20th CENTURY DROUGHTS IN SOUTHERN AFRICA: SPATIAL AND TEMPORAL VARIABILITY, TELECONNECTIONS WITH OCEANIC AND ATMOSPHERIC CONDITIONS

YVES RICHARD*, NICOLAS FAUCHEREAU, ISABELLE POCCARD, MATHIEU ROUAULT and SYLWIA TRZASKA

* Centre de Recherches de Climatologie, Université de Bourgogne, France
b Oceanography, University of Cape Town, South Africa

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ABSTRACT

Southern African rainfall does not show any trend to desiccation during the 20th century. However, the subcontinent experienced particularly severe droughts in the 1980s and at the beginning of the 1990s and the magnitude of the interannual summer rainfall variability shows significant changes. Modifications of the intensity and spatial extension of droughts is associated with changes in ocean–atmosphere teleconnection patterns.

This paper focuses mostly on the well-documented 1950–1988 period and on late summer season (January–March). A principal component analysis on southern African rainfall highlights modifications of the rainfall variability magnitude. The 1970–1988 period had more variable rainfall, and more widespread and intense droughts than the 1950–1969 period.

To investigate the potential modifications of the associated ocean–atmosphere teleconnection patterns, a composite analysis is performed on sea-surface temperature (SST) and National Center for Environmental Protection (NCEP) atmospheric parameters, according to the 5 driest years of both sub-periods. Significant changes are shown in ocean–atmosphere anomaly patterns coincident with droughts for both sub-periods. The 1950–1969 droughts were associated with regional ocean–atmosphere anomalies, mainly over the southwest Indian Ocean region. In contrast, during the 1970–1988 droughts near-global anomalies were observed in the tropical zone, corresponding to El Niño–Southern Oscillation (ENSO) phenomenon.

Within the whole century, significant correlations between Southern Oscillation Index (SOI) and southern African Rainfall Index (SARI) were found in the periods (1900–1933 and 1970–1998) when SOI and SARI experienced high variability, and when southern Africa was affected by intense and extended droughts. During periods of low SOI (1934–1969), correlations became less significant and droughts were less intense and widespread. Copyright © 2001 Royal Meteorological Society.

KEY WORDS: atmospheric conditions; composite analysis; droughts; ENSO; sea-surface temperature; southern Africa

1. INTRODUCTION

With the exception of southwest Africa and some southern African coastal areas, austral summer (i.e. October–March) is the main rainfall season over much of southern Africa. Moreover, the late summer season (January–March) often represents more than 40% of the annual amount. The southern African rainfall time series does not seem to exhibit any trend to desiccation or abrupt shifts during the 20th century (Tyson, 1986; Hulme, 1992, 1996) except over some limited areas like the Lowveld of South Africa (Mason, 1996). However, southern Africa summer rainfall experiences a high degree of interannual variability, with recurrent wet and dry spells. In this way, southern Africa was struck by particularly severe droughts in the 1980s and summers at the beginning of the 1990s (Harsch, 1992), which led to decrease in crop and stock production (Vogel, 1994).

* Correspondence to: Centre de Recherches de Climatologie, Université de Bourgogne, UMR CNRS 5080, France.

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Southern African summer rainfall variability is known to be linked to the El Niño–Southern Oscillation (ENSO) phenomenon (Mo and White, 1985; Lindesay, 1988; Ropelewski and Halpert, 1987, 1989, 1996; Shinoda and Kawamura, 1996; Rocha and Simmonds, 1997). During warm ENSO events, dry conditions generally occurred over much of southern Africa. This influence is strongest in the southeastern part of the subcontinent and to the northeast of South Africa (Matarira, 1990; Richard, 1996) and maximum during the late summer season of January–March (Lindesay, 1988; Lindesay and Vogel, 1990; Poccard, 2000). However, warm ENSO events do not always lead to dry conditions over southern Africa (Mason and Mimmack, 1992). A different hypothesis has been suggested: the stratospheric Quasi-Biennial Oscillation (QBO) may play a significant role in the modulation of the ENSO signal over South Africa (Mason and Tyson, 1992; Mason and Lindesay, 1993; Jury et al., 1994). In South Africa, Kruger (1999) has also shown that the low-frequency rainfall variability (18–20 year Quasi-Periodic Oscillation, see Tyson et al., 1975) could modulate the impact of ENSO events in such a way that, during the ‘wet phases’ of this ‘oscillation’, a moderating effect is evident on the severity of warm ENSO events impacts, so that even above-average rains can be experienced during such events.

