Periodicities, ENSO effects and trends of some South African rainfall series: an update

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The precipitation data for some regions in South Africa were studied for the period 1900–1998. From the 11 regions examined, 8 in South Africa had maximum precipitations in the austral summer months (December, January, February, March), while 3 had maxima in autumn and winter. Annual values showed considerable year-to-year fluctuations (50% to 200% of the mean), while five-year running means showed long-term fluctuations (75% to 150% of the mean). A spectrum analysis indicated periodicities in the ranges 2–3 (quasi-biennial oscillation, QBO), 3–4 (quasi-triennial oscillation, QTO), 6–11, 17–21, 23–26, 32–35 and 55–66 years, some common to, and some different in different regions. The QBO and QTO accounted for a substantial fraction (30–50%) of the total variance. In five-year running means, the effects of QBO and QTO were suppressed considerably. The plots showed distinct peaks, but the spacings varied in a wide range, indicating that predictions based on extrapolation of single peaks are not likely to come true even for decadal averages. El Niño effects for the giant event of 1982/83 were as expected but those for 1997/98 were obscure, almost absent. Running means over 21 years did not indicate linear trends, upwards or downwards. Instead, considerable oscillations were seen, with magnitudes different in different regions (5–25%). On average, high values during 1915/16 decreased considerably (5–8%) up to 1935, oscillated upwards thereafter and recouped by 1980, but decreased considerably thereafter.

Key words: South Africa, rainfall, ENSO, periodicities, predictions, trends

Introduction

Rainfall regimes in different parts of Africa are different, even in smaller regions, though some regional coherence is reported broadly in Sahel, East Africa and South Africa.[1] African rainfall studies fall into several categories such as (a) teleconnections between regional rainfall anomalies and transport, (b) rainfall cycles (periodicities), (c) regional sea-surface temperature (SST) forcing, (d) relationships between atmospheric pressure and circulation patterns and atmospheric modelling, (e) relationship between 2–3-year or quasi-biennial oscillations (QBO) and 3–4-year or quasi-triennial oscillations (QTO), and (f) trends and predictions.

(a) Teleconnections between regional rainfall anomalies and transport

Some major rainfall anomalies are reported to occur simultaneously throughout Africa[2,3] and global teleconnections have been invoked to explain the similarity in rainfall anomalies.[4] Nicholson[2] observed a certain degree of interhemispheric connectivity, but the strongest spatial associations were reported within the northern hemisphere (Sahel) and within equatorial Africa and South Africa. There seemed to be two preferred configurations, namely, precipitation of the same sign over all the African continent, and opposite signs between tropical and subtropical latitudes. Tyson[5] showed that the Sahel and Kalahari had synchronous wet and dry spells while equatorial latitudes and South Africa had opposite rainfalls. Washington and Todd[6] explored the tropical-temperate links in southern Africa and the southwest Indian Ocean daily rainfall, while Todd *et al.*[7] reported on water vapour transport associated with tropical-temperate trough systems over southern Africa and the southwest Indian Ocean.

(b) Rainfall cycles (periodicities)

For South Africa, Dyer[8] noted regional differences and assigned rainfall stations into homogeneous groups. Dyer and Tyson[9] delimited regions of South Africa where specific oscillations were predominant and showed that a quasi 20-year oscillation was predominant in the summer-rainfall region covering the northeastern half of South Africa. This oscillation was used by them for estimating possible future rainfall conditions. Earlier, Tyson *et al.*[10] showed that a 10-year to 12-year oscillation affected the southern coastal region and the adjacent inland area predominantly, while Dyer[11] and Dyer and Gosnell[12] attempted to link the 10-year to 12-year oscillation to the 11-year sunspot cycle. Vines[13] examined data in the southern and northeastern part of South Africa and reported periodicities of 6–7, 10–12 and 16–20 years. Nicholson and Entekhabi[14] found peaks in four bands at 2.2–2.4, 2.6–2.8, 3.3–3.8 and 5.0–6.3 years, common throughout equatorial and southern Africa but only weakly evident in northern Africa. (These authors did observe peaks in the 16–25-year range, but dismissed these on the grounds that the resolution at low frequencies, i.e. high periodicities, was poor.)

(c) Regional SST forcing

A relationship with the El Niño-Southern Oscillation (ENSO) was reported for eastern and southern Africa.[15–17] Janowiak[17] reported that positive rainfall departures in equatorial East Africa and negative departures in South Africa followed ENSO events. Nicholson and Kim[18] made a comprehensive study of the rainfall response to ENSO episodes over Africa. The strongest signals were reported to have appeared in southern, eastern and far northern Africa and the weakest in the Sahel. Nicholson and Entekhabi[19] studied the relationship between rainfall in equatorial and southern Africa and the SST along the southwestern coast of Africa. When comparing the rainfall results with those of SST obtained in a previous study,[20] Nicholson and Kim[18] concluded that the ENSO episodes that influenced rainfall over Africa were those that manifested as SST fluctuations in the low-latitude Atlantic and western Indian Oceans. Mason[21–23] described the temporal variability of SST around South Africa. In recent years, Reason[24] examined the relationship between subtropical Indian Ocean SST dipole events and southern African rainfall, while Reason and Rouault[25] reported an ENSO-like decadal variability in South African rainfall. Rouault *et al.*[26] examined the relationship between southeast tropical Atlantic warm events and southern African rainfall. Reason *et al.*[27] reported results of

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interannual variability in rainfall over the Limpopo Province of South Africa (see also Kruger[28]).

(d) Relationships between atmospheric pressure and circulation patterns and atmospheric modelling

For South Africa, statistical models for seasonal forecasts of southern Africa summer rainfall have been earlier invoked.[29–31] Recently, Engelbrecht[32] reported simulations of climate and climate change with the conformal-cubic atmospheric model. Hewitson and Crane[33] studied the general circulation model (GCM) climate change projections with empirical downscaling.

(e) Relationship between QBO and QTO

A factor complicating the analysis of ENSO and solar activity effects on South African rainfall is their apparent, unexplained modulation by a QBO. Earlier, Labitzke and van Loon[34,35] and van Loon and Labitzke[36] reported that the atmospheric response to solar activity may be governed by the phase of the QBO as measured by the stratospheric zonal wind component over the equator. Mason and Tyson[37] explored this idea for southern African rainfall and showed that solar activity effects on southern African rainfall were modulated by the initial QBO phase (easterly or westerly), and that, although solar forcing is not always a dominant effect, its contribution cannot be discounted and depends on the phase of the QBO (for further details and review see Mason and Jury[38] and Mason and Tyson[39]).

