Sea Surface Temperatures and Australian Winter Rainfall

NEVILLE NICHOLLS

Bureau of Meteorology Research Centre, Melbourne, Australia

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ABSTRACT

A rotated principal component analysis of Australian winter (June–August) rainfall revealed two large-scale patterns of variation which together accounted for more than half of the total rainfall variance. The first pattern was a broadband stretching from the northwest to the southeast corners of the country. The second was centered in the eastern third of the continent. The two patterns were correlated to sea surface temperatures in the Indian and Pacific oceans. The first rainfall pattern was best related to the difference in sea temperatures between the Indonesian region and the central Indian Ocean. The second rainfall pattern was related to equatorial Pacific sea surface temperatures. This relationship reflects the influence of the Southern Oscillation on both sea surface temperatures and Australian rainfall but the relationship between the first rainfall pattern and the difference between Indonesian and central Indian Ocean sea surface temperatures is largely independent of the Southern Oscillation. This sea surface temperature difference may be another factor influencing Australian rainfall, somewhat separate from the well-known effect of the Southern Oscillation.

1. Introduction

Many studies have searched for empirical evidence of relationships between sea surface temperature (SST) anomalies (deviations from the long term mean) and rainfall anomalies. O'Mahony (1961), Priestley (1964) and Priestley and Troup (1966) appear to have been the first to suggest a link between SSTs and *Australian* rainfall fluctuations, based on limited data. Streten (1981, 1983) subsequently found that years of extensive Australian drought were associated with predominantly low SST over the eastern Indian Ocean and the southwest Pacific, particularly at low latitudes. Warmer than normal SSts were usually found in the eastern Pacific in these years. The opposite pattern appeared during extremely wet years. Kep (1984) and Whetton (1986) found positive correlations between SSTs around northern Australia and rainfall in the southeast corner of the continent.

The question that immediately arises is whether these SST anomalies can be regarded as the *cause* of the rainfall anomalies. This question could be addressed by inserting SST anomalies into a general circulation model of the atmosphere (GCM). Voice and Hunt (1984) inserted SST anomalies similar to those Streten found to be associated with Australian drought into a fixed-January GCM and examined the response. Decreased model rainfall was observed over parts of Australia, primarily in the far north. Farther south there was a mixed response, with some areas receiving *increased* rainfall. This model response is very different to the actual rainfall anomalies examined by Streten (1983). All the years Streten used to produce a composite picture of SSTs accompanying drought had below average rainfall over at least 80% of the continent.

The Department of Meteorology at the University of Melbourne has run a series of GCM experiments with SST anomalies similar to those in Streten's study (e.g., Simmonds and Smith 1986; Simmonds and Trigg 1988; Simmonds et al. 1989). As was the case with Voice and Hunt (1984), in parts of Australia precipitation decreased while elsewhere it increased (Simmonds, personal communication). The inability of the GCM experiments conducted thus far to successfully reproduce widespread Australian rainfall fluctuations has prompted the present study which looks for more detail in the SST–rainfall relationship. If SST anomalies do influence Australian rainfall fluctuations, it might be a *global* SST pattern which best represents the forcing, rather than just east Pacific and northern Australian SST anomalies.

A second stimulus for this study is the observed variation in the relationship between Australian rainfall and the El Niño–Southern Oscillation (ENSO) phenomenon. Rainfall over much of Australia tends to be below average during ENSO events (Ropelewski and Halpert 1987) but in some events (e.g., 1986/87) Australian rainfall anomalies are weak or of limited extent while in others (e.g., 1982/83) major, widespread droughts occur. It is conceivable that the differences between events may be related to SST anomalies not closely connected to ENSO (e.g., in the south Indian Ocean).

Corresponding author address: Dr. Neville Nicholls, BMRC, G.P.O. Box 1289 K, Melbourne, Victoria 3001, Australia.

This study differs from earlier studies in several ways. First, more years of data have been used than were used by Streten, Kep or Whetton, and the study also includes the SSTs of the Indian Ocean and the North Pacific. Second, only winter (June–August) rainfall has been considered. It appears feasible that different factors may affect rainfall in different seasons. Here winter rainfall has been selected for analysis because most of Australia's major crops are winter crops. Streten examined annual rainfall totals but the effects of SST anomalies on rainfall might vary seasonally. Kep concentrated on late winter and early spring rainfall, while Whetton examined relationships throughout the year. Finally, the possibility that more than one important mode of variability might affect Australian rainfall has been allowed for in this study. Both Kep and Whetton concentrated on rainfall in the state of Victoria in the southeast corner of the continent. Streten's studies composited years when virtually the entire continent had rainfall anomalies of the same sign. Pittock (1975) has provided evidence, using annual rainfalls, of *two* important modes of variation of Australian rainfall. The existence of two modes might account for the differences in rainfall anomalies between ENSO events and, perhaps, for the apparent inability, up to now, of GCM experiments to simulate continental-scale Australian droughts.