Apart from the global-scale ENSO influence, many authors have pointed out that interannual rainfall variability over large parts of central and eastern South Africa is linked to sea-surface temperature (SST) anomalies over surrounding Indian and South Atlantic oceans (Walker, 1989, 1990; Richard, 1993; Rocha and Simmonds, 1997; Reason and Lutjeharms, 1998; Reason, 1999; Reason and Mulenga, 1999). In this way, warm SST anomalies in the central equatorial Indian Ocean are frequently associated with dry conditions over southern Africa. At a more regional scale, the influences of the Agulhas current system on the southern African rainfall have been investigated. Reason and Mulenga (1999) point out that the SST of Mozambique Channel and immediately east of South Africa show strong links with South African summer rainfall. In the southwest Indian Ocean, which corresponds to the Agulhas recirculation region, interannual events of warming and cooling, whose magnitude is generally at least comparable to those associated with strong ENSO events, are linked to interannual rainfall variability (Reason, 1999). Atmospheric modelling experiments support this link between SST anomalies and southern African rainfall (Reason, 1998).

In the above-cited papers, the teleconnections with SST, both at global or regional scales, are generally considered with the underlying hypothesis of their stability through time. However, noticeable changes have been detected in the world-wide SST patterns at a global scale: a Pacific warming since the mid-1970s (consistent with the intensification of the ENSO warm events), an anomaly in the meridional gradient in tropical Atlantic during the post-1970 period and a long-term warming trend in the Southern Hemisphere extra-tropics (Fontaine et al., 1998). The Indian Ocean warming after 1970 (Trzaska et al., 1996) caused the strengthening of the relationship between the central Indian and central Pacific oceans SST during the more recent period (Lanzante, 1996). Wang and Ropelewski (1995) also found that the ENSO-scale variability could be higher (both in frequency and amplitude) when the climate low frequency ‘basic state’ is relatively warm. These large-scale changes in SST patterns could be responsible for the higher Southern Oscillation Index (SOI)–southern African rainfall relationship that was detected in observed datasets and from results of general circulation model (GCM) simulations (Moron and Ward, 1998; Richard et al., 2000).

This paper focuses on the January–March summer season, considered the rainiest season as well as the most directly related to the tropical circulation (D’abreton and Lindesay, 1993). Rainfall variability and especially drought variability during the 20th century is studied. The hypothesis is that, concurrently with global scale modifications of SST anomaly patterns, southern African rainfall features, and especially droughts, show significant changes.

This paper is organized as follow: data are presented in Section 2. Section 3 is divided into four sub-sections: the first investigates January–March southern African rainfall variability during the 20th century. Drought features variability is developed in the second section. The oceanic and atmospheric conditions associated with southern African droughts are explored in the third section. The statistical relationships between January–March rainfall variability and both SOI and southwest Indian Ocean SST indexes are presented here too. Section 4 provides a discussion of the results, followed by Section 5, which concludes the paper.
2. DATA

2.1. Rainfall

The ‘Centre Recherches de Climatologie’ (CRC) dataset is an original monthly rainfall dataset which has been compiled from more than 570 rain gauges. The rainfall data has been tested and verified on the 1950–1988 period, and it covers the whole of the African continent south of the Sahara (Bigot et al., 1994, 1995). This dataset, with a good spatial density of observation network over southern Africa, has been interpolated onto a regular $1^\circ \times 1^\circ$ grid in order to obtain a relative homogeneous density network (Figure 1). In order to extend the study to the beginning of the century, a synthetic rainfall index, named southern African Rainfall Index (SARI) hereafter, is constructed by extracting 28 grid-points from the Climate Research Unit (CRU) dataset (Hulme, 1992, 1996) over the 1900–1998 period. These points correspond to a rainfall covariance area defined previously (Richard et al., 2000). In this study, the CRC dataset is used in order to capture the spatial behaviour of rainfall, thanks to its good spatial resolution, whereas SARI is used to show the time variations of rainfall at a century scale.

