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SEA-SURFACE TEMPERATURE – SOUTH AFRICAN RAINFALL ASSOCIATIONS, 1910–1989

S. J. MASON
Climatology Research Group, University of the Witwatersrand, Johannesburg 2050, South Africa

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ABSTRACT

The main features of sea-surface temperature variability in the South Atlantic and the south-west Indian Oceans are identified and their interaction with the Southern Oscillation discussed. Most of the variance is explained by coherent features of variability in the South Atlantic Ocean. Tropical and subtropical features dominate the variance, but this may be partly a reflection of data availability. Many of the principal components are associated with rainfall over southern Africa and the strongest associations occur with sea-surface temperatures in the western equatorial Indian Ocean, the Agulhas system, and the central South Atlantic Ocean.

KEY WORDS: sea-surface temperatures; rainfall variability; South Atlantic Ocean; south-west Indian Ocean; southern Africa principal components analysis; quasi-periodic oscillations

INTRODUCTION

Sea-surface temperature anomalies have been found to be closely associated with rainfall in many areas, and increasingly are being found useful as predictors of seasonal rainfall, most notably in tropical regions (e.g. Hastenrath, 1984; Bah, 1987; Janowiak, 1988; Mechoso and Lyons, 1988; Adedoyin, 1989; Ward and Folland, 1991; Chu and He, 1992; Phillips, 1992; Rowell *et al.*, 1992; Fontaine and Bigot, 1993) but also in the mid-latitudes (Phillips, 1992; Zorita *et al.*, 1992; Peng and Mysak, 1993). In the southern African region, associations between sea-surface temperatures and rainfall are evident but a more thorough investigation is required before a seasonal forecasting programme can be established. In this paper, the main features of sea-surface temperature variability in the South Atlantic and the south-west Indian Oceans are identified, described and explained, and, in turn, related to rainfall variability over South Africa.

It is thought that sea-surface temperature anomalies in the south-west Indian Ocean have an important influence upon the formation of southern Africa's tropical and tropical–temperate rain-bearing synoptic systems (Walker, 1989, 1990; Jury and Pathack, 1991). High sea-surface temperatures to the north of Madagascar encourage the development of tropical easterly disturbances over the western equatorial Indian Ocean rather than over the subcontinental interior (Jury and Pathack, 1991), hence resulting in dry conditions over the land. In addition, high sea-surface temperatures throughout most of the Agulhas Current region and the Mozambique Channel are associated with wet conditions over the summer rainfall region (Figure 1), as a result of anomalously high sensible and latent heat fluxes into both the tropical easterly inflow and the temperate systems forming to the south of the country. Important feedback mechanisms between the atmosphere and the ocean help to maintain the anomalous conditions (Walker, 1989; Jury *et al.*, 1993).

Although the interannual sea-surface temperature variability in the South Atlantic Ocean is less than in any of the other oceans in the Southern Hemisphere (Streten, 1981), associations with southern African rainfall variability do occur (Walker, 1989, 1990). Anomalously high sea-surface temperatures in a broad zonal band between the approximate latitudes of 15° and 35°S and in an area immediately to the south of the subcontinent accompany wetter conditions over much of the summer rainfall region (Figure 1). High sea-surface temperatures in this region would enhance atmospheric baroclinicity and hence cyclogenesis,

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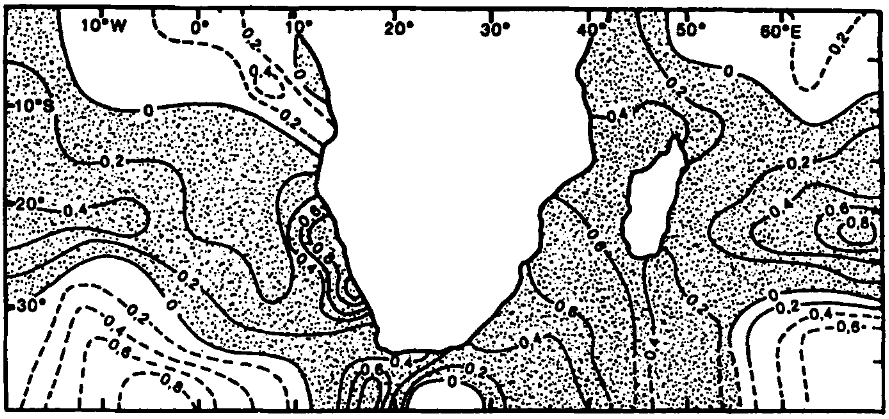

Figure 1. Composite sea-surface temperature differences between composite wet and composite dry late summer seasons for the eastern summer rainfall region (Southern Oscillation influences excluded). During wet years anomalously high sea-surface temperatures are usually evident in the areas of positive difference and anomalously cold sea-surface temperatures in the areas of negative difference. Values are in degrees Celsius. Positive differences are shaded (adapted from Walker, 1990)

which would have important implications for southern African rainfall. In the temperate latitudes of the South Atlantic Ocean, cyclonic activity has been found to be enhanced over both warm water anomalies and along areas of strengthened sea-surface temperature gradients (Brundrit and Shannon, 1989; Walker and Lindesay, 1989). High sea-surface temperatures between the latitudes of 15° and 35°S of the South Atlantic Ocean could imply a poleward shift in the zone of surface westerlies also (Walker, 1989), a phenomenon known to be associated with anomalously wet conditions over the interior (Tyson, 1986).

DATA AND METHODS

S-mode principal components analysis has been used to identify the main features of sea-surface temperature variability in the South Atlantic and the south-west Indian Oceans. The analysis was performed using the seasonal (3-month) mean sea-surface temperature anomalies for 5° grids calculated from the Meteorological Office Historical Sea Surface Temperature data set from 1910 to 1989, giving 316 observations. The analysis was restricted to the area south of the Equator and between 70°W and 70°E and thus includes a total of 210 grids in the South Atlantic and the south-west Indian oceans. Principal components analysis requires that there are no missing observations in the data matrix. Missing values have been replaced by Gaussian noise, thus ensuring that grids with poor data availability are given low weight. Although the use of the correlation matrix is usually recommended only when the units on the original variables are different (Craddock, 1972; Willmott, 1978), which is not the case in this research, the correlation matrix is often used if the variables have differing variances. Large areas of the South Atlantic and the south-west Indian Oceans are known to have a low sea-surface temperature variability (Streten, 1981) and as the atmospheric response to sea-surface temperature anomalies in areas of low variability but high mean can be large (Trenberth, 1991; Zhang, 1993), the principal components analysis was based on the correlation rather than the variance–covariance matrix.

The principal components were rotated to ease interpretability (Christensen and Bryson, 1966; Richman, 1986). Oblique rotations are usually the most successful at retrieving features of variability (Richman, 1981) but the loss of orthogonality is not always desirable and so the Varimax method has been used. There is no theoretical means of defining at which point principal components become physically meaningless. In this paper all principal components explaining less than 5 per cent of the total variance have been ignored. The scores on the principal components were detrended by calculating the residuals from a linear regression line. Warm and cold events have been defined as seasons in which the detrended scores on a principal component have exceeded 2·0 standard deviations above and below the mean respectively.

The detrended principal component scores have been correlated with rainfall totals over South Africa. Rainfall data for 60 rainfall stations evenly distributed over South Africa were obtained from the South African Weather Bureau. In calculating significance levels, adjustments have been made to the degrees of freedom in order to compensate for autocorrelation within the time series. Statistical field significance has been calculated allowing for spatial autocorrelation (Livezey and Chen, 1983). Because correlation may not be an appropriate technique for identifying any association between the sea-surface temperature anomaly patterns and rainfall totals as a result of the non-linearity of the associations, superposed epoch analysis has also been performed to compare the significance of the difference between rainfall receipts during the warmest and the coldest seasons for each principal component. For each rainfall station a Mann–Whitney *U* statistic has been calculated to test for significance in the differences between the rainfall receipts.

