003) and these events were associated with very poor yields. The 1997 El Niño event was particularly intense but wheat yields were not affected in South Africa as the associated drought was limited to the North East of the country (Rouault and Richard, 2003) and the adoption of drought – tolerant cultivars was widespread (Dilley, 2000).

Warm (cold) ENSO events have been associated with reduced (increased) maize production in Zimbabwe (Cane et al, 1994), sugarcane in South Africa (Singels and Bezuidenhout, 1999) and the production of numerous field crops in Australia (Howden et al, 2001; Potgieter et al, 2002; Everingham et al, 2003), Mexico (Adams et al, 1999), and across

North America (Izaurre et al, 1998; Legler et al, 1999; Hill et al, 1998). This investigation finds strong correlations between ENSO indicators and wheat yields in the Northern Cape and Western Cape, with a lead time of a year, but finds that El Niño (La Niña) episodes are not synonymous with reduced (improved) yields. There does appear to be a link between ENSO and wheat yield, but this link is not simply linear during El Niño or La Niña events and consequently the predictability of yields using ENSO is limited. These weak connections may be a result of the many factors that mediate the effects of ENSO in South Africa, from large – scale changes in the manifestation of the ENSO signal in the adjacent oceans, through meso – scale factors such as streamflow (which may be out of phase with ENSO; Landman et al, 2001) and local land characteristics (e.g. soil moisture), to local yield – limiting factors such as weeds, insects and disease as well as farming decisions. Additionally, the length of historical production records is inadequate (<30 years) to determine the ENSO – yield connection conclusively (Barnston and Ropelewski, 1992).

Conclusion

This investigation assesses the relationship between ENSO and the wheat yield in South Africa and explains these changes through the adjustments in rainfall associated with ENSO. Rainfall during El Niño (La Niña) is analysed on timescales from 1 – 24 months and the study finds that some months consistently have the same rainfall response in El Niño or La Niña years; that there has been significant adjustments in the timings of maximum and minimum rainfall anomalies from previous investigations; and there is marked inter – El Niño and inter – La Niña variation in rainfall. The majority of wheat is rainfed and rainfall – yield relationships are found across the country, although there are spatial differences in the timing and characteristics of these connections. The effects of rainfall on the wheat yield are most apparent in the Free State where the most severe droughts of the investigation have resulted in reduced yields, whereas in the Northern Cape and Western Cape wet conditions generally coincide with reduced yields. The wheat anomaly through El Niño (La Niña) events is not consistent in the Western Cape or Free State, possible due to the strongest rainfall – yield relationships being outside the months where rainfall consistently responds to El Niño or La Niña. In the Northern Cape however, yields are consistently improved the year after an El Niño event possibly as it has the most irrigation and it is the only province that

incorporates ENSO into planting strategies. The connections between ENSO, rainfall and wheat yield in South Africa are not simply linear and as a consequence the predictability of yields by ENSO is limited. These relationships appear to be mediated by factors outside this study, such as the hemispheric variation in the evolution of El Niño events (Vera et al, 2004), local scale characteristics or management strategies (Adams et al, 1999).

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References

- Adams, R.M., Houston, L.L., McCarl, B.A., Tiscareno L. M., Matus G, J., Weiher, R.F., (2003) The benefits to Mexican agriculture of an El Niño – Southern Oscillation (ENSO) warning system *Agricultural and Forest Meteorology*, **115**, 183 – 194.
- Arbuthnot, J.D., (1996) Environmental Change and Agriculture, In *Global Climate Change and South Africa*, (eds. Shackleton, L.Y, Lennon, S.J., Tosen, G.R.), Environmental Scientific Association, Cleveland.
- Annecke, D.P., Moran, V.C., (1982) *Insects and Mites of Cultivated Plants in South Africa*, Butterworths, Durban.
- Barnston, A.G., Ropelewski, C.F., (1992) Prediction of ENSO episodes using canonical correlation analysis. *Journal of Climate*, **5**, 1316–1345.
- Baylis, M., Mellor, P.S., Meiswinkle, R., (1999) Horse sickness and ENSO in South Africa, *Nature*, **397**, 574 – 574.
- Callihan, D.M., Erikson, J.H., Herrick, A.B., (1994) Famine Averted: The United States Government Response to the 1991/92 Southern Africa Drought *Management Systems International*, Washington DC.
- Cane, M.A., Eshel, G., Buckland, R.W., (1994) Forecasting Zimbabwean maize yield using eastern equatorial Pacific sea – surface temperature *Nature*, **370**, 204 – 205.
- Christie, P., (2004) *A short course in statistics* Found at: <http://www.bath.ac.uk/~ccsphc/coarse.pdf>
- CIMMYT, (2000) *Wheat in the developing world* Found at: http://www.cimmyt.org/Research/wheat/map/developing_world/wheat_developing_world.htm
- Dai, A., Trenberth, K.E., (1998) Global variation in droughts and wet spells, 1900 – 1995 *Geophysical Research Letter*, **25**, 3367 – 3370.

de Jager, J.M., Potgieter, A.B., van der Berg, W.J., (1998) Framework for forecasting the extent and severity of drought in maize in the Free State Province of South Africa, *Agricultural Systems*, **57**, 351 – 365.

Department of Agriculture (2003) *Abstract of Agricultural Statistics* Department of Agriculture, Pretoria.

Department of Agricultural Engineering, (1997) Biological Productivity In *Environmental Potential Atlas for South Africa* (eds. van Riet, W.F., Claassen, P., van Rensburg, J., van Viegen, T., du Pleiss, L.,) J.L. Schaik, Pretoria.

Dilley, M., (2000) Reducing vulnerability to climate variability in Southern Africa: The growing role of climate information *Climatic Change*, **45**, 63 – 73.

Doerge, T., (1997) Weigh wagon vs yield monitor comparisons. *Crop Insights*, **7**.

Everingham, Y.L., Muchow, R.C., Stone, R.C., Coomans, D.H., (2003) Using southern oscillation index phases to forecast sugarcane yields: a case study for Northeastern Australia, *International Journal of Climatology*, **23**, 1211 – 1218

Fauchereau N., Trzaska, S., Richard, Y., Roucou, P., Camberlin, P., (2003) SST co – variability in the Southern Atlantic and Indian Oceans and its connections with the atmospheric circulation in the Southern Hemisphere *International Journal of Climatology*, **23**, 663 – 677.

Fowler, D.B., (2002) *Winter wheat production manual* Found at http://www.usask.ca/agriculture/plantsci/winter_cereals/Winter_wheat/contents.htm

Funk, C., Michaelsen, J., Verdin, J., Artan, G., Husak, G., Senay, G., Gadain, H., Magadazire, T., (2003) The collaborative historical Africa rainfall model description and evaluation *International Journal of Climatology*, **23**, 47 – 66.

Goddard, L., Graham, N.E., (1999) Importance of the Indian Ocean for simulating rainfall anomalies over eastern and southern Africa *Journal of Geophysical Research*, **104 (D16)**, 19099 – 19116.

- Graham, N.E., (1994) Decadal-scale climate variability in the tropical and North Pacific during the 1970s and 1980s: observations and model results *Climate Dynamics*, **10**, 135 – 162.
- Harrison, M.S.J., (1984) A generalised classification of South African summer rain – bearing synoptic systems, *International Journal of Climatology*, **4** 547 – 560.
- Harrison, M.S.J., (1988) Rainfall and precipitable water relationships over the central interior of South Africa *South African Geographical Journal*, **70**, 100 – 111.
- Harrison D.E., Larkin, N.K., (1998) El Niño – Southern Oscillation sea surface temperature and wind anomalies, 1946 – 1996 *Review of Geophysics*, **36**, 353 – 399
- Harsch, E., (1992) Drought devastates Southern Africa *Drought Network News*, **4**, 17 – 19.
- Hill, H.S.J., Park, J., Mjelde, J.W., Rosenthal, W., Love, H.A., Fuller, S.W., (1998) US Winter Wheat Producer Forecasts by SOI In *Proceedings of the Review of the Causes and Consequences of Cold Events: A La Niña Event 15 – 17 June, 1998, Boulder, USA* Found at <http://www.esig.ucar.edu/laNiña/index.html>.
- Howden, S.M., McKeon, G.M., Meinke, H., Entel, M., Flood, N., (2001) Impacts of climate change and climate variability on the competitiveness of wheat and beef cattle production in Emerald, north – east Australia *Environment International*, **27**, 155 – 160.
- Izaurrealde, R.C., Rosenberg, N.J., Brown, R.A., Legler, D.M., Tiscareño López, M., Srinivasan, R., (1999) Modelled effects of moderate and strong “Los Niños” on crop productivity in North America *Agricultural and Forest Meteorology*, **94**, 259 – 268.
- Jury, M., (1996a) Regional teleconnection patterns associated with summer rainfall over South Africa Namibia and Zimbabwe *International Journal of Climatology*, **16**, 135 – 153.
- Jury, M., (1996b) Statistical Models for Seasonal Forecasts of Southern Africa Summer Rainfall *Climate Prediction Centre Experimental Long – Lead Forecast Bulletins* Found at <http://www.cpc.noaa.gov/products/predictions/experimental/bulletin/Dec96/art21.html>
- Jury, M., (1997) Statistical models for seasonal forecasts of southern Africa summer rainfall *Climate Prediction Centre Experimental Long – Lead Forecast Bulletins*. Found at <http://www.cpc.noaa.gov/products/predictions/experimental/bulletin/Dec97/a30.html>

