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Climatic variability and change over southern Africa: a reflection on underlying processes

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Abstract: Quasi-periodicities in annual rainfall totals over southern Africa have been identified; in particular, an approximately 18-year cycle may be related to interdecadal variability in sea-surface temperatures in the eastern equatorial Pacific and central Indian Oceans. A 10-year cycle along the south coast is related to variability in standing wave 3. Atmospheric anomalies associated with wet and dry years can be related to changes in the frequency, intensity and persistence of important rainfall-producing weather systems and highlight the significance of the strength of the continental heat low and the preferred locations and amplitudes of the westerly troughs. El Niño–Southern Oscillation events and sea-surface temperature anomalies in the Indian and South Atlantic Oceans can influence both the tropical and the temperate atmospheric circulation and moisture fluxes over the subcontinent and thus are significant influences on rainfall variability. Evidence for long-term climatic change is not as definitive as in the Sahel, although there are indications of desiccation in some areas since the late-1970s. Increases in temperatures are of approximately the same magnitude as the hemispheric trends and may be attributable to the enhanced greenhouse effect.

Key words: southern Africa, interannual rainfall variability, atmospheric variability, El Niño–Southern Oscillation, ocean–atmosphere interaction, climatic change.

I Introduction

Southern Africa is a predominantly semi-arid region with high interannual rainfall variability and a pronounced seasonal cycle (Tyson, 1986). Population growth and industrial development in the region have been placing increasing pressure on scarce water resources in recent years. In the Johannesburg area alone, water consumption has more than doubled over the last 30 years despite periodic water restrictions (Mason and

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Joubert, 1995). Predominantly dry conditions have persisted from the early 1980s to the mid-1990s, while water demand continues to rise, particularly in drought years.

Because of the high degree of interannual rainfall variability in the southern African region, skilful seasonal forecasts could greatly assist in water resource planning and for the amelioration of drought and flood impacts (Vogel, 1994). Recently, long-range seasonal forecasts for southern Africa have been produced by universities and the national meteorological services in South Africa and neighbouring countries. The forecasts represent the culmination of a number of years of research into the nature and causes of interannual rainfall variability of the region (Mason *et al.*, 1996).

In this article, progress in understanding the interannual variability of the atmosphere over southern Africa and its association with the surrounding oceans is reviewed. First, the quasi-periodic nature of interannual rainfall variability of the region during the twentieth century is described. The atmospheric characteristics of wet and dry years are then described and related to changes in the disposition of major rain-producing weather systems. Finally, evidence for long-term trends in important climatic parameters during the period of instrumental records is surveyed. The first weather station in southern Africa was founded in the early 1840s, but it was not until the early twentieth century that a network of stations was established across the region. Analyses of trends for surface parameters are therefore restricted to the last eight or nine decades. The emphasis throughout the article is almost exclusively on rainfall variability and its relationship to the atmospheric circulation. Less research has been conducted on temperature variability (van Heerden, 1995) because of the poorer data quality, and because of the greater significance of rainfall to the region.

II Interannual rainfall variability

Southern Africa experiences a high level of interannual rainfall variability, with the coefficient of variation exceeding 40% in the drier western areas (Onesta and Verhoef, 1976; Tyson, 1986). The interannual rainfall variability exhibits statistically significant cyclic variability (Tyson, 1986) and was first identified over 100 years ago (Tripp, 1888), initiating an active research into the question over the next few decades (Nevill, 1908; Cox, 1925; van Reenen, 1925; Peres, 1930; de Loor, 1948). Distinctive oscillations in annual rainfall over South Africa have been verified (Figure 1) and used in long-range seasonal forecasting models (Dyer and Tyson, 1977; Tyson and Dyer, 1978; 1980; Louw, 1982; Currie, 1993). A 10–12-year oscillation accounts for over 30% of the interannual rainfall variance along the south coast of the country; but of greater significance is an 18–20-year oscillation in the north east of the country (Tyson *et al.*, 1975; van Rooy, 1980; Vines, 1980; Dyer, 1975; 1980; 1981a; Kelbe *et al.*, 1983; Lindesay, 1984; Tyson, 1971; 1978; 1980; 1986; Currie, 1991; 1993; Jury and Levey, 1993a; 1993b), which extends into Zimbabwe (Ngara *et al.*, 1983) and Botswana (Jury *et al.*, 1992) (Figure 2). The 18–20-year cycle is even more clearly apparent in streamflow than in rainfall (Abbott and Dyer, 1976; Partridge, 1985; Alexander, 1995).

The low-frequency rainfall variability over southern Africa is thought to be attributable to a number of mechanisms acting in concert. An 18-year oscillation in the luni-solar tide (Currie, 1991; 1993) could act as a resonator for similar cycles in sea-surface temperatures, for example in the South Atlantic (Mason, 1990; Shinoda and Kawamura, 1996). Interdecadal variations in standing wave 1 may be involved in the oscillation

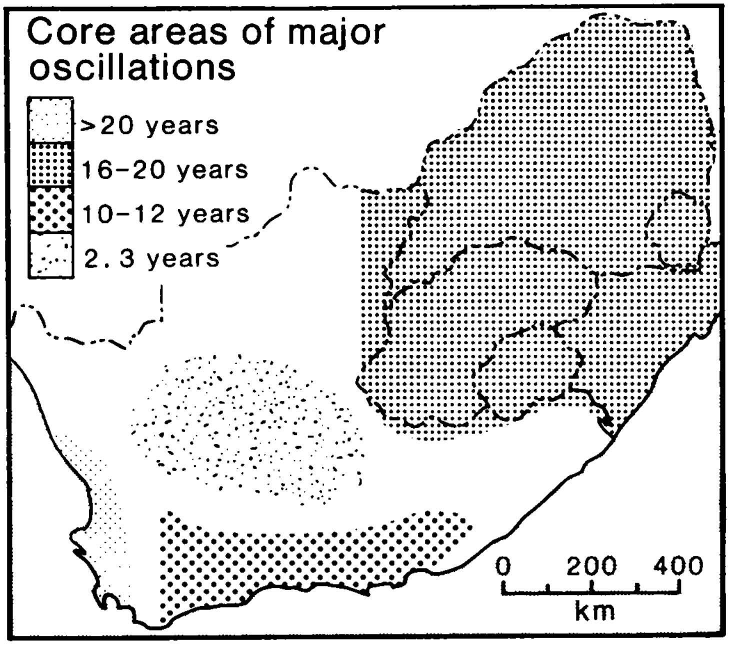

Figure 1 The geographical distribution of core areas of rainfall oscillations over South Africa. After Tyson *et al.* (1975)

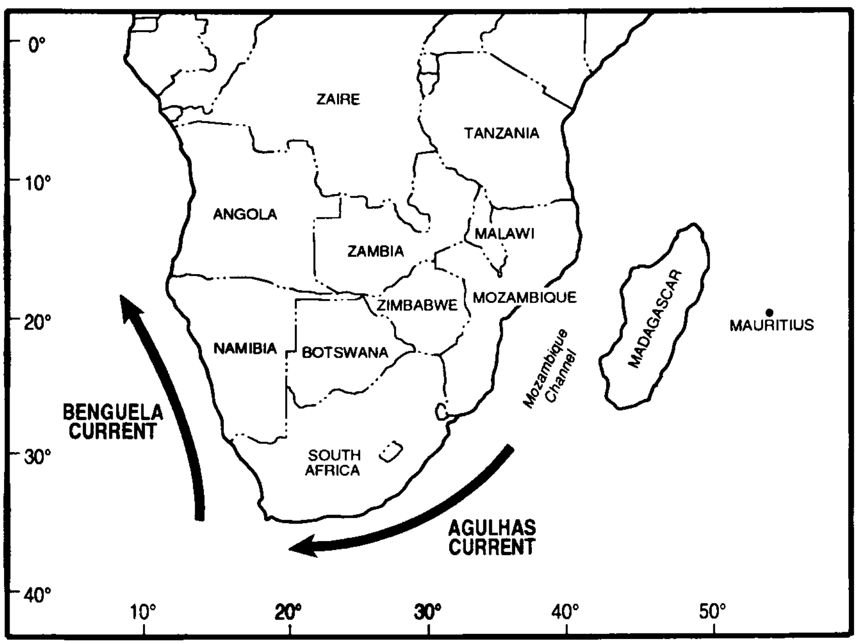

Figure 2 Location map of southern Africa showing the political boundaries, islands and major ocean currents

