The Relationship between El Niño and Drought over Botswana

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ABSTRACT

Numerous studies have shown that drought occurs in Botswana in association with most Pacific ENSO episodes. Using composite analysis, an attempt is made to identify characteristic differences between those episodes during which drought occurs and those in which it does not. The evolution of the Southern Oscillation index (SOI) and of SSTs in key sectors of the Atlantic, Pacific, and Indian Oceans during ENSO episodes between 1946 and 1992 is examined.

The most pronounced contrast is in SSTs in the Atlantic and Indian Oceans. For the ''dry Botswana'' composite, SST anomalies are predominantly positive throughout the latter half of the episode, when drought tends to occur. For the ''wet Botswana'' composite, SST anomalies are overwhelmingly negative in the Atlantic and generally negative or near normal in the Indian Ocean. Differences are also apparent in the seasonal evolution of the SOI and Pacific SSTs. In the Pacific there is weaker and less consistent warming in the wet Botswana composite than in the dry Botswana composite, especially in the central and western Pacific. Also, the SOI is less negative and the low index period is less persistent in the wet Botswana composite.

Because the SOI measures atmospheric, rather than oceanic, response, this may imply a weaker atmospheric response and weaker atmosphere–ocean coupling during the Pacific ENSO episodes that do not evoke drought in Botswana. This, rather than specific patterns of SSTs, appears to be the critical factor. The Pacific ENSO events that produce drought tend to be the Type 1 events identified in earlier studies: those with strong central Pacific warming that persists well into the boreal winter. This is the key to the development of midlatitude teleconnections.

SSTs alone are of limited value in forecasting drought occurrence in Botswana. However, the statistical associations between ENSO and rainfall have some forecast potential. In all six rainfall regions examined, the probability of a wet season is very low at any time during the second half of an ENSO episode, but it is particularly low for the April–June (AMJ) season (i.e., AMJ of the post-ENSO year). During that season the likelihood of rainfall being more than one-half of a standard deviation below average is about 70% or better in all regions.

1. Introduction

It has long been established that ENSO modulates rainfall variability over southern Africa (e.g., Stoeckenius 1981; Harrison 1983; Schulze 1983; Nicholson and Entekhabi 1986, 1987; Lindesay 1988; van Heerden et al. 1988). The effects have been particularly hard-felt in the country of Botswana, which experiences severe drought in conjunction with most Pacific ENSO events. In Botswana's agricultural region in the southeast, rainfall was below normal in the late rainy season of the post-ENSO year in 15 of the 20 ENSO events between 1901 and 1990 (Nicholson and Kim 1997).

ENSO's influence on rainfall in southern Africa appears to be related to its influence on SSTs in the tropical Atlantic and Indian Oceans in proximity to the African continent (Nicholson and Nyenzi 1990). A preliminary study suggests that drought occurs in southern Africa in conjunction with ENSO only if the episode results in a warming in these ocean regions, as well (Nicholson 1997). In this paper, we test this hypothesis by doing a detailed analysis of those episodes with and without abnormally low rainfall over Botswana.

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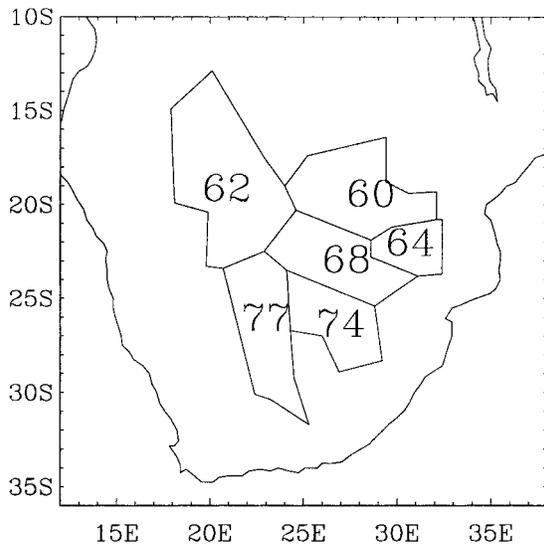E-mail: sen@met.fsu.edu

Fig. 1. Rainfall regions of southern Africa and rainfall stations [from Nicholson (1986a), with regions numbered according to Nicholson et al. (1988)].

To evaluate the rainfall–ENSO relationship, we examine the evolution of the Southern Oscillation index (SOI) and SSTs in key sectors of the Atlantic, Pacific, and Indian Oceans during ENSO episodes occurring between 1946 and 1992. Composite analysis is used to compare the ENSO events that resulted in abnormally low rainfall over Botswana with those that did not. Wet and dry years that occur independently of ENSO are also examined, in order to generalize our findings concerning the factors governing the interannual variability of rainfall in this region.

2. Methodology and data

This study utilizes monthly rainfall data from 122 stations in Botswana and surrounding countries. Most of these station records are from an archive compiled by the first author, but an additional 17 station records and station updates were provided by the Meteorological Services of Botswana. From these records, standardized regional time series (monthly, seasonal, and annual) were produced for the six regions shown in Fig. 1 (regions 60, 62, 64, 68, 74, and 77 in Nicholson et al. 1988). Regions were defined using rainfall characteristics and linear correlation; homogeneity of the regions with respect to interannual variability was confirmed using an F test (Nicholson 1986a). All but one of the regional series commence in 1901 and extend to 1996 or 1997. In the few cases with less than five stations per region, adjustments were made to account for the change of variance with station number, as described in Nicholson (1986a).

The sea surface temperature data utilized in this study are that of the Comprehensive Ocean–Atmosphere Data Set (COADS) (Woodruff et al. 1987, 1992). The
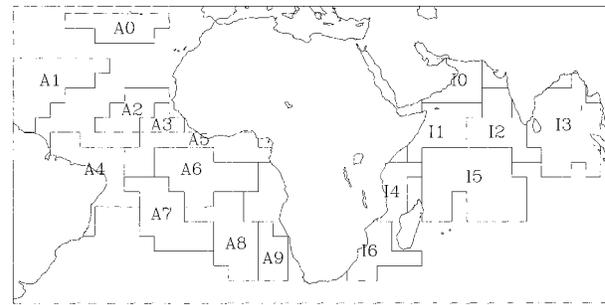

Fig. 2. SST sectors of the Atlantic and Indian Oceans with consistent ENSO signals (from Nicholson 1997).

COADS data consist of "trimmed" monthly averages for $2° \times 2°$ squares. SSTs are expressed as a "normalized" anomaly, that is, a departure from the long-term mean for the analysis period 1946 to 1992, divided by the standard deviation of SSTs during this period. Here, the data have been aggregated to produce spatially averaged time series for 10 sectors in the Atlantic and 7 sectors in the Indian Ocean (Fig. 2) that Nicholson (1997) showed to be homogeneous with respect to SST response to Pacific ENSO episodes. SST time series for several sectors of the Pacific (Niño-1+2, Niño-3, Niño-4) have been obtained from the NOAA Web site (http://nic.fb4.noaa.gov/data/cddb). The SOI was also obtained from the NOAA Web site. It is calculated as monthly standardized values of the Tahiti–Darwin sea level pressure.