(f) Trends and predictions

Kruger and Shongwe[40] studied the temperature trends in South Africa during 1960–2003, while Kruger[41] reported on trends in daily precipitation indices in South Africa during 1910–2004. Tadross *et al.*[42] made regional climate model (RCM)-based projections of changes in southern African summer climate.

This article reports on the analysis of rainfall cycles and trends and ENSO effects over 11 regions in South Africa, and also, in part, revisits some of the earlier predictions.

Data

Precipitation data reported are the monthly precipitation values from the high-resolution gridded (5° × 5°) data sets,[43–45]available on the website www.cru.uea.ac.uk/cru/data/hrg. The climate surfaces were constructed from a new data set of station climatological normals, numbering 19 800 for precipitation. The station data were interpolated as a function of latitude, longitude, and elevation using thin-plate splines. The accuracy of the interpolations was assessed using cross-validation and by comparison with other climatologies (more details are given in New *et al.*[43]). South African data were available for the locations A (1900–1997), B, C (1900–1998), D (1900–1997), E, F, G (1900–1998), H, I (1900–1996), J (1956–1998) and K (1949–1998), with geographical coordinates as shown in Table 1, and on a map of South Africa in Fig. 1.

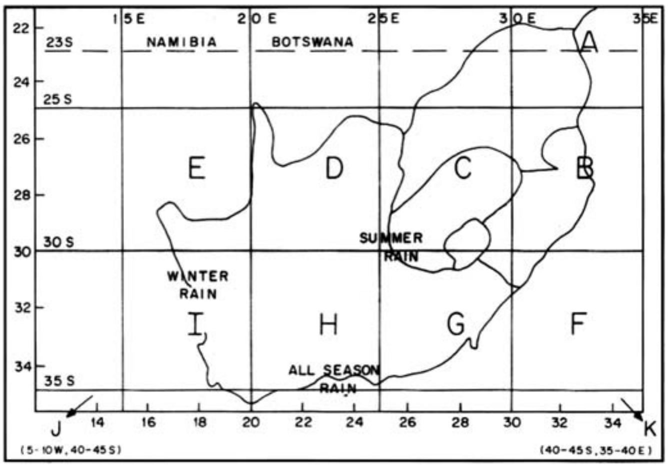

Fig. 1. Map of South Africa and the approximate locations of the 5° × 5° grids A–K.

Data for ENSO parameters, namely the Southern Oscillation Index (SOI) represented by the Tahiti (T) minus Darwin (D) atmospheric pressure difference (T–D), and SST of the Niño 1+2 region in the east Pacific (0–10°S, 90–80°W) were obtained from the Climate Prediction Center, National Oceanic and Atmospheric Administration website (www.cpc.ncep.noaa.gov/data/indices/). Data for global temperatures[46] were obtained from the website http://lwf.ncdc.noaa.gov/oa/climate/research/anomalies/

Climatology of monthly rainfall totals

Figure 2 shows the climatology (average monthly precipitation values, 1900–1996) for these locations. The rainfall data available from the website (www.cru.uea.ac.uk) are given in units of (mm × 10), probably to avoid a decimal point. Hence, in Fig. 2, the ordinate is in units of (mm × 10) and the numbers indicating monthly average rainfalls (horizontal lines, not annual rainfall) are also in units of (mm × 10). Thus, in region A, the January rainfall was 1 483 (mm × 10), i.e. 148.3 mm, the monthly average was 580 (mm × 10), i.e. 58 mm, while the annual rainfall (not shown here) for region A was 6 961 (mm × 10), i.e. 696 mm. As noted by earlier researchers,[5,37] the mean rainfall differs considerably from region to region; regions A–G have peak rainfall in the southern hemisphere summer months (mostly December to March), region H seems to have very little seasonal variation (all season rainfall), and regions I–K have peak rainfall in winter (May–June). Rainfall in regions J and K is very high (J: monthly average ~270 mm, annual ~3 240 mm; K: monthly average ~196 mm, annual ~2 352 mm) compared to the other regions (monthly averages 9.5–93.1 mm, annual 114–1 117 mm).

Table 1. Coordinates of the locations in South Africa for which precipitation data series were studied.

Latitude centring	Longitude centring							
	5–10W (7.5W)	0–5W (2.5W)	0–15E (7.5E)	15–20E (17.5E)	20–25E (22.5E)	25–30E (27.5E)	30–35E (32.5E)	35–40E (37.5E)
20–25S (22.5S)							A	
25–30S (27.5S)				E	D	C	B	
30–35S (32.5S)				I	H	G	F	
35–40S (37.5S)								
40–45S (42.5S)	J							
45–50S (47.5S)								K

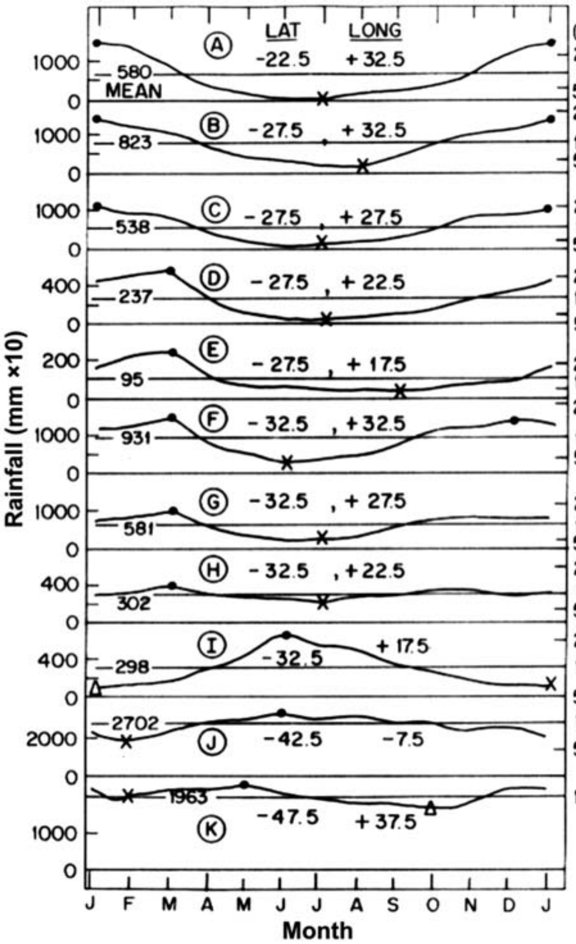

Fig. 2. Climatology (monthly mean precipitations, 1900–1996) for regions A–K of South Africa at 5° × 5° grid latitudes and longitudes as indicated. Maxima are marked by dots and minima by crosses. The ordinate scale is in units of (mm × 10) such that 1 000 means 100 mm. The numbers on horizontal lines are monthly averages in units of (mm × 10), so that 580 for region A means an average monthly value of 58 mm. (The annual value for region A would be 58 × 12 = 696 mm.)