2.2. The ENSO index

The Southern Oscillation Index (SOI) is used rather than the Niño3’s SST index because it has been considered more reliable over almost a 100-year period (1900–1998). Atmospheric pressure at Tahiti and Darwin has not changed through the century, which is not the case for the SSTs (Ropelewski and Jones, 1987). In this study, SOI values are averaged from July (year $-1$) to March (year 0), in order to reduce intermonthly variability.

2.3. Sea-surface temperature

The UK Meteorological Office Sea-Surface Temperature (MOHSST) dataset is utilized in the study. The dataset (Bottomley et al., 1990) is available on a $5^\circ \times 5^\circ$ grid and quasi-global coverage (from $60^\circ$N to $40^\circ$S) over the 1946–1998 period.

Figure 1. Rain gauge network and late summer (January–March) mean rainfall in mm (1950–1988). Thick contour: grid-points selected to determine the SARI (1990–1998)
2.4. Atmospheric circulation parameters

The National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) have completed a reanalysis project to produce a 50-year record of global atmospheric analyses with fixed data assimilation (Kalnay et al., 1996). In this paper, monthly wind, pressure, air temperature and upward longwave radiation flux have been selected at 850 and 200 hPa over the 1950–1988 period. It is important to note that a recent study (Poccard et al., 2000) has shown that different abrupt shifts occur in some NCEP parameters (e.g. in 1967/1968), mainly due to assimilation of observations in the NCEP model and problems concerning land surface processes parameterization. This problem must be kept in mind when interpreting the results.

3. RESULTS

3.1. Rainfall variability during the 20th century

Twenty year running means and running standard deviations (with a 1-year lag) are computed from the standardized SARI time series over the 1900–1998 period. The January–March rainfall during the 20th century does not show any long-term trend of desiccation nor abrupt shift over the southern African region (Figure 2). However, since the beginning of the 1980s, the annual rainfall amount has slightly decreased.

Moreover, the January–March interannual rainfall variability seems to have experienced significant changes, leading to three major sub-periods if the interannual variability magnitude is considered. The strongest rainfall anomalies (more than 2 S.D.) are found at the beginning of the century (e.g. severe drought of 1922) and during recent decades. Anomalies are weaker (not more than 1 S.D.) between 1935 and the middle of the 1960s.

A principal component analysis (PCA) is performed over the 1950–1988 period on the high spatial resolution CRC dataset. The first eigenvector (PC1, not shown, see Richard et al., 2000) extracts 31.9% of the total variance and the others describe less than 10%. This first PC is highly correlated with SARI ($r = 0.97$) over the common period. Both CRC PC1 and SARI highlight modifications of the rainfall variability magnitude, with higher anomalies during the recent period. This could be due to changes in the magnitude of rainfall anomalies and/or changes in the spatial extension of these anomalies. To address these hypotheses more satisfactorily, especially the second one, the CRC dataset is chosen because of its higher spatial resolution ($1^\circ \times 1^\circ$). The goal is to check if the intensity and the spatial extension of droughts are the same for both sub-periods.

3.2. Drought features associated with low and high January–March rainfall variability periods

The CRC dataset only allows the consideration of the 1950–1988 period. According to the above results, there are two different sub-periods, if the magnitude of the interannual variability is considered. The 1950–1969 period has relatively low variability, and 1970–1988 has higher variability. It must be noted that the year 1970 is only indicative and is used to separate two samples for the composite analysis. Both sub-periods are chosen to form two January–March composites selected from the driest quartile of the PC1 scores. During 1950–1969, the composite sample includes 1951, 1960, 1964, 1965 and 1968. During 1970–1988, it includes 1970, 1973, 1982, 1983 and 1987. The Student’s t-test allows the comparison of the 15 or 14 other years of both dry composites to the mean of the two sub-periods (1950–1969 and 1970–1988).

During the low variability period (1950–1969), the spatial extent of droughts affecting southern Africa is not homogeneous (Figure 3(A)). Only 25 of the 104 grid-points have standard deviation anomalies less than −1. They are found mainly over Zimbabwe. The rainfall deficits are less significant in Zambia and the Republic of South Africa (RSA) (except Free State). Tanzania, which is integrated in a different rainfall covariability region (Richard et al., 1998), does not experience these droughts.

Between 1970 and 1988, droughts are more extensive with 48 of the 104 grid-points showing a standard deviation less than −1 (Figure 3(B)). The droughts spread northwards compared to the former sub-period. They affect northern Zambia and Mozambique more significantly. Droughts are also more intense in Namibia and South Africa.