COADS has been used in many studies of marine surface variables and has proven to provide reliable estimates of temperature, wind, and surface pressure (e.g., Deser and Wallace 1990; Ward 1992; Nigam and Shen 1993; Allan et al. 1995). The dataset contains two biases produced by changes in observational practices. The first involves SST estimates based on "bucket," or engine-cooling, water intake data and the second involves the use of anemometer readings versus Beaufort force estimates of wind speed. The number of ships utilizing the "intake" water to measure SSTs increased markedly in the 1940s. For this reason, and because the number of reports increases dramatically following World War II, our analysis begins in 1946, consistent with previous ENSO studies of the first author. The analysis period ends in 1992.

The overall approach of this study is to examine time series of annual rainfall anomalies in six southern African regions that include Botswana, to determine from these which of the ENSO events between 1946 and 1992 were linked to abnormally dry conditions, to examine the temporal evolution of the SOI and SSTs during these events, and to contrast them with the SOI and SSTs during those events in which dry conditions did not occur. The spatial patterns of SSTs are also examined for multiyear wet and dry episodes and individual years and contrasted with those described by Nicholson (1997) as typifying ENSO episodes.

3. Typical rainfall and SST patterns during ENSO episodes

In two previous papers, Nicholson and Kim (1997) and Nicholson (1997) described the results of comprehensive studies of the relationship between ENSO, rainfall over the African continent, and SSTs in the tropical Atlantic and Indian Oceans. Because the current study builds upon this previous work, an overview of the results is presented in this section. In the earlier studies the harmonic method of Ropelewski and Halpert (e.g., 1987, 1989) was applied to 90 regionally averaged rainfall time series for the period 1901 to 1990 and to gridded SSTs in the Atlantic and Indian Oceans in the area 40°N–40°S for the period 1946–79.

In the rainfall study, composites of 20 ENSO episodes were produced to describe the typical sequence of rainfall anomalies during the 24-month period commencing six months prior to the ENSO year and ending six months after that year. From these composite sequences, seasons of maximum positive anomalies and maximum negative anomalies occurring in association with ENSO were identified for each region. These results were used to identify 15 multiregion sectors in which ENSO appears to modulate rainfall in a regular and spatially coherent fashion. The rainfall response was found to be seasonally specific, but with a magnitude, timing, duration, and consistency that vary among the sectors.

The results of this study are shown in Fig. 3 for the three sectors that include parts of Botswana. In all three sectors, the pattern is one of drought in the latter half of the ENSO episode, with maximum negative anomalies occurring early in the post-ENSO year. This is the heart of the rainy season in these regions. For sector 8, into which most of Botswana falls, negative anomalies persist from September of the ENSO year to June of the following year. Positive anomalies are apparent throughout most of the first half of the episode, but their magnitude and the timing of their maxima vary among the three sectors. This tendency for above-average rainfall early in the ENSO episode and below-average rainfall later in the episode is evident over most of Africa.

In the SST study, composites of the eight episodes between 1946 and 1979 were produced, and sectors of coherent SST response to ENSO were identified. These sectors are shown in Fig. 2. The seasonal evolution of SSTs during ENSO years is depicted in Fig. 3 for two of these sectors. Throughout most of the analysis domain, there is a tendency for a "cold phase" during the first half of the ENSO cycle and a "warm phase" in the second half. This is evident both from the SST anomaly time series in Fig. 3 and from the spatial patterns of SST anomalies shown in Fig. 4. Over the continent as a whole, and in Botswana in particular (Fig. 3), rainfall tends to be enhanced during the cold phase and reduced during the warm phase.
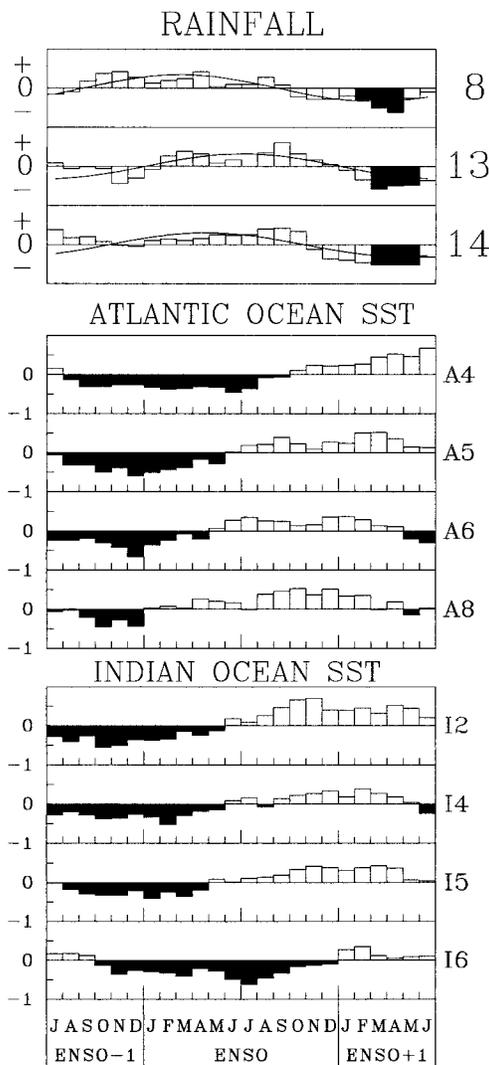

FIG. 3. ENSO composite rainfall and SST anomalies for select sectors shown to have a coherent ENSO signal (see Figs. 1 and 2 for sector location). Time series commence in Jul in the year prior to ENSO and continue to Jun of the year following ENSO. Rainfall sectors are those identified by Nicholson and Kim (1997) as having a coherent response to ENSO, and amplitude is an index based on rank. Sector 8 includes regions 60, 64, 68, and 74 of Fig. 1; sector 13 includes region 62; and sector 14 includes region 77. The SST sectors are examples chosen from those identified by Nicholson (1997) as having a coherent response to ENSO, and the units are standard departures.

4. Results

a. Interannual variability of rainfall over Botswana

The time series of regionally averaged annual rainfall departures for the six regions that include stations in Botswana are shown in Fig. 5. The year is defined as the period from July to June, to avoid dissecting the rainy season when tabulating annual departures. There are many parallel trends in these regions, and interregional correlations (Table 1) are high. Most range from
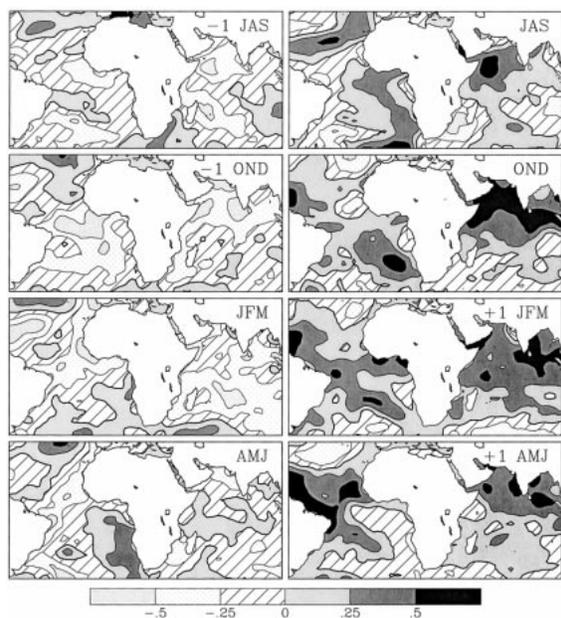
FIG. 4. SST evolution in the Atlantic and Indian Oceans during Pacific ENSO events of the period 1946–79 (from Nicholson 1997). Composites are for three-month seasons commencing during JAS of the year prior to ENSO. Shading represents positive anomalies, with progressively darker shading indicating anomalies of 0° to 0.25°C, 0.25° to 0.5°C, and greater than 0.5°C. Negative anomalies are indicated by right hatching (0° to 0.25°C), left hatching (0.25° to 0.5°C), and dots (greater than 0.5°C).
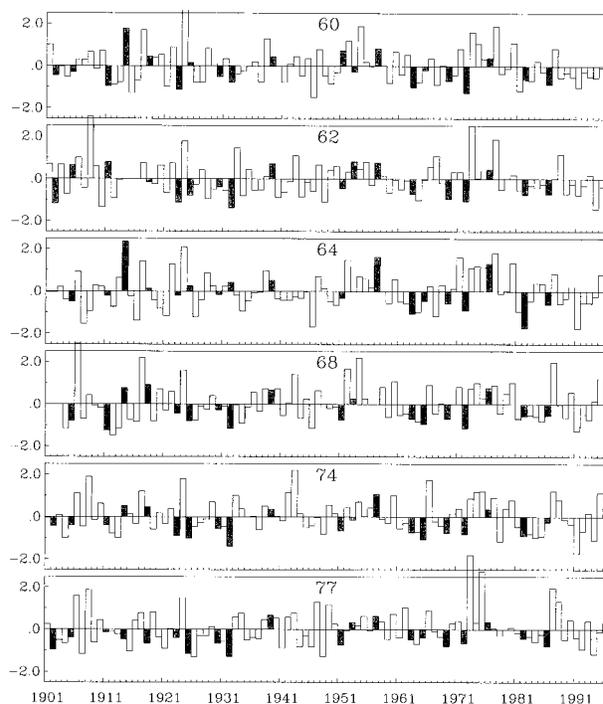