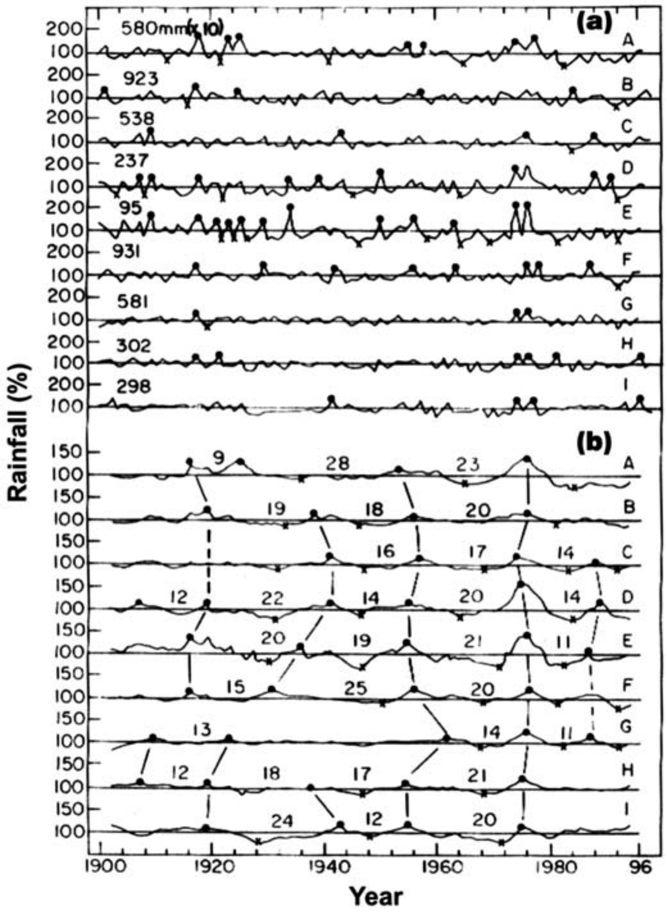

Fig. 3. Plots of (**a**) yearly values and (**b**) five-year running means of percentage rainfall (precipitation) in regions A–I of South Africa. (Number 580 on the horizontal line for region A represents an average monthly value of 58 mm.) Major peaks are marked with dots, major troughs with crosses, and numbers in (**b**) are spacings (in years) between successive peaks.

Rainfall cycles and trends

Year-to-year variations

Annual values of every series were expressed as percentages of the overall (1900–1996) mean of that series. Figure 3a shows the plots (percentage of average monthly mean of each region) for series A–I. (Again, the values are average monthly means in units of (mm × 10), thus 580 is actually 58 mm—the average monthly rainfall for region A. The annual value for region A (not shown) would be 696 mm.) Peaks are marked with dots and troughs with crosses. As can be seen, there are considerable year-to-year fluctuations (50–200% of the mean), more in some series than in others. To suppress short-term fluctuations, five-year running means were calculated. These are shown in Fig. 3b. The plots are now smoother and the fluctuations are smaller (70–150% of the mean), but the peak spacings (indicated by numbers) vary in a wide range (9–28 years). Similar peaks are joined by vertical lines and the peaks during 1974–1976 seem to be almost simultaneous. Dyer and Tyson[9] reported that a quasi 20-year oscillation predominated in the summer rainfall region covering the northeastern half of South Africa and estimated above-normal rainfall for the intervals 1972–1981 and 1991–2000, and drier conditions for the in-between interval 1981–1990. In Fig. 3b, 1974–1976 had above-normal rainfall and 1980–1984 had below-normal rainfall, but the predicted above-normal rainfall during 1991–2000 does not seem to have occurred, at least until 1996 when the data series ends. However, it seems that whereas 1997–1999 also had low or normal rainfall, 2000 was a highly anomalously wet year with devastating floods, so much so that Mason[47] commented that a return to a wet phase appeared to have occurred. So, in a restricted sense (for only one year during 1991–2000), the prediction of Dyer and Tyson seems to have come true.

Recently, Reason and Rouault[25] reported the connection of ENSO-like decadal variability with South African rainfall. The results reported above are not directly comparable to theirs, because they are annual values whereas they studied summer- and winter-rainfall series separately and their main emphasis was on the comparison of the smoothed summer and winter series with SST-MSLP (sea-surface temperature–mean sea level pressure). However, their plot of seven-point running means of summer-rainfall values showed maxima in years 1910, 1920, 1937, 1941, 1956, 1975 and 2000, yielding spacings in successive maxima of 10, 17, 4, 15, 19 and 25 years (range 4–25 years), by no means near-decadal.[25] Their winter-rainfall maxima were in 1905, 1914, 1942, 1954, 1974 and 1990, yielding spacings in successive maxima of 9, 28, 12, 20 and 16 years (range 9–28 years), again by no means near-decadal.

Thus the spacings in their plots were just as erratic as those shown in Fig. 3b (9–28 years). In any case, periodicities (decadal or otherwise) can be ascertained accurately only by a spectral analysis, as is shown in the following section.