2. Data

a. Sea surface temperatures

The Comprehensive Ocean–Atmosphere Data Set (COADS) produced by the Cooperative Institute for Research in Environmental Sciences (Slutz et al. 1985) was used to provide time series of SSTs over the Indian and Pacific oceans (Atlantic Ocean SSTs were also examined but no interesting relationships were found with Australian rainfall). Only data since 1946 have been used in this study. The earlier data were eliminated to minimize problems due to changes in observing techniques. The COADS data used here ended in 1979.

The SST observations were averaged in 10 degree latitude–longitude boxes (e.g., 0°S–10°S, 150°E–160°E) for each month from 1946 to 1979. The June, July and August SSTs were then averaged to produce a mean winter SST for each box for each year. Not all 10 degree boxes had complete records for each winter over the 34 years studied. At least 20 years, and usually more than 30, of winter mean SSTs were available from almost every box between latitudes 40°S and 60°N. Outside this belt the data were very sparse and have not been used.

b. Australian district average rainfall

The Australian Bureau of Meteorology, for the purpose of monitoring rainfall, divides the country into 107 districts. The boundaries of the districts are chosen so that all rainfall stations within a specific district are in a similar rainfall regime (Coughlan 1979). All rainfall stations in a district have their rainfalls averaged to provide a district average rainfall for each month. District average rainfalls for each district from 1946 to 1979 were used in this study. A district average rainfall was available for each district for every winter in this period.

The 107 rainfall districts cover a variety of different rainfall regimes. Those located in the north of the continent generally receive most of their rainfall in the summer (December–February). Some of these districts receive very little rainfall in winter. For example, District 1, in the far northwest, has a mean winter rainfall of only 26 mm while District 97, on the west coast of Tasmania, receives 781 mm on average. Despite the large range of winter rainfalls, all the districts have been used together in the analyses in this study. This approach has been used previously with success (e.g., Pittock 1975) indicating that rainfall *anomalies* exhibit spatial scales large enough to encompass different rainfall regimes.

c. Southern Oscillation index

Many studies have demonstrated that the ENSO phenomenon affects Australian rainfall (e.g., McBride and Nicholls 1983; Nicholls 1988). Partial correlation has been used here to isolate the relationship between SSTs and rainfall from the effects of ENSO (see sections 3c and 4c). To do this an index of ENSO is needed. The Southern Oscillation index [here defined as the difference in surface atmospheric pressure between Tahiti (17°S, 150°W) and Darwin (12°S, 131°E), standardized to a mean of zero and a standard deviation of 10] has been used for this purpose. Monthly values of the index were provided by the National Climate Centre of the Australian Bureau of Meteorology. The June, July and August values were averaged to provide a winter value of the index.

3. Method

a. Principal component analysis of rainfall

Principal components of the correlation matrix of district average winter rainfalls were calculated to provide rainfall indices. The first ten eigenvalues of the correlation matrix are shown in Fig. 1. The error bars in the figure represent the standard error for each eigenvalue, calculated using the method of North et al. (1982). The first two eigenvalues are well separated from the others but not from each other. They form an effectively degenerate couplet. Eigenvalues three and four form another degenerate couplet, again separated from the others. All the remaining eigenvalues are degenerate. The first four components account for nearly

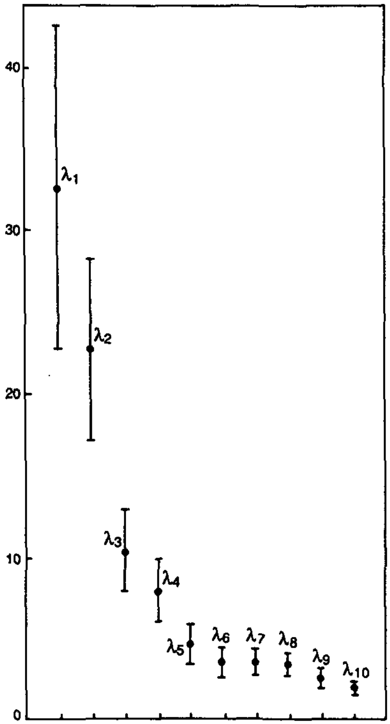

FIG. 1. Schematic diagram of the first ten eigenvalues of the correlation matrix of Australian winter rain. The error bars represent the standard error for each eigenvalue.

75% of the total variance in the district rainfalls; the first two components alone account for 55%.

Richman (1986) demonstrated that the large sampling errors of unrotated components which form degenerate multiplets may lead to the components being mixed up and not reproducing underlying patterns. He recommended rotation of components that form degenerate multiplets. The first two components were therefore rotated, using the Varimax and Promax k = 2 procedures. The Varimax procedure is the most common orthogonal rotation; the Promax k = 2 is one of the oblique rotations recommended by Richman (1986). The results of rotating the first four components were also examined.