PRINCIPAL COMPONENTS OF SEA-SURFACE TEMPERATURE VARIABILITY IN THE SOUTH ATLANTIC AND SOUTH-WEST INDIAN OCEANS

Eight rotated principal components, each explaining greater than 5 per cent of the total variance, have been identified and are illustrated in Figure 2. The boundaries of the areas have been defined by the 0·5 loading contour. Together the principal components explain 75 per cent of the total sea-surface temperature variance within the region. It should be remembered that the proportion of the variance has been underestimated because of the inclusion of Gaussian noise within the data matrix. Table I gives a breakdown of the variance captured by each principal component separately.

The first principal component, PC1, describes the well-known region-wide warming and cooling of the entire Benguela system (Weare, 1977; Lough, 1986; Shannon *et al.*, 1986; Parker *et al.*, 1988) and extends far westward along the Equator. It explains 17·3 per cent of the total variance (Table I). Benguela events have been attributed to wind stress anomalies over the western equatorial and eastern Atlantic Ocean (Hirst and Hastenrath, 1983a, b; Hastenrath, 1985; Horel *et al.*, 1986; Shannon *et al.*, 1986; Weisburg and Colin, 1986) and anomalous oceanic circulation features inhibiting upwelling (Hisard *et al.*, 1986; Philander, 1986; Shannon *et al.*, 1986). Decreased evaporation rates during periods of weakened wind stress are an important factor in the persistence of warm events (Druyan, 1988). In contrast to the North Pacific Ocean (Barnett and Davis, 1975) and North Atlantic Ocean (Weare, 1977), but similar to the South Pacific Ocean (Newell and Weare, 1976; Weare *et al.*, 1976), it is the eastern boundary current that is the main feature of variability in the South Atlantic Ocean rather than the western boundary current.

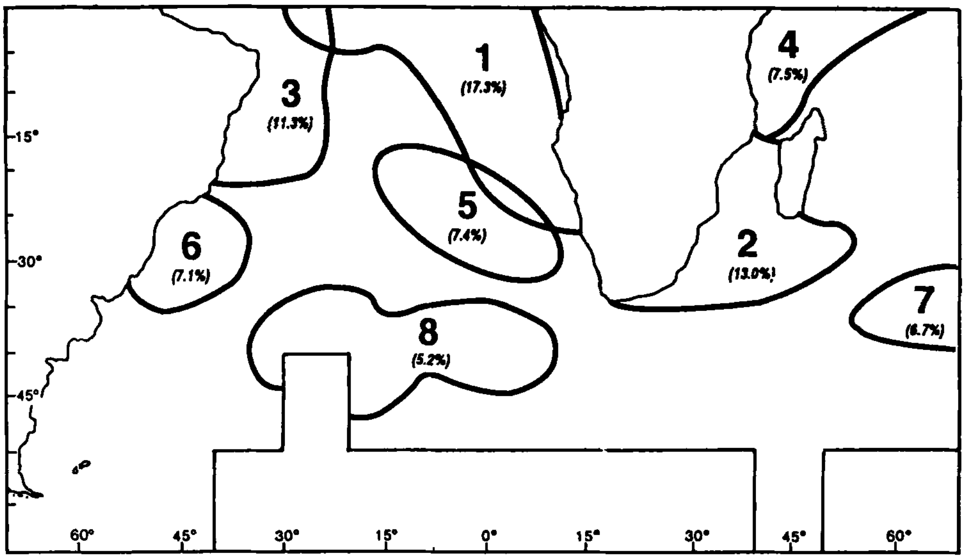

Figure 2. Core areas of sea-surface temperature coherence as determined from principal components analysis with the varimax rotation

Table I. Variances and cumulative variances associated with the first eight principal components describing non-seasonal sea-surface temperature variability within the South Atlantic and the south-west Indian Oceans

Principal component	Variance (percentage of total)	Cumulative variance (cumulative percentage of total)
1	17·3	17·3
2	13·0	30·3
3	11·3	41·6
4	7·5	49·1
5	7·4	56·5
6	7·1	63·6
7	6·2	69·8
8	5·2	75·0

It is thought that warm events in the region, sometimes termed 'Benguela Niños' (Boyd, 1988; Brundrit, 1988), are associated with the occurrence of similar events in the South Pacific Ocean (Walker *et al.*, 1984; Semazzi *et al.*, 1988), in which case the two phenomena should have similar quasi-periodic behaviour and should be correlated, although not necessarily simultaneously. The spectral characteristics of the eight principal components of sea-surface temperatures are illustrated in Figure 3. The first principal component exhibits significant quasi-periodic behaviour (Figure 3(*a*)), with significant peaks at 2·3 years, 3·6 years, and 12·5 years ($p > 0{\cdot}995$) and one at 21·9 years ($p > 0{\cdot}99$). The quasi-periodicity at 2·3 years suggests an association with the Quasi Biennial Oscillation, whereas the one at 12·5 years possibly corresponds with 8–10-year oscillations evident in the southern Benguela (Taunton-Clark and Shannon, 1988). Only the spectral peak at about 3·6 years shows any similarity to the Southern Oscillation. The 5–6-year oscillation previously identified in the region (Nicholson and Entekhabi, 1987; Walker, 1987; Nicholson, 1989) is not evident beyond the 99 per cent level. Despite an apparent lack of spectral similarities, warming events in the Benguela and Peru currents have been noted to occur concurrently, although the Benguela events are less frequent (Walker *et al.*, 1984). The principal component scores indicate that warm events have occurred in 1923–1924, 1934, 1963, and 1984 (Gillooly and Walker, 1984; McLain *et al.*, 1985; Lamb *et al.*, 1986; Shannon *et al.*, 1986) but only the first and last of these have occurred in close conjunction with low phases of the Southern Oscillation. A Benguela event also developed during the last few months of 1993, after the prolonged Pacific warm conditions of 1991–1993. Cold events have occurred in 1932, 1943, 1946, and 1958. The 1932 cold event occurred about a year after a low phase in the Southern Oscillation Index, whereas the 1946 event occurred at about the same time as the Southern Oscillation was in its high phase.

The Benguela events appear to be most clearly defined during July–September (Andrews and Hutchings, 1980), in contrast to the South Pacific Ocean and so, if the two phenomena are associated, a simultaneous correlation with the Southern Oscillation Index is unlikely. Table II presents the correlation between the Southern Oscillation Index and sea-surface temperature principal component scores for each season separately, and confirms the absence of a simultaneous association at any time of year. At a 3-month lag, however, changes in the Southern Oscillation Index precede similar changes in sea-surface temperatures in the eastern South Atlantic Ocean for all seasons except July–September, the season during which the Benguela events are most pronounced. Consequently, the possibility of using El Niño events as predictors of similar events in the eastern South Atlantic Ocean is not strong.