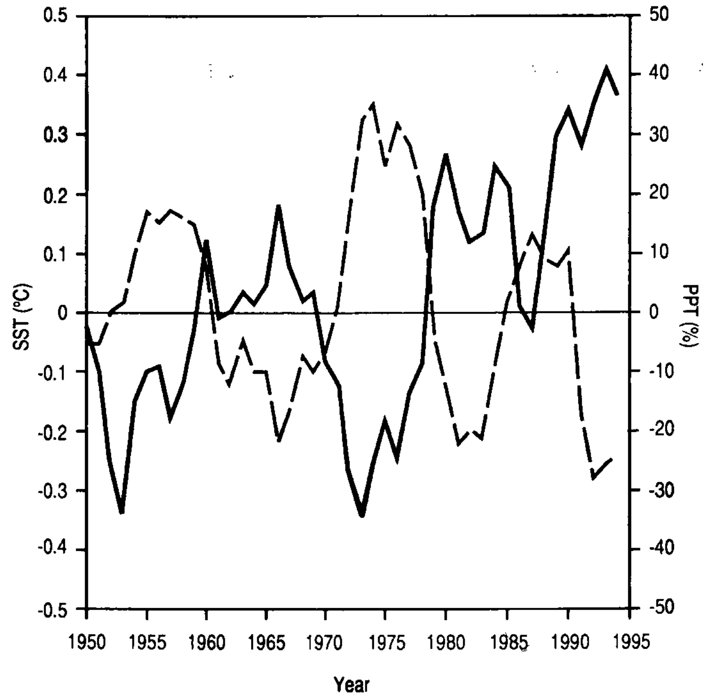

Figure 3 Seven-month running mean sea-surface temperature anomalies averaged over the eastern equatorial Pacific Ocean (180–90° W , 10° S–5° N) and rainfall percentages over South Africa

(Tyson, 1986), and may respond to an approximately 20-year cycle in annual sea-surface temperature anomalies averaged over the eastern equatorial Pacific Ocean (180–90° W, 10° S–5° N) (Figure 3; Hurrell and van Loon, 1994) and in the central Indian Ocean (Jury *et al.*, 1996). The sea-surface temperature cycle is in anti-phase with the rainfall cycle, implying that below-average temperatures in the eastern Pacific Ocean are associated with above-average rainfall over southern Africa. Such a phase relationship is consistent with El Niño–southern African rainfall associations as discussed below. Although the 18–20-year cycle in sea-surface temperatures is only weakly reflected in the Southern Oscillation index, such interdecadal variability is important in influencing the variability of the standing waves in middle and high latitudes of the Southern Hemisphere (Hurrell and van Loon, 1994) and may affect southern Africa via the temperate atmosphere.

The 10–12-year rainfall oscillation of the south coast of South Africa has been linked to sea-surface temperatures to the south of the subcontinent (Mason, 1990), to solar variability (Vines, 1980; Mason and Tyson, 1992; Currie, 1991; 1993) and to changes in the position of standing wave 3 (Vines, 1980; Tyson, 1981; 1986). A regular variation in pressure differences throughout the troposphere between Gough Island, to the south west of the subcontinent, and Marion Island, to the south east, is in anti-phase with the rainfall oscillation and is indicative of variations in the longitudinal position of the first ridge of wave 3 (Tyson, 1981). Variability in standing wave 3 is thought to be responsible for an 11-year rainfall cycle in southeast Australia and New Zealand (Vines, 1980) as a result of its important influence on blocking in this sector (Trenberth, 1975; 1980b; Trenberth and

Mo, 1985). Although atmospheric blocking is generally weak and infrequent in the vicinity of southern Africa on intraseasonal time-scales (Trenberth and Mo, 1985; Kidson, 1988), there is coherence in the 11-year rainfall cycles between New Zealand, South America and South Africa (Vines, 1980; 1982).

Quasi-biennial oscillations have been detected in wave 3 over New Zealand (Trenberth, 1975; 1980a), but are less defined near southern Africa. However, rainfall cycles with periods of about 2.3 years are identifiable over South Africa and Zimbabwe (Figure 1) (Tyson, 1971; Nicholson and Entekhabi, 1986; Jury *et al.*, 1992; Jury and Levey, 1993a; 1993b) and may be associated with the stratospheric Quasi-Biennial Oscillation (QBO) of equatorial zonal winds (Mason and Tyson, 1992; Mason and Lindesay, 1993; Jury *et al.*, 1994; Mason *et al.*, 1994). The stratospheric QBO may interact with the Walker circulation over eastern southern Africa: upper-tropospheric westerlies off the east coast of southern Africa, that are associated with convection and upper-level divergence over southern Africa, are strengthened during westerly phases of the QBO (Figure 4; Jury, 1992; Jury *et al.*, 1994; Jury and Pathack, 1993; 1997). However, further work is required to investigate the possible influence of tropospheric quasi-biennial oscillations (Trenberth, 1979; 1980a; Ropelewski *et al.*, 1992).

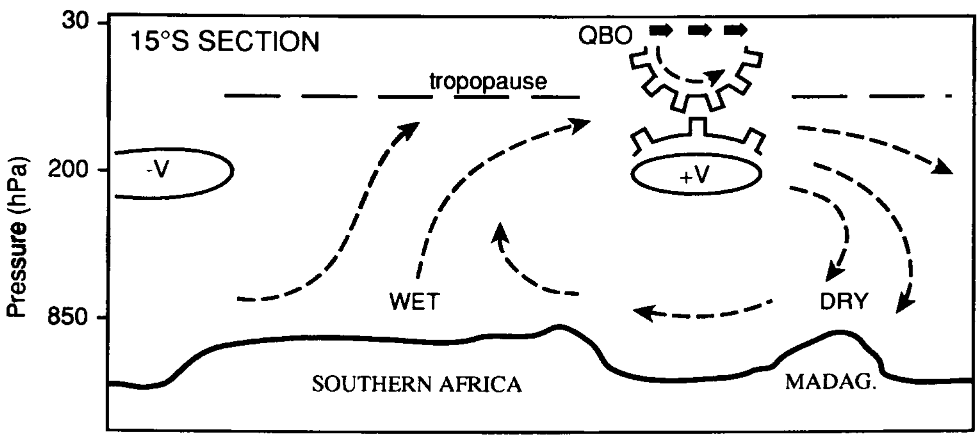

Figure 4 Schematic diagram illustrating the interaction of the stratospheric Quasi-biennial Oscillation of zonal winds and the Walker circulation over eastern southern Africa. After Jury *et al.* (1994)

Weaker rainfall oscillations with periods of 3.5–7 years are ubiquitous and are generally indicative of an influence of tropical sea-surface temperatures, including El Niño–Southern Oscillation events (Vines and Tomlinson, 1985; Nicholson, 1986; Nicholson and Entekhabi, 1986; 1987; Lau and Sheu, 1988; Jury *et al.*, 1992; Jury and Levey, 1993a; 1993b) as discussed below. Over Namibia, 2.7 and 6.0-year cycles are evident (Dyer and Marker, 1978), but have not been related to any physical mechanisms. Over Madagascar, 2.3- and 6-year cycles are associated with interactions between the stratospheric QBO, the northwest monsoon and subtropical standing waves (Jury *et al.*, 1995).

III Atmospheric circulation during wet and dry conditions

Rainfall variability is caused by changes in the frequency, duration and intensity of large-scale weather systems that are responsible for the number of days with significant rainfall (Harrison, 1983; Taljaard, 1989) rather than the number of raindays (Rubin, 1956; Harrison, 1983), or the length of the rainfall season (Nicholson and Chervin, 1983). The main weather systems that are responsible for rainfall over southern Africa have been classified (Tyson, 1986) and will be covered in some detail here. The reader is referred to the extensive literature on the subject.

Significant contributors of rainfall to the summer rainfall region of South Africa and Zimbabwe are tropical-temperate troughs and their associated cloud bands (Harangozo and Harrison, 1983; Harrison, 1984a; 1984b; 1984c; Smith, 1985; Tyson, 1986; Diab *et al.*, 1991; Lyons, 1991; van den Heever, 1994). The tropical temperate troughs form when a tropical low is coupled to a temperate westerly wave via a subtropical trough (Figure 5a), forming a northwest to southeast cloud band along the leading edge of the westerly trough (Harangozo and Harrison, 1983; Harrison, 1984c; van den Heever, 1994). An important feature of sustained wet spells is the equatorward transport and easterly momentum on the trailing edge of the upper ridge (Lyons, 1991; Levey and Jury, 1996). In the absence of a midlatitude link, truncated troughs form and are possibly more common than the elongated troughs (Jury, 1997a). The tropical-temperate troughs are frequently responsible for floods during the second half of the summer (Walker and Lindesay, 1989; Lindesay and Jury, 1991; Jury, Lindesay *et al.*, 1993), but are generally shorter lived during early summer because of increased westerly shear (Barclay *et al.*, 1993). Total rainfall volume from individual trough events depends upon the availability of atmospheric moisture, atmospheric stability, the strength of upper-level divergence and the speed of movement of the trough (Harrison, 1988; van den Heever, 1994). The tropical low is usually located over southeast Angola or southwest Zambia (Jury and Pathack, 1993) forming preferentially during the period December–March at the furthest southwestern limit of the Intertropical Convergence Zone. The tropical low or easterly trough can provide significant rainfall to the north of about 20° S away from the influence of westerly disturbances (Taljaard, 1981; 1986; Tyson, 1986; Preston-Whyte and Tyson, 1987; Muller and Tyson, 1988; Diab *et al.*, 1991), although heavy, prolonged rains are more likely when coupling does occur.