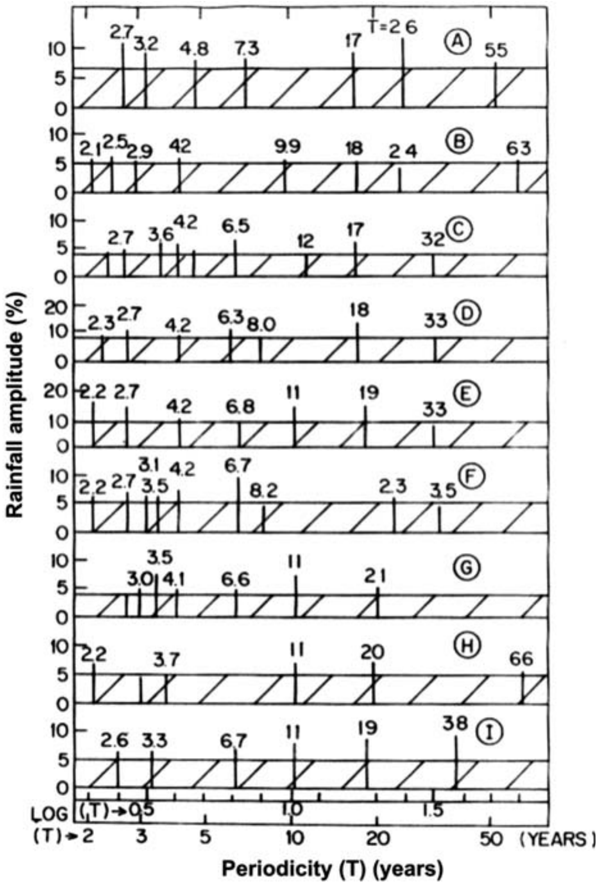

Fig. 4. Spectra (percentage amplitudes versus periodicities detected by MEM-MRA) of the series 1900–1996 of annual values of rainfalls in regions A–I of South Africa. The hatched portions are the 2σ limits and values protruding above these are significant at a better than 95% confidence level.

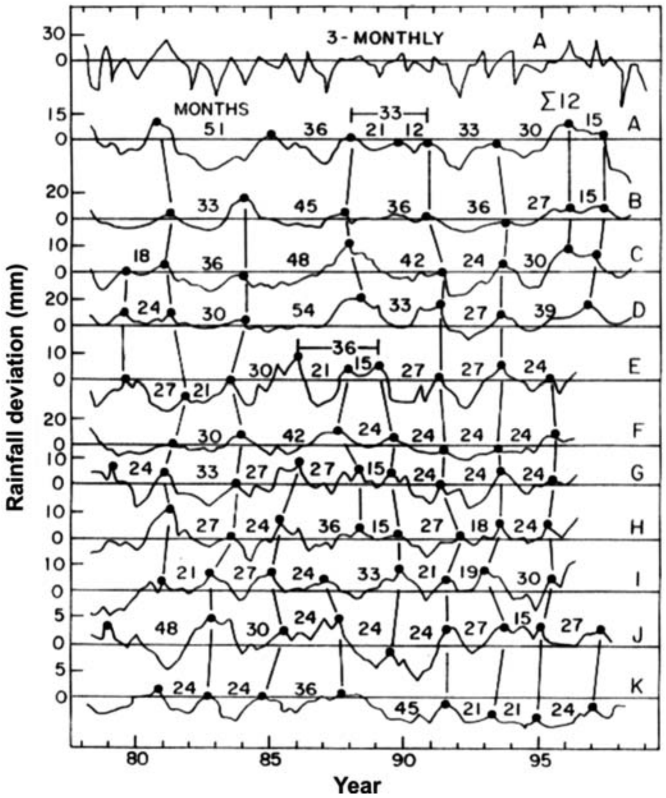

Fig. 5. **Top plot**: three-monthly rainfall values of region A for the 20-year interval 1978–1998. **Other plots**: smoothed three-monthly values (running means over four successive values) for regions A–K. Peaks are marked by dots and similar peaks for different regions are connected by vertical lines. Numbers indicate spacings (in months) of successive peaks.

Spectral analysis

The time series of annual values in Fig. 3a were subjected to spectral analysis. The method used was the Maximum Entropy Method[48,49] (MEM), which locates peaks more accurately than the conventional Blackman and Tukey[50] (BK) method. However, the amplitude (power) estimates in MEM are not very reliable.[51–53] Hence, MEM was used only for detecting all the possible peaks T_k (k = 1 to n), using length of the prediction error filter (LPEF) as 50% of the data length. These T_k were then used in the expression:

$$f(t) = A_o + \sum_{k=1}^{n} [a_k \sin(2\pi t / T_k) + b_k \cos(2\pi t / T_k)] + E$$
$$= A_o + \sum_{k=1}^{n} r_k \sin(2\pi t / T_k + \varphi_k) + E$$

where $f(t)$ is the observed series and E the error factor. The amplitude r_k is obtained as a square root of the sum of the squares of a_k and b_k, while the phase ϕ_k is obtained as tan(inverse) of the ratio (b_k/a_k). A multiple regression analysis (MRA)[54] was then carried out to estimate A_o (a_k, b_k), and their standard errors (by a least-squares fit). From these, amplitudes r_k and their standard error σ_k (common for all r_k in this method, which assumes white noise) were calculated. Any r_k exceeding 2σ is significant at a 95% (*a priori*) confidence level. This simple method will be termed as MEM-MRA.

Figure 4 shows the spectra (amplitudes versus periodicities detected by MEM-MRA of each series). As can be seen, strong periodicities are in the QBO (2–3 year periodicity) region. These contribute about 30–50% of the total variance. Other periodicities are near 3.5, 4.2 (QTO, 3–4-year periodicity), 6.5, 11 (period of the sunspot cycle?), 20, 35 and 60 years, but none of these contributes more than 10% variance. That should be the reason why predictions based on the extrapolation of any one of these may not come true.

Reason and Rouault[25] supposedly indicated that the 20-year periodicity is of great importance. This is not true. As reported above, their summer and winter rainfall data are shown as seven-point running means, hence the QBO, QTO and the 6.5-year periodicities are negated. In the smoothed plots too, the 20-year wave is not at all evident. In their plot of summer rainfall, the spacings in successive peaks are 10, 17, 4, 15, 19 and 25 years (a wide range of 4–25 years, average 15 years), and in the winter plot, the spacings in successive peaks are 9, 28, 12, 20, 16 years (a wide range of 9–28 years, average 17 years). Thus, a striking 20-year periodicity does not exist, and if it did, it would be closer to 15–16 years. The values for years 1900–2000 of these plots were subjected to a spectral analysis using MEM-MRA. There was no 20-year periodicity (or for that matter, any other periodicity) significant at a 2σ level, either in the summer or in the winter series.