The second principal component, PC2 (Figure 2) explains 13·0 per cent of the total variance and corresponds with Walker's (1989) first principal component in the south-west Indian Ocean. It involves region-wide warming and cooling throughout the Agulhas system, including the Mozambique Channel. Since the early part of the century a number of warm events have occurred, namely in 1915, 1917, 1940, 1942, 1943, 1945, 1952, 1961, 1978, and 1981. Cold events occurred in 1930, 1935, 1945, 1951, and 1965. Agulhas events are most well developed during January–March. There have been no attempts to relate directly the occurrence of Agulhas warm events with the Southern Oscillation but an association could be

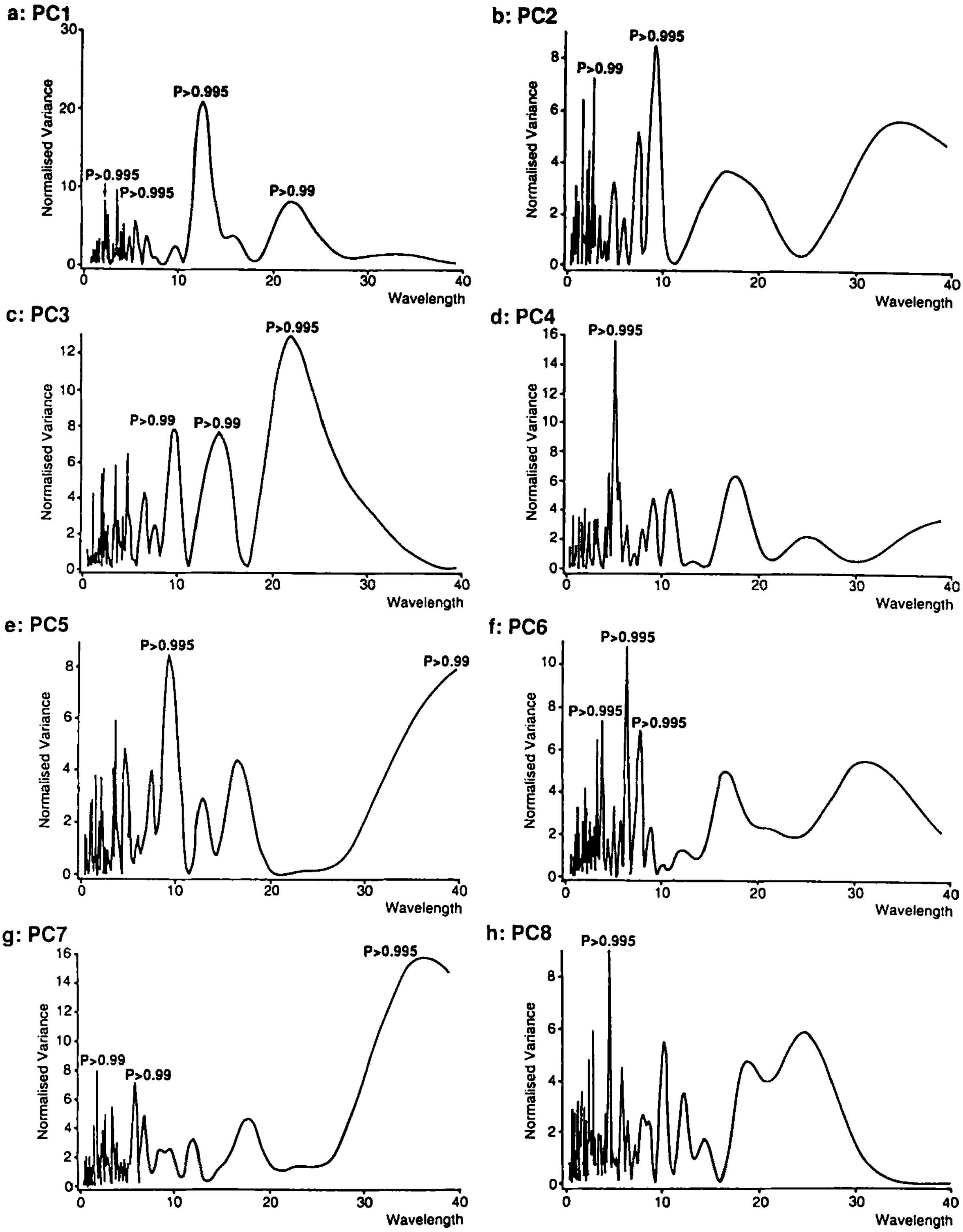

Figure 3. Plots of normalized variance against wavelength of scores for the first eight principal components of sea-surface temperatures in the South Atlantic and the south-west Indian oceans. The boundaries of the areas are defined by the 0·5 loading contour. Peaks significant at greater than 0·99 are indicated

implied. To the north of the Agulhas area, sea-surface temperatures north of 5°S in the Indian Ocean vary in phase with temperatures in the South Pacific Ocean (Suppiah, 1988) and in the Agulhas region are coherent with quasi-periodicities along the west coast at wavelengths associated with the Southern Oscillation (Nicholson and Entekhabi, 1987; Nicholson, 1989). In addition, atmospheric circulation anomalies over southern Africa associated with El Niño–Southern Oscillation events are also associated with strengthened flow of the Agulhas Current (Walker, 1989). It is therefore not surprising that the scores on PC2 during January–March are significantly correlated with the Southern Oscillation Index during January–March (Table II).

The quasi-periodic characteristics of sea-surface temperatures in the Agulhas system are much weaker than those in the Benguela (Figure 3(*b*)). Nevertheless, significant peaks at 2·7 years and 9·1 years ($p > 0·99$) are evident. Despite the correlations, there are also no oscillations suggesting an association with the Southern Oscillation; in particular, there is no evidence of a previously reported 5–6 year oscillation (Nicholson, 1989).

The first two principal components of sea-surface temperature variability in the South Atlantic and the south-west Indian Oceans both border the coast of southern Africa and confirm that sea-surface temperature variability along the east and west coasts is anomalously high (Streten, 1981). Combined, Benguela and Agulhas events explain almost one-third of the total variance in the region (Table I).

Table II. Seasonal simultaneous and 3-month lag correlation coefficients and significance levels between the Southern Oscillation Index and sea-surface temperature principal component scores, 1910–1911 to 1988–1989

	Principal component	Simultaneous correlation	Significance level	Lagged correlation	Significance level
January–March	1	−0·058	0·614	−0·219	0·053
	2	−0·290	0·010	−0·159	0·163
	3	0·098	0·389	−0·068	0·551
	4	−0·380	0·001	−0·348	0·002
	5	−0·172	0·129	−0·158	0·165
	6	0·025	0·827	0·002	0·986
	7	0·117	0·304	0·157	0·166
	8	0·309	0·006	0·416	0·000
April–June	1	0·145	0·203	0·214	0·058
	2	0·099	0·385	−0·088	0·441
	3	−0·088	0·438	−0·110	0·336
	4	−0·157	0·168	−0·344	0·002
	5	−0·093	0·412	−0·152	0·182
	6	−0·136	0·232	−0·014	0·902
	7	−0·183	0·107	0·046	0·685
	8	0·012	0·914	0·149	0·191
July–September	1	0·047	0·678	0·039	0·730
	2	0·015	0·896	0·065	0·566
	3	0·030	0·790	−0·137	0·227
	4	−0·125	0·271	−0·026	0·823
	5	−0·058	0·612	−0·077	0·503
	6	−0·160	0·159	−0·104	0·363
	7	−0·137	0·229	−0·176	0·121
	8	−0·093	0·414	−0·121	0·289
October–December	1	−0·135	0·234	0·253	0·024
	2	0·021	0·852	−0·027	0·810
	3	0·127	0·265	−0·042	0·711
	4	−0·235	0·037	0·059	0·605
	5	−0·163	0·152	0·002	0·989
	6	−0·358	0·001	0·113	0·321
	7	0·169	0·136	0·024	0·834
	8	0·318	0·004	−0·195	0·085

The third principal component, PC3, describes a further 11·3 per cent of the variance and is located in the western equatorial Atlantic Ocean extending southward to about 25°S (Figure 2). As appears to be typical of the South Atlantic Ocean, PC3 displays quasi-periodic behaviour at a number of wavelengths (Figure 3(*c*)), with significant oscillations at 9·6 and 14·4 years ($p > 0{\cdot}99$) and at 21·9 years ($p > 0{\cdot}995$). Oscillations of 2–4 years have been reported to propagate westward across the equatorial Atlantic Ocean (Hamilton and Allingham, 1988) but there is no evidence of 2–4 year oscillations in PC3 beyond the 99 per cent level. The peak at 14·4 years may be associated with a 14–15 year oscillation in rainfall over north-east Brazil (Hastenrath, 1985). As the spectral characteristics suggest, PC3 is uncorrelated with the Southern Oscillation (Table II). Warm events have occurred during 1944–1946 and 1964 and cold events in 1934, 1948, 1979, 1980, and 1981 and are probably the result of anomalous atmospheric circulation features over the equatorial Atlantic Ocean (Hisard *et al.*, 1986; Philander, 1986; Weare, 1977). The feature is most apparent in April–June, which suggests that it is a result of a faltering in the strengthening of winds, which normally occurs in May, resulting in the development of a zonal temperature gradient because of a strong westward surface current of warm water from the Gulf of Guinea (Hisard *et al.*, 1986; Philander, 1986). Variations in advection within the equatorial Atlantic Ocean therefore seem responsible for the occurrence of PC3.