- Koch, B.H., (1996) The degradation of natural resources In *Global Climate Change and South Africa*, (eds. Shackleton, L.Y., Lennon, S.J., Tosen, G.R.,) Environmental Scientific Association, Cleveland.
- la Cock, G.D., (1986) The Southern Oscillation, environmental anomalies, and mortality of 2 southern African seabirds. *Climate Change*, **8**, 173 – 184.
- Landman, W.A., Klopper, E., (1998) 15 – year simulation of the December to March rainfall season of the 1980s and 1990s using canonical correlation analysis (CCA) *Water SA*, **24**, 281 – 285.
- Landman, W.A., Mason, S.J., (1999a) Operational long – lead prediction of South African rainfall using canonical correlation analysis *International Journal of Climatology*, **19**, 1073 – 1090.
- Landman, W.A., Mason, S.J., (1999b) Change in the associate between Indian Ocean sea surface temperatures and summer rainfall over South Africa and Namibia *International Journal of Climatology*, **19**, 1477 – 1492
- Landman, W.A., Mason, S.J., Tennant, W.J., (2001) Statistical downscaling of GCM simulations to streamflow *Journal of Hydrology*, **252**, 221 – 236.
- Le Roux, N.J., Olivier, J., (1996) Modelling hail frequency using a generalised additive interactive technique *South African Geographical Journal*, **78**, 7 – 12.
- Legler, D.M., Bryant, K.J., O'Brian, J.J., (1999) Impact of ENSO – Related Climate Anomalies on Crop Yields in the U.S. *Climate Change*, **42**, 351 – 375.
- Lindesay, J.A., (1988) South African rainfall, the Southern Oscillation and a Southern Hemisphere semi – annual cycle. *Journal of Climatology*, **8**, 17 – 30.
- Lizcano, G., Todd, M.C., (2005) Non – ENSO control on Southern Africa precipitation variability *Philosophical Transactions: Mathematical, Physical and Engineering Sciences of the Royal Society*, **363**, 61 – 62.
- Mason, S.J., (1990) Temporal variability of sea surface temperatures around southern Africa: a possible forcing mechanism for the eighteen – year rainfall oscillation? *South African Journal of Science*, **86**, 243 – 252.

Mason, S. J., (1996) Climatic change over the Lowveld of South Africa. *Climatic Change*, **32**, 35–54.

Mason, S.J., Jury, M.R., (1997) Climatic variability and change over southern Africa: a reflection on underlying processes *Progress in Physical Geography*, **21**, 24 – 50.

Mason, S.J., Goddard, L., (2001) Probabilistic precipitation anomalies associated with ENSO *Bulletin of the American Meteorological Society*, **82**, 619 – 638.

Meigh, J.R., McKenzie, A.A., Sene, K.J., (1999) A grid – based approach to water scarcity estimates for Eastern and Southern Africa *Water Resource Management*, **13**, 85 – 115.

Mulenga H.M., Rouault, M., Reason, C.J.C., (2003) Dry summers over northeastern South Africa and associated circulation anomalies *Climate Research*, **25**, 29 – 41.

New, M., Todd, M., Hulme, M., Jones, P., (2001) Precipitation measurements and trends in the twentieth century *International Journal of Climatology*, **21**, 1889 – 1922.

Nicholson, S.E., (1997) An analysis of the ENSO signal in the tropical Atlantic and western Indian Oceans *International Journal of Climatology*, **17**, 345 – 375.

Nicholson, S.E., Kim, J., (1997) The Relationship of the El Niño – Southern Oscillation to African Rainfall, *International Journal of Climatology*, **17**, 117 – 135.

Olivier, J., van Rensburg, P.A.J., (1995) Links between the Southern Oscillation and hail in the Transvaal: a preliminary assessment *South African Journal of Science*, **91**, 145 – 148.

Peterson, A., (1969) *Wheat* Oxford University Press, Oxford.

Poccard, I., Fauchereau, N., Mulenga, H.M., Richard, Y., (2001) Key role of tropical/extratropical atmospheric dynamics over Atlantic in the teleconnection between ENSO and South Africa droughts *CLIVAR workshop on Tropical Atlantic Variability* Found at <http://www.clivar.org/organization/atlantic/TAV/abstracts.htm>.

Potgieter, A.B., Hammer, G.L., Butler, D., (2002) Spatial and temporal patterns in Australian wheat yield and their relationship with ENSO *Australian Journal of Agricultural Research*, **53**, 77 – 89.

- Purchase, J., Ybema, S., Barnard, A., Bruin, F., Potgieter, H., Walsh, T., Hatting, H., Botha, A., Nel, C., Maritz, M., van Rensburg, B., van der Merwe, M (1998) *Crop Science Annual Wheat Newsletter*, **42**.
- Preston A., Washington R., Todd, M.C., (2000) An improved understanding of inter – annual and intraseasonal variability of southern African rainfall using NCEP/NCAR reanalysis data *In Proceedings of the 6th International Conference on Southern Hemisphere Meteorology and Oceanography 6 – 9 April, 2000, Santiago, Chile*.
- Reason C.J.C., Mulenga, H., (1999) Interannual warm and cool events in the subtropical/mid – latitude South Indian Ocean region *Geophysical Research Letters*, **26**, 215 – 218.
- Reason C.J.C., Rouault, M., (2002) ENSO – like decadal variability and South African rainfall *Geophysical Research Letters*, **29**, 10.1029/2002GL014663
- Reason C.J.C., Allan, R.J., Lindesay, J.A., Ansell, T.J., (2000) ENSO and climatic signals across the Indian Ocean Basin in the global context: part I, interannual composite patterns *International Journal of Climatology*, **20**, 1285 – 1327.
- Reason C.J.C., Rouault, M., Melince, J.-L., Jagadheesha, D., (2002) Interannual winter rainfall variability in SW South Africa and large scale ocean – atmosphere interactions *Meteorology and Atmospheric Physics*, **80**, 19 – 29.
- Richard, Y., Pocard, I (1998) A statistical study of NDVI sensitivity to seasonal and interannual rainfall variations in Southern Africa *International Journal of Remote Sensing*, **19**, 2907 – 2920.
- Richard, Y., Trzaska, S., Roucou, P., Rouault, M., (2000) Modification of the southern African rainfall variability/ENSO relationship since the late 1960s *Climate Dynamics*, **16**, 883 – 895.
- Richard, Y., Fauchereau, N., Pocard, I., Rouault, M., (2001) XXth Century droughts in Southern Africa Spatial and temporal variability, teleconnections with oceanic and atmospheric conditions *International Journal of Climatology*, **21**, 873 – 885.