Although subtropical troughs contribute to widespread rainfall over much of southern Africa, the heaviest falls are usually associated with cut-off lows or deep west-coast troughs (Figure 5b). These systems have been responsible for a number of severe flooding events (Taljaard, 1985; Tyson, 1986; Jury and Levey, 1993b), such as in September 1987 (Triegaardt *et al.*, 1988) and March 1988 (Jury, Lindesay *et al.*, 1993). Cut-off lows are most frequent during the transition seasons when the meridional temperature and pressure gradients are strongest (van Loon, 1971) and are important contributors of early and late-season rainfall (Taljaard, 1985; 1986). The high interannual variability of the frequency of cut-off lows is largely responsible for the high variability of rainfall during the transition seasons (Taljaard, 1985), especially March (Dyer, 1982). Cut-off lows frequently form in conjunction with an anticyclonic ridge to the south of the subcontinent and provide an onshore flow from the warm Agulhas Current to the eastern escarpment (Figure 5c) (Triegaardt *et al.*, 1988). Along the southeast coast, ridging anticyclones can provide a large proportion of the total rainfall (Miron and Lindesay, 1983; Miron and Tyson, 1984; Tyson, 1984; 1986; Taljaard and Steyn, 1991; Jury and Levey, 1993b), particularly when

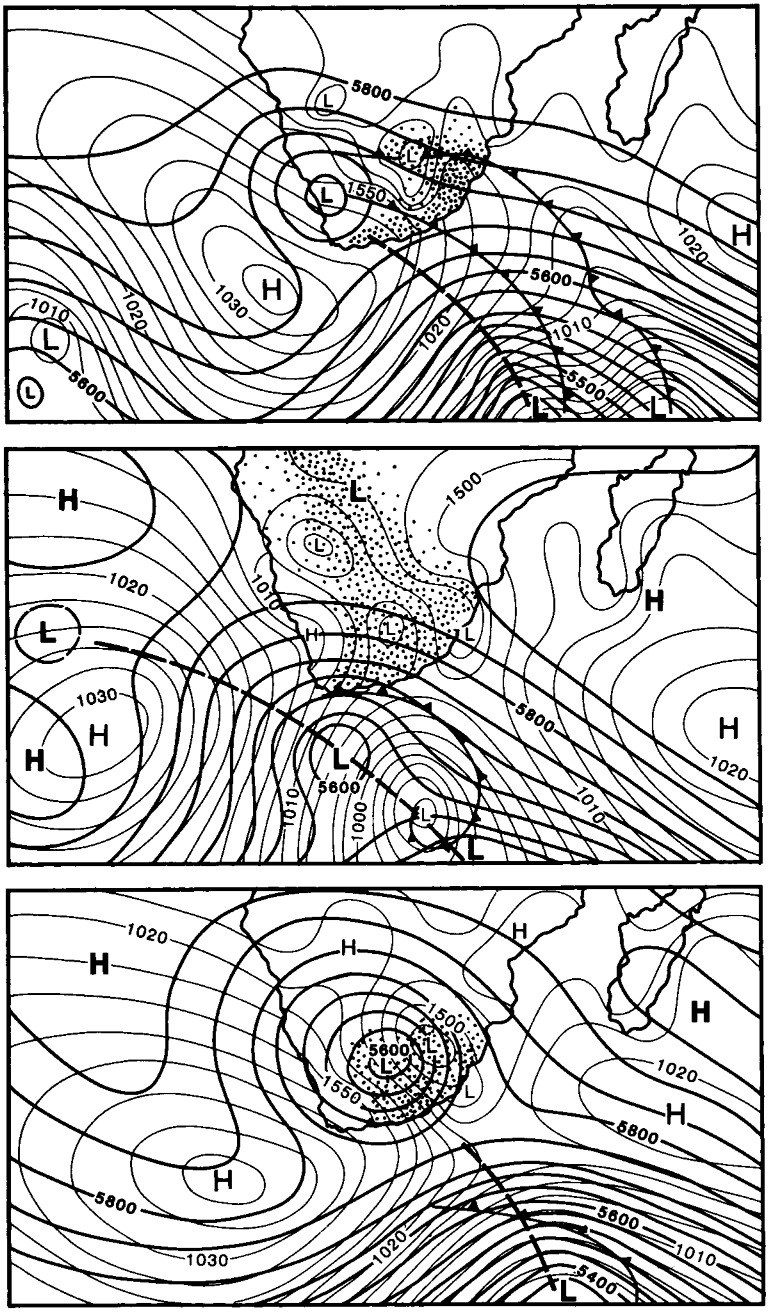

Figure 5 Synoptic chart for (a) 23 January 1981, showing the formation of a tropical-temperate trough; (b) 27 August 1970, showing the formation of a cut-off low; and (c) 9 September 1981, showing the formation of a cut-off low and ridging anticyclone. Light lines show isobars at mean sea level (hPa) over the oceans and contours of the 850 hPa surface (gpm) over the land; heavy lines show contours of the 500 hPa surface (gpm). Areas receiving precipitation are stippled. After Tyson (1986)

the onshore flow is strengthened by a low pressure inland (Carte, 1979) and uplift is facilitated by favourable upper-atmospheric conditions (Kelbe, 1984). Ridging anticyclones often originate from 'budding' of anticyclones from the South Atlantic Ocean (Taljaard, 1967; Taljaard and Steyn, 1991).

Some of the heaviest rains over southern Africa are associated with the infrequent passage of tropical cyclones across the coastal margins of Mozambique and eastern South Africa. Cyclones frequently form and move southward along the Mozambique Channel, but occasionally fail to recurve seaward (Diab *et al.*, 1991; Jury, Pathack and Waliser, 1993). They provide only a minimal percentage of the total rainfall over South Africa, but the occasional event can result in excessive falls (Kreft, 1953; Diab *et al.*, 1991). For example, more than 800 mm was received north of Durban in one day from cyclone Demoina in January 1984 (Poolman and Terblanche, 1984) (Figure 6). However, tropical cyclones are more frequently associated with dry conditions over southern Africa: when the tropical cyclone remains in the Mozambique Channel, air subsides over the subcontinent and flow is offshore (Matarira, 1990; Jury and Pathack, 1991; Jury, 1992; 1993).

Over the southwestern and southern coasts, rainfall is predominantly from midlatitude cyclones during winter and the transition seasons (Taljaard, 1981; Muller and Tyson, 1988). Heavier rainfall is generally received when the cyclones are anomalously far north and intensified by ridging to the west (Brundrit and Shannon, 1989; Taljaard, 1989). The ridging provides southerly inflow of cold air into the low pressure cell increasing the cyclonic vorticity of the upper trough. Occasionally cut-off lows provide heavy precipitation during the winter (Stranz and Taljaard, 1965), but as in the transition seasons, ridging anticyclones can provide significant rainfall on the southeast coast in isolation of the cut-off lows. At times, before the anticyclone ridges to the south of the subcontinent, a zonal pressure gradient generates southerly meridional flow: the onshore flow provides winter rains to the south coast. The undercutting action is important in summer rainfall events also and can promote uplift over much of South Africa (Tyson, 1984; 1986).