Despite evidence for weak interannual sea-surface temperature variability north of 5°S in the Indian Ocean (Suppiah, 1988), the fourth principal component, PC4, is located in the equatorial western part of the ocean, extending southward towards the northern Mozambique Channel (Figure 2) and explains 7·5 per cent of the total variance. Sea-surface temperatures in the region are strongly associated with the Southern Oscillation during January–March and October–December (Table II) (Suppiah, 1988). At a 3-month lag the association between the Southern Oscillation and January–March scores on PC4 is weaker than the simultaneous lag and so should not be used for predictive purposes (Davis, 1976; Katz, 1988; Brown and Katz, 1991). Similarly, a significant lag association between the January–March Southern Oscillation Index and April–June principal component scores may be a reflection of the strong autocorrelation in both time series and so should, again, probably not be used for forecasting. The association with the Southern Oscillation is reflected in the oscillations in scores on PC4 at 5·2 years ($p > 0{\cdot}995$) (Figure 3(*d*)), which is the only significant peak, beyond $p = 0{\cdot}99$. The 5·2-year quasi-periodicity corresponds to 5–6-year oscillations found along the east coast of southern Africa by Nicholson (1989) and Nicholson and Entekhabi (1987). Warm events are most apparent during April–June, whereas cold events are most developed in January–March. The warm events of 1924, 1941, 1947, and 1982 all occurred close to the time of low phases of the Southern Oscillation, whereas the cold events of 1917 and 1971 occurred at the time of high phases. Cold events were evident in 1934, 1939, and 1940 also but were unrelated to extremes in the Southern Oscillation Index.

The fifth principal component, PC5, occurs in the subtropical latitudes of the eastern South Atlantic Ocean between about 15° and 30°S (Figure 2) and corresponds with the main feature of annual sea-surface temperature variability in the eastern South Atlantic Ocean (Walker, 1989). At 7·4 per cent of the total variance (Table I), PC5 explains a similar proportion to PC4. The feature is unrelated to the Southern Oscillation at all times of the year (Table II) and does not reflect any similar spectral characteristics (Figure 3(*e*)). An oscillation at 9·3 years ($p > 0{\cdot}995$) is the only significant oscillation in the sea-surface temperatures in the eastern South Atlantic Ocean. The feature is strongest during January–March and April–June, with warm events having occurred in 1920, 1922, 1940, 1949, 1972, and 1973, and cold events in 1918, 1940, 1945–1946, and 1970. A tentative suggestion for the occurrence of PC5 is that it reflects variability in the leakage of warm Agulhas waters, in the form of Agulhas Rings, into the South Atlantic Ocean, which can result in the presence of anomalously warm pools of water within this region (see e.g. Lutjeharms *et al.*, 1991).

Variability in the western boundary current of the South Atlantic Ocean is highlighted as only the sixth principal component (Figure 2). In reality the feature probably extends further south to cover most of the Brazil Current system and also probably is more significant than this analysis suggests because of poor data availability in the south-west part of the region. Nevertheless, the feature explains 7·1 per cent of the total variance (Table I). Oscillations at 3·8 and 6·5 years ($p > 0{\cdot}995$) (Figure 3(*f*)) suggest an association with the Southern Oscillation but this is apparent only in October–December (Table II). An additional oscillation is evident at 7·9 years ($p > 0{\cdot}995$). Warm events have been observed in 1936, 1958, 1959, 1961, and 1965–1966 and cool events in 1917 and 1965 and are most evident during April–June.

The seventh principal component occurs in the central South Indian Ocean between about 30° and 40°S (Figure 2) and is the first component to be identified in mid-latitude regions. The dominance of the principal components analysis by low-latitude features of variability is likely to be only partly real. Data availability is poorer in the higher latitudes and so the Gaussian noise used to replace the missing values will tend to weaken the coherence of mid-latitude features of sea-surface temperature variability in the data matrix. Consequently, like the western South Atlantic Ocean, the importance of PC7, which explains 6·2 per cent of the total variance (Table I), is probably underestimated. Possible causes of the coherent sea-surface temperature variability in the central South Indian Ocean include variability in the recycling of Agulhas waters and meridional migrations of the mid-latitude sea-surface temperature gradients. Warm events have occurred in 1914, 1918, 1946, 1950–1951, and 1968 and cold events in 1916, 1924, 1957, 1964, and 1967. The feature is strongest in January–March. A quasi-periodicity of 1·9 years ($p > 0{\cdot}99$) (Figure 3(*g*)) is too short to be associated with the Quasi-Biennial Oscillation but one of 6·0 years ($p > 0{\cdot}99$) indicates a possible association with the Southern Oscillation. However, scores on PC7 are uncorrelated with the Southern Oscillation Index for all seasons (Table II).

Likewise, poor data availability in the mid-latitudes of the South Atlantic Ocean is probably responsible for the underestimation of the importance of the eighth principal component. PC8 explains 5·2 per cent of the total variability (Table I) and appears to involve coherent warming and cooling over a large area south of about 35°S and across about 45° of longitude in the central South Atlantic Ocean (although it should be remembered that the spatial extent of the principal component relative to the low-latitude components is exaggerated by the map projection). The feature occurs within a region of strong sea-surface temperature gradients, including the Subtropical Convergence, and so probably reflects changes in the strength and position of oceanic thermal fronts and may be associated with shifts in preferred storm tracks and changes in storm frequencies. There is a lack of strong quasi-periodicities in the scores on the principal component (Figure 3(*h*)) with only one significant oscillation at 4·6 years ($p > 0{\cdot}995$). Warm events have occurred in 1921, 1939, 1951, 1952, 1979, and 1981 and cold events in 1913, 1914, 1926, and 1969 and are most apparent in January–March.

ASSOCIATIONS BETWEEN THE PRINCIPAL COMPONENTS OF SEA-SURFACE TEMPERATURE VARIABILITY AND RAINFALL OVER SOUTH AFRICA

Wet years over the summer rainfall region of South Africa are known to be associated with distinct local sea-surface temperature anomaly patterns (Figure 1) (Walker, 1989, 1990). A simple comparison of Figure 1 with Figure 2 suggests that rainfall over the summer rainfall region increases (decreases) during Agulhas warm (cold) events and during Benguela cold (warm) events. Positive associations between rainfall and principal components scores may also be evident with PC5 in the eastern South Atlantic Ocean and negative associations with PC4, PC7, and PC8. Correlations between the seasonal principal component scores and rainfall totals have been calculated for the 79-year period 1910–1911 to 1988–1989 for each season separately. Field significance statistics for the summer and winter rainfall regions have been determined. A Mann–Whitney *U* statistic has also been calculated to test differences in rainfall receipts between periods with the five highest seasonal principal component scores and the five lowest.