- Rouault, M., White, S.A., Reason, C.J.C., Lutjeharms, J.R.E., Jobard, I., (2002) Ocean – atmosphere interaction in the Agulhas Current region and a South African extreme weather event *Weather and Forecasting*, **17**, 655 – 669.
- Rouault, M., Richard, Y., (2003) Intensity and spatial extension of drought in South Africa at different time scales *Water SA*, **29**, 489 – 500.
- Rook, J.M., (1996) Annex I: Macro – level benefits and implication of long lead climate forecasting for drought risk management In *Drought Risk Management in Southern Africa Volume II: Technical Annexes* (eds. Gibberd, V., Rook, J.M., Sear, C.B., Williams, J.B.,) Natural Resources Institute, University of Greenwich, UK.
- Scott, D.B., (1990) *Wheat diseases in South Africa Technical Communication 220*, CTP Book Printers, Pretoria.
- Singels, A., Bezuidenhout, C.N., (1999) The relationship between ENSO and rainfall and yield in the South African sugar industry *South African Journal of Plant and Soil*, **16**, 96 – 101.
- Simmons, S.R., Oelke, E.A., Anderson, P.M., (1995) *Growth and Development Guide for Spring Wheat: University of Minnesota Agricultural Extension Folder* Found at <http://www.extension.umn.edu/distribution/cropsystems/DC2547.html>.
- Swann, M., Washington, R., New, M., (2003) Tropical oceans and the predictability of southern African rainfall in the HadCM3 coupled climate model *CLIVAR Exchanges*, **27**.
- Taljaard, J.J., (1985) *Cut – off lows in the South African region. South African Weather Bureau Technical Paper, 14*, South African Weather Bureau, Pretoria.
- Todd, M.C., Washington, R., (1998) Extreme daily rainfall in southern African and South West Indian Ocean tropical – temperate links *South African Journal of Science*, **94**, 64 – 70.
- Todd, M.C., Washington, R., (1999) Circulation anomalies associated with tropical – temperate troughs over Southern African and the South West Indian Ocean, *Climate Dynamics*, **15**, 937 – 951.
- Todd, M.C., Washington, R., Clarke, R.A., Kniveton, D., (2002) Brown locust outbreaks and climate variability in southern Africa *Journal of Applied Ecology*, **39**, 31 – 42.

- Todd, M.C., Washington, R., Palmer, P., (2004) Water vapour transport associated with tropical temperate trough systems over Southern Africa and the Southwest Indian Ocean *International Journal of Climatology* **24**, 555 – 568.
- Trzaska, S., Fauchereau, N., Pocard, I., Camberlin, P., Richard, Y., Philippon, N., (1996) Stability of the relationship between regional rainfall in Africa and ENSO *In Proceedings of the 25th Conference on Hurricanes and Tropical Meteorology, Annual Congress of the American Meteorological Society, 29 April – 3 May, San Diego, USA* Found at <http://ams.confex.com/ams/pdfpapers/36204.pdf>.
- Tyson, P.D., (1986) *Climatic Change and Variability in Southern Africa*, Oxford University Press, Oxford.
- Tyson, P.D., Preston – Whyte, R.A., (2000) *The Weather and Climate of Southern Africa* Oxford University Press South Africa, Cape Town.
- Tyson, P.D (1996) South Africa's Climate and Variability In *Global Climate Change and South Africa* (eds. Shackleton, L.Y, Lennon, S.J., Tosen, G.R.), Environmental Scientific Association, Cleveland.
- Tyson, P.D., Cooper, G.R.J., McCarthy, T.S., (2002) Millennial to multi–decadal variability in the climate of southern Africa. *International Journal of Climatology*, **22**, 1105 – 1117.
- United States Department of Agriculture (USDA)., (1999) *South African Wheat Production* Found at: <http://www.usda.gov/agency/oce/waob/jawf/profiles/html/saf/safwht.html>.
- United States Geological Survey (USGS)., (2002) *Historical El Niño Crop Production Relationships in Southern Africa*, Found at <http://www.geog.ucsb.edu/~chris/pubs/HistoricalElNiñoCropProductionRelationshipsInSouthernAfrica.pdf#search='Historical%20El%20Niño/%20Crop%20Production%20Relationships%20in%20Southern%20Africa'>
- van Riet, W (1997) Land use In *Environmental Potential Atlas for South Africa* (eds. W.F., Claassen, P., van Rensburg, J., van Viegen, T., du Pleiss, L) J.L. Schaik, Pretoria.
- Vera, C., Silvestri, G., Barros, V., Carril, A., (2004) Differences in El Niño response over the Southern Hemisphere *Journal of Climate*, **17**, 1741 – 1753.

Washington, R., Todd, M.C., (1999) Tropical – temperate links in Southern Africa and Southwest Indian Ocean satellite – derived daily rainfall *International Journal of Climatology*, **19**, 1601 – 1616.

Walker, N.D., Lindesay, J.A., (1989) Preliminary observations of oceanic influences on the February – March 1988 floods in central South Africa *International Journal of Climatology*, **11**, 609 – 627.

Wolter, K., Timlin, M.S., (1993) Monitoring ENSO in COADS with a seasonally adjusted principal component index *In Proceedings of the 17th Climate Diagnostics Workshop, Climate Analysis Center, National Oceanic and Atmospheric Administration, Oklahoma, USA.*

Wolter K., Timlin, M.S., (1998) Measuring the strength of ENSO – how does 1997/98 rank? *Weather*, **53**, 315 – 324.

Zar, J.H., (1984) *Biostatistical Analysis 2nd Edition* Prentice Hall, London.

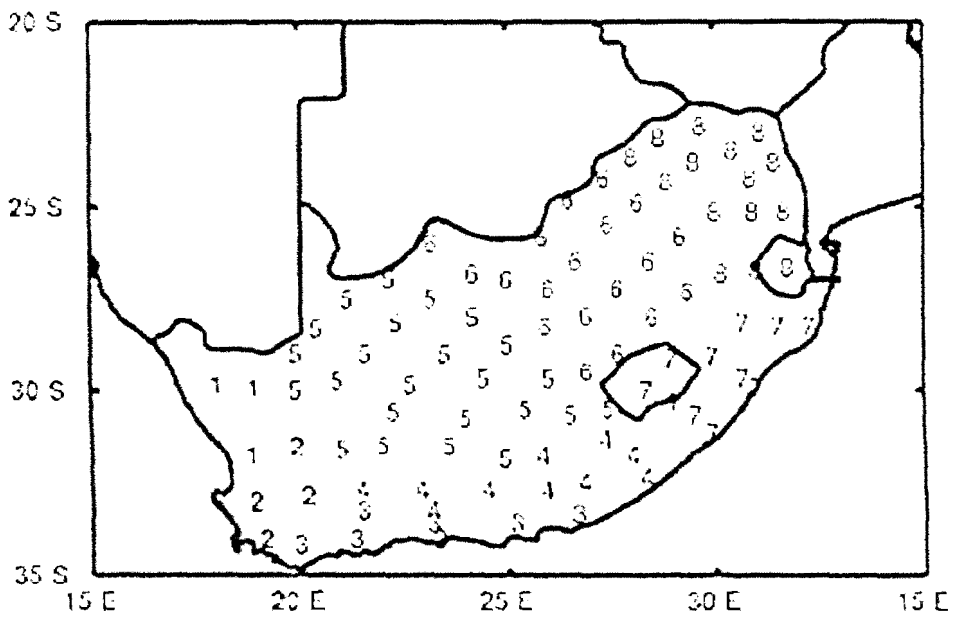


Figure 1 The eight homogeneous rainfall areas of South Africa as defined by the South African Weather Service: North - Western Cape (1); South - Western Cape (2); South Coast (3); Southern Interior (4); Western Interior (5); Central Interior (6) KwaZulu - Natal (7); North - Eastern Interior (8). Taken from Rouault and Richard (2003).