FIG. 5. Time series for regionally averaged rainfall departures for regions 60, 62, 64, 68, 74, and 77 (see Fig. 1) for the years 1901–96. Units are percent standard departure from the mean, with the annual totals calculated for the period Jul of the indicated year to Jun of the following year. ENSO years are shaded.

0.48 to 0.75, based on 90–92 correlation pairs. Even the lowest correlations, 0.36 and 0.37 for correlations of region 64 with regions 62 and 77, are significant at better than the 1% significance level. The regions differ, however, with respect to the consistency of the rainfall response to ENSO (see Fig. 5). Of the 22 ENSO episodes between 1901 and 1994, the number in which rainfall was below average ranged from 13 of 22 in region 62 to 18 of 22 for region 77. For regions 68 and 74, the ones of greatest agricultural importance for Botswana, rainfall was below average in 15 of 21 and 17 of 22 episodes, respectively.

The ENSO episodes that did not evoke a negative response were fairly consistent among the regions. Of those occurring since 1951, the expected reduction in rainfall failed to occur in 1957 and 1976 in all regions. In 1953 it failed to occur in three of the six regions. In contrast, rainfall was below the mean in every region during the ENSO years 1963, 1965, 1969, 1972, 1982, and 1991 and in five of the six regions in 1951 and 1994.

b. Comparison of ENSO episodes with and without dry conditions over Botswana

To determine what controls the development of dry conditions over Botswana during ENSO episodes, a comparison is made between those episodes with below-

average rainfall in most of the region and those without prevailing dry conditions. Based on the results in section 4a, composites were produced for the episodes in 1953, 1957, and 1976 and for the remaining eight episodes occurring since 1951. These are termed the ''wet Botswana'' and ''dry Botswana'' composites, respectively. The seasonal evolution of the SOI and SSTs in select sectors of the Pacific, Atlantic, and Indian Oceans is examined using three-month seasons commencing in July prior to the ENSO year and ending in June of the year following ENSO. The Pacific sectors examined include Niño-1+2 (0°–10°S, 90°–80°W), Niño-3 (5°N–5°S, 150°–90°W) and Niño-4 (5°N–5°S, 160°E–150°W). The Atlantic and Indian Ocean sectors examined are shown in Fig. 3.

For each parameter, composites are formed for the

TABLE 1. The correlation coefficient between all possible pairs of regions, for regions 60, 62, 64, 68, 74, and 77. Location of regions is shown in Fig. 1.

	60	62	64	68	74	77
60	1.00	0.52	0.75	0.73	0.62	0.48
62	0.52	1.00	0.37	0.52	0.64	0.65
64	0.75	0.37	1.00	0.65	0.48	0.36
68	0.73	0.52	0.65	1.00	0.74	0.53
74	0.62	0.64	0.48	0.74	1.00	0.67
77	0.48	0.65	0.36	0.53	0.67	1.00
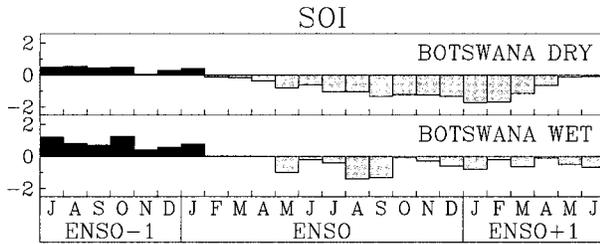
FIG. 6. Eight-season evolution of the SOI composited for ENSO episodes with and without drought over Botswana.
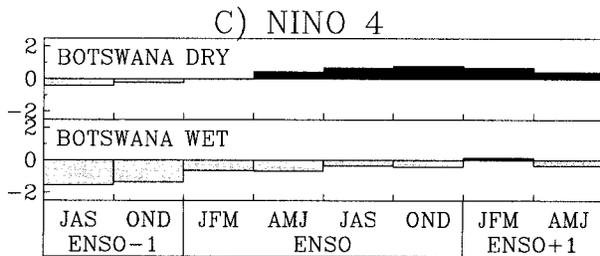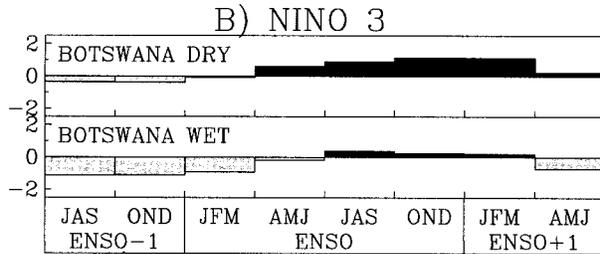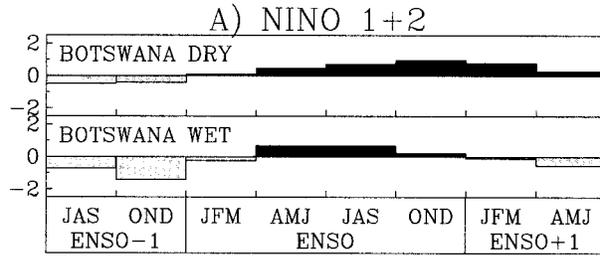

FIG. 7. Eight-season evolution of Pacific SSTs composited for ENSO episodes with and without drought over Botswana. SST units are degrees Celsius, representing a departure from a long-term monthly mean. (a) SSTs in Niño-1+2 (0°–10°S, 90°–80°W). (b) SSTs in Niño-3 (5°N–5°S, 150°–90°W). (c) SSTs in Niño-4 (5°N–5°S, 160°E–150°W).

episodes of the dry Botswana composite and for the episodes of the wet Botswana composite. Of particular relevance are the conditions during the three seasons when drought is anticipated in response to ENSO: October–December [OND (0)], January–March [JFM (+1)], and April–June [AMJ (+1)]. For the SOI and Pacific SSTs individual episodes were also examined, in order to determine the consistency of the contrasts, but these are presented only for the SOI.

