Possibilities to forecast early summer rainfall in the Lesotho Lowlands from the El-Niño/Southern Oscillation

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Abstract

Lesotho is located approximately at latitude 30°S in the interior of Southern Africa. The mesocale climate is complicated and governed by various weather systems. The inter-annual rainfall variability is great, resulting in low food security, since the growing of crops is almost exclusively rain-fed. Reliable forecasts of austral summer rainfall, especially early summer rainfall (October-December), are thus valuable. Earlier research has shown that the El Niño/Southern Oscillation signal from the Pacific can be discerned in Southern Africa. In general the signal from the El Niño/Southern Oscillation is strongest in the later part of the early summer. October, November and early summer rainfall are significantly correlated with certain preceeding values of the Southern Oscillation Index (SOI), but weakly so. December rainfall and aggregate November-December rainfall are significantly correlated fairly strongly (r = 0.5 approximately) with certain preceeding SOI values. Lead times of four months seem to be attainable. A contingency analysis basically yields similar results, working on the assumption that the response is non-linear in the sense that a certain threshold of the strength of the Southern Oscillation has to be surpassed to "trigger" a rainfall response in Lesotho. For wet Decembers the average monthly SOI for the preceeding months May to November is positive during all months. For dry Decembers it is negative.

Introduction

The Lesotho Lowlands are located in western Lesotho and encompass 5 000 km^2. The Lowlands have a north-south extension of 200 km and a width of 25 km. They border the plains of the eastern Free State and have an approximate elevation of 1 750 m above sea level. To the east the foothills rise into the Lesotho mountains, which rise to elevations higher than 3 000 m. It is in comparison with these elevations that western Lesotho is called lowlands (Fig. 1). The 1886/87-1992/93 mean annual precipitation over the Lowlands is 735 mm (Hydén, 1996a). However, the mean annual precipitation varies considerably between years, the lowest being 426 mm and the highest 1 097 mm in the mentioned 107-year series.

A majority of the Basotho live in the Lowlands from rain-fed agriculture. Rainfall variability is thus of great importance for food security. The ability to forecast rainfall in the austral summer would contribute to improving food securtiy. This is especially true, if droughts could be forecast so much in advance that farmers could switch to more drought resistant crops and adjust the planted acerage to expected rainfall. It is against this background that meteorological droughts and rainfall variability in Lesotho have been studied by this author (Hydén, 1996a, b, c, 1998) and others (De Baulny, 1977, 1979, 1981; Eckert, 1980; Elderidge, 1987, 1993; Jayamaha, undated (after 1979); Makhoalibe, 1985; Molapi and Sekoli, 1989; Sekoli, 1981; Sharma and Makhoalibe, 1988; Sharma and Makhoalibe, undated (after 1984); SWECO, 1977; World Bank, 1990; Zinyowera, 1978).

Since the 1930s, when Walker analysed the correlation between Indian rainfall and air pressure differences over the Pacific, the so-called Southern Oscillation has been believed to influence the rainfall variability of the southern hemisphere as well.