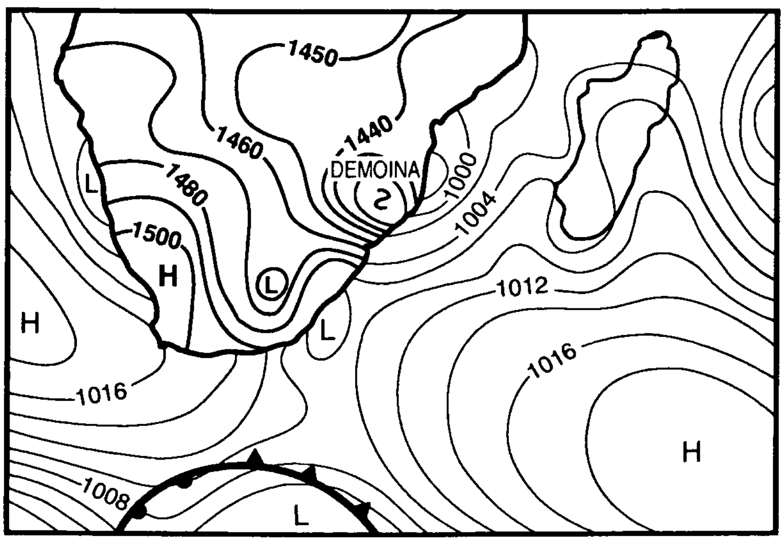

Figure 6 Synoptic chart for 29 January 1984, showing tropical cyclone Demoina as it moved inland over the southern Mozambique coast. After Poolman and Terblanche (1984)

Other synoptic systems provide rainfall over southern Africa (Tucker, 1971; Miron and Lindesay, 1983; Miron and Tyson, 1984; Tyson, 1986; Preston-Whyte and Tyson, 1987; Diab *et al.*, 1991), but contribute to a lower proportion of the annual rainfall than the systems described above. That interannual rainfall variability over southern Africa can be related to changes in the incidence, persistence and strength of these important synoptic systems is confirmed by the observed similarity between the atmospheric conditions associated with wet or dry conditions at a range of different temporal scales (Tyson, 1986).

Conceptual models of the atmospheric circulation during wet and dry conditions have been proposed by Tyson (1986). The concepts illustrated in Figure 7 are undergoing scrutiny using numerical weather prediction model data products, but many of the essential features remain valid. Dry summers are dominated by confluent upper winds which reduce the potential for convection over southern Africa and often are accompanied by an upsurge of tropical disturbances in the southwest Indian Ocean, representing an eastward shift in the preferred location for summer convection (Figure 7) (Harangozo and Harrison, 1983; Tyson, 1986; Jury and Pathack, 1991; 1993; Jury *et al.*, 1992; 1994; Jury, 1992; 1996). Variability in summer convection over southern Africa can be monitored by changes in outgoing longwave radiation (Jury and Waliser, 1990; Jury, Valentine and Lutjeharms, 1993; Jury *et al.*, 1992; 1995), which confirm that decreases in convection over the subcontinent during dry years are often compensated by increases to the east of Madagascar (Jury and Pathack, 1991; 1993; Jury *et al.*, 1992; 1994; Jury, 1992; 1996). Similarly, higher geopotential heights over the subcontinent indicate weaker subtropical troughs during dry years (Hofmeyr and Gouws, 1964; Tyson, 1981; 1984; 1986; Taljaard, 1981; 1989; Matarira, 1990; Matarira and Jury, 1992; Shinoda and Kawamura, 1996) and allow the persistence of the temperate circulation throughout the summer season (Taljaard, 1989), which is anomalously far north (Tyson, 1986). Such changes are consistent with a weakened divergence of moisture from the equatorial Indian Ocean during dry years (Figure 8) (D'Abreton and Lindesay, 1993; D'Abreton and Tyson, 1995).

Although there is some consensus about the significance of longitudinal displacements of convection, the significance of latitudinal displacements on an interannual basis is less clear. The equatorward withdrawal of summer rains during drought years is unclear (Nicholson and Chervin, 1983), but when the tropical convergence zones lie further north and weaken, rainfall over much of the subcontinent decreases (Torrance, 1979; Lindesay and Jury, 1991; van den Heever, 1994; Shinoda and Kawamura, 1996). Decreased rainfall over southern Africa is often offset by increased rainfall over east Africa (Ogallo, 1988).

The Hadley circulation responds to the longitudinal shifts of convection, weakening over southern Africa during dry years. Simultaneously, Hadley cell-mass overturning becomes more vigorous to the east of the subcontinent (Lindesay, 1988; Lindesay and Jury, 1991; Jury, 1996). A strengthened Hadley circulation over southern Africa is associated with increased rainfall in the region, but also is responsible for strengthened westerlies further to the south because of an increase in the poleward transport of angular momentum (Tyson, 1986). Over the east coast and southwestern Indian Ocean there is evidence for a reversal of a Walker cell between wet and dry years, which would indicate the presence of a convective 'dipole' (Figure 4) (Jury, 1992; Jury *et al.*, 1994; Shinoda and Kawamura, 1996). Over the South Atlantic Ocean the Walker cell is weaker and lies closer to the equator because of the cold Benguela Current. Westerly upper zonal winds over the equatorial Atlantic are generally observed during the early months of a dry rainfall

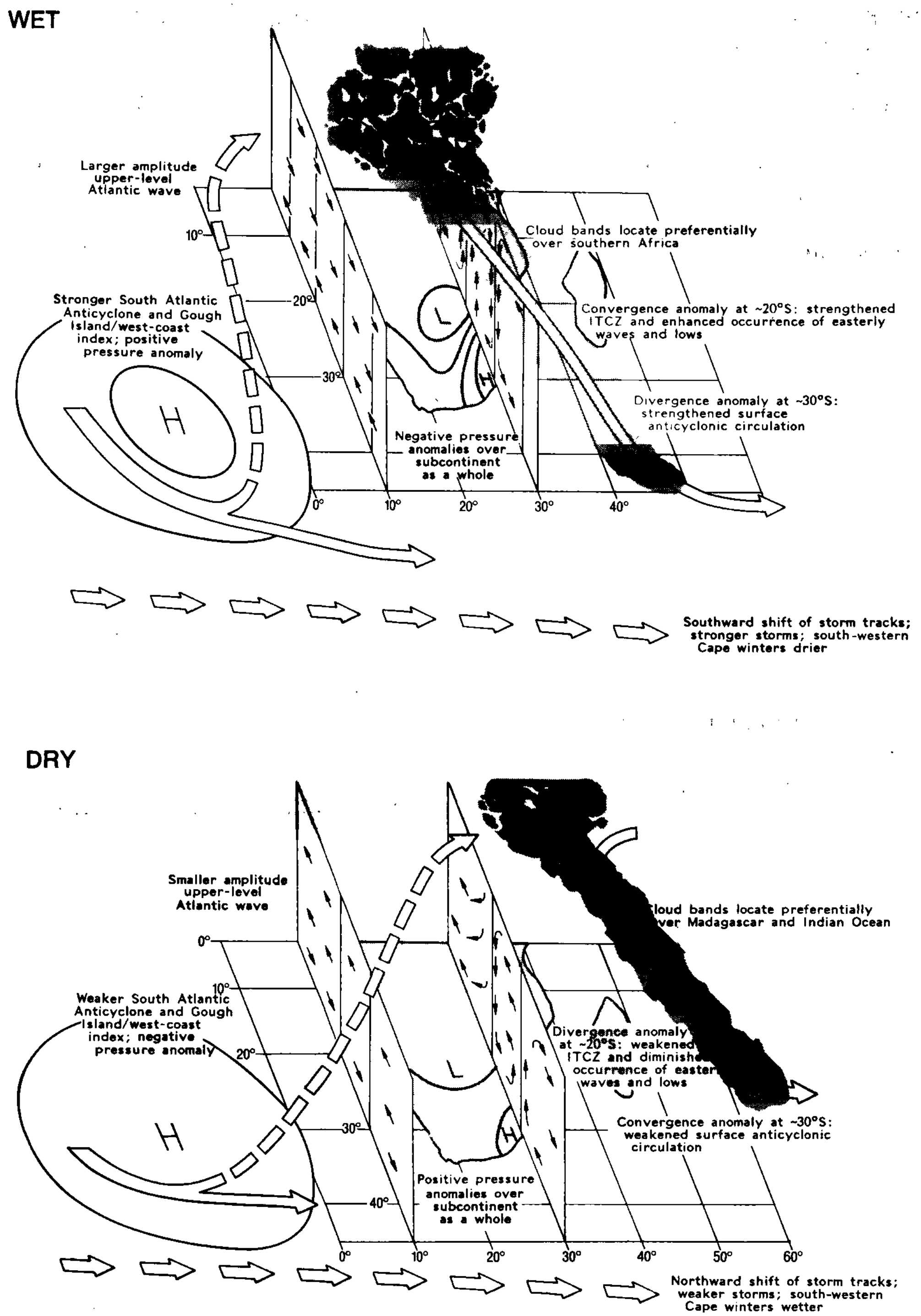

Figure 7 Models of the anomalous meridional circulations over southern Africa during spells of predominantly (a) wet and (b) dry conditions. After Tyson (1986)