1) CONDITIONS IN THE PACIFIC SECTORS

Some difference is apparent in the seasonal development of the SOI and Pacific SSTs in the two sets of episodes, but it is not particularly marked (Fig. 6). In both composites, the SOI is positive early in the episode, and a negative, or low-index, phase begins early in the ENSO year. The positive values are stronger in the wet Botswana composite and the low-index phase is weaker, but these contrasts are not consistently apparent in individual episodes. The most consistent contrast in SOI evolution between the episodes with and without drought is the persistence of the low-index phase, especially during the 9-month period when ENSO tends to produce drought in Botswana. In the three wet Botswana cases, the SOI does not remain strongly negative for more than 3 or 4 consecutive months, compared to 6–12 consecutive months in all but one of the nine dry Botswana cases. Since the SOI measures atmospheric, rather than oceanic, responses, this might be indicative of a weaker atmospheric response and weaker atmosphere–ocean coupling during the ENSO episodes that do not evoke drought in Botswana.

Somewhat stronger contrast is apparent in the SST evolution in the Pacific. The warming is much weaker in the wet Botswana composites than in the dry Botswana composites, especially in the central and western Pacific Niño-3 and Niño-4, respectively, in Figs. 7b and 7c). In those sectors, positive SST anomalies are apparent from AMJ of the ENSO year through AMJ of the following year in the dry Botswana composites. By comparison, positive anomalies are extremely weak and temporally limited in the wet Botswana composites. The situation is somewhat different in Niño-1+2 (the region of upwelling off the South American coast, Fig. 7a). Warming is evident in both the wet and dry Botswana

composites, but it is weaker and peaks several months earlier in the wet case. An examination of individual episodes (not shown) suggests that the most consistent difference between those with and without drought in Botswana is apparent in the SST evolution in the central and western Pacific. The contrast noted above is generally seen in each individual episode comprising the composites. Anomalously warm temperatures are apparent during the Botswana rainy season in all eight dry Botswana episodes and in six of the episodes during the specific season (January to June of the post-ENSO year) when drought is most likely to occur in conjunction with ENSO. In contrast, warm temperatures are evident in the central and western Pacific in only one of the three wet Botswana cases, the 1957 episode. For Niño-1+2, the contrast seen between the wet and dry Botswana composites does not consistently distinguish individual episodes.

Thus, the ENSO episodes that produce drought in Botswana are generally distinguished from those that
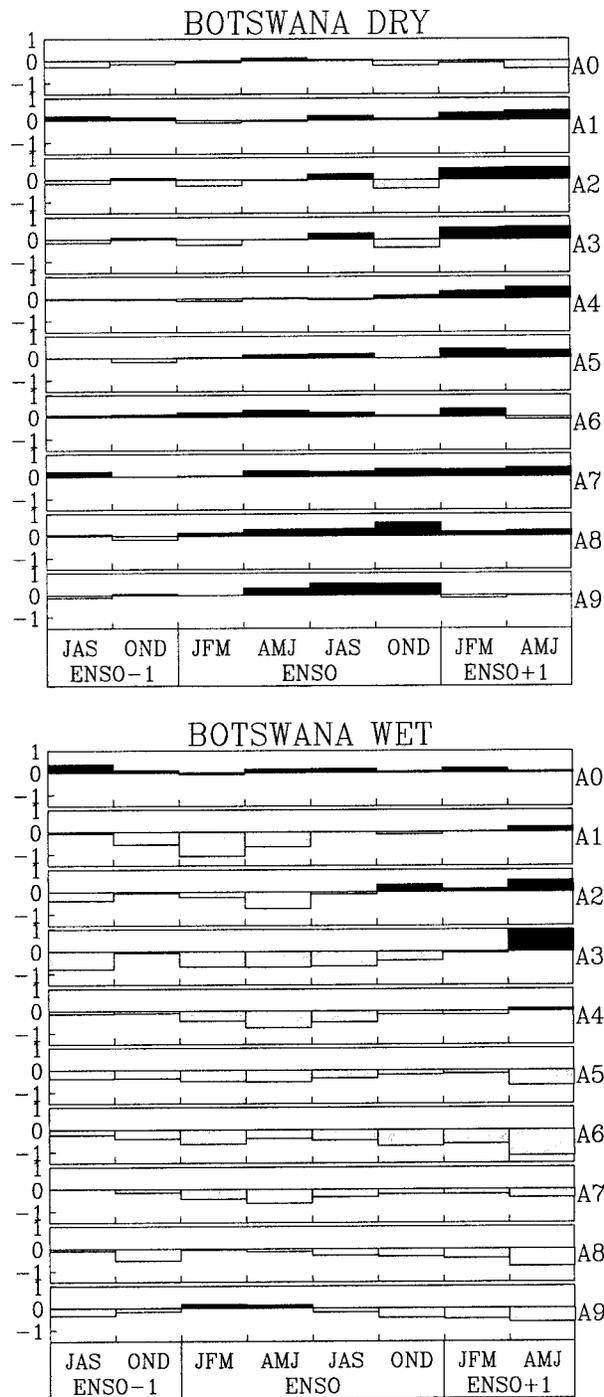
BOTSWANA DRY

BOTSWANA WET

Fig. 8. Eight-season evolution of Atlantic SSTs composited for episodes with and without drought in Botswana. Locations of sectors are shown in Fig. 2. SST units are degrees Celsius, representing a departure from a long-term monthly mean.

do not, on the basis of 1) strongly negative SOI anomalies and 2) well-developed and persistent SST anomalies extending to the central and western Pacific. This implies that the drought-producing episodes are those with strong and widespread atmospheric response. The

occurrence of a more localized SST anomaly in Niño-1+2, near the South American coast, is not a critical factor.

A comparison with the results of Schonher and Nicholson's (1989) study of ENSO's influence on California rainfall may help to explain these observations. That study found that for ENSO to enhance rainfall over the state as a whole, the Pacific SST anomalies must persist into the rainy season (i.e., well into the boreal winter, coincident with the summer rainy season of Botswana). The events that affected the state as a whole were generally those classified as Type 1 events by Fu et al. (1986). These episodes are characterized by particularly strong warming in the central Pacific that persists well into Northern Hemisphere winter (i.e., to the end of the ENSO year or beginning of the post-ENSO year, when the rainy season occurs in Botswana). The remaining episodes, termed Types 2 and 3, are characterized by less intense warming and/or warming confined to the eastern Pacific, and a return to normal temperatures before the winter season.

Furthermore, for ENSO's influence to extend throughout the state, strong tropical–midlatitude teleconnections are required. Such teleconnections are evident in both hemispheres during typical ENSO events (Horel and Wallace 1981; Karoly 1989) but can arise only when equatorial westerlies overlie a tropical heat source, such as a warm ocean (Webster 1981). Since equatorial westerlies are most common in winter and in the central Pacific, this would account for the correspondence between enhancement of rainfall statewide and Type 1 events.