The geographical patterns of the first two unrotated components were rather similar to their rotated counterparts, irrespective of whether Varimax or Promax was used, or whether two or four components were rotated. In order to decide which set of components to use for the remainder of the study, the correlation matrix was examined, as suggested by Richman (1986). The spatial correlations of the district with the highest loading on each component to each of the other 106 districts were plotted to provide information on the scale and orientation of the anomaly features and compared to the principal component. This was done for the unrotated components and for the components after rotation using Varimax and Promax, rotating both two and four components. Subjective comparison between the district-to-district correlation fields and the corresponding components indicated that the rotated components more correctly revealed the underlying correlation fields compared with the unrotated components. Rotation by either Varimax or Promax, and rotation of either two or four components, produced similar patterns. Throughout the remainder of this paper the rainfall components used are the Varimax rotations of the first two components.

b. *Correlations with SSTs*

Time series of the scores of the two rotated components of Australian winter rainfall were correlated with SSTs in the 10 degree latitude–longitude boxes over the Indian and Pacific oceans. All the correlations were calculated using at least 20 years of data; most used more than 30 years. A correlation with a magnitude of 0.44, calculated with 20 pairs of data, is significant at the 5% level, and 0.36 for 30 pairs.

SSTs in selected boxes were also correlated with district average rainfalls over all Australia. The boxes selected were those with strong correlations with either of the two rotated components of rainfall.

c. *Partial correlations*

The SSTs in parts of the Indian and Pacific oceans are known to be correlated with ENSO. It is feasible, therefore, that the correlations examined here between SSTs and the rotated rainfall components may not imply a direct relationship but, rather, that both the SSTs and Australian rainfall are influenced by ENSO. Partial correlations were calculated to check this. Partial correlation coefficients indicate the strength of the relationship between two variables once the effects of a third variable has been removed; here it is the effect of ENSO on SSTs and the rotated rainfall components that is removed. The square of the partial correlation coefficient indicates the proportion of the residual variance (i.e., the variance *not* associated with ENSO) of the SSTs which is associated with the residual variance of the rainfall component (Johnston 1980). If the SST *directly* forces the atmospheric anomalies resulting in the fluctuations in the strength of the rainfall components, then the correlation pattern should still exist in the partial correlation patterns. Otherwise, we can conclude that the observed correlations between SSTs and rainfall simply reflect the effects of ENSO on both.

4. Results

a. *Rotated principal components of winter rainfall*

The structure of the first two principal components of Australian winter district average rainfall, after Varimax rotation, is shown in Fig. 2. The isopleths indicate the correlations between district rainfall and the com-

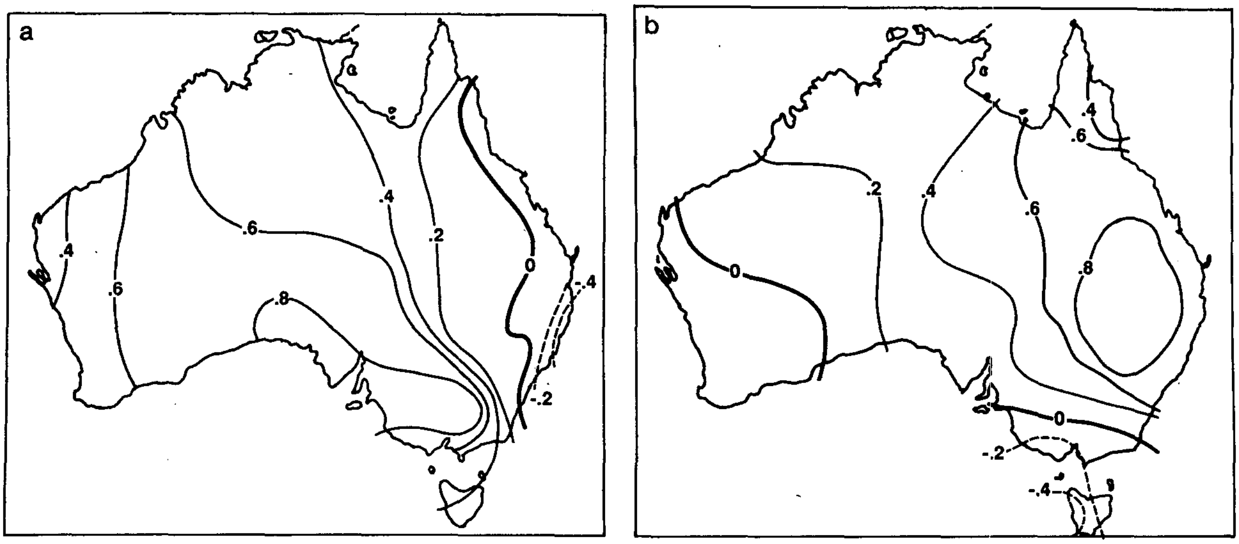

FIG. 2. Correlations of district rainfall with (a) the first rotated principal component of Australian winter rainfall and (b) the second rotated principal component.

ponent. As noted above, inspection of the matrix of correlations between district rainfalls indicated that these two components do represent important modes of rainfall fluctuations.