The SST and atmospheric parameter anomalies for both dry sub-periods are presented and analysed in this section. The statistical significance is tested with a Student’s t-test, except for the wind for which the Hottelling test is used.

Figure 4(A) shows a SST anomaly composite for the low variability sub-period (1950–1969). Significant anomalies are not widespread. Nevertheless, negative anomalies are observed in the subtropical southwest Indian Ocean (Mozambique Channel, Agulhas Current and Agulhas retroflection) and in the southwest Atlantic Ocean.

Previous studies (Walker, 1989; Reason and Mulenga, 1999) have depicted a positive correlation between summer rainfall and regional SST. Particularly, Walker describes a mechanism associated with local oceanic ‘warm events’, which are preceded by easterly wind anomalies across the southwest Indian Ocean over source regions of the Agulhas Current. These ‘warm events’ correspond to higher rainfall. Is this an observation of the inverse mechanisms during the ‘cold events’ associated with the 1950–1969 droughts?
Figure 4. Composite anomalies for the 1950–1969 dry quartile. Solid line: positive anomalies. Dashed line: negative anomalies. Shading: statistical significance at the 95% level. (A) SST. (B) 200-hPa geopotential level. (C) 200-hPa wind speed. (D) OLR.
The January–March 1950–1969, 850-hPa NCEP temperature composite (not shown) is consistent with the SST composite. Over this sub-period, the 200-hPa geopotential composite (Figure 4(B)) shows marked negative anomalies above the abnormally cold water and air masses of the western subtropical Indian and Atlantic oceans. These low features indicate a northward displacement of the jet stream. The westerly winds are significantly abnormally strong near 20°–25°S over Argentina and South Africa (Figure 4(C)). On the other hand, the westerly winds are abnormally weak near 35°–40°S. The result for southern Africa could be a reduction of deep convection that would be displaced to the northeast above the Indian Ocean (Figure 4(D)). This outgoing longwave radiation (OLR) dipole pattern between southern African subcontinent and Indian Ocean is consistent with the results of Jury (1992, 1996), Jury et al. (1992) and Jury and Pathack (1993). They highlighted that summer convection variability over southern Africa can be monitored by spatial changes in OLR, and that decreased convection over the subcontinent during dry years is often compensated for by increased convection to the east of Madagascar.

Unlike the former two decades, the 1970s and 1980s droughts are associated with warm and more widespread SST anomalies (Figure 5(A)). Moreover, the concerned sectors are not located in the subtropical latitudes, but are more centred on the equator. These warm anomalies correspond to those observed during ENSO events (Nicholson, 1997). Four droughts of the 1970–1988 period correspond to the end of ENSO events (1970, 1973, 1983 and 1987). During the first sub-period, none of the driest years corresponds to ENSO. Only the January–March 1982 drought cannot be considered to be associated with ENSO that only developed in spring of that year.

The 850-hPa NCEP air temperature composites also show positive anomalies above low latitudes of the East Pacific, west of South America and east equatorial Atlantic Ocean (not shown). Strong abnormal high temperatures are also observed over most of the southern African subcontinent. Abnormal high features at 200 hPa are found in the Tropics (Figure 5(B)) with substantial wind anomalies (Figure 5(C)). Tyson (1984), Matarira and Jury (1992), Shinoda and Kawamura (1996) have shown that higher geopotential heights over the subcontinent indicate weaker subtropical troughs during dry years. Todd and Washington (1999) also found enhanced 200-hPa geopotential heights in the tropical zone during dry Januarys. In addition, the upper-level easterly wind anomalies above the Central and West Pacific Ocean and westerly anomalies above the equatorial Atlantic typical of ENSO, westerly anomalies above Southern Africa and the nearby Atlantic and Indian oceans are observed (Figure 5(C)). They are significant south of South Africa and over the Mozambique Channel and are accompanied by marked negative OLR anomalies (Figure 5(D)). Positive anomalies of OLR mean a deficit in deep convection above the subcontinent and a decrease of rainfall above southern Africa.