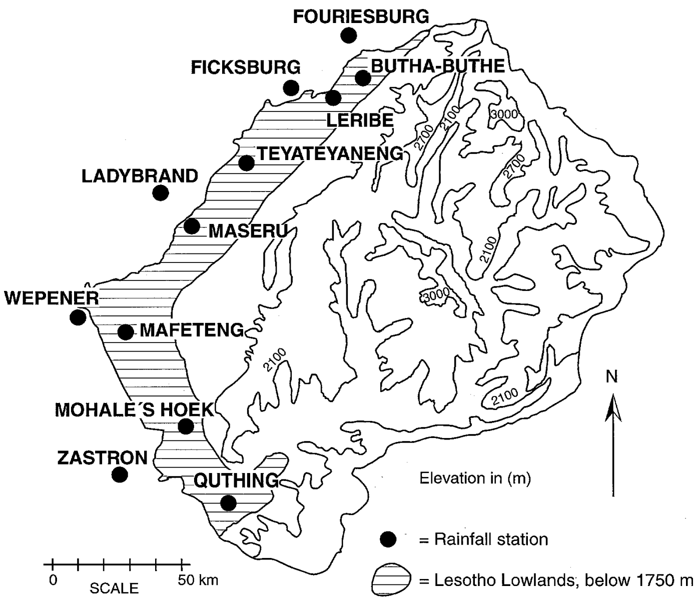

Figure 1
Topographic map of Lesotho and location of rainfall stations

Research has shown that the Southern Oscillation in turn is connected to the El Niño/La Nina phenomenon, i.e. the anomolous warming and cooling of the Pacific off the coast of Peru. Many authors have investigated the influence of the El Niño/Southern Oscillation (ENSO) on rainfall in Southern Africa (Harrison, 1983; Janowiak, 1988; Jury et al., 1994; Van Heerden et al., 1988; Lindesay et al., 1986; Lindesay, 1988; Lindesay and Vogel, 1990; Mason and Lindesay, 1993; Matarira and Unganai, undated (after 1994); Ropelewski and Halpert, 1987, 1989, 1996; Walker and Bliss, 1932) (Table 1).

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TABLE 1
RELATIONSHIP BETWEEN RAINFALL IN SOUTHERN AFRICA AND THE SOUTHERN OSCILLATION IN LITERATURE

Author(s)	Analysis	Results
Harrison, 1983	SOI correlated with zero lag *Cocos island 850 mbar zonal wind *eastern Free State rainfall	 r=0.81 r=0.66
Janowiak, 1988	D-M rain east of 20 east between 15-30 south analyzed during 19 ENSO events	9 dry summers in 11 warm events, -10% à -20% rain in Lesotho; 5 wet summers in 8 cold events, +10% rain in Lesotho
Jury et al., 1994	*J-F 1953-88 25-29 south, 22.5 - 30 east South Africa rain correlated with zero lag SOI; *1953-92 J-F rain (P) vs. SOI, SOI>+/-0.8, P>+/-0.4	r=0.56 50% probability for SOI low phase and drought, 80% probability for SOI high phase and above normal rainfall
Lindesay et al., 1986	Median differences between high and low (SOI>+/-0.4) phase rainfall 1935-83 during O-M, O-D and J-M	NW-SE area of significant differences
Lindesay, 1988	*3 month rainfall 1935-1983 zero lag correlated with SOI *Bloemfontein (probably) monthly rain correlated with SOI	All four seasons weakly correlated, O-D best, about 0.2 November r=0 December r=0.35
Lindesay and Vogel, 1990	Coincidence between droughts and ENSO events 1820-1920 in the summer rainfall area of SA	24 droughts, 14 coinciding with strong ENSO events, 7 with weak ENSO events
Mason and Lindesay, 1993	Influence of quasi-biennial oscillation (QBO) on zero lag relation between J-M 1953-89 59 station rainfall in SA and SOI	QBO westerly, r=0.5 in Lesotho from Fig. 1a QBO easterly r=0.4 from Fig. 1b
Matarira and Unganai, undated (after 1994)	1951-89 3 month regional rainfall in i.a. region no 13, covering i.a. the Free State	Rain (O-D)=-0.1+0.4SOI(JUL) r=0.48 Rain(N-J)=-0.04+0.6SOI(S) r=0.62 Rain(D-F)=-0.4+0.6SOI(O) r=0.63 Rain(J-M)=-0.03+0.5SOI(N) r=0.61 Rain(F-A)=0.01+0.5SOI(N) r=0.60
Ropelewski and Halpert, 1987	Dry ENSO events in South East Africa November-March	17 dry seasons in 22 ENSO events. Of 11 driest seasons, 7 occurred during ENSO events
Ropelewski and Halpert, 1989	Ditto, N-A, high SOI=upper quartile	12 wet seasons in 15 high SOI years, 3 wettest seasons associated with high SOI
Ropelewski and Halpert, 1996	N-A rainfall during low SOI years, base years and high SOI years in South-East Africa	605, 665 and 775 mm 50% N-A rain in low SOI, base period and high SOI years, respectively
Van Heerden et al., 1988	*53 district 1921-95 average rain in SA correlated with SOI *November-March rain *December rain *December rain and ASO SOI in Lesotho	r=0.52(D rain, ASO SOI) r=0.43(March rain, SON SOI) Weak r for J and F rain and lagged SOI 12 dry summers in 14 warm events 8 wet summers in 12 cold events 13 dry Decembers in 14 warm events 10 wet Decembers in 12 cold events r=0.4-0.5 from Figure 2a
Walker and Bliss, 1932	Southern Africa rainfall (Salisbury, Durban, Cape Town) correlated with 10 parameter SOI	D-F:r=0.56 D-F rain vs. Jn-A SOI: r=0.44
(SA=South Africa)		