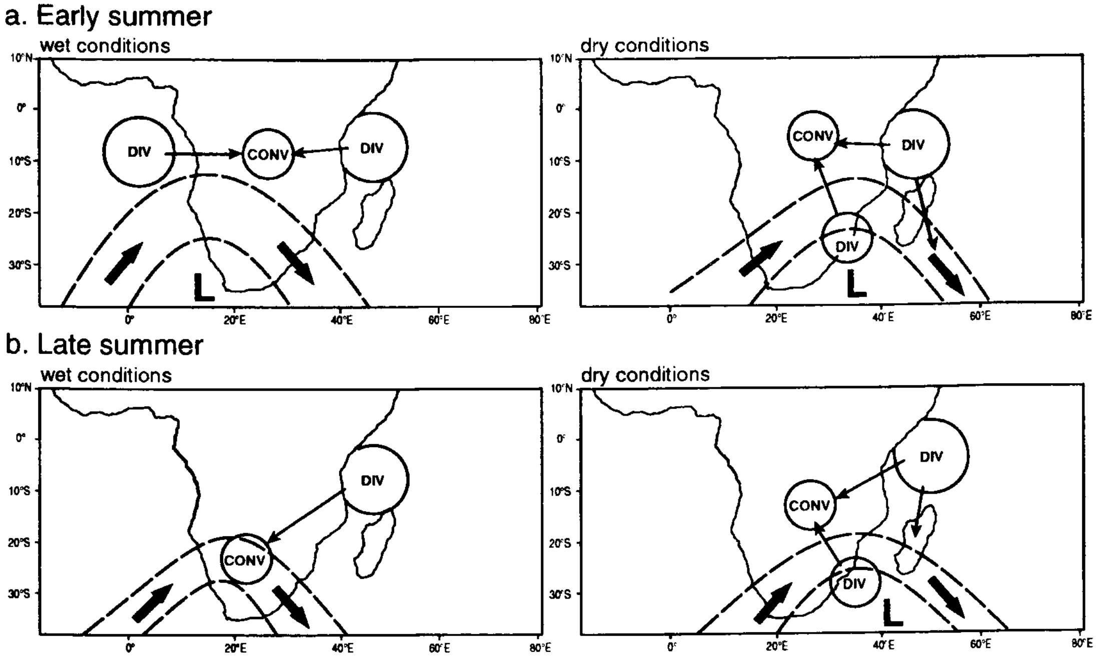

Figure 8 Models of the convergence and divergence fields over southern Africa during wet and dry early and late summers – (a) wet and (b) dry conditions. After D'Abreton and Tyson (1995)

season (Jury *et al.*, 1994; 1995) and are possibly coupled with Pacific Ocean variability in a wave 1 pattern (Park and Schubert, 1993; Jury, 1995; Janicot *et al.*, 1996).

Atmospheric variability is greater over the subtropics of the Indian Ocean than over similar latitudes of the South Atlantic, both intraseasonally (Vowinckel, 1955; McGee and Hastenrath, 1966) and interannually (Dyer, 1981b). Accordingly, the Indian Ocean Anticyclone has a significant influence on interannual rainfall variability over southern Africa. During dry years, the Indian Ocean Anticyclone is typically weaker than normal so that the northeasterly inflow over the east coast diminishes (Matarira, 1990; Matarira and Jury, 1992; Jury and Pathack, 1993; Hastenrath *et al.*, 1995; Jury *et al.*, 1992; 1995; Jury, 1996). The northeasterly inflow is an important source of atmospheric moisture throughout the summer rainfall season (D'Abreton and Lindesay, 1993; D'Abreton and Tyson, 1995), as, for example, during the 1988 floods (Jury, Lindesay *et al.*, 1993).

In the midlatitudes, variability of the atmosphere over the Indian Ocean is greater than over the South Atlantic (Physick, 1981). Wet conditions over southern Africa are frequently associated with strengthened ridging to the south west of the subcontinent near Gough Island (Longley, 1976; Taljaard, 1981; Tyson, 1981; Miron and Tyson, 1984). The strengthened ridging is indicative of a large asymmetric westerly wave (Hofmeyr and Gouws, 1964). Embedded within a generally diffluent flow pattern, cyclonic curvature occurs in the tropics and anticyclonic curvature in the midlatitudes, such that baroclinic troughs (Tyson, 1986; Barclay *et al.*, 1993) or cut-off lows (Taljaard, 1985) develop over the subcontinent, mainly during early summer (D'Abreton and Lindesay, 1993; D'Abreton and Tyson, 1995). Similarly in winter, high pressure over Gough Island is associated with wet conditions (King and van Loon, 1958) from southerly meridional flow, ridging anticyclones and temperate cyclones. Further east, a deep anticyclonic cell over southern Madagascar is associated with wet summers (Matarira, 1990; Jury and Pathack, 1993) and may be indicative of Marion Island blocking (Tyson, 1984). The blocking can result in the persistence of westerly disturbances over the subcontinent (Tyson, 1986).

The longitudinal disposition of long waves in the westerlies is crucial in determining the volume of rainfall that falls over southern Africa. For good rains, a northwest to southeast aligned trough needs to be located over the subcontinent (D'Abreton and Lindesay, 1993; van den Heever, 1994; D'Abreton and Tyson, 1995; 1996; Jury, 1996). If the trough is displaced towards the east coast, has a low amplitude, diminished upper outflow or the trailing ridge is weak (Lyons, 1991), rainfall is more patchy and less intense. In addition to kinematic effects, thermodynamic instability is often controlled by the confluence of water vapour over southern Africa, most of which originates from tropical sources over the northern Mozambique Channel and Congo Basin (D'Abreton and Tyson, 1995). The increase in water vapour over southern Africa during wet years not only provides additional precipitable water but also encourages atmospheric instability, stronger convection and improved precipitation efficiency (Harrison, 1988; Barclay *et al.*, 1993).

IV Causes of interannual climatic variability

It has been shown in the previous section that interannual rainfall variability over southern Africa is largely determined by the preferred longitude of subtropical convection, and by shifts and changes in amplitude of the westerly waves. Skilful seasonal forecasts of rainfall over the subcontinent depend upon both atmospheric memory and on the forecaster's ability to explain such variability.

1 El Niño–Southern Oscillation events

El Niño–Southern Oscillation (ENSO) warm events are frequently associated with drought over much of southern Africa (Stoeckenius, 1981; Mo and White, 1985; Nicholson and Entekhabi, 1986; Janowiak, 1988; Ropelewski and Halpert, 1987; 1989; Halpert and Ropelewski, 1992; Main and Hewitson, 1995; Moron *et al.*, 1995; Shinoda and Kawamura, 1996; Rocha and Simmonds, 1997a) and are partly responsible for continental-scale (Nicholson and Chervin, 1983; Nicholson, 1981; 1986) and wider teleconnections (Harnack and Harnack, 1985). Analyses of the global and continental-scale influence of ENSO warm events suggest that the influence on rainfall is strongest in the southeastern part of the subcontinent and to the north east of South Africa (Ropelewski and Halpert, 1987; 1989; Matarira, 1990; Shinoda and Kawamura, 1996; Rocha and Simmonds, 1997a). Correlations between the Southern Oscillation index and rainfall are reduced near the border between Zimbabwe and South Africa (Harrison, 1984d), but the association strengthens again in a northwest to southeast band across South Africa (Dyer, 1979; Lindesay *et al.*, 1986; Lindesay, 1988; van Heerden *et al.*, 1988; Jury and Pathack, 1993; Jury *et al.*, 1994; Hastenrath *et al.*, 1995; Jury, 1996) and illustrates the ENSO influence on the preferred location of tropical-temperate troughs (Lindesay, 1988). The influence on hail frequencies is opposite to that of rainfall, with an increase (decrease) in the frequency of hail days during El Niño (La Niña) years (Olivier and van Rensburg, 1995). Although the association with rainfall appears to be temporally stable

(Lindesay and Vogel, 1990), El Niño (La Niña) years are not always synchronous with dry (wet) conditions in the region (Mason and Mimmack, 1992).