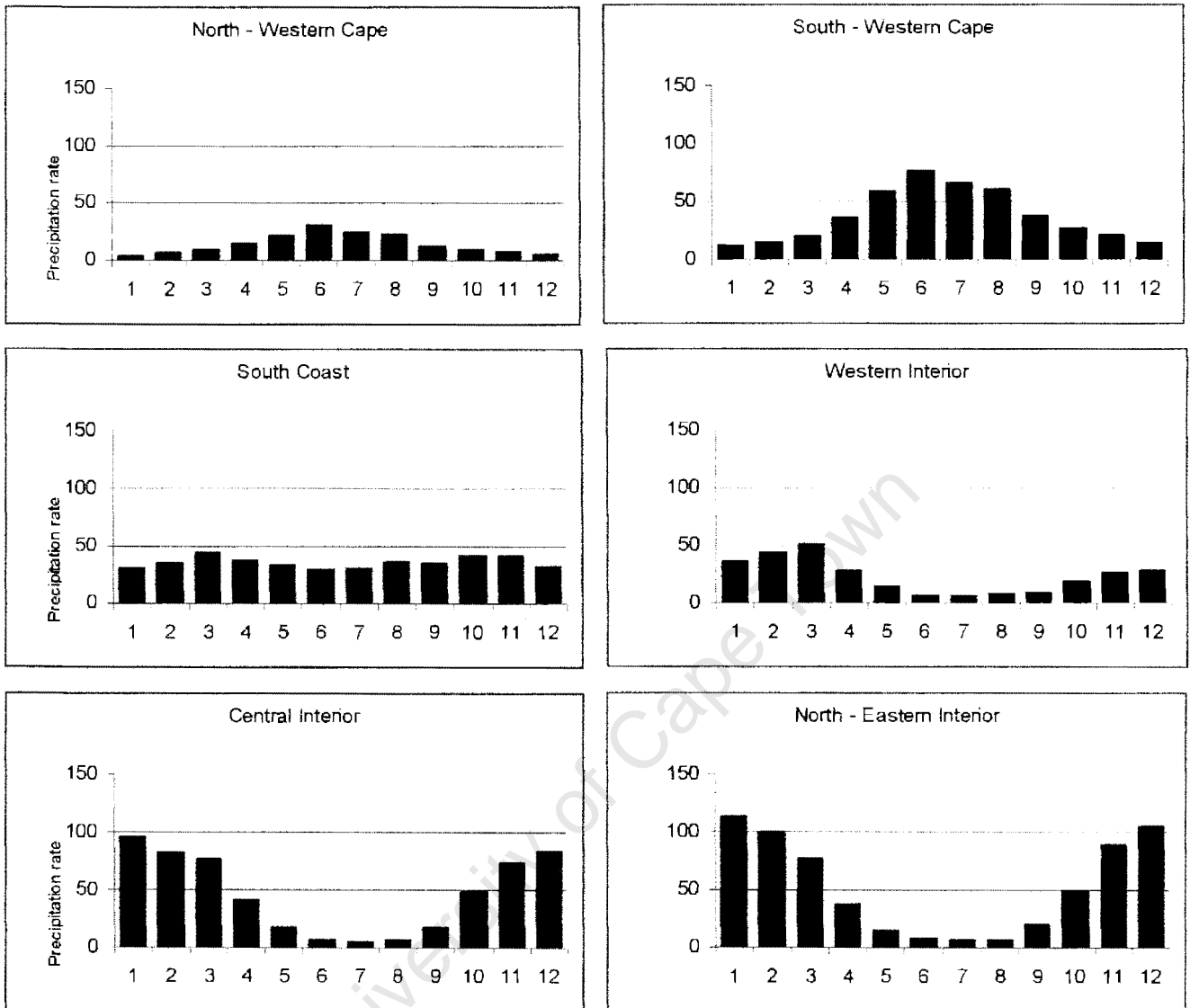


Figure 2 The 1921 – 2000 monthly precipitation rate (mm) for the 6 homogeneous rainfall areas covering the three main wheat growing areas.

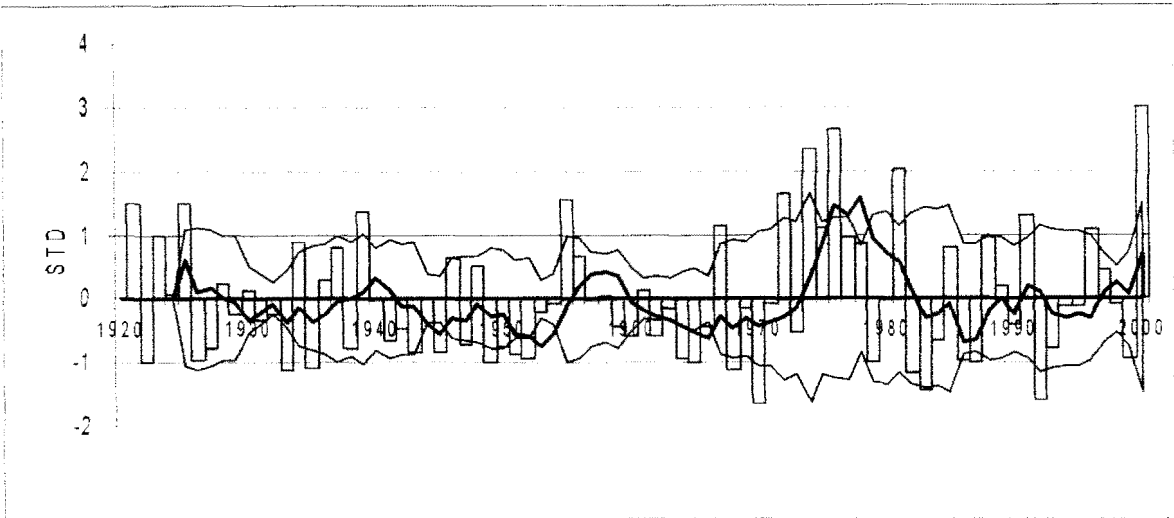


Figure 3 Late summer (January – March) rainfall from 1921 - 2000. Bars: Jan – Mar standardised rainfall. Central curve: 5 – year running mean rainfall. Shading: 5 – year running standard deviation.

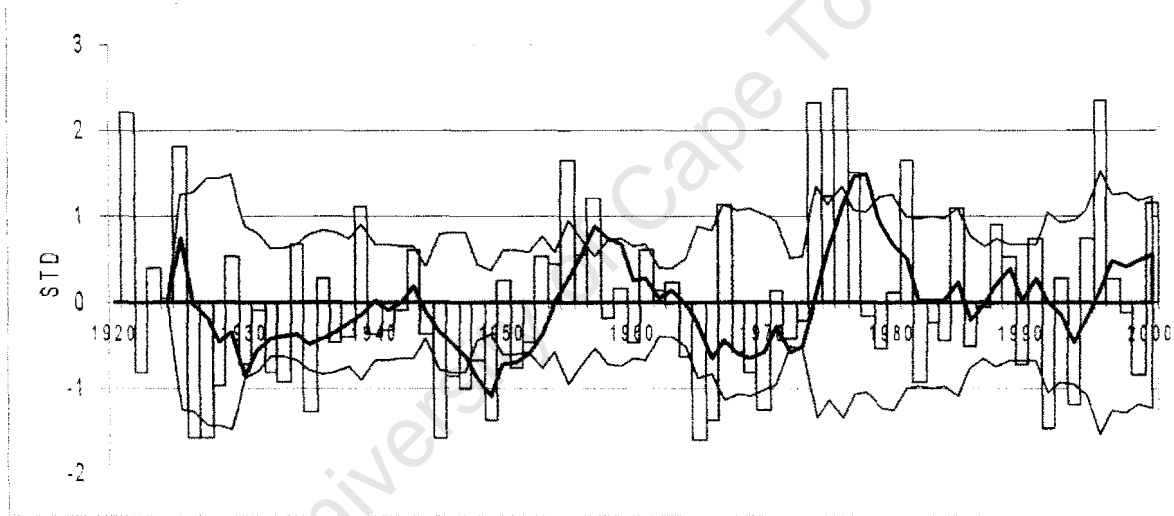


Figure 4 Total annual (January – December) rainfall from 1921 - 2000. Bars: Jan – Dec standardised rainfall. Central curve: 5 – year running mean rainfall. Shading: 5 – year running standard deviation.