Exactly how this teleconnection works and how the ENSO signal is transmitted from the Pacific to Southern Africa is not fully understood. Negative values of the Southern Oscillation Index (SOI) (warm events) include sustained subsident motion through the mid-troposphere and an equator-ward shift and strengthening of mid-latitude westerlies. Postive values of the SOI (cold events) bring increased rainfall, derived from increased latent heat released in the tropics which modulates the position of a subtropical standing wave and associated Hadley anomaly (Jury et al., 1994).

During El Niño events westerly upper level winds are enhanced downstream over the tropical Atlantic Ocean, bringing dry air and strengthening the high pressure cell over Botswana and thus reducing rainfall over Southern Africa. The central tropical Indian Ocean sea surface temperature changes in sympathy with the eastern Pacific with a lag of one or two months. Dry El Niño years increased monsoon flow recurvature into tropical cyclones in the south-west Indian Ocean produces a "dipole", giving increased convective rainfall east of Madagascar, which in turn is offset by drought over Southern Africa (Jury, 1996).

These findings by Jury and others make it likely that there exists a simultaneous, non-lagged relationship somehow between the Southern Oscillation and rainfall in Southern Africa.

Already Walker and Bliss (1932) analysed the persistence of the Southern Oscillation by plotting June-August SOI 1875-1930 together with December-February SOI. The parallelism of the two plots suggested that if for example December-February rainfall has a close relationship with contemporary SOI it should have a corresponding relationship with the SOI of the previous June-August period, i.e. there should be a six months foreshadowing. Van Heerden et al. (1988) found a strong relationship between summer monthly SOI values and corresponding summer monthly rainfall in South Africa. They further found that lag correlations between winter three-month mean SOI values and individual summer month district rainfall were equally significant, due to the persistence of the SOI through the southern winter and summer. They recognised the significance those results had for possible long-range rainfall predictions. Matarira and Unganai (undated, after 1994) recognised the SOI persistence and used it to work out lagged correlation between preceeding SOI and rainfall in various regions in Southern Africa. A value for the July to October SOI of about -1.5 or below indicated a high probability of a below normal rainy subsequent summer. An SOI of +0.5 and above indicated a high chance of a normal to above normal rainy subsequent summer.

These findings of Walker and Bliss, Van Heerden et al and Matarira and Unganai - together with the findings of Jury and others - make it likely that the SOI of preceeding months might be used successfully to predict rainfall in the southern summer.

The Lesotho Lowlands area is a fairly small area of 5 000 km^2. It might be feared that distant teleconnections would not be discernible in the mesoscale climate of such a relatively small area. However, it has been shown (Hydén, 1996a) that there is a strong correlation between Lesotho Lowlands regional rainfall and rainfall over the much larger summer rainfall region of South Africa.

The research presented in this paper is part of an on-going project to find suitable meteorological and oceanographic predictors to forecast rainfall in the Lesotho Lowlands, e.g. the SOI and the sea surface temperatures in the Pacific, Indian and Atlantic Oceans. The purpose of this paper is to study the strength of the SOI signal in Lesotho Lowlands regional rainfall. In Southern Africa the only attention paid to defining optimal forecast periods has been to divide the summer season into the early, mainly temperate half and the later, tropical half (Mason, 1997). Rainfall forecasts for the late summer are important from an agricultural point of view because rainfall during the tasselling and grain filling, typically occuring during January and February, might be more critical than during the beginning stages of crop growth than rainfall during the beginning stages of crop growth (Mjelde et al., 1997). Their research concerning east-central Texas corn and sorghum producers also shows considerable expected economic value of perfect early growing season forecasts. For Southern Africa there are indications that early summer rainfall is more difficult to predict than late summer rainfall.This paper attempts to answer the following three questions for the Lesotho Lowlands for certain periods of early summer (October-December) standardised rainfall:

- **SOI persistence:** How persistent is the SOI, comparing winter and early summer SOI?
- **Lagged correlation:** Is rainfall significantly correlated with SOI values during certain preceeding months?
- **Rainfall during extreme SOI events:** Is the frequency of rainfall below and above average rainfall during years with low preceeding SOI values significantly different from the corresponding frequencies during years with normal preceeding SOI values? Is the same true for years with high preceeding SOI values?