The Benguela system is thought to be of considerable climatic significance, apparently being responsible for rainfall variability over the Sahelian region (Folland *et al.*, 1986; Lough, 1986; Parker *et al.*, 1988; Semazzi *et al*, 1988; Adedoyin, 1989; Street-Perrott and Perrott, 1990), with warm events associated with periods of drought, and for wet conditions over Angola (Hirst and Hastenrath, 1983a) and north-east Brazil (Mechoso and Lyons, 1988). Over the summer rainfall region of South Africa sea-surface temperature variability associated with Benguela events, PC1, shows no significant correlation with rainfall at any time of year and is correlated with winter rainfall region totals only during the dry season of January–March (statistical field significance, $p > 0{\cdot}93$). There is, in addition, no significant difference between rainfall received during warm events and that received during cool events. It is quite possible that the increase in summer rainfall in the winter rainfall region experienced when sea-surface temperatures in the western South Atlantic Ocean increase is actually evidence of the joint association of rainfall and PC1 with the Southern Oscillation at this time of year (Table II). From Figure 1 it appears that rainfall is negatively associated with sea-surface temperatures in the southern section. An out-of-phase association of sea-surface temperatures in the north and south sections of the west coast is evident (Walker *et al.*, 1984; Walker, 1987; see also Tyson, 1986) but this feature has not been identified in the principal components analysis in this study. It is therefore not possible to rule out an association between sea-surface temperature variability along the west coast and rainfall variability over South Africa, although it seems likely that an association is evident only locally along the west coast (Shannon *et al.*, 1986; Lindesay, 1989).

Rainfall over the summer rainfall region is associated with sea-surface temperatures in the Agulhas system, PC2, all year except during the dry July–September season (Figure 4). Wetter (drier) conditions are experienced over almost the entire country when sea-surface temperatures in the Agulhas system rise (fall) in January–March ($p > 0{\cdot}99$), April–June ($p > 0{\cdot}995$) and October–December ($p > 0{\cdot}94$), although Agulhas warm events are associated with significantly wetter conditions than cool events only in January–March. During the late rainy season of January–March warm events enhance the tropical and temperate circulations associated with wet conditions over the summer rainfall region (Walker, 1989) by fuelling the influx of warm, moist air from the east and by enhancing cyclogenesis to the south (Figure 5(*a*)). The coupling of the tropical and temperate systems results in the formation of tropical–temperate troughs across the country,

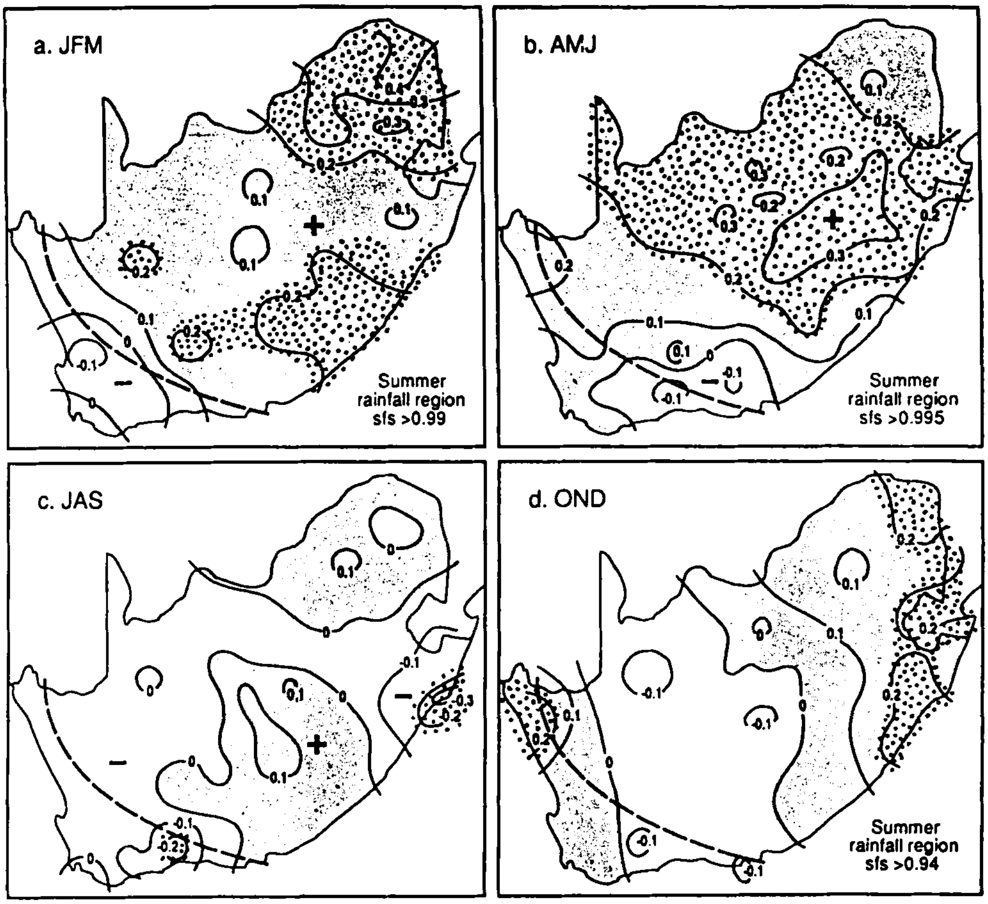

Figure 4. Zero-lag Pearson correlation coefficients between seasonal principal component scores on PC2 and rainfall totals: (*a*) January–March, (*b*) April–June, (*c*) July–September, and (*d*) October–December. Areas of positive correlation are shaded grey. Dotted regions indicate areas where correlations are significant at the 90 per cent level. Statistical field significance (sfs) is indicated where it exceeds 90 per cent. The dashed line marks the boundary between the summer (to north-east) and winter (to south-west) rainfall regions

indicative of conduits of the poleward transfer of heat and momentum, thus enhancing rainfall further (Harrison, 1986) (Figure 5(*b*)). The formation of tropical–temperate troughs is most frequent during the January–March season at which time sea-surface temperatures in the Agulhas system can have their greatest influence. The significance of PC2 in affecting local atmospheric circulation and rainfall anomalies is evident despite a negative association with the Southern Oscillation during January–March (Table II). In effect, during a high (low) phase of the Southern Oscillation, when rainfall over southern Africa is anomalously high (low), cooler (warmer) sea-surface temperatures in the Agulhas region would tend to diminish (enhance) rainfall over the subcontinent. It is therefore possible that the Agulhas system is partly responsible for the occasional faltering of the association between the Southern Oscillation and southern African rainfall