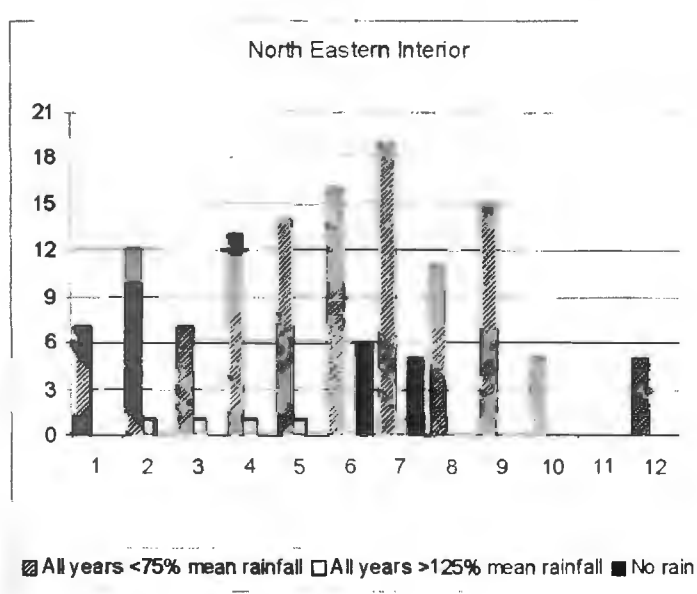
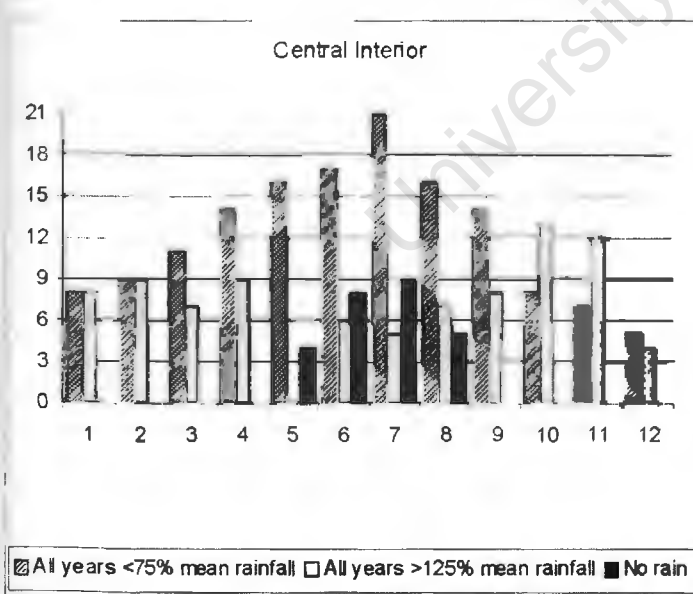
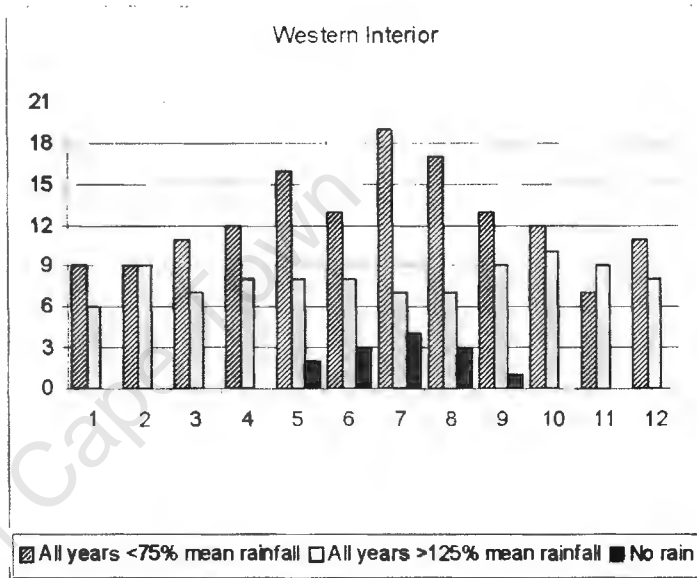
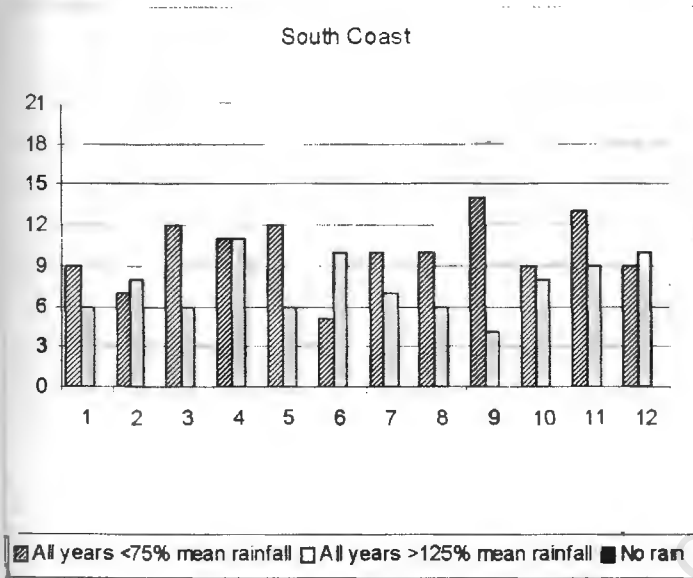
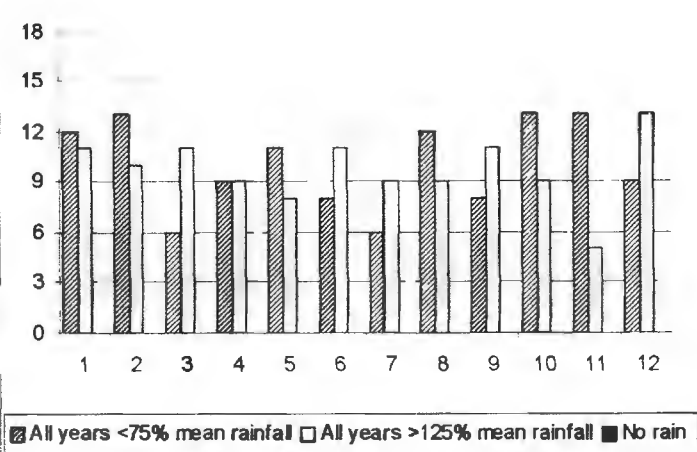
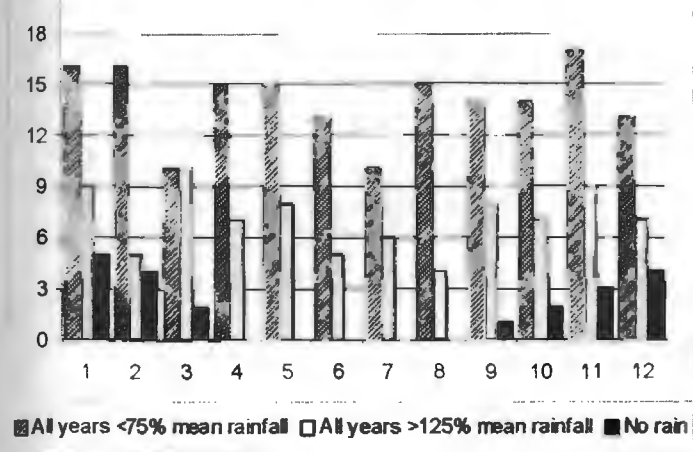


Figure 5 The frequencies of no rain, unusually dry (<75% of the 1921 – 2000 monthly mean) and anomalously wet (>25% more than the 1921 – 2000 monthly mean) for the 1974 – 2000 period. Months are shown along the x – axis and the number of years receiving these conditions are shown on the y - axis. ENSO years are shown separately, but these years are included in these figures.