Methods

Monthly rainfall records in millimeters have been made available through the Lesotho Meteorological Services for the following seven stations in the Lesotho Lowlands for the 46-year period 1951-96: Butha-Buthe, Leribe, Teyateyaneng, Maseru Old Airport, Mafeteng, Mohale's Hoek and Quthing. The rare gaps in the records have been filled with data from adjacent rainfall stations in South Africa, for which data have been provided by the South African Weather Bureau. The location of the stations is shown in Fig. 1. The quality of the data has been checked and found adequate (Hydén, 1996a). The start of the time series was set at 1951 to coincide with other meteorological and oceanographic parameters available from that year onwards.

Eckert (1980) computed a Lowlands rainfall series 1920/21-1978/79 as an arithmetical mean. It has been shown (Hydén, 1996a) that this method gave almost identical results as with using weights as outlined by Thiessen (1911). The Lesotho Lowlands regional rainfall has therefore been computed for 1951-96 as a seven station arithmetical mean. The mean and the standard deviation have then been calculated and the regional time series standardised. Six standardised regional rainfall (SRR) series have been computed to cover early summer rainfall: October, November, December, October + November, November + December, and October + November + December. The six series are shown in Figs. 2a-2f. The six means are 70, 88, 91, 158, 179 and 249 mm respectively. The standard deviations are 43, 39, 38, 56, 56 and 67 mm respectively.

The standardised Tahiti minus the standardised Darwin sea level pressure data, under the heading standardised data, were used, as the data were retreived from the Internet on November 20, 1997 from NOAA.

To answer the first question about the persistence of the SOI the average of June, July and August SOI is compared with the average of October, September, and December SOI.

On the assumption that one month is needed to model the forecast, distribute the results and act on them, the SOI was computed for preceeding periods lagged at least one month. For example, October rainfall was correlated with May, June, July and