### 3.4. Relationship between SARI, southwest Indian Ocean SSTs and SOI over the whole century

Two distinct oceanic regions have been highlighted by previous composite analysis. Droughts of the 1950–1969 period—marked by a relatively low interannual variability—are associated with significant negative SST anomalies, mainly in the southwest Indian Ocean. In contrast, droughts of the more recent period (1970–1988)—marked by a high January–March rainfall variability—are associated with significantly positive SST anomalies over the Pacific region, in a pattern that corresponds to the ENSO signal. The aim of this section is to investigate the variations within the whole century of the statistical relationship between southern African January–March rainfall (through the SARI index), the SOI, and the SSTs of the southwest Indian Ocean.

Figure 6 shows the variation of SOI values from 1900 to 1998. The 20-year running mean and standard deviation envelopes are superimposed. SOI (Figure 6) and SARI (Figure 2) interannual variability seem to follow the same behaviour: strong variability from the beginning of the century to 1930, then weak up to the end of the 1960s and strong again from the 1970s. Allan et al. (1995) have already discussed this SOI decadal variability. Based on these observations, we have divided the 20th century into three parts (1900–1933, 1934–1969 and 1970–1998) to study the relationship variability between SARI and SOI. Correlations between SARI and SOI are calculated over the 1900–1998 period and over the three former sub-periods. For the whole period, the correlation value is 0.44 (Table I), a correlation level similar to
Figure 5. Composite anomalies for the 1970–1988 dry quartile. Solid line: positive anomalies. Dashed line: negative anomalies. Shading: statistical significance at the 95% level. (A) SST. (B) 200-hPa geopotential level. (C) 200-hPa wind speed. (D) OLR

Table I. Correlation between SARI and SOI

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<td>0.47*</td>
<td>0.15</td>
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* Correlations that are significant at the 95% confidence level.

Lindesay’s (1988) result. The correlation is 0.47 for the first sub-period, 0.15 for the second and 0.56 for the last. This confirms the temporal instability of the statistical relationship between SOI and southern African rainfall variability, and is in accordance with the results of Moron and Ward (1998).

Globally, there is a correspondence between periods of strong variability and strong teleconnections. This seems to confirm that southern African rainfall anomalies are only sensitive to ENSO, when it exhibits a strong interannual variability. Nevertheless, caution must be addressed because, even in a strong variability period, both 1925–1926 and 1997–1998 strong ENSOs were not associated with droughts.

The SST index is constructed for the southwest Indian Ocean (referenced as SWIOSST). This area corresponds to the negative anomaly area for 1950–1969 (Figure 4(A)). January–March SST is averaged between 20° and 30°S and between 30° and 60°E. This index can only be considered to be reliable for the second part of the century. There is a decrease in observations during World War II and 1945 has been discarded from the sample. Figure 7 shows the evolution of the standardized index SWIOSST for 1946–1998. SWIOSST’s 20-year running mean and standard deviation envelopes are superimposed. There is a marked increase of the mean values, consistent with the temperature increase in the subtropical and extra-tropical latitudes of the Southern Hemisphere (Fontaine et al., 1998). Thus, there is a lack of cold event in that area from 1965.

As for SOI, correlation coefficients between southern African rainfall (SARI) and SWIOSST are calculated over the 1946–1998 period and for the 1946–1969 and 1970–1998 sub-periods (Table II). For the global period, the correlation is significant at the 95% confidence level but the value is weak because SARI is not characterized by a trend, contrary to SWIOSST. However, the correlation for both sub-periods and the evolution of those correlations underline several points (Table II). For the 1946–1969 sub-period, the association between southern African droughts and cold southwest Indian Ocean SST is almost systematic, especially for intense droughts (not showed). This confirms the results from the 1950–1969 composites (see Section 4). After 1970, the association between droughts and cold SST does not occur (not shown), and the correlation coefficient drops (Table II). A possible reason is a decrease in the amplitude of the cold events due to an increase of mean Indian Ocean SST (Figure 7). Another possibility is that stronger southern African droughts associated with ENSO events mask the relatively dry periods of January–March 1984 and 1994 which occurred in association with cold SWIOSST.

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4. DISCUSSION

Three points in the above results need to be highlighted and discussed:

(i) There is a similarity between the spatial scale of southern African droughts and the ocean-atmosphere mechanisms during both sub-periods. During 1970–1988, the droughts are more intense and more widespread, and the associated oceanic and atmospheric abnormal conditions are more global and coherent. In contrast, the 1950–1969 droughts are less extensive and less coherent and they are only connected to regional oceanic and atmospheric anomalies (southwest Indian Ocean).