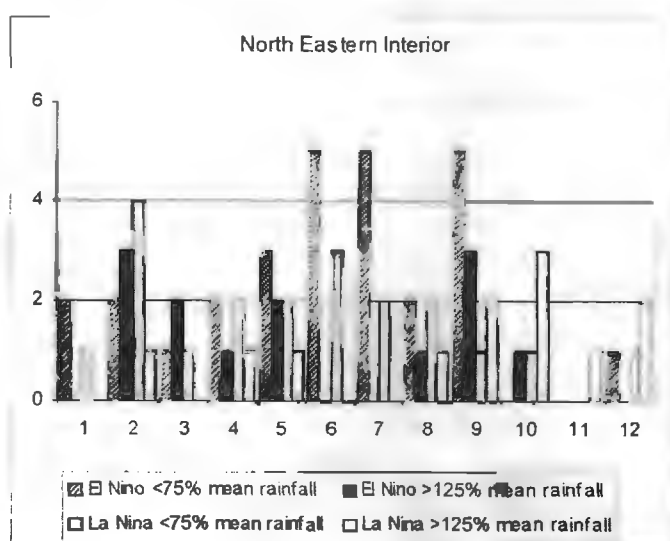
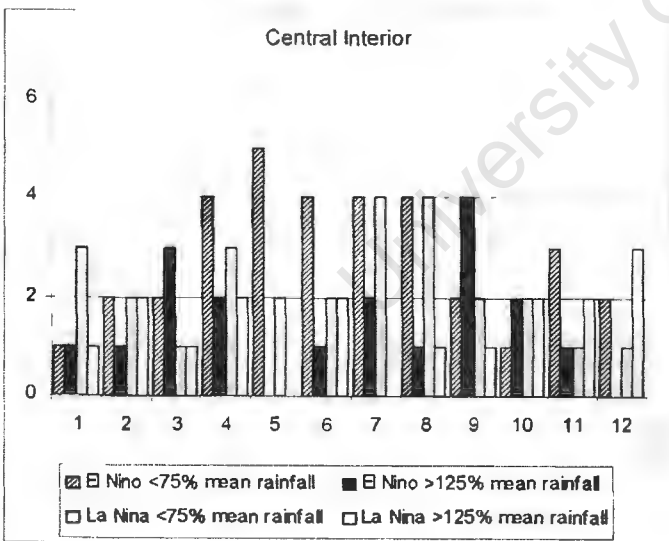
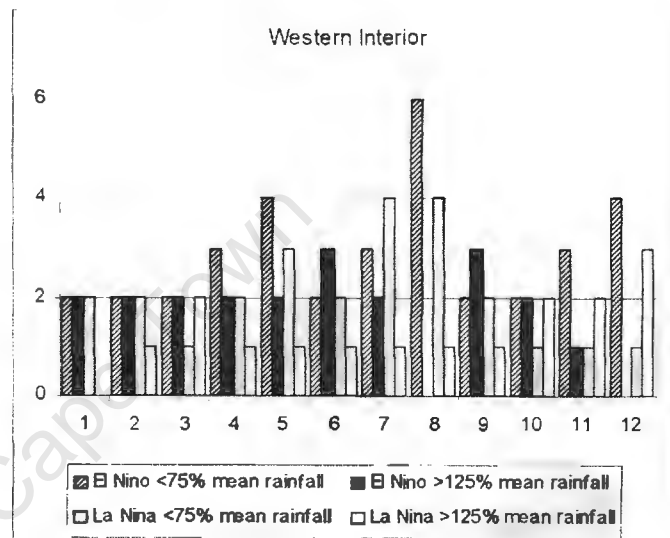
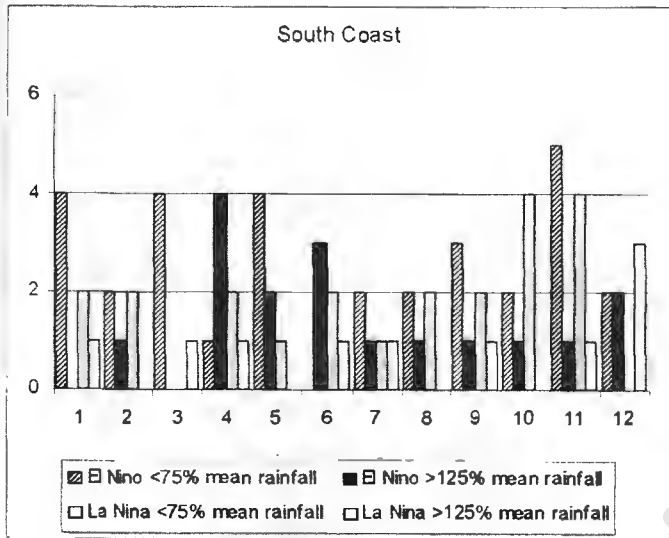
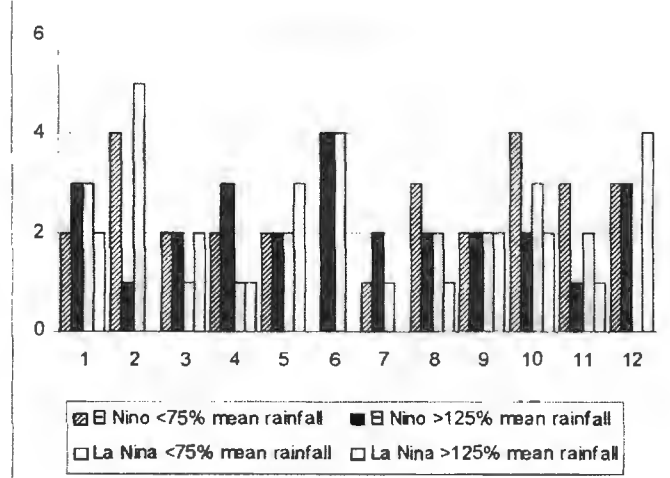
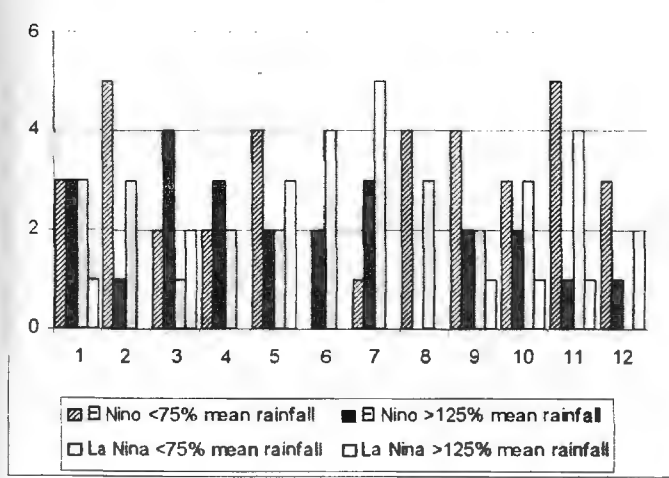


Figure 6 Monthly rainfall response to the six (five) El Niño (La Niña) events 1974 – 2000. The mean rainfall refers to the monthly 1921 – 2000 mean. The frequency of these conditions is on the y – axis.

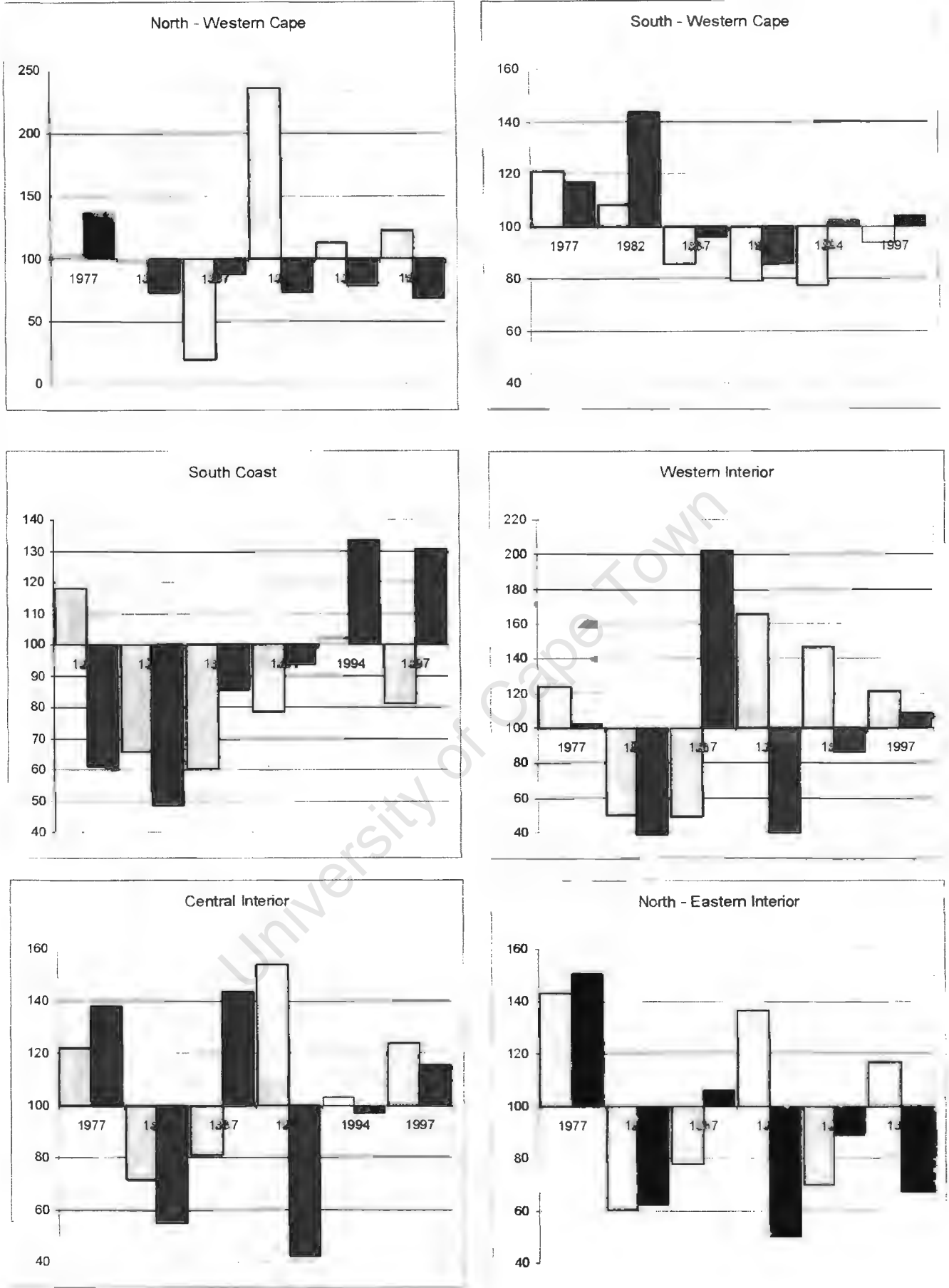


Figure 7 Total late summer (Jan – Mar) rainfall in each rainfall area for each El Niño episode expressed as a percentage of the 1921 – 2000 late summer average (i.e. 100 corresponds to the average rainfall). Light (dark) shading is for the year of the El Niño (following El Niño).