Quasi-biennial and quasi-triennial oscillations

Since a large fraction of the total variance of any of these series is in the QBO and QTO regions, a detailed examination of the data at a fine resolution (say three-monthly) would be interesting. Figure 5 shows the plots for the restricted 20-year interval 1978–1998. Figure 5 (top) shows the three-monthly rainfalls (JFM, AMJ, JAS, OND, four values per year) for region A. Some QBO and QTO are seen but with much scatter. Hence, running means were calculated for four successive three-monthly values. The smoothed three-monthly values for region A are shown in the second plot. Now, smooth QBO and QTO waves are seen, but the spacings between successive peaks (indicated by numbers, in months) vary in a wide range (15–51 months), indicating that the QBO and QTO are irregular (almost random) and beyond the reach of predictions. The other plots show the smoothed three-monthly running means for the regions B–K. All show irregular QBO and QTO. Some peaks are similar for some regions (indicated by vertical lines), but the spacings are smaller in regions E–K (many near 24 months) compared to spacings in regions A–D (30 months or more), indicating considerable regional differences in QBO and QTO characteristics. This might have important implications for the origins of the QBO and QTO, which are most probably not random occurrences. The irregularity of the spacings is probably due to the presence of more than one QBO or QTO frequency.

El Niño effects

Trenberth[55] mentions 'different flavours of El Niño'. During 1900–1998, there were several El Niño events, but two of them (1982–1983 and 1997–1998) were most prominent and occurred in the last few decades. Figure 6 shows the plots for some years before, during and after the El Niño of 1982–1983. The two top plots are for the Southern Oscillation Index represented by the Tahiti (T) minus Darwin (D) atmospheric pressure difference (T–D), and SST anomalies of the El Niño 1+2 regions in the east Pacific (0–10°S, 90–80°W). The El Niño interval from May 1982 to November 1983 is marked by thick vertical lines (the other vertical lines mark the month January, J) and the negative values of (T–D) and the positive values of SST anomalies for this interval are shaded black. The other plots are de-seasoned (climatology subtracted) monthly precipitation deviations for the eleven regions A–K as follows: de-seasoned means the average values for January, February etc. are calculated separately for the whole interval 1900–1998, thus yielding 12 average values for the 12 months January–December—this is climatology. Then, from the January value of every year, the average January value (climatology) is subtracted. The difference is considered the rainfall anomaly for January, and similarly for February to December. Thus, a continuous series of rainfall anomalies is obtained for each region, plotted as plots 3–11 for regions A–K. (Note that the ordinate scale is mm × 10. Thus, 1 000 means 100 mm). These can be compared with any other parameters, such as SST anomalies. In Fig. 6, negative deviations are shaded black. The following may be noted:

(i) In region A (third plot), there are prominent rainfall decreases (droughts, shaded black) during October 1982 to April 1983, coinciding with the El Niño. However, there are similar decreases before the El Niño during November 1981 to May 1982 and after the El Niño during October 1983 to May 1984. Thus severe droughts occurred before and after the El Niño, indicating that there may be other physical processes causing droughts in the region.

(ii) Regions B–H also show droughts of more or less extent during the El Niño, indicating that the 1982–1983 El Niño had a forcing effect on the rainfall of many regions of South Africa.

(iii) Regions A–D (most of the summer rainfall region of South Africa) did not experience periods of significant above-normal rainfall during the 1982–1983 El Niño. In the remainder of the summer rainfall region of South Africa (regions E and G) and also region F over the Indian Ocean, anomalously high rainfall during the El Niño only occurred towards the end of the El Niño period. These results strengthen the general idea that El Niño is related with dry conditions over the summer rainfall region of South Africa.

(iv) Quiroz[56] mentions the El Niño of 1982–1983 as a season of extraordinary climate anomalies. Most of the summer rainfall region of South Africa clearly experienced generally dry conditions during the El Niño.

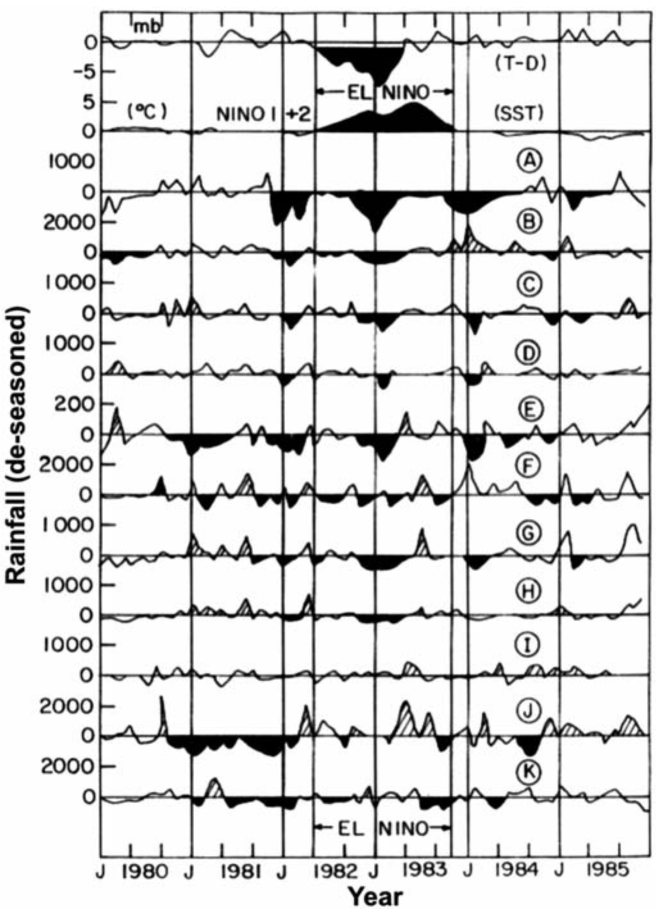

Fig. 6. Plots of monthly values for 1980–1985. The El Niño of May 1982 to November 1983 is marked by thick vertical lines and negative values of (T–D) (**top plot**) and positive SST anomalies (**second plot**) are shaded black. In other plots showing rainfall values in regions A–K, negative values (droughts) are shaded black and positive values (excess rainfall) are hatched. The ordinate scale is in units of (mm × 10). Thus, 1 000 means 100 mm.

These results using annual values are in general agreement with those of Reason *et al.*[27] using summer values for the Limpopo region of northern South Africa, which state that El Niño 3.4 SST anomalies show a robust relationship with dry spell frequency during 1979–2002 (which includes the 1982–1983 event). On the other hand, the decadal relationship mentioned by Reason and Rouault[25] is not very meaningful because they have used seven-point running means, so the major QBO and QTO effects in rainfall are lost. What remains is a mixture of insignificant higher periodicities (decadal range, if decadal means 10 and *more,* not just 10 and near). The SST-MSLP has very prominent variations in the QBO and QTO ranges (more in QTO, see details in Kane[57]), but Reason and Rouault[25] have carried out an empirical orthogonal function (EOF) analysis and selected only the EOF representing the decadal to multidecadal band of SST-MSLP. Thus, whereas the main relationship between rainfall and SST-MSLP would be in the QBO and QTO regions, these have been negated in the decadal averaging and the results give the relationship between two comparatively insignificant series. It is no surprise then that their correlation was only about 0.50, which they claimed as significant at a 2σ level (probably true), but in my view is too low for considering as a meaningful relationship, and certainly is not useful for any meaningful predictions (a correlation of 0.50 implies a variance of only 0.25 or 25% of real relationship and 75% of random component).