The influence of ENSO events is strongest during the peak summer rainfall months of December–March when warm and cold events have reached maturity and when the upper westerlies have retreated poleward south of Africa. This delayed rainfall response is useful in operational forecasting (Cane *et al.*, 1994; Hastenrath *et al.*, 1995; Jury, 1996; Mason *et al.*, 1996) and, in part, is indicative of a lagged and seasonally dependent response of the atmosphere in the Southern Hemisphere (Arkin, 1982; Meehl, 1988). The spatial pattern of the rainfall response illustrates the influence of ENSO events upon the formation of tropical-temperate troughs. The details of the atmospheric response to El Niño (La Niña) events are largely consistent with the characteristics associated with dry (wet) conditions as discussed above. To the north, a strengthening of surface westerly flow during Pacific warm events causes a concomitant diminution in moisture convergence over southern Africa, giving rise to hot, dry conditions. Warmer than usual tropical sea-surface temperatures in the central Indian Ocean that coincide with Pacific warm events (as discussed below) produce a weaker landward pressure gradient over the east coast, further diminishing low-level confluence over the subcontinent. Tropical convection accordingly is weakened over southern Africa, but strengthened to the east over the Indian Ocean (Lindesay *et al.*, 1986). An eastward shift in the preferred longitude of convection is therefore apparent, and similar eastward shifts in convection have been observed in the Australasian sector during Pacific warm events (Allan, 1988; 1991). In the subtropics, the westerly jet stream advances northward to 20° S while troughs weaken in amplitude (Lindesay, 1988). The Southern Hemisphere standing waves are known to respond to ENSO events (Pittock, 1973; Trenberth, 1975; 1979; 1980b; Rogers and van Loon, 1982). In the southern African sector a northward shift of the westerlies occurs during warm events and is consistent with a decrease in meridional overturning and an increase in the equator-to-pole temperature gradient (Lindesay, 1988).

2 The Quasi-biennial Oscillation

The ENSO influence on rainfall over southern Africa may be stronger when the stratospheric Quasi-biennial Oscillation (QBO) is in its westerly phase (Mason and Lindesay, 1993), although an additive effect of the QBO has been proposed (Jury, 1996). When the QBO is in easterly phase (westerly phase) drought (wet) conditions occur during warm-phase (cold-phase) years, as in 1991–92 (Jury, 1995). The QBO is thought to interact with the Walker circulation over the western Indian Ocean (Jury *et al.*, 1994; Jury and Pathack, 1993; 1997): lower stratospheric easterly zonal winds would provide upper-tropospheric wind stress that would enhance Walker cell overturning with a descending limb over southern Africa and a rising limb over the ocean to the east (Figure 4). During westerly phase years, the Walker cell would be reversed and with a rising limb over southern Africa, and convection and rainfall over the subcontinent would be enhanced. However, the association between the stratospheric QBO and climate variability occurs, its influence over southern Africa is significant (Mason and Tyson, 1992; Jury, 1993; Mason *et al.*, 1994).

3 Sea-surface temperature anomalies

Higher than average sea-surface temperatures in the central equatorial Indian Ocean are frequently responsible for dry conditions over southern Africa (Walker, 1990; Walker and

Shillington, 1990; Mason, 1995; Jury, 1992; 1995; 1996; Jury and Pathack, 1993; 1997; Rocha and Simmonds, 1997a). The association with rainfall is a reflection of a correlation between Indian Ocean sea-surface temperatures, the overlying monsoon and ENSO events (Cadet, 1985; Suppiah, 1988; Meehl, 1993; Jury *et al.*, 1994; Mason, 1995). During Pacific El Niño conditions, the northern Indian Ocean is warmer than normal, probably in response to associated changes in wind stress and the radiation budget (Hastenrath *et al.*, 1993; Latif *et al.*, 1994; Latif and Barnett, 1995; Nagai *et al.*, 1995). The warming of the Indian Ocean could be important in the transmission of the El Niño signal to southern Africa (Rocha and Simmonds, 1997b). Occasionally, Indian Ocean warm events occur independently of ENSO forcing (Cadet, 1985) and observational evidence indicates that strengthening of convection and latent heat release over the warmer oceanic areas occurs at the expense of convergence over the subcontinent (Jury and Pathack, 1993; Mason, 1995; Jury, 1992; 1995; 1996). A warmer Indian Ocean is associated with an increased frequency of tropical cyclones (Jury, 1993), which would weaken surface easterlies over the subcontinent to the west of the vortex over the ocean (Rocha and Simmonds, 1997a). However, warm-phase ENSO conditions are often accompanied by increased westerly shear in the subtropics, suppressing tropical cyclone formation. With two conflicting effects of warmer sea-surface temperatures, but increased westerly shear, the correlation between the Southern Oscillation and tropical cyclone days over the Indian Ocean is near zero. Instead, the stratospheric QBO is more strongly implicated: the easterly phase favours tropical cyclone formation and increased convection over Madagascar (Jury, 1993). The overall effect of a warmer western tropical Indian Ocean is to strengthen tropical easterly disturbances over the ocean at the expense of convection over the subcontinent. The sea-surface temperature variance of the Indian Ocean is low during the rainfall season (Streten, 1981) and so the association with rainfall is possibly weaker than it otherwise would be (Shinoda and Kawamura, 1996), although correlations reach a strong peak during austral summer (Jury, 1996).

Modelling studies testing the atmospheric sensitivity to imposed sea-surface temperature anomalies confirm that moisture convergence and simulated rainfall over the subcontinent are reduced during Indian Ocean warm events (Mason *et al.*, 1994; Jury and Pathack, 1997; Rocha and Simmonds, 1997b). Low-level westerly anomalies are simulated over the northern Mozambique Channel (Jury and Pathack, 1997) and are consistent with observations during the summer of 1991–92 (Jury and Lutjeharms, 1993). The low-level westerlies would provide a link between centres of reduced convection over Botswana and increased convection over the southwest Indian Ocean near Mauritius (Figure 4) (Jury, 1993; Jury *et al.*, 1994; 1995; Shinoda and Kawamura, 1996; Jury and Pathack, 1993; 1997).

Associations between sea-surface temperatures in the equatorial Indian Ocean and rainfall over southern Africa appear to be nonlinear. While dry conditions are frequently associated with a warmer than average western tropical Indian Ocean, this area is an important source of atmospheric moisture throughout the summer rainfall season and becomes the dominant source in the second half of the summer (Barclay *et al.*, 1993; D'Abreton and Lindesay, 1993; D'Abreton and Tyson, 1995; 1996) implying that an increase in sea-surface temperatures here could enhance rainfall over southern Africa (Lindesay and Jury, 1991; Hulme *et al.*, 1996). General circulation model sensitivity experiments do not readily emulate all the observed features of atmospheric variability associated with tropical Indian Ocean sea-surface temperature variability. Simulated responses to increased sea temperatures in the tropical Indian Ocean or tropical eastern

Pacific invariably indicate a large response in the Indian Ocean subtropics, whereas the modelled reduction of rainfall over southern Africa is usually small. Similarly, the imposition of below-average sea-surface temperatures fails to produce much enhancement of rainfall over southern Africa (Jury *et al.*, 1996; Tennant, 1996), nor much weakening of convective activity over the Indian Ocean. The alternating Walker cell model of Jury *et al.* (1994) (Figure 4) is seen to be driven by tropical Indian Ocean sea-surface temperatures, although upper-level near-equatorial easterly anomalies are not a consistent observed feature of dry conditions over the subcontinent (Tyson, 1986; Lindesay, 1988; Mason *et al.*, 1994; Jury, 1996; Rocha and Simmonds, 1997a; 1997b). Relatively weak zonal flow anomalies are evident in the equatorial band during dry years. What emerges is that different circulation regimes surrounding southern Africa operate to determine interannual rainfall variability in the region. The dominant mode, associated with ENSO, involves a Walker cell reversal as illustrated in Figure 4, while secondary modes may involve alternative atmospheric anomalies. Clearly the structure of the Walker circulation over southern Africa and the Indian Ocean is complex and regional responses to sea-surface temperatures and global forcing require further examination (Janicot *et al.*, 1996).

In the subtropical latitudes of the Indian and Atlantic oceans (20–35° S), below (above) average sea-surface temperatures are generally associated with dry (wet) conditions over southern Africa (Walker, 1990; Jury, 1992; Mason and Tyson, 1992; Jury and Pathack, 1991; 1993; Jury, Valentine *et al.*, 1993; Hastenrath *et al.*, 1995; Mason, 1990; 1995; Shinoda and Kawamura, 1996; Rocha and Simmonds, 1997a). The atmospheric mechanisms involved are less well understood than for anomalies in the equatorial Indian Ocean, although variability in the surface temperatures of the Agulhas Current may have an effect on moisture fluxes into the overlying atmosphere (Walker and Mey, 1988; Mey *et al.*, 1990; Jury and Levey, 1993b; Jury, 1994; Rouault *et al.*, 1995; D'Abreton and Tyson, 1995; 1996). The supply of moisture to subtropical troughs (Walker, 1990) and ridging anticyclones (Lutjeharms *et al.*, 1986) would be reduced under cooler than average Agulhas Current temperatures. However, it is the meridional sea-surface temperature gradients to the south and south east of the subcontinent that are possibly of greatest significance, particularly in non-ENSO years. Strong sea-surface temperature gradients can result in enhanced westerly momentum fluxes and explosive cyclogenesis because of enhanced baroclinicity of the overlying atmosphere (Sanders and Gyakum, 1980). In the Agulhas gyre region, sea temperatures have been shown to have an important effect on cyclogenesis (Brundrit and Shannon, 1989). Temperature gradients in the South Atlantic Ocean are similarly important (Walker and Lindesay, 1989).