These same considerations are relevant for Botswana, where there is considerable midlatitude influence on rainfall. The Type 1 warming pattern is evident in the dry Botswana composites and, of the six events between 1950 and 1982 that were classified as Type 1, five produced drought in Botswana [the 1986 and 1991 events were not classified by Fu et al. (1986) or by Schonher and Nicholson (1989)]. The exception was the 1957 event, noted earlier as one with SSTs fitting the dry Botswana pattern. That episode produced drought in much of southern Africa; however, in parts of Botswana the drought conditions were offset by heavy rains in January of 1958. The remaining two wet Botswana episodes, 1953 and 1976, were Types 2 and 3, respectively. The warming pattern typical of Types 2 and 3 (weaker warming, evident mainly in the eastern Pacific, and an early return to normal) is evident in the wet Botswana composites.

2) Conditions in the Atlantic and Indian Oceans

The most pronounced contrast between the wet and dry composites is apparent in the evolution of SSTs in the Atlantic and Indian Oceans. Except for A0 in the northern Atlantic (Fig. 8) and I6 in the southern Indian
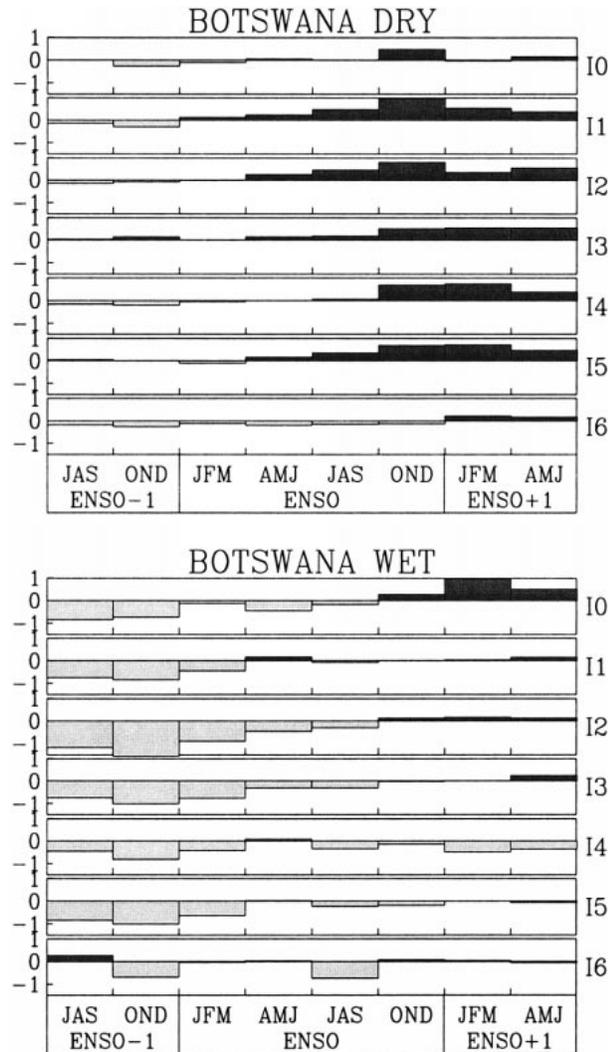
BOTSWANA DRY

BOTSWANA WET

FIG. 9. Eight-season evolution of Indian Ocean SSTs composited for episodes with and without drought in Botswana. Locations of sectors shown in Fig. 2. SST units are degrees Celsius, representing a departure from a long-term monthly mean.

Ocean (Fig. 9), SST anomalies for the dry Botswana composite are predominantly positive throughout the latter half of the ENSO episode, that is, during the period when the dry anomalies tend to occur over Botswana. A warming trend is also evident through the course of the episode. For the wet Botswana composite (Fig. 8), consisting of the 1953, 1957, and 1976 episodes, SST anomalies are overwhelmingly negative in the Atlantic sectors, except A0, and a warming trend is apparent only in A1 and A2; cooling trends during the course of the episode are apparent in sectors A6, A8, and A9. In the Indian Ocean, warming trends are apparent in all regions except I6, in both the wet and dry composites (Fig. 9). However, in the wet composite, the trend is one from strongly negative anomalies early in the ENSO episode to near-normal conditions in the latter half of

the episode, while the trend is from near-normal to strongly positive anomalies in the dry Botswana composite.

It is clear from Figs. 8 and 9 that the differences between SSTs in the dry Botswana and wet Botswana composites are overwhelmingly positive in both the Atlantic and Indian Oceans throughout the course of ENSO, except for sectors A0 and I6. This implies that warm anomalies in the tropical Atlantic and Indian Oceans tend to promote drought over Botswana, while cold anomalies tend to promote higher rainfall. This is consistent with the results of Nicholson (1997), indicating wet conditions during the cold phase of the first half of ENSO and dry conditions during the warm phase of the second half of ENSO. Differences between the wet Botswana and dry Botswana composites are particularly apparent in the equatorial and southern Atlantic sectors (A4–A9) in the latter half of the episode. In the Indian Ocean, strong differences are already apparent between these composites early in the ENSO episode.

An examination of the individual ENSO episodes shows that there is diversity among the episodes that compose each composite. However, the differences between the composites are large in comparison with the difference between the episodes within the composites.

c. Forecast potential of SST–rainfall relationships

In view of the agricultural and economic implications of drought in a semiarid country such as Botswana, forecasting the occurrence of drought is of the utmost urgency. Because of the capability of the scientific community at large to forecast ENSO occurrences, it is of particular importance to be able to forecast whether or not an episode produces drought. For any of the observed relationships with rainfall to have forecast potential, they must be quantified and should consistently distinguish the ENSO episodes that result in drought from those that do not.

The results described in section 4b demonstrate that, although some differences are apparent in the Pacific sector between ENSO episodes producing drought in Botswana and those that do not, the main contrast is evident in SST patterns in the Atlantic and Indian Oceans. Anomalously warm temperatures in these sectors promote drought over Botswana and surrounding regions of southern Africa, while anomalously cold temperatures promote high rainfall. The magnitude and consistency of the SST differences between drought and no-drought episodes suggest that these might have forecast potential.

To test this, we correlate rainfall anomalies in each of the six Botswanan regions with SST anomalies in each of the Atlantic and Indian Ocean sectors shown in Fig. 2. Correlations were carried out for rainfall anomalies of the JFM and AMJ seasons of the post-ENSO year with SSTs in the same season and up to three seasons prior. There are few significant correlations with

TABLE 2a. Correlation between rainfall anomalies in the JFM season of the post-ENSO year and SSTs in Indian Ocean sector I5. Data are given for the six rainfall regions indicated and for correlations both with SSTs in the concurrent season (indicated by 0) and in the previous two seasons (indicated by −1 and −2). The 1% and 5% significance levels are approximately 0.38 and 0.29, respectively.

Region	0	−1	−2
60	−0.23	−0.42	−0.32
62	−0.43	−0.36	−0.15
64	−0.20	−0.40	−0.28
68	−0.18	−0.33	−0.17
74	−0.29	−0.30	−0.12
77	−0.37	−0.28	−0.01

the Atlantic sectors and these appear to be random. There are strong, negative correlations for various sectors of the Indian Ocean, but in most sectors these do not reach the 5% significance level. The strongest correlations are for sector I5, the central, equatorial Indian Ocean (Table 2a). The influence of SSTs in region I5 is particularly strong during the JFM season, the core of the rainy season over Botswana. Region I5 has significant correlations during this season with each of the six rainfall regions. The highest, −0.43, is with region 62. Generally, the simultaneous rainfall–SST correlations are lower than with SSTs leading by one season. This suggests strong forecast potential. Correlations with rainfall in the AMJ season are high only for regions 62, 68, and 74, but the high correlations include, in most cases, all Indian SST sectors but I6 (Table 2b). This last point is interesting in that I6 is the sector in closest proximity to the rainfall regions. Again, the correlations are negative, indicating for both seasons that cold SSTs in the Indian Ocean tend to promote high rainfall over Botswana. Correlations are also evident one or more seasons in advance, as are well-developed SST anomalies (Nicholson 1986b).