The first component is dominated by a broad band of strong, positive correlations from the northwest to the southeast of the country. The strongest correlations are in the southeast of the continent. There is a strip of negative correlations along the east coast. The second component represents rainfall fluctuations in the eastern half of the continent, centered about 30°S, 150°E. There are small negative correlations in the southwest and southeast.

These components are quite similar to the unrotated annual rainfall components found by Pittock (1975) who related them to the Southern Oscillation and to the latitude of the subtropical ridge.

b. *SST correlations*

The correlations of the two components with SST are shown in Fig. 3. The two correlation patterns are very different. The pattern of correlations with the first rainfall component is dominated by positive correlations around Indonesia and strong negative correlations in the central Indian Ocean. Positive correlations between Australian rainfall and SSTs around Indonesia have been noted previously (e.g., Streten 1981, 1983; Kep 1984; Whetton 1986). The strongest correlation in Fig. 3a is −0.69 with SSTs in the 10°–20°S, 80°–90°E box. Kep (1984) found strong negative correlations between SSTs in this area and rainfall in the southeast corner of the continent in a much smaller dataset than that used here. There is also a weaker band of positive correlations in the southeast Pacific evident in Fig. 3a. Correlations with SSTs in the east and central Pacific are weak.

The correlations with the second rotated component of rainfall (Fig. 3b) are strongest in the central equatorial Pacific. These correlations tend to confirm the results of Streten (1981, 1983). A broad area of rather weak negative correlation throughout the central and eastern Pacific is also evident in Fig. 3b. Another area of negative correlation is found in the north Indian Ocean. Weak positive correlations surround Australia.

In Fig. 4 the correlations between Australian district rainfall and SSTs in the central equatorial Pacific box (0°–10°S, 170°W–180°) and the difference in SST between Indonesia (0°–10°S, 120°–130°E) and the central Indian Ocean (represented by the 10°–20°S, 80°–90°E box) are shown. The difference in SST between Indonesia and the central Indian Ocean is closely related to rainfall in a broad northwest–southeast band, and negatively correlated with east coast rainfall (Fig. 4a). The central equatorial Pacific SST is best related to eastern rainfall (Fig. 4b).

c. *Partial correlations*

The SSTs over much of the Pacific and Indian oceans are strongly correlated with the Southern Oscillation index in the Southern Hemisphere winter (Fig. 5). As noted in section 3c, partial correlations between SSTs and the first two rotated principal components of Australian winter rainfall were calculated to determine how independent of the Southern Oscillation the SST-rainfall correlations were. The partial correlations are shown in Fig. 6.

The partial correlations with the first component are similar to the total correlations (compare Figs. 3a and

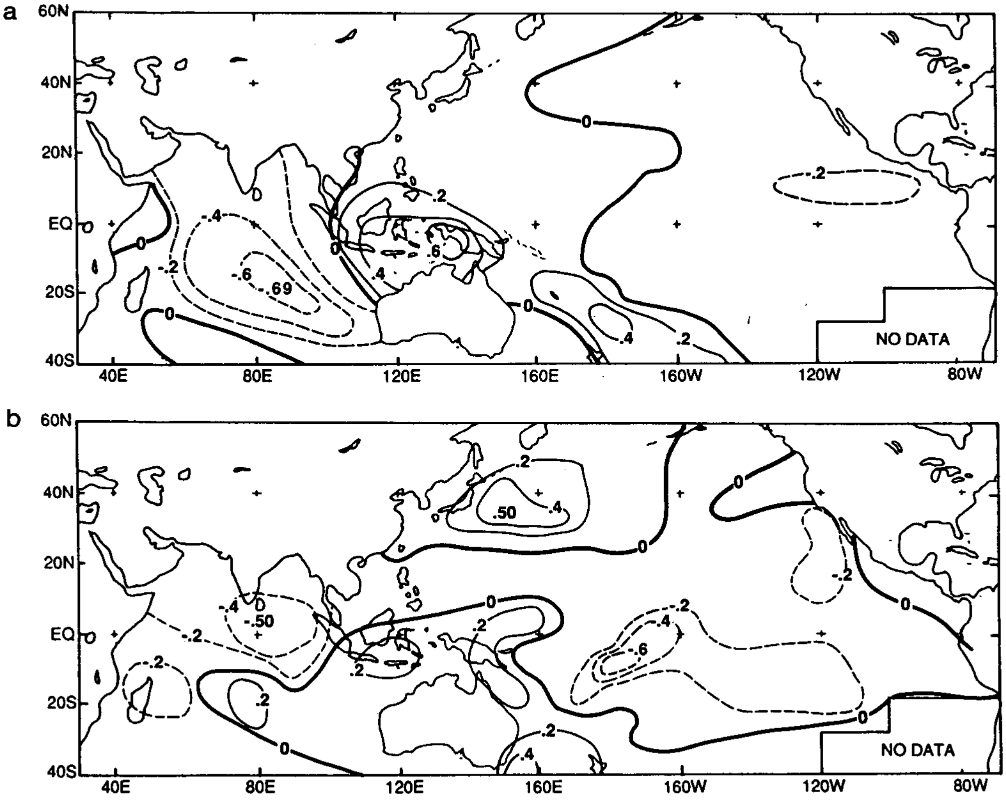

FIG. 3. Correlations between SSTs and (a) the first rotated principal component of Australian rainfall and (b) the second rotated principal component.