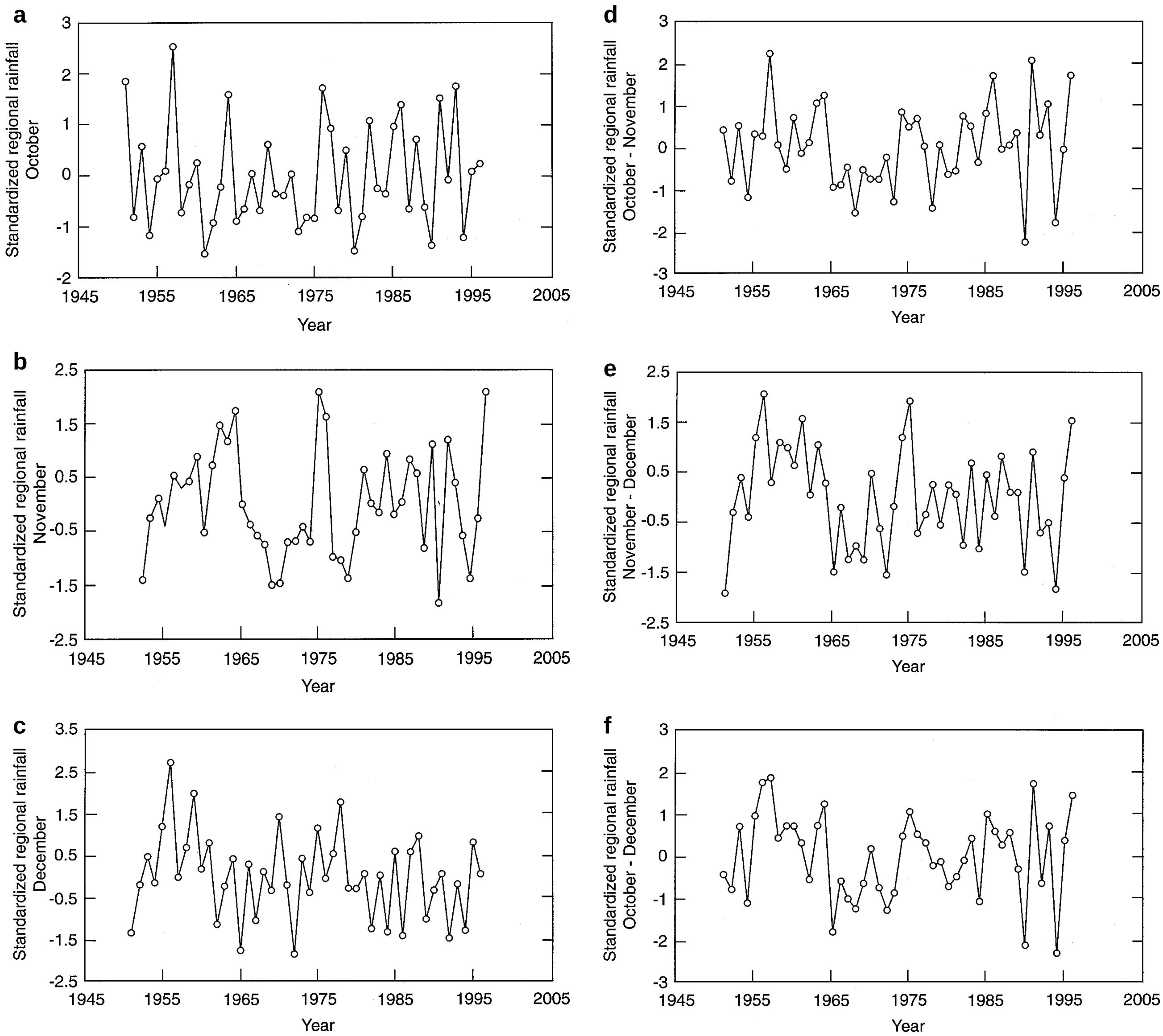

Figure 2

Standardised regional rainfall 1951-1996 a) October. b) November. c) December. d) October+November. e) November+December. f) October+November+December.

August SOI values to study how the correlation develops with time.

To study if the correlation is strengthened by working with SOI average values over longer periods of time, October rainfall was also correlated with the average SOI values for July and August; June, July and August; May, June, July and August. Thus Ocotber rainfall was correlated with seven different SOI values. Similar correlations were performed for the other five SRRs, giving a total of 42 researched cases.

To answer the second question the Pearson correlation coefficient " r" is computed for each rainfall period between rainfall and the seven preceeding SOI values. The hypothesis that the correlation coefficient is zero is tested as follows: If the sample r of 46 observations is greater than 0.29, the hypothesis is rejected on the 95% level of significance. When the correlation coefficient significantly differs from zero, the linear regression equation is computed for each rainfall period. The computations have been performed with the STATISTICA computer program.

$$Y = a + bX$$

where:

Y = the SRR for the period in question
X = the SOI value for certain preceeding periods
a,b = constants

To answer the third question a contingency analysis is performed based on two thresholds, equal in size but of opposite sign. The relationship between SRR and SOI values of certain preceeding periods is studied, when the SOI value was less than or equal to -1.0 and greater than or equal to +1.0, the threshold values being chosen rather arbitrarily. Jury et al. (1994) followed the method by Ogallo et al. (1994) and performed a contingency analysis for the period 1953-92 with the thresholds ±0.8 standard deviations for SOI. It is noted that the average SOI for the 46-year period in this paper deviates somewhat from zero. But for the consistency of the analysis the two thresholds have been kept the same throughout the analysis. These years are called low SOI (LSOI) years and high SOI

(HSOI) years respectively. The years inbetween when SOI is higher than -1.0 and lower than +1.0, are called normal SOI (NSOI) years.

In the contingency analysis a fourfold table is applied and the test statistic chi square is computed. The test statistic is compared with chi square with one degree of freedom on the 95% level of significance, 3.841. If the test statistic is greater than 3.841, then one accepts the hypothesis that the frequencies of SRR below and above average rainfall during years with LSOI and HSOI years are significantly different from the corresponding frequencies during NSOI years. The average SRR is also computed for these LSOI and HSOI years.