These results, in conjunction with the robust ones described in section 4b, suggest that the overall pattern of SST anomalies in these two oceans, rather than SSTs in specific sectors, controls rainfall. This is the case for Sahelian Africa, where a pattern of cool temperatures in the North Atlantic and warm temperatures in the South Atlantic promotes drought (e.g., Rowell et al.
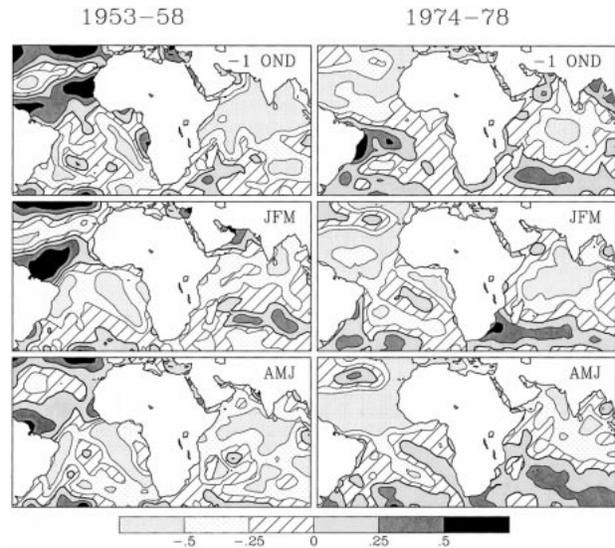

FIG. 10. SST anomalies during the OND, JFM, and AMJ seasons during two multiyear wet periods: 1952/53 to 1957/58 and 1973/74 to 1977/78.

1992; Ward 1992). A comparable situation exists in the southern Indian Ocean, where the SST gradient, rather than local sea temperatures, appears to be an important determinant of South African rainfall (Mason and Jury 1997; Mason 1995). To test the role of the spatial configuration of SSTs, we examined the SST patterns in two other situations: extended wet and dry periods, and wet and dry year composites that do not include ENSO years. The dry periods (see Fig. 5) are 1961/62 to 1965/66 and 1981/82 to 1986/87, each of which includes two ENSO years. The wet periods are 1952/53 to 1957/58 and 1973/74 to 1977/78, each of which includes one or two ENSO years.

The prevailing pattern of SSTs during the wet periods is one of cold anomalies in most of the Atlantic and Indian Oceans throughout the rainy season (Fig. 10). Exceptions are the southern Indian Ocean, especially during the 1970s wet period, and parts of the northern Atlantic, especially during the 1950s wet period. The patterns for the dry period of the 1980s sharply contrast with these, in that the anomalies are warm in most of

TABLE 2b. Correlation between rainfall anomalies in the AMJ season of the post-ENSO year and SSTs in seven sectors of the Indian Ocean. Data are given for the three rainfall regions indicated and for correlations both with SSTs in the concurrent season (indicated by 0) and in the previous two seasons (indicated by −1 and −2). The 1% and 5% significance levels are approximately 0.38 and 0.29, respectively.

	lag	I0	I1	I2	I3	I4	I5	I6
62	0	−0.40	−0.34	−0.38	−0.28	−0.02	−0.40	−0.11
	−1	−0.22	−0.29	−0.22	−0.32	−0.32	−0.49	−0.26
	−2	−0.12	−0.25	−0.21	−0.16	−0.25	−0.26	−0.17
68	0	−0.33	−0.29	−0.32	−0.26	−0.04	−0.35	−0.23
	−1	−0.30	−0.29	−0.22	−0.32	−0.22	−0.34	−0.32
	−2	−0.17	−0.28	−0.20	−0.20	−0.28	−0.22	−0.09
74	0	−0.32	−0.31	−0.32	−0.30	−0.02	−0.38	−0.10
	−1	−0.26	−0.31	−0.25	−0.26	−0.18	−0.32	−0.19
	−2	−0.14	−0.33	−0.31	−0.28	−0.28	−0.32	−0.17

1962–66 1982–87

FIG. 11. As in Fig. 10, but for the multiyear dry periods: 1961/62 to 1965/66 and 1981/82 to 1986/87.
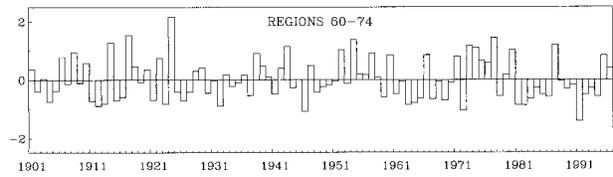

FIG. 12. Time series for regionally averaged rainfall departures for a sector including regions 60, 64, 68, and 74 (see Fig. 1) for the years 1901–96. Units are percent standard departure from the mean, with the annual totals calculated for the period Jul of the indicated year to Jun of the following year.

the Atlantic and Indian Oceans throughout the rainy season (Fig. 11). During the 1960s dry period, warm anomalies are much more prevalent than during either wet period, but they are strongly dominant only in the Atlantic. Thus, the SST patterns during these wet and dry periods are quite similar to those during the cold and warm phases of ENSO, which are associated with, respectively, wet and dry conditions over Africa.

The six wettest and six driest years used to produce the wet and dry composites are selected from the areally averaged time series of all stations in regions 60, 64, 68, and 74. These were chosen because they form a highly coherent region; all four are located within ENSO sector 8 of Nicholson and Kim (1997). The time series representing this area is shown in Fig. 12. From this time series the six wettest and six driest non-ENSO years were selected. These are indicated in Table 3. Figures 13 and 14 show the SST patterns averaged for three three-month periods that encompass the rainy season over Botswana. Except during the OND season, there is little contrast between the wet year composite and dry year composite. Nor is there any consistent pattern in SSTs among the six individual wet years or among the six individual dry years.

In view of the consistent associations of warm SSTs–dry conditions and cold SSTs–wet conditions evident in ENSO episodes and in multiyear dry and wet episodes, the above result is surprising. Clearly, the presence or absence of predominantly warm or cold conditions over

the oceans surrounding Africa is an insufficient discriminator between dry and wet conditions over Botswana and nearby regions. Nevertheless, the patterns in Figs. 13 and 14 represent the patterns in the most extreme non-ENSO years of the period 1946–92 and, in view of results for multiyear periods and for ENSO episodes, some relationship might be expected. It may be that in the case of individual warm or cold years, the atmosphere has insufficient time to adjust to the underlying SST patterns. Although ENSO events also represent individual years, they are by definition episodes of strong atmospheric and oceanic adjustment. This may be indicative of the atmosphere being the primary factor in modulating the character of the rainy season, with multiple states being possible even when SST patterns are similar. This would strongly limit the forecast potential based on SSTs.

d. Statistical probabilities of anomalous conditions based on ENSO

In section 4b, several differences were noted, on average, between ENSO events that produce drought in Botswana and those that do not. However, a look at individual years shows that, like SST patterns, these are not infallible discriminators. Additional prognostic information may be obtained on the basis of statistics alone.