In the northern Benguela region, Atlantic Niños have been identified (Weare, 1977; Gillooly and Walker, 1984; Walker *et al.*, 1984; McLain *et al.*, 1985; Lamb *et al.*, 1986; Lough, 1986; Shannon *et al.*, 1986; Parker *et al.*, 1988; Semazzi *et al.*, 1988; Taunton-Clark and Shannon, 1988; Agenbag, 1996; Jury, 1997b), but may not have as significant an effect on rainfall over southern Africa as sea-surface temperatures in the Pacific or the Indian oceans (Walker, 1990; Mason *et al.*, 1994; Mason, 1995; Jury, 1997b). South of about 15° S, sea temperatures are relatively cold and the surface layer flow is strongly divergent and capped by a strong inversion (Nicholson and Entekhabi, 1987; D'Abreton and Tyson, 1995; 1996). Anomalies in the southern Benguela are probably only symptomatic of changes in wind stress (Walker, 1987). Further north, however, sea-surface temperature anomalies do influence moisture fluxes over the west coast of Angola (Hirst and Hastenrath, 1983a; 1983b) and in early summer could have an important influence on moisture flux convergence over southern Africa (D'Abreton and Lindesay, 1993; D'Abreton and

Tyson, 1995). Warm events in the tropical Atlantic Ocean have an important effect on late-summer rainfall over Namibia. When sea-surface temperatures off Angola increase above normal, the recurvature of trade winds over Angola is confined to the coastal strip, where rainfall may increase by a factor of two or more, while the area downstream experiences a reduced convective potential (Jury, 1997b).

Associations between sea-surface temperatures in the midlatitudes of the Atlantic and Indian Oceans and rainfall over southern Africa have been identified, although the atmospheric mechanisms involved are poorly understood (Walker, 1990; Mason *et al.*, 1994; Mason, 1990; 1995). The sea temperature anomalies are probably associated with variability in the westerly waves and the surface passage of cyclones and anticyclones (Mason *et al.*, 1994; Mason, 1995). Data quality is often suspect south of 40° S, but warming of the southern oceans may favour diffluent jet stream patterns which lead to increased amplitudes of westerly waves. This has implications for cold snaps during late winter and enhanced ridging anticyclones and increased rainfall over the southeastern coast of South Africa.

4 Atmospheric temperature variability

Temperature variability over southern Africa is a response to changes in advection, adiabatic heating and cooling, turbulent mixing and changes in radiation (Schulze, 1960; Lengoasa, 1988; Levey, 1996). Above-average summer temperatures occur during anomalously dry years over southern Africa (Hulme, 1996), mainly because of the predominance of anticyclonic conditions (Tyson, 1986), which allow adiabatic heating of descending air over the subcontinent and increases in solar radiation given less cloud cover (Halpert and Ropelewski, 1992). During ENSO warm-phase years temperatures over southern Africa are accordingly higher than average. However, the strongest determinant of temperature variability is the airflow. In all seasons the temperature anomalies increase in the direction of wind with increasing distance from the coastline where the air first reached the subcontinent. In consequence, the eastern part of southern Africa experiences above-average temperatures during westerly or northwesterly airflows (Lengoasa, 1988). Over the western part of the subcontinent, however, temperatures increase with easterly airflows, particularly along the west coast because of adiabatic heating of berg winds descending from the interior plateau (van Rooy, 1936; Lengoasa, 1988).

Winter temperatures at Cape Town during the past century have exhibited an approximately 8–9-year cycle in variability. Poleward shifts in the westerlies and increased continental airflows accompany the warmer periods in summer as well as in winter (Levey, 1996). Warmer than average sea-surface temperatures to the southwest of the subcontinent are associated with warm periods over Cape Town and may be a result of decreased turbulent mixing and increased insolation associated with a southward shift in the westerlies.

V Evidence for long-term climatic change

1 Rainfall

The question of whether or not southern Africa has been undergoing progressive desiccation has been debated for well over 100 years. Early opinions were conflicting

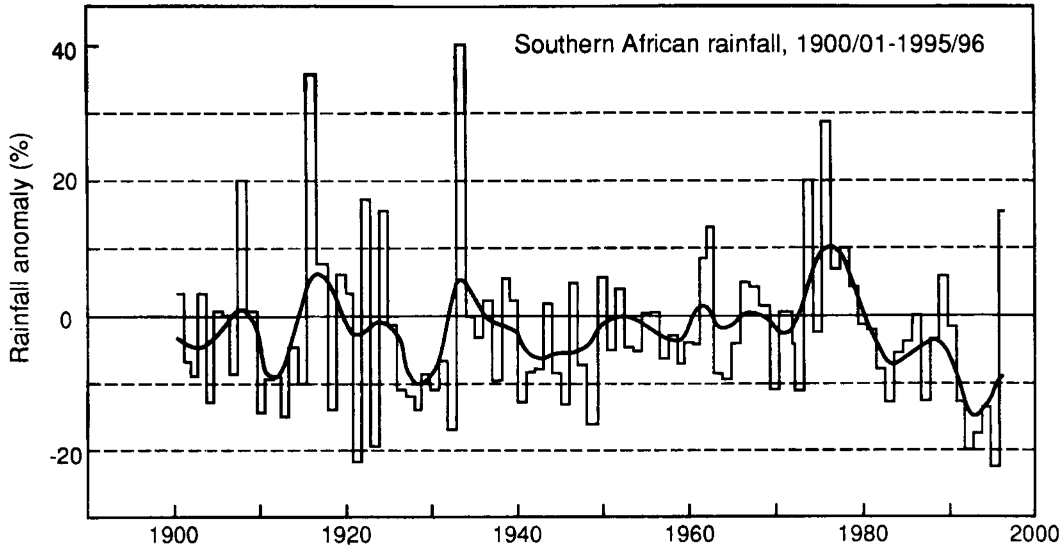

Figure 9 Southern Africa rainfall trends from 1900–1901 and 1995–96 as per cent anomalies from the 1961–90 average. Annual totals are for the July to June rainfall year. The smooth curve shows variations on timescales longer than ten years. The index is calculated from a gridded data set derived from about 500 rainfall stations. Reproduced from Hulme *et al.* (1996) with permission

(Wilson, 1865; Barber, 1910; Schwarz, 1919; Cox, 1926; Thompson, 1936; Vorster, 1957; Brook and Mametse, 1970), while more recent studies suggest that there is no evidence of progressive desiccation over Zimbabwe (Marume, 1992; Unganai, 1992), Botswana (Nicholson, 1989) or most of South Africa (Tyson *et al.*, 1975; Dyer, 1976; Tyson, 1980; Mason, 1996b). A decrease in the effectiveness of rainfall for maize-growing in southern Zambia has been reported (Kruss *et al.*, 1992). New evidence suggests that there has been an approximately 10% decrease in midsummer rainfall (December–February) between 1931–60 and 1961–90 over northern Botswana, Zimbabwe and eastern South Africa (Figure 9) (Hulme, 1992; 1996; Hulme *et al.*, 1996; Gondwe *et al.*, 1997). In more recent decades, a decrease in mean annual rainfall over the eastern lowveld of South Africa is evident (Mason, 1996b). The 1980s and early 1990s were dry over much of the subcontinent (Nicholson, 1993) and interdecadal variability may have resulted in the perception of progressive desiccation, although the effects of abrupt warming in tropical sea-surface temperatures in the mid-1970s and an increase in the frequency of El Niño events (Trenberth, 1990; Kerr, 1992; van Loon *et al.*, 1993; Allan *et al.*, 1995; Graham, 1994; 1995; Wang, 1995; Trenberth and Hoar, 1996), should not be ruled out (Mason, 1996b).

Historical records demonstrate that interannual rainfall variability over Zimbabwe (Unganai, 1992), South Africa (Mason, 1996b) and other parts of southern Africa (Hulme, 1992) is increasing. The implications are that flood years and droughts are becoming more frequent and severe. The increase in interannual rainfall variability is not matched by secular trends in intraseasonal variability (Dyer, 1982), although there are indications that the frequency of extreme flood events over South Africa may be on the rise (Mason and Mimmack, 1995; Jury and Majodina, 1997). Changes in the frequency of extreme events are sensitive to small changes in climate (Mearns *et al.*, 1984; Wigley, 1985; Rind *et al.*, 1989;

Katz and Brown, 1992; Katz and Acero, 1994) and it has therefore been suggested that tests for climatic change should focus on changes in the frequency of extremes rather than on changes in climatic means (von Storch and Zwiers, 1988). The observed increase in frequency of extreme events is consistent with an increase expected as a result of an enhanced greenhouse effect (Joubert *et al.*, 1996; Mason and Joubert, 1997).