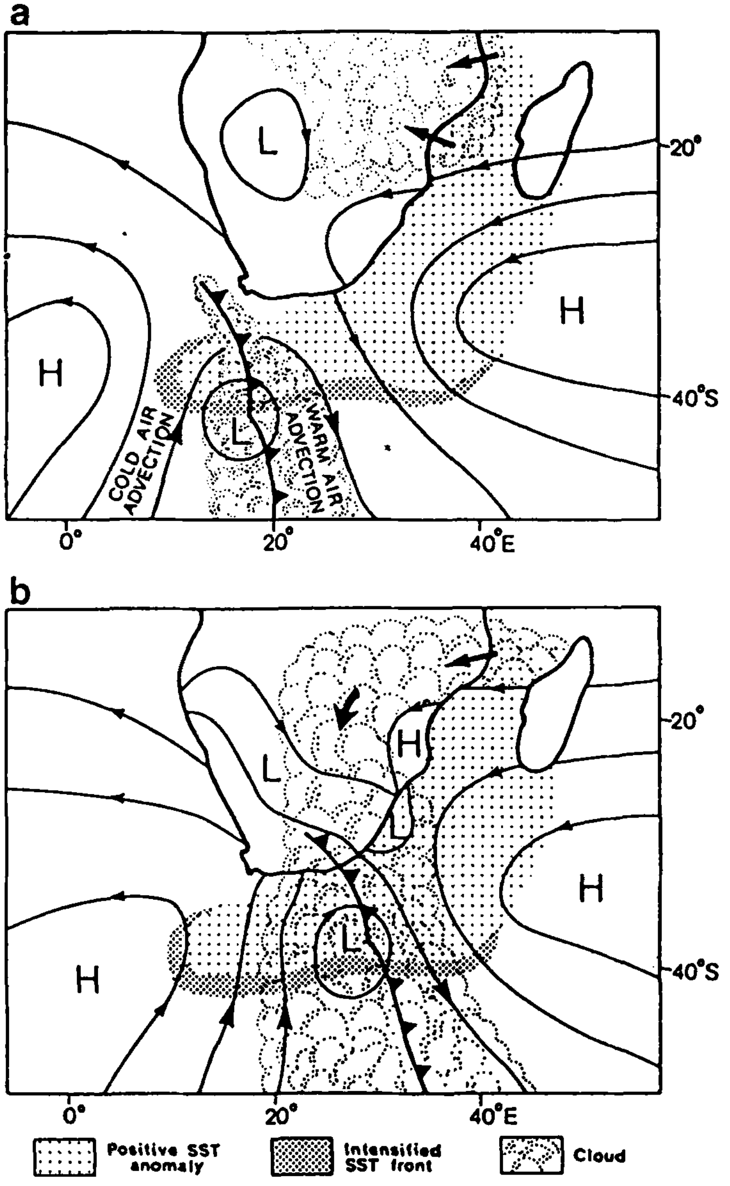

Figure 5. Schematic representation of enhanced tropical and extratropical circulations associated with Agulhas warm events (PC2): (*a*) the enhancement of the tropical and temperate circulation and (*b*) subsequent coupling to form a tropical–temperate trough. Sea-level pressures are shown over the ocean and 850 hPa geopotential heights over the subcontinent (from Walker, 1989)

(Mason and Mimmack, 1992; Mason and Lindesay, 1993, 1994) and explains why wet (dry) conditions are more apparent during Agulhas warm (cool) episodes when years of Southern Oscillation influence are ignored (Walker, 1989, 1990). The weaker associations between sea-surface temperatures in the Agulhas region and rainfall during October–December and April–June presumably occur as a result of the enhancement of early and late-season tropical–temperate troughs, respectively.

The absolute values of sea-surface temperatures in the western equatorial Atlantic and Indian Oceans are very high and occur close to the South American and African convective centres, respectively, and so, potentially, sea-surface temperature variability in these regions could have important climatological implications (Trenberth, 1991; Zhang, 1993). Although PC3 in the western equatorial Atlantic Ocean is many thousands of kilometres from southern Africa it is not impossible for atmospheric teleconnections to be established. Variations in convective activity in the Southern American convective centre can affect rainfall over southern Africa by its influence on westerly waves (Harrison, 1986). The westerly waves are affected by changes in the poleward transport of westerly momentum originating from the South American tropical heat source. Shifts in the location of the South American convective centre affect the location of

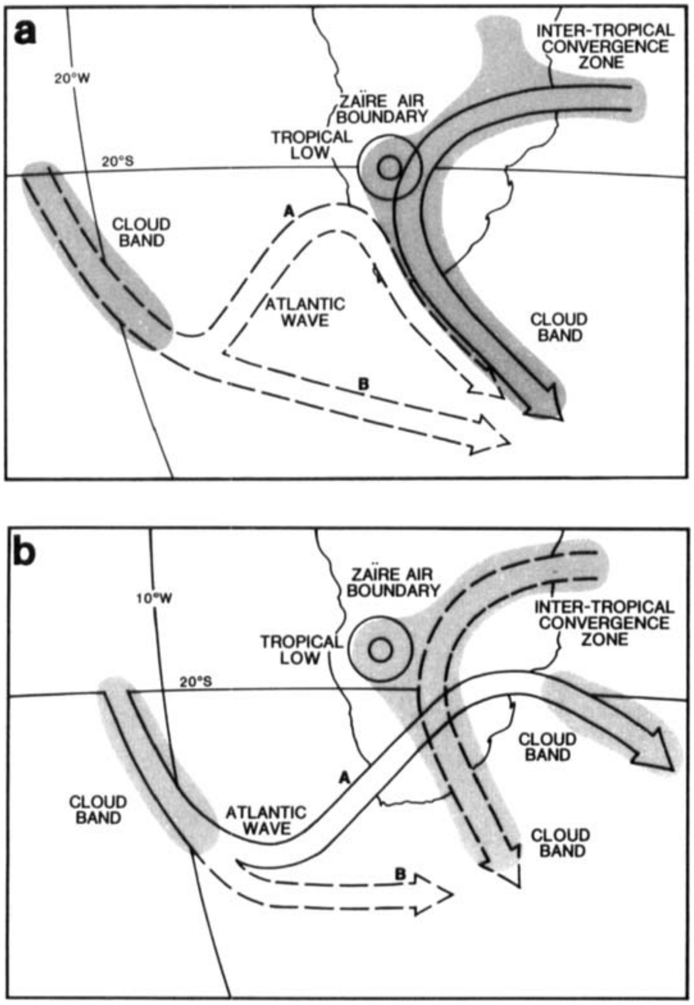

Figure 6. Schematic representation of major features of the 200 hPa circulation over southern Africa: (*a*) in summer on rain days with dominant flow (solid arrow) originating in the tropical easterlies and secondary flow (broken arrows) in the Atlantic wave (on no-rain days the Atlantic wave (A) is displaced eastward as in (*b*); (*b*) in the transitional seasons of spring and autumn when the dominant flow is associated with the Atlantic wave (from Harrison, 1986)

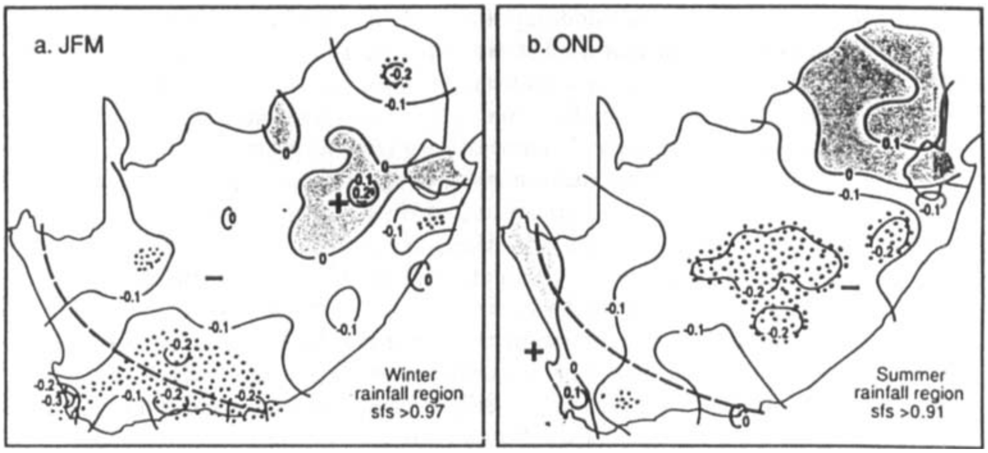

Figure 7. Zero-lag Pearson correlation coefficients between seasonal principal component scores on PC3 and rainfall totals: (*a*) January–March and (*b*) October–December. Areas of positive correlation are shaded grey. Dotted regions indicate areas where correlations are significant at the 90 per cent level. Statistical field significance (sfs) is indicated where it exceeds 90 per cent. The dashed line marks the boundary between the summer (to north-east) and winter (to south-west) rainfall regions

the semi-permanent Atlantic Ocean cloud band, which is aligned along the leading edge of the westerly wave. A weakening and westward withdrawal of the wave is associated with wet conditions over southern Africa (Figure 6). It is therefore theoretically plausible that rainfall variability over South Africa is associated with sea-surface temperatures in the western equatorial Atlantic Ocean. In fact associations are evident for the January–March rainfall totals of the winter rainfall region ($p > 0{\cdot}97$) and for early season rainfall (October–December) over the summer rainfall region of ($p > 0{\cdot}91$) (although in both cases there is no significant difference in rainfall receipts between warm- and cool-event years). An increase in sea-surface temperatures in the western equatorial Atlantic Ocean occurs concurrently with diminishing summer rainfall over the winter rainfall region and early season rainfall over the summer rainfall region (Figure 7). The enhanced convective activity in the South American tropical heat source during warm periods would result in an increase in the poleward transport of angular momentum and a strengthening of the westerly wave in the Atlantic sector, an increase in the equatorward transport of momentum over southern Africa and hence dry conditions over the subcontinent (Figure 6(*b*)).