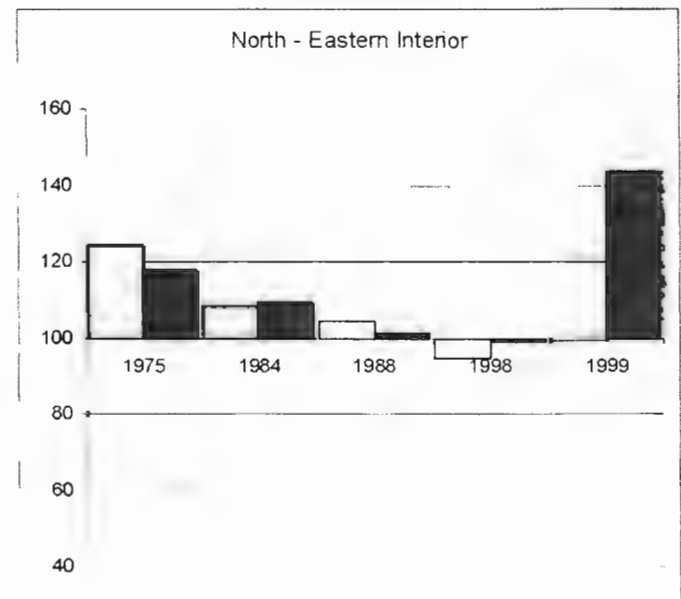
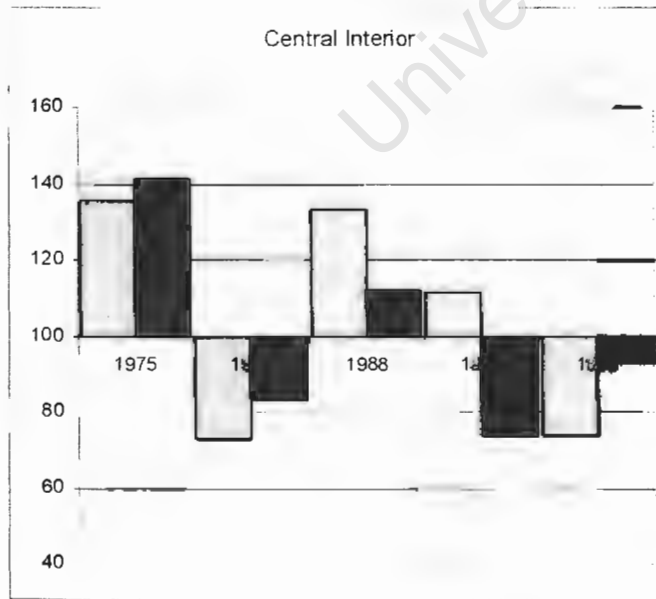
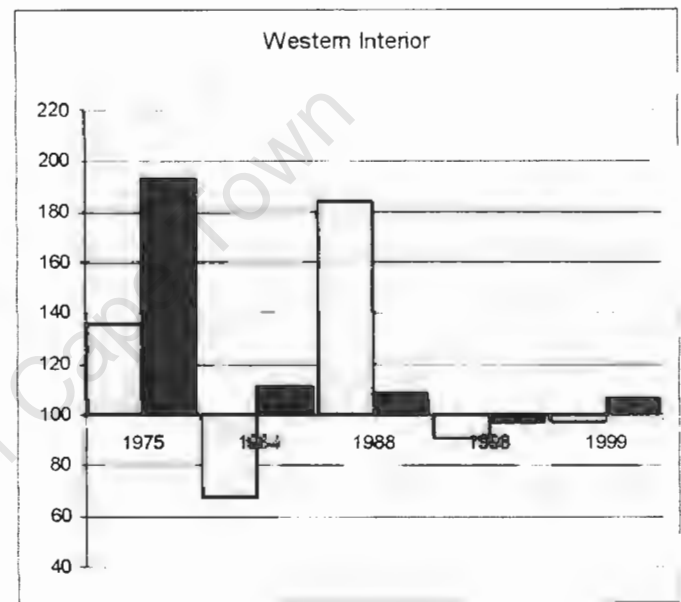
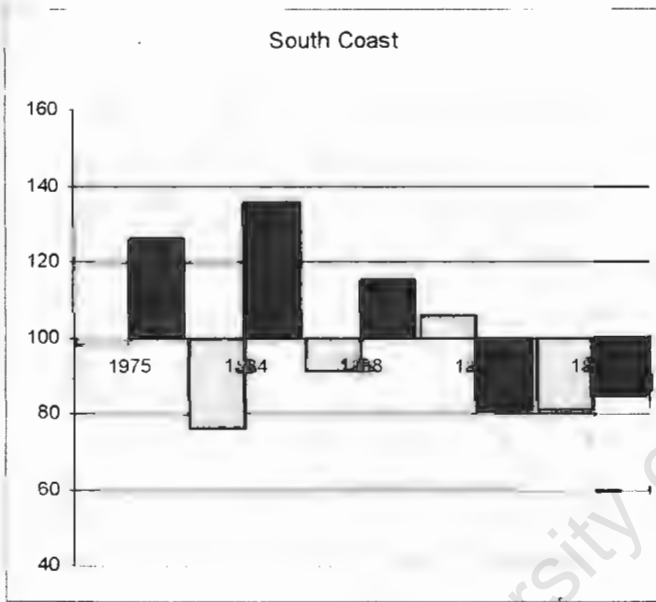
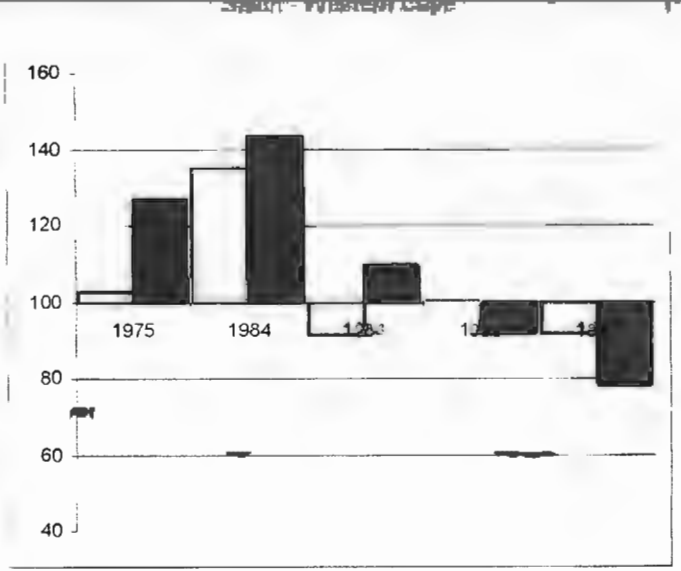
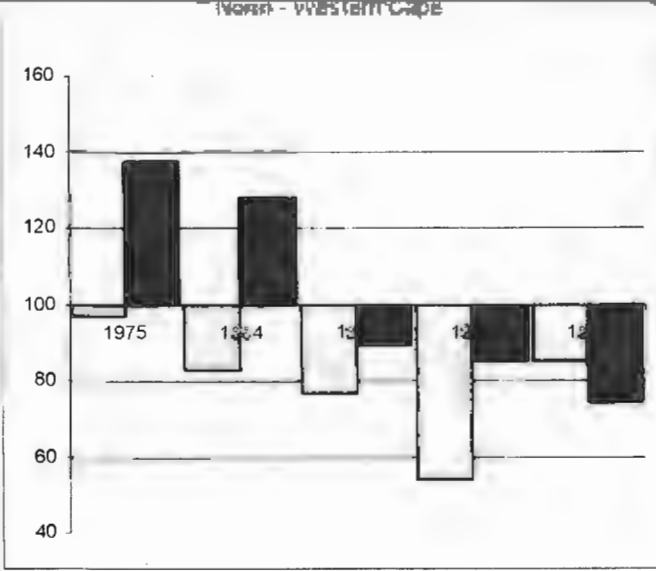
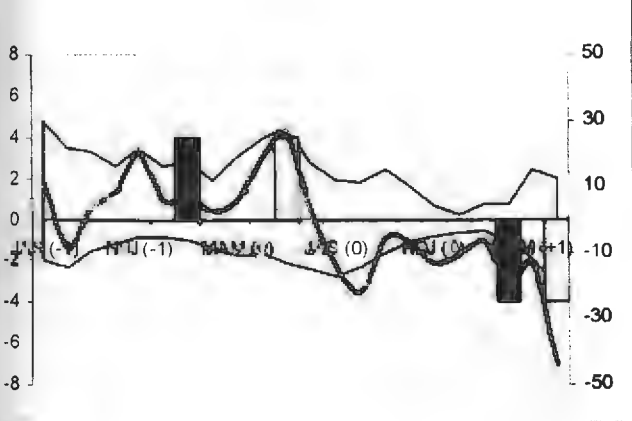
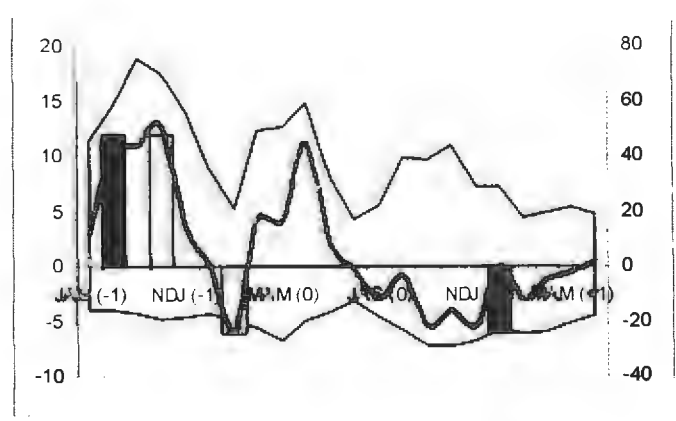