Mason (1997) compared statistical and general circulation model (GCM) seasonal forecast methods. In the long run GCM forecasts should provide higher forecast skills because of the non-linearity of the ocean-atmosphere system, which is exceptionally difficult to reproduce in statistical methods. By 1996 all current statistical methodologies used by members of the South African Long-lead Forecast Forum used linear statistical methods. Theoretically one might view the cases when the contingency analysis gives significant results as a kind of non-linear relation, simply represented by the average SRR for the LSOI, NSOI and HSOI years respectively (Fig. 5).

Results

The persistence of the SOI is illustrated by the fact that the June-August SOI has the same sign as the October-December SOI during 34 out of 46 years. The two time series are shown in Fig. 3, which shows a fairly close agreement between the two curves. The coeffficient of correlation is 0.74.

The results of the lagged correlation analysis are given in Table 2 for those cases when the correlation coefficient does not significantly differ from zero and in Table 3 for those cases when it does differ significantly from zero.

Table 4 gives the results for the contingency analysis. For the HSOI years there was only one case when the contingency analysis yielded significant results. It was when November rainfall was correlated with the June SOI value. Square X was 4.96 but only from four years during all of which the SRR was above average.

Discussion

The significant correlation coefficients between October, November, October+November,and October+November+December rainfall and preceeding SOI values are all less than 0.4 and thus not promissing to be used as predictors. For December rainfall the highest correlation coefficient is 0.48 from July+August+September +October SOI. The slope of the linear regression line is 0.52 (Fig. 4a). The highest correlation is thus obtained when the "longest" SOI value from July to October is used as predictor. Considering the length of the lead time it is worth noticing that as early a predictor as July SOI yields a correlation coefficient of 0.45. Van Heerden et al. (1988) found December rainfall in Lesotho to be significantly correlated with August + September + October SOI with r = 0.4 to 0.5 from their Fig. 2a. The corresponding correlation coefficient for the Lesotho Lowlands is 0.46, which agrees well.

For November+December rainfall the highest correlation coefficent is 0.53 from July SOI. The slope of the linear regression line is 0.54 (Fig. 4b). This is an encouraging result since July is the second longest lead time, providing a lead time of four months.

The October+November+December rainfall is significantly correlated with preceeding SOI only during July, when r = 0.31. This correlation is considerably weaker than the 0.48 found by Matarira and Unganai (undated, after 1994) for their region no. 13, covering the Eastern Cape and the Free State.

The contingency analysis basically confirms that the SOI signal is much clearer during LSOI years than during HSOI years. The scatterplot for December rainfall and October SOI is shown in Fig. 5. The SOI thresholds are shown and also the linear regression

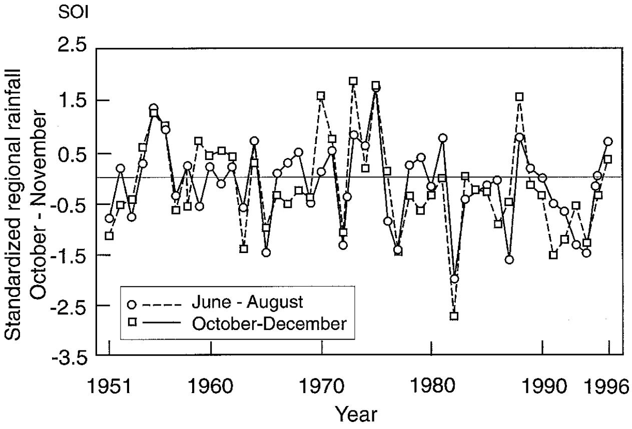

Figure 3
Average SOI for June-August and October-December, 1951-1996

TABLE 2
CORRELATION COEFFICIENT r BETWEEN STANDARDIZED REGIONAL RAINFALL AND SOI VALUES FOR CERTAIN PRECEEDING PERIODS. r NOT SIGNIFICANTLY DIFFERENT FROM ZERO.