6a). Removal of the effects of the Southern Oscillation has slightly weakened the positive correlations with SSTs around Indonesia but has had little effect on the negative correlations in the central Indian Ocean. SSTs in this latter area are not closely related to the Southern Oscillation (Fig. 5). The strong gradient in SST correlation off the northwest coast of Australia has not been weakened appreciably by removing the effects of the Southern Oscillation, indicating that this pattern is largely independent of the Southern Oscillation. The

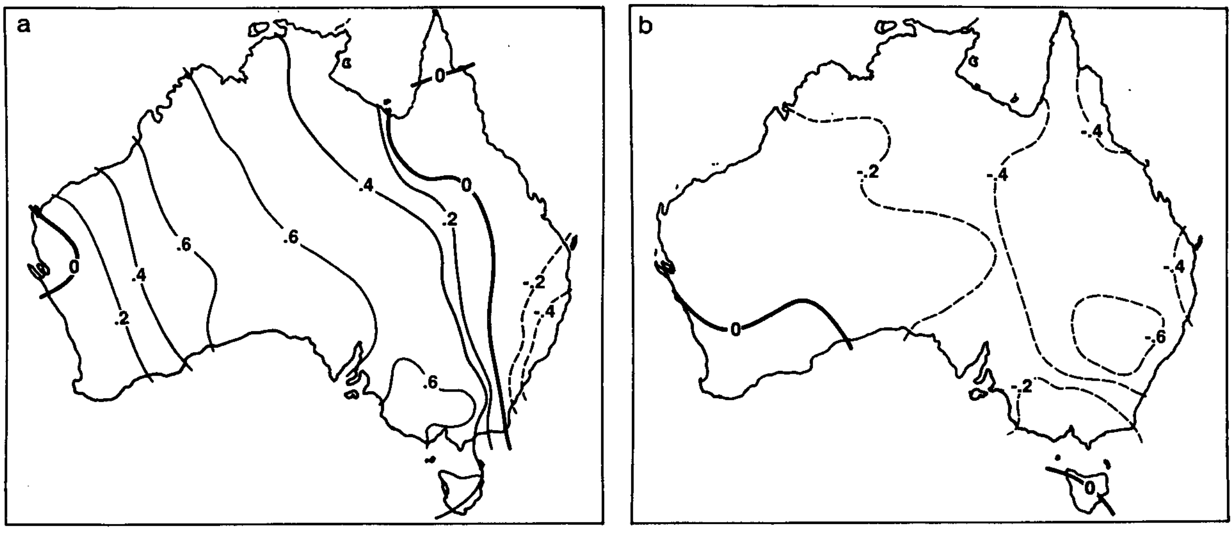

FIG. 4. Correlations between winter rainfall and (a) the difference in SST between Indonesia and the central Indian Ocean and (b) the SST in the central equatorial Pacific Ocean.

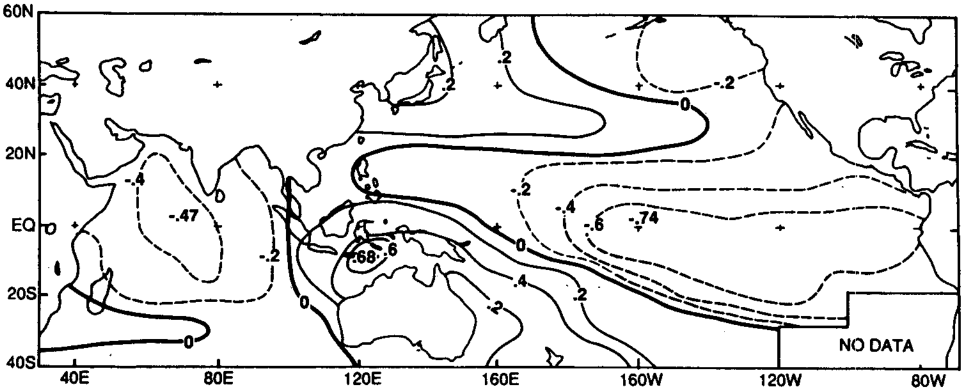

FIG. 5. Correlations between SSTs and the SOI.

weak negative correlations in the eastern equatorial Pacific (Fig. 3a) are related to the Southern Oscillation (Fig. 5) and have disappeared in the partial correlations (Fig. 6a).