Figure 7 shows similar plots for 1995–1998 where the El Niño interval (March 1997 to July 1998) is enclosed in thick vertical lines and negative (T–D) values and positive SST anomalies are shaded black. (The ordinate scale is in units of mm × 10, such that 1 000 means 100 mm.) For some regions, data for 1998 or 1997–1998 were missing and only regions A–C and H–K are considered. Except for region A, where droughts seem to be associated with the El Niño, the El Niño effects are dubious, with positive and negative rainfall deviations spread throughout 1995–1998. Reason *et al.*[27] reported somewhat similar results and some strange characteristics of the 1997–1998 El Niño are documented in Kane.[58] An interesting aspect has been recently pointed out by Landman and Mason.[59] They mentioned:

> The El Niño–Southern Oscillation (ENSO) signal in Indian Ocean sea-surface temperatures has weakened since the late-1970s, resulting in important changes in the association between tropical western Indian Ocean sea-surface temperatures and December–February rainfall over South Africa and Namibia. Prior to the late-1970s, warm events in the tropical Indian Ocean occurred frequently in association with ENSO warm events, and both were typically associated with anomalously dry conditions over much of South Africa and Namibia. Over the most recent two decades, however, sea-surface temperature variability in the tropical western Indian Ocean has become significantly less dependent upon ENSO. At the same time, warm (cold) events in the tropical western Indian Ocean have become associated with wet (dry) conditions over the northeastern half of South Africa and northern Namibia since the late-1970s. These changes in rainfall–sea-surface temperature associations can be successfully simulated using a general circulation model. Such changes in the climate system have important implications for the predictability of southern African rainfall, and highlight the need for an operational forecast system to predict Indian Ocean sea-surface temperatures.

In a recent review, Mason[47] had the following to say:

> Since the late-1970s, El Niño episodes have been unusually recurrent, while the frequency of strong La Niña events has been low. Prolonged/recurrent warm event conditions of the first half of the 1990s were the result of the persistence of an anomalously warm pool near the date line, which, in turn, may be part of an abrupt warming trend in tropical sea-surface temperatures that occurred in the late-1970s. The abrupt warming of tropical sea-surface temperatures has been attributed to the enhanced-greenhouse effect, but may be indicative of inter-decadal variability: earlier changes in the frequency of ENSO events and earlier persistent El Niño and La Niña sequences have occurred. Most forecasts of ENSO variability in a doubled-CO_2 climate suggest that the recent changes in the tropical Pacific are anomalous. Of potential concern, however, is a possible reduction in the predictability of ENSO events given a warmer background climate.

Further:

> The El Niño influence on rainfall over southern Africa occurs largely because of a weakening of tropical convection over the subcontinent. A warming of the Indian Ocean during El Niño events appears to be important in providing a teleconnection from the equatorial Pacific Ocean. The abrupt warming of the tropical Pacific and Indian oceans in the late-1970s is probably partly responsible for increasing air temperatures over southern Africa, and may have contributed to a prolongation of predominantly dry conditions. A return to a wet phase appears to have occurred, despite the persistence of anomalously high sea-surface temperatures associated with the late-1970s warming, and a record-breaking El Niño in 1997-1998.

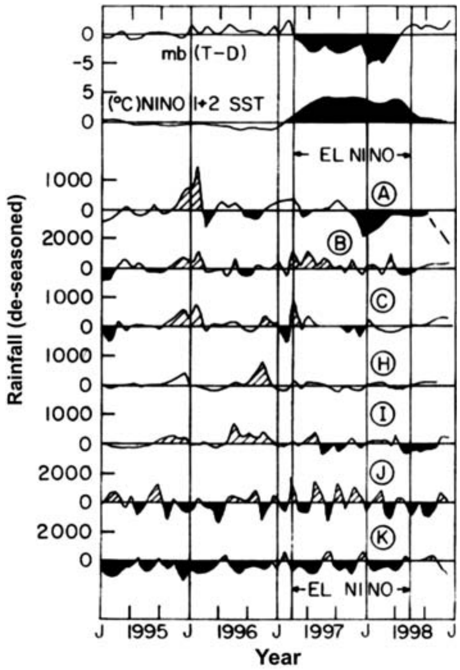

Fig. 7. Plots of monthly values for 1995–98. The El Niño of March 1997 to May 1998 is marked by thick vertical lines and negative values of (T–D) (**top plot**) and positive SST anomalies (**second plot**) are shaded black. In other plots showing rainfall values in regions A, B, C, H, I, J, K, negative values (droughts) are shaded black and positive values (excess rainfall) are hatched. The ordinate scale is in units of (mm × 10). Thus, 1 000 means 100 mm.

It is obvious, therefore, that drastic imbalances have occurred in recent decades, and that ENSO and other relationships established before the 1970s are no longer valid. A new approach with changed inputs is necessary for estimating the future climate behaviour of South Africa, as is being done by Landman and Mason[31] and others.

Rainfall trends over South Africa

In view of the multiple periodicities seen in the precipitation series, long-term trends will be difficult to identify. Some small periodicities can be suppressed by calculating running means over a fairly long interval, for example, 21 years. Figure 8 shows the plots of 21-year running means for (a) rainfall percentages for regions A–I, (b) average rainfall for A–I and for the whole of South Africa, and (c) global temperatures for land (full line) and sea (crosses).[46] The following may be noted:

(i) None of these trends is monotonically upwards or downwards. Hence, fitting linear trends is meaningless.

(ii) The numbers are percentages and indicate long-term oscillations different in different regions, with ranges from 9–26%, with some spacings of 30 years or more.

(iii) After 1980, there seems to be a significant decrease in regions A–G. (The plots are 21-year running means and the error is much less than 0.5%, while the decreases from the 1980 level to the 1989–1990 level are more than 5%).