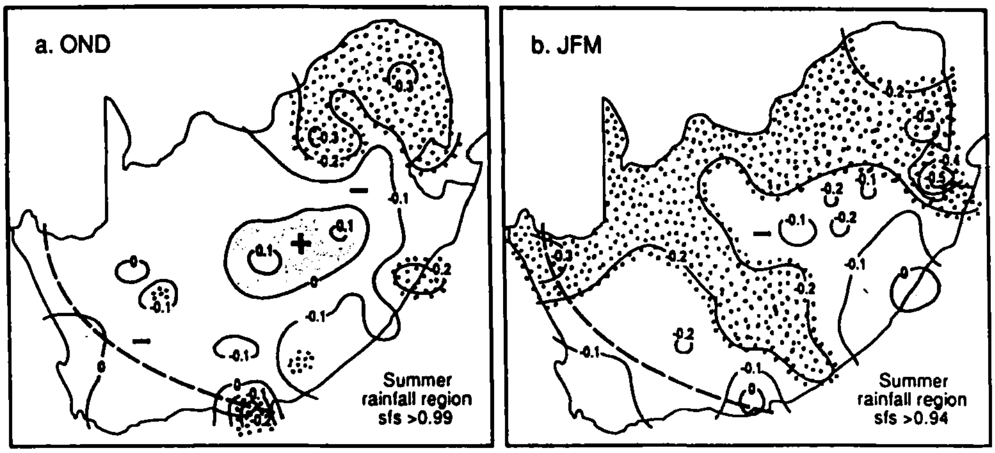

Figure 8. Zero-lag Pearson correlation coefficients between seasonal principal component scores on PC4 and rainfall totals: (*a*) October–December and (*b*) January–March. Areas of positive correlation are shaded grey. Dotted regions indicate areas where correlations are significant at the 90 per cent level. Statistical field significance (sfs) is indicated where it exceeds 90 per cent. The dashed line marks the boundary between the summer (to north-east) and winter (to south-west) rainfall regions

Teleconnections with the western equatorial Indian Ocean, PC4, are much less remote and associations with rainfall variability over the summer rainfall region during the early and peak rainfall seasons of October–December and January–March are stronger than those associated with the western equatorial Atlantic Ocean ($p > 0.99$ and $p > 0.94$ respectively) (Figure 8). The decrease in rainfall experienced when sea-surface temperatures rise in the equatorial Indian Ocean is partly the result of the negative association between PC4 and the Southern Oscillation at this time of year. The intercorrelations between rainfall, PC4, and the Southern Oscillation also explain why observed sea-surface temperatures in the western equatorial Indian Ocean are significantly lower during wet years compared with dry years when all years are considered, but that the significance of the region diminishes when years in which the Southern Oscillation was at an extreme phase are ignored (Walker, 1989, 1990). However, as Figure 1 suggests, even when the Southern Oscillation influence is excluded, sea-surface temperatures in the area of PC4 may be important in their own right. Anomalously warm sea-surface temperatures in the western equatorial Indian Ocean may favour an eastward shift in the African convective centre located over the interior of the subcontinent during wet years (Jury and Pathack, 1991). An eastward shift in the convective centre is known to be associated with dry conditions over South Africa.

Rainfall over the summer rainfall region of South Africa is significantly associated with sea-surface temperatures in the subtropical latitudes of the eastern South Atlantic Ocean, PC5, in all seasons except October–December (Figure 9). According to Walker (1989, 1990; see Figure 1) rainfall should be positively

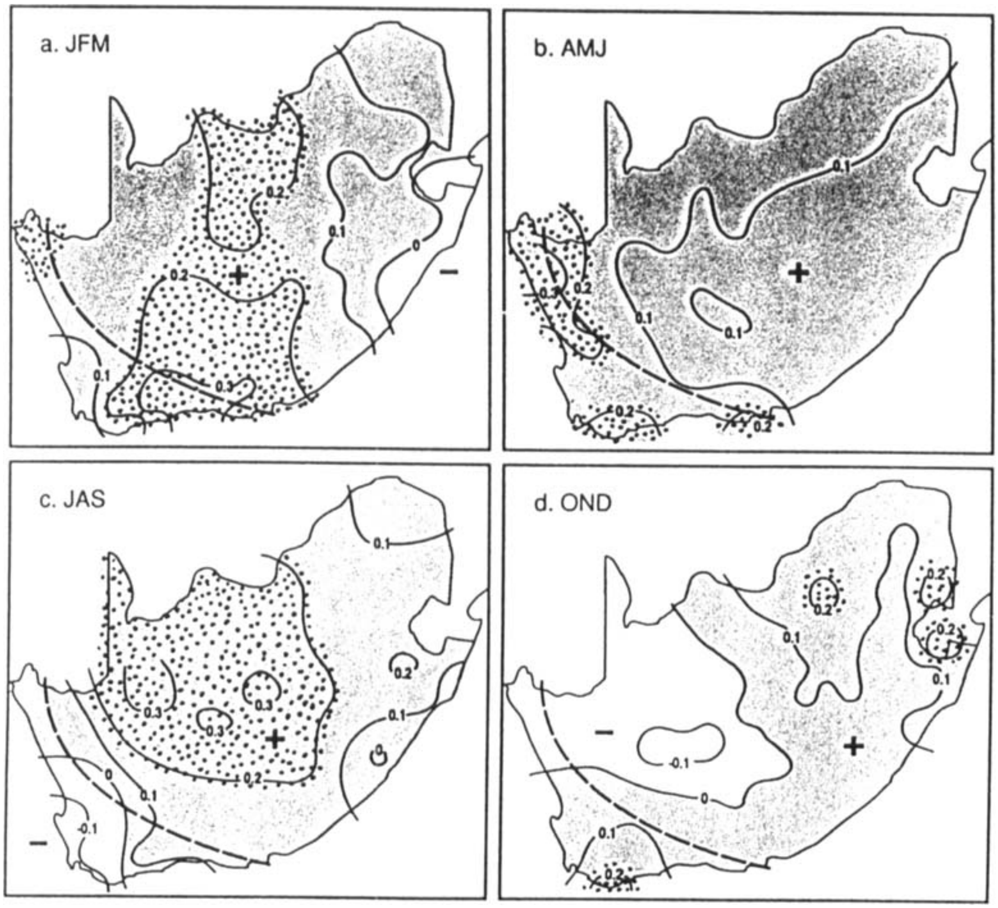

Figure 9. Zero-lag Pearson correlation coefficients between seasonal principal component scores on PC5 and rainfall totals: (*a*) January–March, (*b*) April–June, (*c*) July–September, and (*d*) October–December. Areas of positive correlation are shaded grey. Dotted regions indicate areas where correlations are significant at the 90 per cent level. Statistical field significance (sfs) is indicated where it exceeds 90 per cent. The dashed line marks the boundary between the summer (to north-east) and winter (to south-west) rainfall regions