Much larger changes are evident between the total correlations between SSTs and the second rainfall component (Fig. 3b) and the corresponding partial correlation (Fig. 6b). The weak positive correlations around Australia have disappeared. The negative correlations in the east equatorial Pacific have disappeared or even been replaced by positive correlations. The changes in the correlation pattern when the effects of the Southern Oscillation are removed indicates that the pattern was largely the result of this phenomenon. The correlation of the Southern Oscillation with the second rainfall component is greater than with the first component (0.55 versus 0.31).

5. Discussion

This study has isolated two patterns or modes of variation of Australian rainfall that seem to operate,

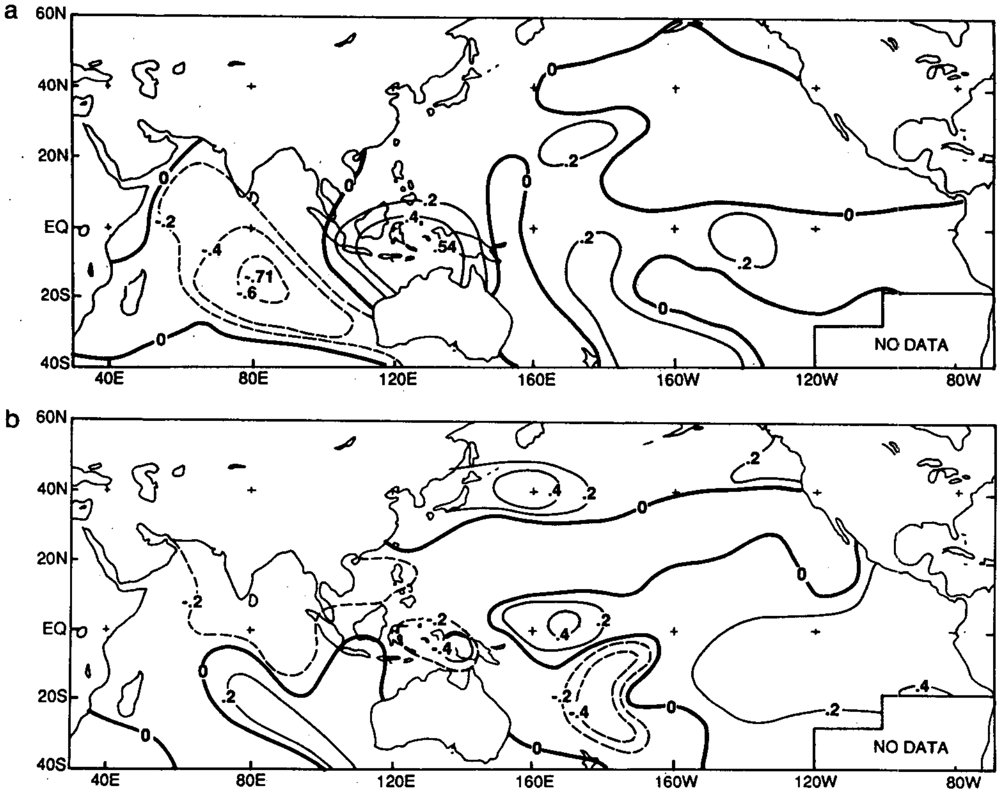

FIG. 6. Partial correlations between SSTs and (a) the first rotated principal component of Australian rainfall, after removal of effects of SOI, and (b) the second rotated principal component of Australian rainfall, after removal of effects of SOI.

to some degree at least, independently of each other. Pittock (1975), using annual rainfall, also isolated two similar patterns of rainfall fluctuations. The two patterns isolated in this study are each associated with a separate, specific pattern of correlations with SSTs. One rainfall pattern (the second) is closely associated with the Southern Oscillation and removal of the effects of this phenomenon also removes most of the correlation with SSTs.

The other rainfall pattern (the first, which accounts for over 30% of the total variance in Australian winter district average rainfall) is less closely associated with the Southern Oscillation. Even after the effects of the Southern Oscillation are removed by partial correlation this pattern is closely related to the difference in SST between the Indonesian region and the central Indian Ocean. The correlation between the first rotated principal component of Australian winter rainfall and the difference in SST between 0°–10°S, 120°–130°E and 10°–20°S, 80°–90°E, is 0.75.

Time series of the amplitudes of the two rotated rainfall components (PCP1 and PCP2), the Southern Oscillation index (SOI), SST in the box 0°–10°S, 170°W–180°, and the SST difference between 0°–10°S, 120°–130°E and 10°–20°S, 80°–90°E are all shown in Fig. 7. The relationships between the variables and the temporal scale of these relationships are indicated by these time-series plots. The relationships are mainly on an interannual time scale, rather than being the result of parallel trends or long-period variations.

One of the annual patterns of rainfall variations found by Pittock (1975) resembles the first pattern found in this study. Pittock demonstrated that this pattern was related to the latitude of the subtropical ridge along the east coast of the continent. Here it has been demonstrated that the rainfall pattern is related to events off the *northwest* coast of the continent. The correlation between the latitude of the east coast subtropical ridge and the SST gradient from Indonesia to the central Indian Ocean was −0.59. This suggests that the latitude of the east coast ridge may be determined, to some extent at least, by the SST gradient off the *northwest* coast of the continent.