Table 4 summarizes the probability of wet, dry, and normal conditions during ENSO for the second half of the ENSO episode, that is, during OND (0), JFM (+1), and AMJ (+1). The wet and dry classes are defined as positive or negative departures exceeding 0.5 standard deviations, and normal is defined as all anomalies with values less than 0.5 standard deviations. A look at the regional rainfall time series for the period 1901–95 shows that, depending on the region, about 25 to 30 of these years fall into the dry class and about 20 to 25 fall into the wet class.

TABLE 3. The six wettest and driest non-ENSO years of the period of 1946–96. Years run from Jul of one calendar year to Jun of the following, in order to include one annual rainy season.

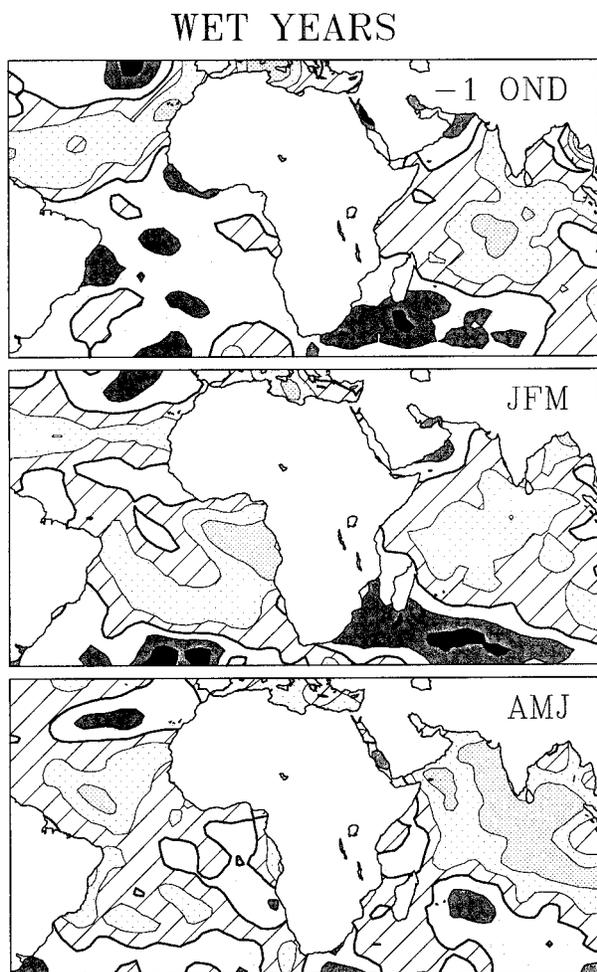| Wet	1952/53	1954/55	1973/74	1974/75	1977/78	1980/81
Dry	1946/47	1964/65	1967/68	1978/79	1981/82	1983/84

WET YEARS

DRY YEARS

FIG. 13. SST anomalies as in Fig. 10, but for the wet composite, composed of the years 1952/53, 1954/55, 1973/74, 1974/75, 1977/78, and 1980/81. Shading as in Figs. 4, 10, and 11.
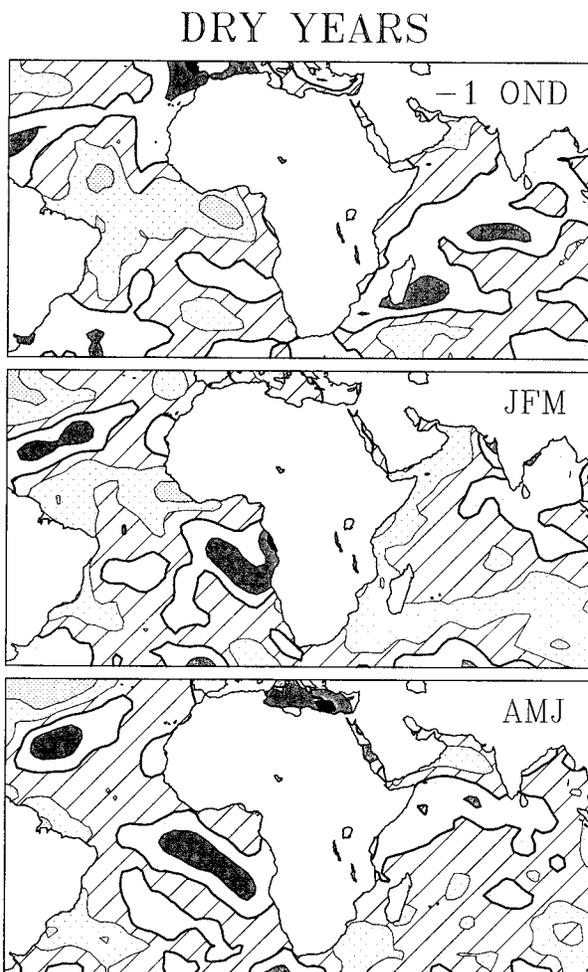
FIG. 14. SST anomalies as in Fig. 10, but for the dry composite, composed of the years 1946/47, 1964/65, 1967/68, 1978/79, 1981/82, and 1983/84. Shading as in Figs. 4, 10, and 11.

The probability of above-normal rainfall is low at any time during the second half of an ENSO episode, but it is particularly low for the AMJ season. Of the six regions and 11 episodes evaluated, positive anomalies occurred in only two cases. The occurrence of abnormally dry conditions in AMJ (+1) ranges from 7 of 10 episodes for region 74 to 8 of 11 episodes for region 62.

Earlier in the season this relationship is not quite so strong. For JFM (+1) the number of wet cases varies from none of 11 episodes to 3 of 11 episodes for the various regions, while the occurrence of dry conditions ranges from 4 of 10 episodes for region 77 to 7 of 11 episodes for region 62. Early in the rainy season [OND (0)], drought is more likely than wet conditions in all regions but one; however, it occurs in at most 4 of 10 or 11 episodes. Normal conditions of rainfall are generally the most likely at this time.

The statistics in Table 4 suggest that wet conditions (i.e., departures in excess of 0.5 standard deviations)

TABLE 4. Frequency of above-average, below-average, and normal rainfall, by region and season, for ENSO episodes between 1946 and 1992. The above- and below-normal categories are defined by positive or negative rainfall anomalies, respectively, in excess of 0.5 standard departures. The numbers in the table indicate the number of episodes in which the anomaly in the indicated season falls into each category. Seasons are Oct–Dec of the ENSO year [OND(0)] and Jan–Mar and Apr–Jun of the post-ENSO year [JFM(+1) and AMJ(+1)]. The total number of episodes is either 10 or 11, depending on the availability of data in various regions and seasons for the 1997 ENSO episode.

	OND(0)			JFM(+1)			AMJ(+1)		
Region	−	0	+	−	0	+	−	0	+
60	3	6	2	6	2	3	5	5	1
62	4	4	3	7	2	2	8	2	1
64	4	5	1	5	4	1	5	5	0
68	4	7	0	6	2	2	5	5	0
74	4	6	0	5	5	0	7	3	0
77	2	4	5	4	5	1	3	7	0

are extremely unlikely during the rainy season commencing late in the ENSO year. Further examination of the data used to produce this table shows that it is also unlikely that rainfall will exceed the long-term mean during this rainy season. During AMJ of this rainy season (i.e., during the post-ENSO year) the likelihood of rainfall being more than 0.5 standard deviations below average is about 70% or better in all regions, and the probability of wet conditions is extremely low in all regions. For JFM of that year, the likelihood varies from about 40% to over 60%, depending on the region.