Figure 8 Total annual rainfall in each rainfall area for each La Niña episode expressed as a percentage of the 1921 – 2000 annual average (i.e. 100 corresponds to the average rainfall). Light (dark) shading is for the year of the La Niña (following La Niña).

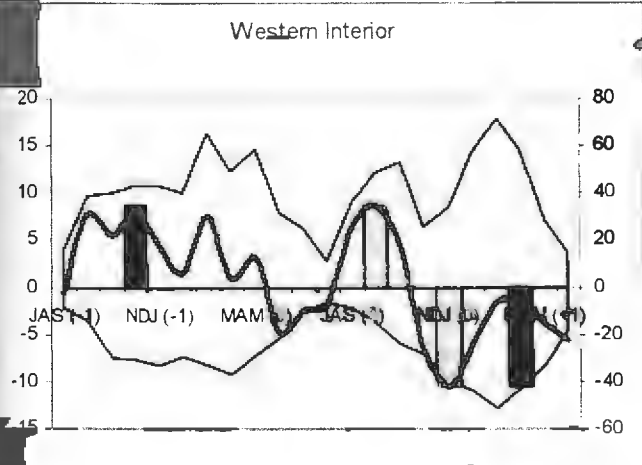
North - Western Cape



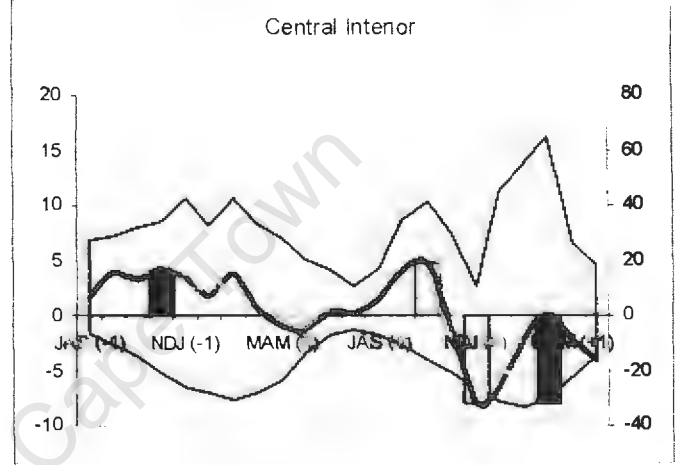
South Coast



Western Interior



Central Interior



North Eastern Interior

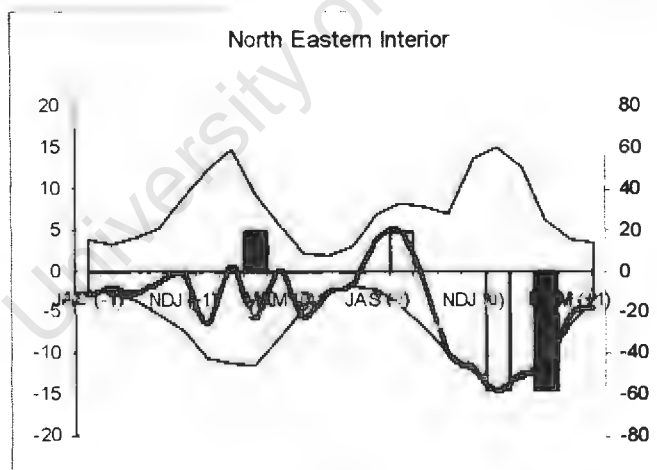


Figure 9 A 24 – month El Niño event, that commences “in July prior to the low – index year of the Southern Oscillation (designated July -1) and continued until June of the year after the low – index year (designated June +1)” has been used and the maximum positive (wet) and negative (dry) 3 – month running rainfall anomalies have been calculated. The maximum anomalies (mm) for this study are shown with the light bars and the results of the study by Nicholson and Kim (1997) in the dark bars. The magnitude of both sets of bars relates to the findings in this investigation. The heavy line is the 3 – month running rainfall mean for this study. The shading shows the maximum rainfall anomalies between these 6 El Niño events and these values correspond with the secondary y – axis. The two studies use different homogeneous rainfall areas, but here roughly the same geographical areas have been compared.

			North - Western Cape	South - Western Cape	South Coast	Western Interior	Central Interior	North - Eastern Interior
Annual (Jan - Dec) Rainfall (in mm)	1921 - 2000	mean rainfall	172.4	450.7	432.5	280.7	559.7	628.6
	1974 - 2000	mean rainfall	162.3	499.3	458.9	306.3	579.6	656.6
Late Summer (JFM) Rainfall (in mm)	1921 - 2000	mean rainfall	20.4	48.5	111.2	131.7	255.7	291.2
		max rainfall	58	153	263	440	437	718
		min rainfall	3	12	54	42	108	139
	1974 - 2000	mean rainfall	23.7	56.5	116.1	147.3	266.7	310.2
		max rainfall	55	153	263	440	427	718
		min rainfall	3	12	54	46	108	145

Table 3 Mean annual rainfall and late summer (Jan - Mar) rainfall (in mm) for 1921 – 2000 and for 1974 – 2000.

Rainfall Area	Western Cape			Northern Cape			Free State		
	North Western Coast	South Western Coast	South Coast	North Western Coast	South Western Coast	Northern Interior	Northern Interior	Central Interior	North - Eastern Interior
Months in the year before production where rainfall totals correlate with yields.	Feb (-0.38)	Feb (-0.42)	Feb (-0.33)			April (-0.33)	Feb (-0.41)	Dec (0.47)	Dec (0.33)
		Aug (-0.33)				Aug (-0.40)	Apr (-0.45)		
Months in the year of production where rainfall totals correlate with yield	July (0.42)	Aug (-0.36)	July (-0.39)		Jan (-0.38)	Aug (-0.41)	Sept (0.43)	Sept (0.36)	Mar (0.36)
	Sept (0.36)				Feb (-0.32)			Oct (0.34)	Oct (0.39)

Table 4 All months with significant (at the 95% confidence level) correlations between rainfall totals and wheat yields. The strength and type of relationship is given in brackets.

		Western Cape	Northern Cape	Free State
Total 1984 - 2000 period	Mean yield	1.56	4.90	1.30
	Minimum yield	1.02 (1986)	3.10 (1984)	0.51 (1985)
	Maximum yield	2.04 (1995)	6.67 (1999)	2.05 (2000)
	Yield variation (Tonnes ha ⁻¹)	1.02	3.57	1.54
	Yield variation as a % of mean	0.65	0.73	1.18
El Nino year (0)	Minimum yield	1.30 (1987)	4.23 (1991)	0.88 (1994)
	Maximum yield	1.86 (1994)	6.60 (1994)	1.93 (1987)
	Yield variation (Tonnes ha ⁻¹)	0.55	2.37	1.05
	Yield variation as a % of 1984 - 2000 mean	35	48	81
	Number of El Nino years with yields above the mean	1	1	2
Year after the El Nino (+1)	Minimum yield	1.11 (1988)	4.97 (1998)	0.78 (1995)
	Maximum yield	2.04 (1995)	5.69 (1995)	1.9 (1988)
	Yield variation (Tonnes ha ⁻¹)	0.93	0.72	1.12
	Yield variation as a % of 1984 - 2000 mean	59	15	86
	Number of El Nino years with yields above the mean	3	4	2

Table 5 Mean, minimum and maximum yields for the 1984 – 2000 period and for the year of and the year following the El Niño.