The SST gradient in the Indian Ocean and the latitude of the subtropical ridge along the east coast might be linked through the occasional appearance of large-scale cloud bands, oriented northwest–southeast across the continent. Tapp and Barrell (1984) have examined various characteristics of these bands which occur mainly during winter. On average about two bands appear each month between April and September and they last typically for about 4 days. The cloud in the band usually appears first about 12°S, 100°E and may extend east-southeast for several thousand kilometers, on many occasions reaching the east coast. Tapp and Barrell (1984) provide some excellent satellite photographs of these major synoptic cloud features. Wright (1988a,b) has demonstrated that interannual rainfall variations over southeast Australia are related to the frequency of occurrence of these "northwest cloud bands" which he concludes are indicative of tropical–extratropical interactions. The proximity of the origin of these cloudbands to the two areas of the extrema of the SST correlations with the rainfall patterns suggests that the *gradient* of SST in the east Indian Ocean might be the cause of interannual changes in frequency of the bands. Tapp and Barrell (1984) suggested that an enhanced gradient of SST across the region where the cloud first appears may assist in the formation of the band.

Alternatively, it might be that the gradient of SST anomalies in the east Indian Ocean *and* the interannual changes in the frequency of occurrence of northwest cloud bands (and thus rainfall fluctuations) are both attributable to atmospheric circulation changes. Tapp and Barrell (1984) note that for a cloud band to form,

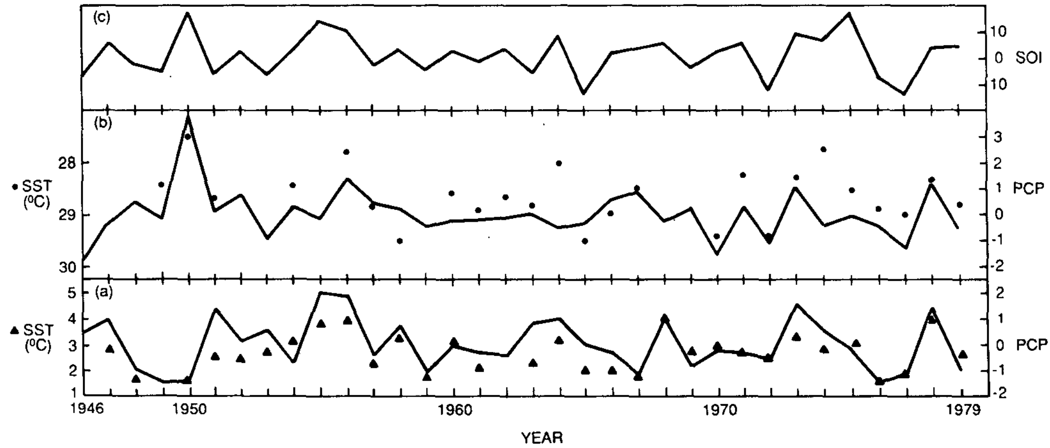

FIG. 7. Time-series plots of (a) amplitude of first rotated principal component of Australian rainfall (PCP1—full line) and gradient in SST between 0°–10°S, 120°–130°E and 10°–20°S, 80°–90°E (SST—full triangles); (b) amplitude of second rotated principal component of Australian rainfall (PCP2—full line) and SST in 0°–10°S, 170°W–180° (SST—full circles); (c) Southern Oscillation index (SOI—full line).

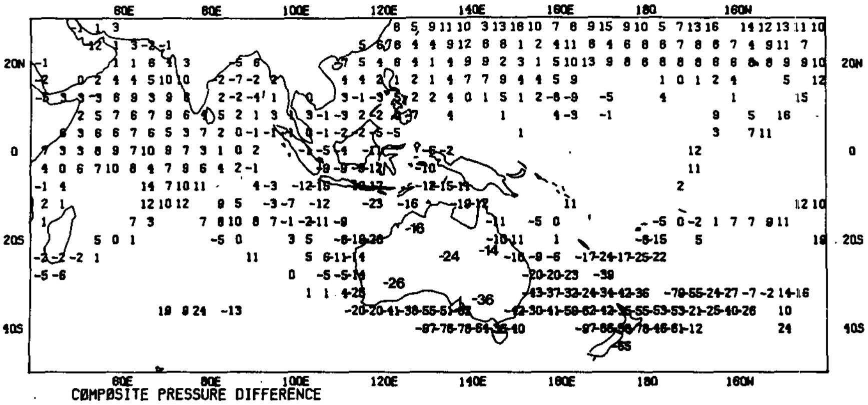

FIG. 8. Difference in atmospheric pressure between four years with large SST gradient between Indonesia and the central Indian Ocean and four years with weak SST gradient. Pressure differences (in tenths of hPa) are shown for 4° latitude–longitude boxes and for five Australian stations. See text for details of stations and years used.

a pronounced long-wave trough off the west coast, extending at least to 15°S, is needed. The presence of several such troughs during the winter might produce, as well as several cloud bands, colder than normal SSTs in the central Indian Ocean. Thus, the SST pattern might not be the cause of the atmospheric circulation anomalies leading to the rainfall fluctuation, but the consequence.