2 Air and sea-surface temperatures

Over the last century, there has been a warming of more than 1°C over South Africa (Hughes and Balling, 1997) and of 0.5°C over southern Africa as a whole (Figure 10) (Hulme, 1996; Hulme *et al.*, 1996). Most of the warming has occurred during the last three decades, consistent with rapid warming in Southern Hemispheric temperatures (Hulme, 1996). Over South Africa, the warming trend is not ubiquitous (Mühlenbruch-Tegen, 1992; Levey, 1996) and may be mainly an urban effect (Hughes and Balling, 1997). The warming trend is most evident in autumn maximum temperatures (Mühlenbruch-Tegen, 1992; Levey, 1996) and is also detectable in an increase in extreme temperature maxima (Jury and Majodina, 1997).

Warming trends are evident in sea-surface temperatures around southern Africa, as well as in the surface air temperatures. The warming is strongest to the west of South Africa where trends of up to 1°C over the last 100 years are evident (Paltridge and Woodruff, 1981; Taunton-Clark and Shannon, 1988; Shannon *et al.*, 1990; Agenbag, 1996; Villacastín-Herrero *et al.*, 1996). The reasons for the trend are unclear, although changes in wind stress and the leakage of Agulhas waters into the Atlantic Ocean may be partly responsible (Shannon *et al.*, 1990; Agenbag, 1996). In the Indian Ocean interdecadal sea-surface temperature variability is associated with a strengthening of the south Indian Ocean semi-permanent anticyclone (Allan and Reason, 1995; Allan *et al.*, 1995).

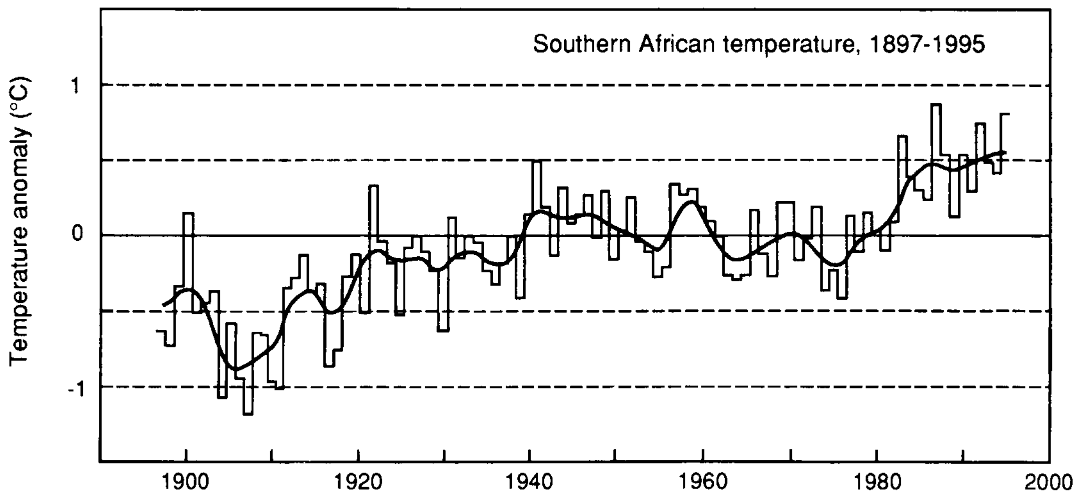

Figure 10 Southern Africa temperature trends from 1897 to 1995 expressed as anomalies from the 1961–90 average. The smooth curve shows variations on timescales longer than ten years. The index is calculated from a gridded data set derived from about 100 temperature stations. Reproduced from Hulme *et al.* (1996) with permission

3 Atmospheric circulation

The detection of long-term trends in the atmospheric circulation of the Southern Hemisphere is hampered by the relative paucity of data compared to the Northern Hemisphere. Nevertheless, significant changes in the relative importance of standing waves 1 to 4 have occurred (Trenberth, 1979; 1980b). It is possible that the changes in the standing waves are interdecadal rather than long term (van Loon and Rogers, 1984), but an abrupt increase in the amplitude of wave 3 after 1977 is of interest: changes in the geopotential heights at 50–60° S indicate the development of a ridge at about 30–80° W in the Atlantic sector and a trough at about 90° E in the Indian Ocean sector (Trenberth, 1979; Rogers and van Loon, 1982; van Loon *et al.*, 1993; Hurrell and van Loon, 1994). An increase in tropical atmospheric convection after 1977 caused midtropospheric temperatures to rise at all latitudes and strengthened the equator-to-pole temperature gradient. The strengthened meridional gradient was responsible for a deeper circumpolar trough and stronger zonal winds in the midlatitudes. The Southern Hemisphere standing waves are sensitive to variability in tropical convection because of the weak orographic forcing of the waves compared to the Northern Hemisphere (Pittock, 1973; 1980). Modelling studies suggest that the sensitivity of the atmosphere is greatest during January (Albrecht *et al.*, 1986; Meehl and Albrecht, 1988), when rainfall over most of southern Africa is at its peak, although observed changes in wave 3 are greatest during the winter (van Loon *et al.*, 1993).

The apparent languishing of the semi-annual oscillation has been attributed to these post-1977 changes in the standing waves. The semi-annual oscillation is critically dependent upon differences in the phases of the annual cycles of temperature at 50° S and 65° S (van Loon, 1967; Carleton, 1981; Mo and White, 1985; Meehl, 1991). At 50° S, which is ocean dominated, the ocean heat storage delays the summer temperature maximum and winter minimum, while at 65° S the continental influence of Antarctica results in a temperature maximum during December, followed by a gradual decrease to a poorly defined minimum ('coreless winter') in late winter, followed by rapid warming. The semi-annual oscillation is thus sensitive to changes in the ocean heat storage at 50° S, which in turn is affected by meridional heat transport from tropical latitudes. The implications for southern Africa are significant since the total annual rainfall of the region is strongly influenced by the amplitude of the semi-annual cycle: rainfall being higher when the amplitude is greater (Theron and Harrison, 1991).

VI Conclusions

Rainfall over southern Africa during the period of instrumental records exhibits quasi-periodicities. The dominant period is near 18 years over much of the summer rainfall region of eastern South Africa. The cycle may be forced by interdecadal variability in sea-surface temperatures, possibly impacting the disposition of subtropical standing waves. The standing waves, in particular wave 3, are additionally related to a 10-year cycle along the south coast and which has an expression in sea-surface temperatures in the Agulhas Current system. Rainfall cycles of 3.5–6 years associated with the El Niño–Southern Oscillation phenomenon are also detectable over southern Africa. Over Zimbabwe and Madagascar the dominant cycle in summer rainfall is one at 2.3 years and is consistent with the stratospheric Quasi-biennial Oscillation of zonal winds.

The dominant rainfall cycles are likely to be a response of the subtropical atmospheric circulation to changes in tropical heating anomalies. The interaction between tropical easterly disturbances and westerly troughs over southern Africa largely defines the interannual climate variability over most of the subcontinent. Easterly disturbances tend to form further to the east when sea-surface temperatures in the equatorial Indian Ocean are above normal and/or when the Southern Oscillation is in its low phase. Similarly, in the midlatitudes, rainfall over the subcontinent is affected by longitudinal shifts and changes in the amplitude of the westerly waves. Wet spells occur when a high amplitude wave lies over southern Africa with a strong ridge to the west. Since the midlatitude standing waves are sensitive to variability in tropical heating it is not surprising that a response of the midlatitude atmosphere to El Niño–Southern Oscillation events is detectable in the southern African region. Rainfall variability in the region is associated not only with sea-surface temperature variability in the tropical Pacific Ocean but also with sea temperatures in the Indian and South Atlantic Oceans, as well as the stratospheric Quasi-biennial Oscillation. Considerable progress in the understanding of atmospheric variability over southern Africa has been made over the last few years, although details of the coupling of convection, atmospheric circulation and sea-surface temperatures over the tropical Indian Ocean, and of the significance of variability in the westerly waves, require further research.

Evidence for long-term climatic change is not as definitive as in the Sahel, although over Zimbabwe, northern Botswana and eastern South Africa there are indications of desiccation since the late-1970s. Over the same period, rapid increases in air temperatures are detectable and are of approximately the same magnitude as the hemispheric trends. The warming trends are in excess of urbanization effects, so that a greenhouse signal may be evident locally. This may have important implications for the water balance, even in the absence of any significant rainfall trend, since evaporation losses from the surface are likely to increase.

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