(iv) The bottom plots (b) show the average percentages for regions A–I and for South Africa as a whole (an independent estimate, given in the website of precipitation www.cru.uea.ac.uk). The two plots are very similar, show oscillations between 1914–1936, 1936–1948, 1948–1961, 1961–1967, 1967–1974 and 1974–1980, and a large decrease from 1980 to 1989, with magnitudes of 5–10%. Recently, Kruger[41]

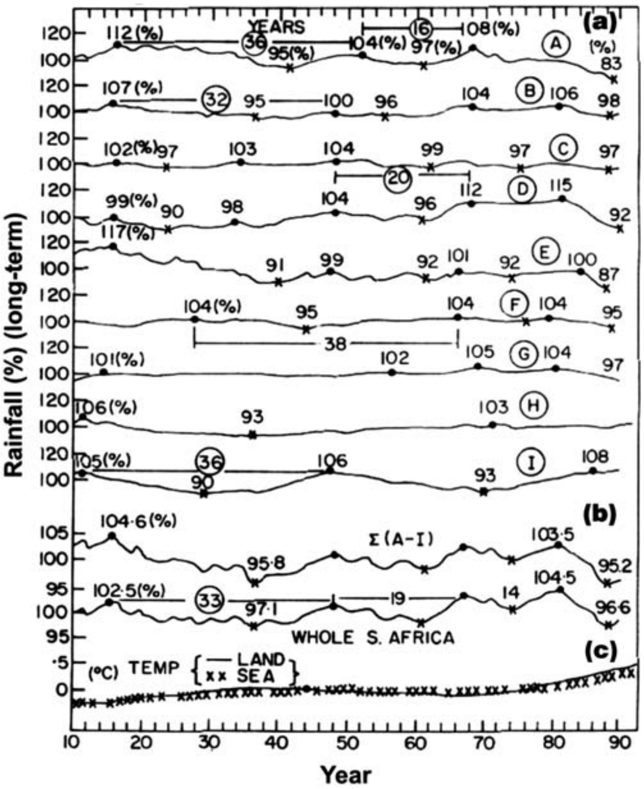

Fig. 8. Running means over 21-yearly values of (**a**) percentage rainfall in regions A–I, (**b**) average rainfall of regions A–I and an independent rainfall estimate for the whole of South Africa, and (**c**) global temperatures for land (solid line) and sea (line of crosses). Peaks are marked by dots, troughs with single crosses, and the numbers show the percentage values. Some spacings are indicated by circled numbers (in years).

reported that 'some significant changes in (precipitation) indices, averaged over specific areas in South Africa, could be identified. These include areas with significant increases and decreases in annual precipitation, increases in the longest annual dry spell indicating more extreme dry seasons, increases in the longest annual wet spells indicating more extreme wet seasons, and increases in high daily precipitation amounts. The conclusion is that, while in the largest part of South Africa there has been no real evidence of changes in precipitation over the past century, there are, however, some identifiable areas where significant changes in certain characteristics of precipitation have occurred over the period 1910 to 2004'. Kruger[28] mentioned previously that for the period 1955–1991 (the latter half of Fig. 8), the 1960s and 1980s had below-normal rainfall while the 1950s and 1970s had above-normal rainfall, the turning points being 1959–1960, 1970–1971, 1980–1981 and 1991–1992. This is partly evident in Fig. 8, but the spacing of about 10 years (implying a 20-year full cycle) is not evident (the spacings of 19 and 14 years during 1948–1990 and 1910–1950 are equivalent to a long-term swing of about 33 years). However, Kruger[28] made an interesting observation, namely, during the epochs of above-normal rainfall, the El Niño effects are less severe than those during epochs of below-normal rainfall (the opposite is true for La Niña). Kripalani and Kulkarni[60,61] have also made a similar comment for the all-India summer monsoon rainfall.

(v) The bottom plot (c) of land temperature (full line) shows a steady increase during 1910–1944 (–0.230°C to +0.074°C = +0.304°C), a slight decrease during 1944–1966 (+0.074°C to –0.037°C = –0.111°C), a slow increase during 1966–1974 (–0.037°C to +0.029°C = + 0.066°C), and a rapid increase during 1974–1992 (+0.029°C to +0.469°C = +0.440°C). The bottom plot (c) of sea temperature (line of crosses) is almost the same as for land temperature except that from 1974 onwards, sea temperatures increased less (+0.073°C to +0.263°C = +0.190°C). In any case, the temperature patterns in (c) are not similar to those of the average rainfall patterns in (b). However, these are global temperatures, while a more relevant comparison would be with temperature trends over South Africa itself. Kruger and Shongwe[40] have shown such temperature trends for South Africa but only for 1960–2003, so only 1960–1990 in Fig. 8 can be compared. Kruger and Shongwe[40] report a positive trend in the annual average temperatures of 24 stations, such that a 21-year running mean would also show a smooth positive (upward) trend, just like the global trend during 1960–1990. Thus, neither the global temperature trend nor the localised South African temperature trend (both smoothly upward from 1960 onwards) match the fluctuations of rainfalls depicted in the plots (b).

Using the data available until the mid-1970s, Tyson *et al.*,[10] apart from postulating regions of rainfall variability based on spectral analysis, concluded that there were no significant trends. Here, it is shown that there are long-term trends but that they are not linear. Rather, they fluctuate downwards in some intervals, upwards in others and decrease greatly after 1980.

Regarding alternating extended wet and dry spells during the 20th century in South Africa, the series of anomaly maps showing the temporal and spatial variability of annual rainfall in Tyson,[5] updated in Tyson and Preston-Whyte,[62] give a convincing illustration of the extent of the 20th-century variability patterns until the end of the 1980s. Obviously, the environment has changed considerably in recent decades.