The circulation changes associated with changes in the Indonesia–central Indian Ocean SST gradient were investigated by compositing surface meteorological variables available in the COADS data. The COADS data in four years with strong SST gradient between Indonesia and the central Indian Ocean (1955, 1956, 1968, 1978) were composited and compared with a composite of four years with weak SST gradient (1959, 1967, 1976, 1977). The differences in pressure are shown in Fig. 8. The COADS data were, for this figure, averaged in 4° latitude–longitude boxes. Only boxes which had data for all eight years are shown. Also shown are the differences in pressure between the two groups of years for five Australian stations, to provide continuity across the continent. The stations were Halls Creek (18°S, 128°E), Kalgoorlie (31°S, 121°E), Alice Springs (24°S, 134°E), Charleville (26°S, 146°E) and Mildura (34°S, 142°E). The major difference between the two composites was a broad region stretching from Indonesia to east of New Zealand with significantly lower pressures when the SST gradient was large. The largest absolute pressure differences (over 5 hPa) between the composites were found around *southeast* Australia with smaller absolute differences around northwest Australia. Significantly more cloud and higher humidity was present over Indonesia and off northwest Australia in the large SST gradient composite. These results confirm those of Wright (1988a,b) using different data and more years.

The results presented here, along with those of Pittock, Wright, and Tapp and Barrell, lead to speculation about the sequence of events relating the Indian Ocean SST gradient, pronounced west coast troughs (identified by Tapp and Barrell as being associated with northwest cloud band formation), the cloudbands themselves, the latitude of the *east* coast ridge, and rainfall fluctuations over southeast Australia. It might be that a pronounced long-wave trough off the *west* coast provides the stimulus for the generation of the cloudband (Tapp and Barrell 1984) which in turn results in intensification of the trough, through tropical–extratropical interaction (Wright 1988a,b), as it approaches the *southeast* of the continent. The consequent lowering of pressure, with the greatest reduction south of the latitude of the subtropical ridge, would shift the ridge northward. This sequence of events would account for the relationships between events off the west and east coasts of the continent, and the intermediate relationships with the cloudbands.

This linking of the coasts does not, however, reveal whether the SST gradient in the Indian Ocean can be considered the forcing factor. The causality involved in the relationships between the SST gradient, the anomalous trough stretching from Indonesia to southeast Australia, the latitude of the east coast ridge, and Australian rainfall fluctuations might be examined with a GCM experiment. If the SST gradient is the *cause* of the rainfall fluctuations over Australia, then a GCM experiment with an imposed anomalously large SST gradient might be expected to reproduce the broad anomalous trough found in the composite of strong gradient winters. Other empirical work with the COADS data (e.g., calculation of fluxes) might provide further information about whether the SST gradient can be regarded as the causal variable.

Whatever such studies reveal about causality, it is quite clear that events in the eastern Indian Ocean have an important influence on Australian winter rainfall. This area has not been considered in studies with GCMs attempting to simulate Australian rainfall fluctuations through the insertion of SST anomalies. Perhaps this is the reason for the less than perfect simulations produced thus far. The existence of this relationship with a pattern of SSTs *not* closely associated with the Southern Oscillation might also be the reason for the variation, noted in the Introduction, in the observed relationship between Australian rainfall and ENSO. Further work on the interaction between the atmosphere and ocean in the eastern Indian Ocean seems necessary if we are to develop a more complete understanding of the factors affecting Australian rainfall. Studies of possible relationships of Indian Ocean SSTs with Australian rainfall in other seasons are underway.

If further work does indicate that Indian Ocean SSTs play a forcing role on Australian rainfall fluctuations then their potential use in seasonal prediction could be considered. McBride and Nicholls (1983) demonstrated that lag relationships exist between Australian rainfall and the Southern Oscillation, indicating that seasonal rainfall prediction is feasible for parts of the continent, although with rather low levels of expected skill. If the Indian Ocean SST gradient is independent of the Southern Oscillation and did show strong autocorrelation it might add to the skill obtainable in seasonal rainfall prediction. As a preliminary check of this the correlations between monthly values of the SST gradient from May to August were calculated. Strong lag correlations were found. For instance there was a correlation of 0.48 between the May and August gradients. Much stronger correlations were found at one and two month lags (up to a correlation of 0.82 between July and August). The strong autocorrelations indicate that the Indian Ocean SST gradient may indeed assist in seasonal prediction of Australian rainfall. They seem too strong to be the result of simple direct atmospheric forcing of the SST gradient. Some form of ocean–atmosphere interaction may be the cause of these persistent anomalies.

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