(ii) In spite of the large differences between the anomaly patterns during the droughts of the both sub-periods, two major similarities are observed:
   – The enhanced meridional temperature gradient for the subcontinent and the nearby Indian Ocean. In both sub-periods, the thermal gradient increases between the temperate/subtropical latitudes and the low latitudes compared to normal years. Before 1970, this increase is linked to abnormally cold temperatures south of 20°S; after 1970 to abnormally warm temperatures north of 20°S.
   – The atmospheric circulation, mainly noticeable at 200 hPa. In both sub-periods, upper level anomalies suggest a stronger and further north jet stream than usual. The scheme can thus be drawn as follow: a strengthening and a northward displacement of the jet stream could lead to a displacement of cyclonic systems tracks further north, a reduction of the tropical influences from a decrease of easterly wind component, less tropical temperate troughs and then less rains over the summer rainfall area.

(iii) The correspondence between periods of:
   – high SOI interannual variability;
   – high southern African rainfall variability;
   – intense and extended southern African droughts; and
   – strong and significant southern African rainfall/SOI correlations.

Table II. Correlation between SOI and SWIOSST

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<td>$R$</td>
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<td>0.49*</td>
<td>0.32</td>
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* Correlations that are significant at the 95% confidence level.
The higher frequency and/or intensity of ENSO events could be a consequence of the tropospheric warming in the Tropics observed since 1960 (Flohn and Kapala, 1989). Nevertheless, during the period 1910–1930, high fluctuations of SOI occurred, although slightly lower to the fluctuations experienced in the 1970s and 1980s (Allan et al., 1995). The similarity between those two periods lies more in the increase in temperature than in the level of temperature observed (WMO, 1999). These two periods have experienced an increase in SST and they correspond to high interannual fluctuations of SOI. During the transition period (1934–1969), both SST and SARI variations are weaker. This could lead to the hypothesis that the strong ENSO events occurring during periods of SOI’s enhanced interannual variability induce the most severe southern African droughts. Nevertheless, even during enhanced variability and correlation periods, strong ENSO events were not systematically accompanied by severe droughts (e.g. the strong 1925–1926 ENSO was associated with slightly higher than normal rainfall). Also in the recent period, when the teleconnection is the highest, the strong 1997–1998 ENSO was not associated with drought. Several studies have shown that the Indian Ocean plays an important role in the association between ENSO and southern African rainfall. The enhanced association of the 1970–1988 period has thus been related to the warming Indian Ocean (Richard et al., 2000). But internal dynamics of the Indian Ocean-atmosphere system during the 1997–1998 event (Webster et al., 1999) is also likely to be responsible for the lack of the association observed in 1997–1998.

5. CONCLUSION

The aim of this paper was to study the rainfall variability and changes in interannual variability amplitude of 20th century droughts in southern Africa. An analysis of the oceanic and atmospheric conditions linked to these changes was conducted.

There are no significant changes in the January–March rainfall totals during the last century. However, summer rainfall shows a change in the intensity of interannual variability. Furthermore, the spatial extension of droughts shows three distinct successive periods. The 1900–1933 and 1970–1998 periods have strong amplitude in their interannual variability, while the 1934–1969 period has a weak amplitude. The two well documented 1950–1969 and 1970–1988 sub-periods were the focus of our attention. The second (1970–1988), characterized by strong interannual rainfall variability, experienced more intense and more widespread droughts than the former (1950–1969). The SST and atmospheric parameter composites show that droughts before and after 1970 are not associated with the same anomaly patterns. The 1950–1969 droughts are linked to regional oceanic and atmospheric anomalies. The 1970–1988 droughts are associated with global tropical oceanic and atmospheric conditions mainly linked to ENSO. Even though the anomaly patterns associated with southern African droughts are different between both sub-periods, there are some similar features which are noted: the enhanced surface thermal meridional gradient to the south and southeast of the subcontinent and the strengthening and northward displacement of the jet stream over southern Africa. Further investigations are needed to understand better the physical mechanisms responsible for the droughts, as well as a better knowledge of why, in the recent period, some ENSO events (e.g. in 1997–1998) are not accompanied by droughts over Southern Africa.

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REFERENCES