General circulation model experiments have been suggesting that the unprecedented global warming in the 20th century may result in a more intense hydrological cycle, with an associated increase in the frequency and/or magnitude of heavy precipitation. Testing for South Africa, Fauchereau *et al.*[63] mentioned that there was no significant trend in the Southern Africa Rainfall Index across the century, but parts of South Africa experienced a significant shift toward increasing probabilities of extreme rainfall. However, they also mentioned that the increase in rainfall variability over the latter decades of the 20th century was merely a return to similar conditions that existed in the early decades of the century, when it was significantly cooler than it is currently. They concluded that over the course of what climate alarmists call a century of unprecedented global warming, and contrary to the implications of nearly all 2 × CO_2 GCM experiments, there has been no net change in either South African rainfall variability or the mean value of the Southern African Rainfall Index. The results shown in the bottom of Fig. 8 are slightly different. From a high level in 1915–1916, values oscillated downwards and decreased by about 5–10% but recovered in 1980 before decreasing considerably thereafter (~8%). This pattern is not similar to the pattern of land-sea global temperature variations.[46]

Predictions

Using extrapolations of long-term periodicities, predictions have been attempted. Dyer and Tyson[9] used a quasi 20-year oscillation and estimated that the intervals 1972–1981 and 1991–2000 would possibly have above-normal rainfall, while 1981–1990 would be drier than normal. Whereas estimates for 1972–1981 and 1981–1990 came true, the above-normal rainfall during 1991–1996 did not occur. (In 1997–1998, the strong El

Niño should have caused below-normal rainfall, which did not occur; however, this cannot be interpreted as above-normal rainfall.) However, 2000 was a year of abnormally-high rainfall, so Dyer and Tyson's prediction is partially vindicated.

Predictions are made using two general methods—statistical methods and dynamically-based (GCM) methods. Workers have often reported relationships between rainfall and parameters like Atlantic SST.[24,26,64] Rouault *et al.*[26] stated that, whereas warm events may be associated with unwelcome floods along the Angolan and Nambian coast, increased rainfall elsewhere can sometimes alleviate droughts in other regions of southern Africa. Recently, several workers reported seasonal forecasts for western, eastern and central Sahel, and for East Africa and South Africa. These involve integration of three European models (UKMO unified model, the ECMWF T63 model and the ARPEGE model) in a nine-member ensemble, neural networks, or multivariate regression analyses, where ENSO is only one of the parameters (not necessarily an important one) and global SST and/or SST in nearby oceans is generally an important parameter, the anomalies of which may or may not be related to Pacific SST anomalies. Several other parameters are also used. For South Africa, Jury[29] used as many as 49 predictors (e.g. SSTs, upper winds, surface pressure and wind, QBO, satellite cloud cover, cloud albedo), one-third of which were related to ENSO, another one-third to transition of Indian monsoon and one-fourth to conditions in the south Atlantic. Nevertheless, the prediction skills are only modest to moderate. For example, for South Africa during the giant El Niño event of 1997–1998, Jury,[29] Greischar *et al.*,[65] Landman,[66] and Thiaw and Barnston[67] gave a forecast of below-average rainfall in the austral summer of 1997–1998, which turned out to be only partly true; rainfall was deficit in the west (Namibia), almost normal in the south, and excessive in the southeast of South Africa. For the 1998–1999 summers, Greischar *et al.*,[65,69] Thiaw and Barnston[68] and Landman and Mason[70] predicted excess rainfall for South Africa, but droughts seem to have occurred there. Thus, these attempts cannot be considered as successful. We suspect that presently unpredictable, almost random, components are very prominent and vitiate the predictions.

Conclusions

The precipitation data for some regions in South Africa were studied for 1900–1998. The following was noted:

(1) From the 11 regions of South Africa examined, 8 had maximum precipitations in the summer months (January, February, March), whereas 3 had maxima in autumn and winter.

(2) Annual values showed considerable year-to-year fluctuations (50% to 200% of the mean).

(3) When smoothed by calculating five-year running means, long-term fluctuations were still large (70% to 150% of the mean).

(4) A spectrum analysis indicated periodicities in the ranges 2–3 (QBO), 3–4 (QTO), 6–11, 17–21, 23–26, 32–35 and 55–66 years, some common to, and some different in different regions.

(5) The QBO and QTO accounted for a substantial fraction (30–50%) of the total variance. Since there was generally more than one peak in QBO and QTO, the net effect was almost a random-like (unpredictable) component. With such a large random component, statistical predictions of annual values to any reasonable degree of accuracy cannot be expected. (This does not apply to seasonal forecasts based on GCMs). In five-year running means, the effect of QBO and QTO got suppressed considerably. The plots did show distinct peaks, but the spacings varied in a wide range, indicating that predictions based on extrapolation of single periodicities (obtained in the spectral analysis) are not likely to come true even for decadal averages. Dyer and Tyson[9] reported that a quasi 20-year oscillation predominated in the northeastern half of South Africa (probably regions A and B) and estimated that the intervals 1972–1981 and 1991–2000 may possibly have above-normal rainfall, while 1981–1990 may be drier than normal. Whereas the estimates for 1972–1981 and 1981–1990 came true, the predicted above-normal rainfall during 1991–1999 did not occur. However, 2000 was a year of abnormally-high rainfall, partially vindicating Dyer and Tyson's[9] prediction.

(6) Regarding El Niño effects for the two giant events of 1982–1983 and 1997–1998—most of the summer rainfall region of South Africa had droughts during 1982–1983. For 1997–1998, effects were obscure, almost absent.

(7) Running means over 21 years did not indicate linear trends, upwards or downwards. Instead, considerable oscillations were seen, different in different regions (5–25% of the mean). On average, high values during 1915–1916 decreased considerably (5–8%) up to 1935, oscillated upwards thereafter and recouped by 1980, but decreased considerably thereafter (2–10%, statistical uncertainty less than 0.5%).

In short-term fluctuations, the (quantitatively) strong influence of QBO and QTO is somewhat disconcerting. There is a plethora of periodicities even in narrow ranges of 2–3 years and 3–4 years and the peak separations are irregular. Random series do yield a plethora of periodicities, most of which are statistically insignificant or of borderline significance. Hence, a substantial part of the QBO and QTO appears to have an almost random nature, beyond the reach of predictions made a few years before a specific wet or dry spell. However, many peaks seemed to be similar in the different regions, indicating the possibility of at least a partial common physical cause. This needs further exploration. The long-term fluctuations involve many periodicities and except for the 11-year periodicity (possibly corresponding to the sunspot cycle), these do not have ready explanations. Also, since each explains only about 10% variance and stationarity is not guaranteed, predictions based on its extrapolation are likely to prove erroneous. El Niño effects, though prominent in earlier years, were mostly obscure for the giant event of 1997–1998, indicating that some drastic environmental changes have occurred in recent decades. Since 1960, the trends in temperatures were consistently upward, but rainfalls had fluctuations. Running means over 21-yearly values could not have data uncertainties, and yet, the trends even in nearby locations do not seem to be similar. Can local effects be so overpowering? It is likely that global changes may not keep up to the climatological expectations, particularly from model studies;[71,72] but the changes may induce changes in the synoptic circulation over South Africa, which in turn may cause different trends over different regions.[32,33,42]

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