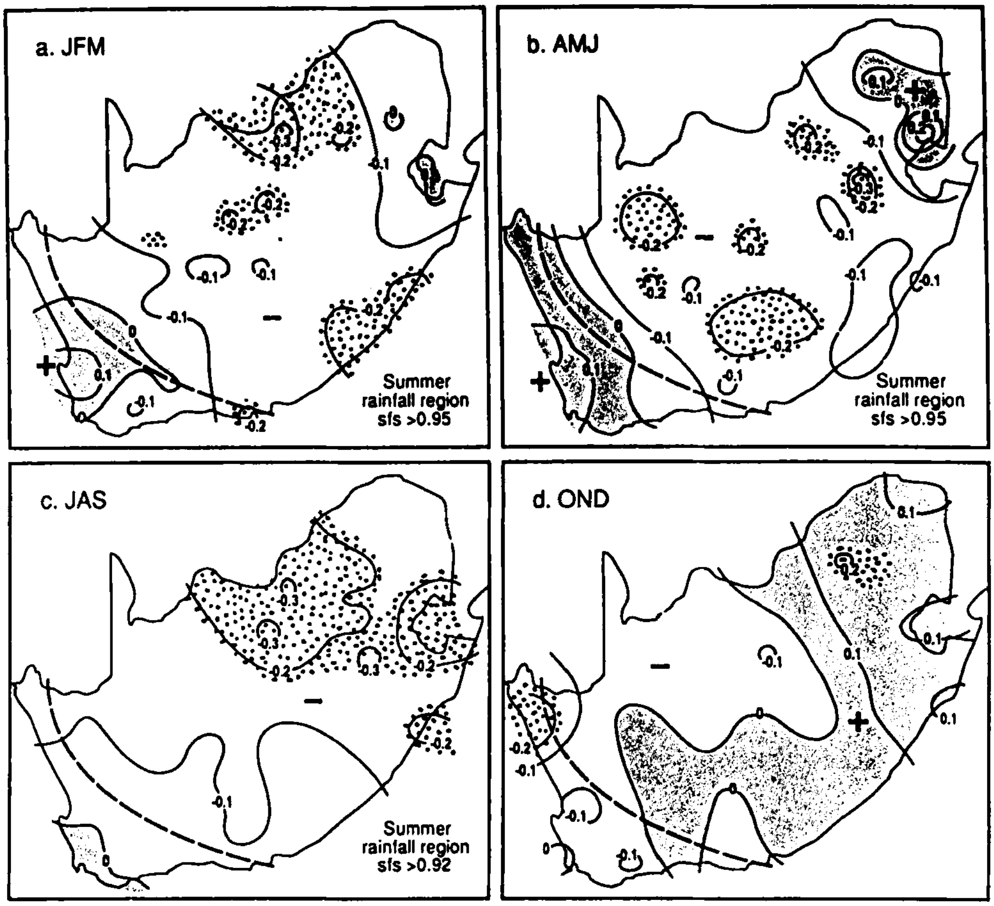

Figure 10. Zero-lag Pearson correlation coefficients between seasonal principal component scores on PC8 and rainfall totals: (*a*) January–March, (*b*) April–June, (*c*) July–September, and (*d*) October–December. Areas of positive correlation are shaded grey. Dotted regions indicate areas where correlations are significant at the 90 per cent level. Statistical field significance (sfs) is indicated where it exceeds 90 per cent. The dashed line marks the boundary between the summer (to north-east) and winter (to south-west) rainfall regions

associated with PC5, which appears to contradict the negative association evident in January–March ($p > 0{\cdot}95$), April–June ($p > 0{\cdot}95$) and July–September ($p > 0{\cdot}92$). At the same time there is no difference between the rainfall received in warm and cool years. A careful examination of Figure 1, however, indicates that PC5 lies within a region of insignificant sea-surface temperature anomalies during the wettest and driest years and so the results of the correlation analysis may not be spurious. Increasing sea-surface temperatures in the region may result in a decrease in surface pressures to the west of the subcontinent. A weakening of the South Atlantic anticyclone is associated with drier conditions over South Africa.

Sea-surface temperatures in the western boundary current of the South Atlantic Ocean, PC6, are significantly associated with early season rainfall totals over the summer rainfall region ($p > 0{\cdot}98$). Rainfall tends to decrease as sea-surface temperatures off the coast of southern Brazil rise and rainfall receipts are lower in warm years than in cool years. A strong correlation between PC6 and the Southern Oscillation Index during October–December (Table II) at least partly explains why the principal component is apparently associated with rainfall variability over South Africa. It is also possible that warm events in the western South Atlantic Ocean indicate a westward shift of the South Atlantic anticyclone and hence a weakening of surface pressures immediately to the west of southern Africa.

No association is apparent between sea-surface temperatures in the central South Indian Ocean (PC7) and rainfall over South Africa. This feature of sea-surface temperature variability occurs in the temperate latitudes to the east of southern Africa and hence lies downstream. In contrast, rising sea-surface temperatures in temperate latitudes of the central South Atlantic Ocean (PC8) are associated with wetter conditions over the winter rainfall region in January–March ($p > 0{\cdot}99$) and April–June ($p > 0{\cdot}97$) and over the summer rainfall region in January–March ($p > 0{\cdot}95$) and July–September ($p > 0{\cdot}97$) (Figure 10). Rising sea-surface temperatures in the mid-latitudes of the South Atlantic Ocean suggest a southward shift of storm tracks and perhaps a strengthening of the baroclinic zone, resulting in wetter conditions.

CONCLUSIONS

The main features of sea-surface temperature variability in the South Atlantic and the south-west Indian Oceans have been identified. Eight principal components of sea-surface temperature each explaining over 5 per cent of the total variance together explain 75 per cent of the variance. The components are broadly consistent with those identified in earlier similar analyses, but the results presented here consider the whole of the South Atlantic Ocean and extend further south. They also include the south-west Indian Ocean and thus give an indication of the relative importance of features of variability either side of the subcontinent to an extent not given before.

Coherent features of spatial sea-surface temperature variability are more evident in the South Atlantic Ocean than in the south-west Indian Ocean. The greatest variability of sea-surface temperature occurs around the coast of southern Africa in the Benguela and Agulhas systems. The first two principal components (which pick up both systems) explain almost a third of the total variance. The first component describes a spatially coherent warming and cooling over a large area of the south-eastern and equatorial Atlantic Ocean. It illustrates El Niño type behaviour and is, in fact, correlated with its Pacific Ocean counterpart during January–March. It appears to be of minimal climatic significance to South Africa, however. In contrast, sea-surface temperatures off the east coast associated with the second principal component enhance both tropical and temperate synoptic systems bringing rainfall to the subcontinent and can thus significantly affect rainfall receipts throughout most of the year. Its main effect is during January–March when Agulhas warm events enhance the formation of tropical–temperate troughs. A negative association with the Southern Oscillation dampens the climatic significance of both phenomena and may be responsible for the occasional faltering of the association between the Southern Oscillation and rainfall over South Africa.

Sea-surface temperatures in the western equatorial Atlantic and Indian Oceans also appear to be climatically significant. Anomalous convection over the western Atlantic Ocean may have an effect on the westerly waves affecting South Africa, whereas sea-surface temperature anomalies over the western equatorial Indian Ocean have an influence through the easterly tropical disturbances. Sea-surface temperatures in the Brazil Current, the subtropical eastern and the central temperate latitudes of the South Atlantic Ocean apparently affect westerly disturbances bringing rain to South Africa.

The principal components identified have been located mainly in the tropical and subtropical latitudes. The poor spatial coherency of temperate sea-surface temperature anomalies may be partly an indication of data availability, however. Spatially coherent sea-surface temperature variability in the central-southern South Atlantic Ocean, for example, does extend across a wide longitudinal zone and may be more important than the available data indicate.

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