Rainfall period	Period of SOI values	Correlation coefficient
October	June	-0.19
	July	-0.20
	August	-0.29
	July+August	-0.27
	June+July+August	-0.26
November	June	0.12
	August	0.20
	September	0.26
	August+September	0.24
	July+August+September	0.28
	June+July+August+September	0.26
October+November	May	-0.26
	June	-0.07
	July	0.06
	August	-0.09
	July+August	-0.01
	June+July+August	-0.03
	May+June+July+August	-0.10
October+November +December	May	-0.06
	June	0.13
	August	0.16
	July+August	0.26
	June+July+August	0.23
	May+June+July+August	0.17

TABLE 3
CORRELATION COEFFICIENT r BETWEEN STANDARDIZED REGIONAL RAINFALL (SRR) AND SOI VALUES FOR CERTAIN PRECEEDING PERIODS. r SIGNIFICANTLY DIFFERENT FROM ZERO. LINEAR REGRESSION EQUATIONS SRR=a+bSOI

Rainfall period	Period of SOI values	Correlation coefficient	SRR=a+bSOI
October	May	-0.38	-0.020-0.429SOI
	May+June+July+August	-0.31	0.046-0.406SOI
November	July	0.31	0.029+0.317SOI
December	July	0.45	0.042+0.461SOI
	August	0.41	0.072+0.416SOI
	September	0.39	0.031+0.353SOI
	October	0.47	0.080+0.455SOI
	September+October	0.45	0.060+0.455SOI
	Aug.+Sept.+Oct.	0.46	0.070+0.479SOI
	Jul.+Aug.+Sept.+Oct.	0.48	0.069+0.521SOI
November+December	June	0.30	0.055+0.396SOI
	July	0.53	0.049+0.541SOI
	August	0.42	0.074+0.428SOI
	September	0.45	0.036+0.409SOI
	August+September	0.45	0.059+0.450SOI
	July+August+September	0.51	0.064+0.542SOI
	Jun.+Jul.+Aug.+Sept.	0.49	0.071+0.575SOI
Oct.+Nov.+Dec.	July	0.31	0.029+0.316SOI

TABLE 4
CONTINGENCY ANALYSIS AT 95% LEVEL OF SIGNIFICANCE FOR LSOI YEARS WITH SOI LESS THAN OR EQUAL TO -1.0

Rainfall period	Predictor SOI	Chi square	Number of LSOI years	Number of years with below average rainfall	Average SRR anomaly during LSOI years
November	July	4.68	9	8	-0.64
December	October	4.41	11	9	-0.82
Nov.+Dec.	July	7.03	9	8	-0.94
	August	3.87	11	8	-0.57
	July-Sept.	4.73	10	8	-0.81
	June-Sept.	5.88	8	7	-0.82

(SRR = standardised regional rainfall)
(LSOI = low SOI)

line and the average SRR during LSOI, NSOI and HSOI years. The 11 individual LSOI years are also marked in Fig. 5.

In summary December and November+December rainfall are significantly correlated with preceeding SOI values. The frequency of November and December rainfall below and above average rainfall during LSOI years is significantly different from the corresponding frequency during NSOI years, when July SOI and October SOI values are used as predictors, respectively.

The development of the average monthly SOI during the 11, 24 and 11 driest, normal and wettest Decembers (approximately corresponding to 25, 50 and 25 % of the 46 Decembers) is shown in Fig. 6. Although there is great variation between years, the three average curves show a remarkable consistency. The dry Decembers are preceeded by the lowest SOIs, the wet Decembers by the highest SOIs. The normal Decembers are preceeded by SOIs that fall in between the "dry" and the "wet" SOIs. It can be seen from Fig. 6 that the maximum SOI deviation between the curve for normal and dry December occurs already during the month of July. The maximum SOI deviation between the curve for normal and wet December occurs during the month of September.

The SOI anomalies cause reversals in the Walker circulation over the Pacific and also in the circulation over the Indian Ocean, where the SOI signal might be relayed to Southern Africa through anomalies in the Hadley circulation. This mechanism might be valid within a month as a non-lagged relationship. It is fortunate that, due to the SOI persistence, the rainfall in southern Africa might be forecasted from preceeeding SOI anomalies. The authors' approach should rather be seen as a kind of two-tier approach, starting with the SOI anomalies during preceeding months as indicators of SOI anomalies and rainfall during later months. This point is further illustrated by the fact that the December SOI anomaly during the 11 wettest (driest) years is +0.93(-1.05), while the monthly SOI average anomaly during the preceeding months of May to October ranges from +0.15 to +0.66 (-0.32 to -0.85), c.f. Fig. 6. Not only are thus the December SOIs in these cases of the same sign as the SOIs during the preceeding months, they are also numerically larger.