5. Dynamical mechanisms linking ENSO and rainfall in Botswana

The mechanisms governing climatic variability over southern Africa are quite complex (Mason and Jury 1997). For this reason, it is difficult to speculate on the specific dynamical mechanisms linking ENSO to this region. This is particularly true for Botswana, because most of the studies that provide a perpective on this question have dealt with the summer rainfall region of South Africa and have considered mainly the midsummer season (November–January), when ENSO has its greatest influence there (Nicholson and Kim 1997). The ENSO response over Botswana shows notable contrasts with that region, including a maximum response that is several months later (February to May), when the main controls on rainfall have switched from midlatitude to tropical influences (Bhalotra 1973). The sources of moisture and the patterns of moisture transport are likewise different in the mid- and late summer seasons (d'Abreton and Lindesay 1993; Taljaard 1986, 1990), as are the pressure and wind patterns associated with ENSO (Nicholson 1997). Nevertheless, some results of prior studies may be relevant to understanding the mechanisms of the ENSO–rainfall linkage over Botswana.

The model simulations of Goddard and Graham (1999), which likewise dealt with the November–January period, show that an atmospheric response to Indian Ocean anomalies is essential for rainfall in southern Africa to respond to Pacific ENSO. This is in agreement with our conclusions, based on the SOI and on SST–rainfall associations. The model simulations further suggest that the rainfall response to ENSO appears to be related to the influence of both oceans on the Walker circulation over southern Africa and the consequences of this influence for low-level moisture transport.

Various observations support these conclusions. In late summer, when ENSO has its greatest influence on rainfall in Botswana, the southwestern Indian Ocean is generally the source of moisture over southern Africa (Taljaard 1986, 1990). It is advected from this region into southern Africa via a semipermanent anticyclone off the east coast. When the late summer season is dry, as in the post-ENSO year, the atmospheric circulation changes in such a way that vapor transport from the east is diminished over southern Africa, and the mois-

ture is advected instead into areas farther north, for example, into northern Mozambique and Malawi (d'Abreton and Tyson 1995). Harrison (1983) has noted atmospheric circulation changes that are consistent with this shift. Much of the region's rainfall is associated with diagonal cloud bands (Harrison 1984; Harangozo and Harrison 1983; Kumar 1978; Archarya and Bhaskara Rao 1981a,b). These are displaced eastward late in ENSO events, and the associated rainfall moves northward.

Other atmospheric circulation changes over southern Africa have also been linked to ENSO events: westerly wind anomalies over Africa at 200 mb (Arkin 1982), shifts in the Walker and Hadley circulations (Lindesay 1988), changes in the offshore zonal winds (Shannon et al. 1986; Schumann 1992), a weakening of the South Atlantic and southern Indian Ocean highs, and a decrease in northerly flow in the region of the Agulhas Current (Nicholson 1997). Additional links to SSTs include surface latent and sensible fluxes and modulation of surface currents (Walker 1990). However, the most important link between rainfall over southern Africa and SSTs during ENSO events appears to be related to moisture transport and to the atmospheric responses influencing that transport.

6. Summary and conclusions

This study has identified several characteristic contrasts between Pacific ENSO episodes that produce drought in Botswana and episodes that do not. The most pronounced contrast between the wet and dry composites is apparent in the evolution of SSTs in the Atlantic and Indian Oceans. In all but two of the 17 SST sectors, SST anomalies for the dry Botswana composite are predominantly positive throughout the latter half of the ENSO episode, when the dry anomalies over Botswana tend to occur. A warming trend is also evident throughout the course of the episode. For the wet Botswana composite, SST anomalies are overwhelmingly negative in all but one of the Atlantic sectors, a warming trend is apparent in only two sectors, and in three sectors a cooling trend occurs. In the Indian Ocean, warming trends are apparent in both the wet and dry composites in all sectors except I6 (just off the coast). Temperatures are, however, notably higher in the dry case, increasing from near normal to strongly positive in the latter half of the episode. In contrast, in the wet composite the trend is one from strongly negative anomalies early in the ENSO episode to near-normal conditions in the latter half of the episode.

Clearly, anomalously warm temperatures in the Atlantic and Indian Ocean regions surrounding Africa are generally associated with drought over Botswana and other regions of southern Africa, while anomalously cold temperatures are associated with high rainfall. Furthermore, the Indian Ocean appears to play a more important role. These results are consistent with earlier

results of Nicholson and Kim (1997), showing wet conditions during the cold phase early in ENSO episodes and dry conditions during the warm phase late in ENSO episodes.

This suggests that SSTs in the Atlantic and Indian Oceans exert some degree of control on the interannual variability of rainfall in this region, but the nature and extent of the impact is not clear. The warm–dry/cold–wet association shown for ENSO episodes is also evident for extended, multiyear wet and dry episodes in Botswana. However, this association is not apparent in individual wet and dry years that were not associated with ENSO. Thus, SSTs alone are inadequate discriminators between wet and dry conditions, and the correlations between rainfall and SSTs in specific sectors of the Atlantic and Indian Oceans are generally relatively weak. Notably, the correlations are weakest with the sectors in closest proximity to the sector I6, just off the east coast. Collectively, these results may indicate that the overall spatial patterns of SSTs, rather than SSTs in specific sectors, modulate rainfall variability. Such a conclusion has been drawn for regions of West Africa (e.g., Lamb 1978; Ward 1998).

Our interpretation of these results is that large-scale atmospheric response to SSTs is the overriding factor controlling rainfall variability. This conclusion is supported by the relationships, shown in section 4c, between the occurrence of drought and the evolution of the SOI and Pacific SSTs. In the ENSO episodes that were not associated with drought in Botswana, changes in the SOI (an atmospheric measure) tended to be weak and short-lived. This suggests a weaker atmospheric response and weaker atmosphere–ocean coupling during these episodes. Those episodes are also characterized by weaker and less consistent warming in the central and western Pacific. This may preclude the development of strong teleconnections to higher latitudes [see section 4b(1)].

Furthermore, this interpretation is also consistent with the lack of demonstrated SST–rainfall relationships in individual warm or cold years; the atmosphere may have insufficient time to adjust to the underlying SSTs in such cases. Although ENSO events also represent individual years, they are by definition episodes of strong atmospheric and oceanic adjustment. Thus, it is likely that the atmosphere is the primary factor modulating the character of the rainy season, with multiple states being possible even when SST patterns are similar. This conclusion, based solely on observations, agrees with that of Goddard and Graham (1999), based on model simulations. That study found that a rainfall response occurs over southern Africa only when ENSO produces an atmospheric response over the Indian Ocean. Observations would likewise support their conclusion that the mechanism linking the oceans to southern African rainfall involves modulation of large-scale atmospheric circulation patterns and moisture transport.

If these conclusions are correct, they imply that local sea surface temperatures have limited potential for forecasting drought occurrence in Botswana and elsewhere in southern Africa. However, the statistical associations between ENSO and rainfall provide at least some forecast potential. In all six rainfall regions examined, the probability of a wet season is very low at any time during the second half of an ENSO episode, but it is particularly low for the AMJ season (i.e., AMJ of the post-ENSO year). During that season, the likelihood of rainfall being more than one-half of a standard deviation below average is about 70% or better in all regions. For JFM of that same year, the likelihood varies from about 40% to over 60%, depending on the region. Consideration of the specific characteristics of ENSO episodes, particularly the evolution of SST and pressure patterns in the Pacific, can probably improve these statistics.

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