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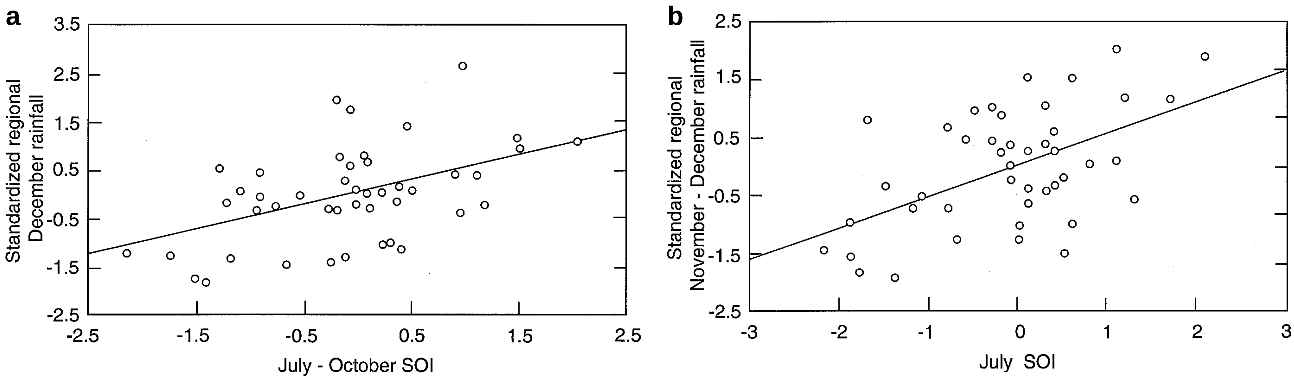

Figure 4

Linear correlation analysis. a) Standardised regional December rainfall vs. July-October SOI. b) Standardised regional November+December rainfall vs. July SOI

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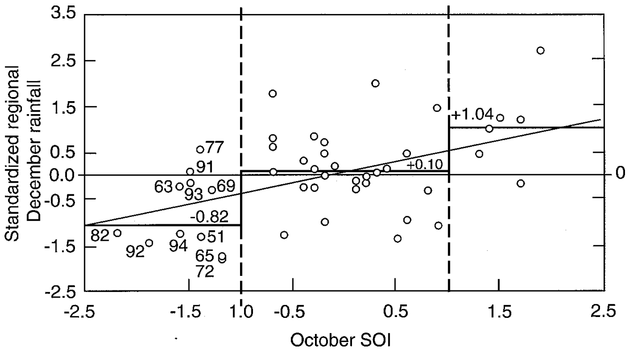

Figure 5

Standardised regional December rainfall vs. October SOI. Correlation and contingency analysis

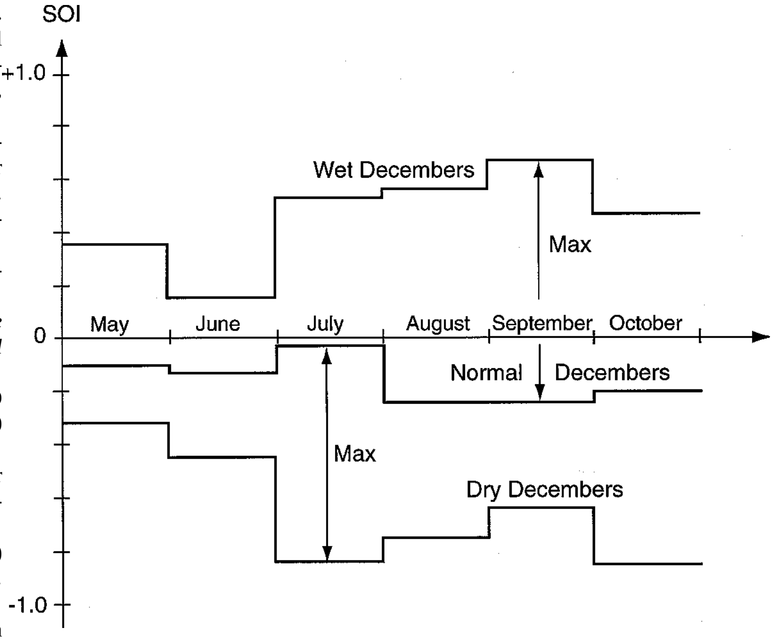

Figure 6

Average monthly SOI from May to October during years with wet, normal and dry Decembers

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