Seasonal Relationships between Australian Rainfall and the Southern Oscillation

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(Manuscript received 23 February 1983, in final form 26 July 1983)

ABSTRACT

Correlations between indices of the Southern Oscillation (SO) and areal average rainfall for 107 Australian rainfall districts for the period December 1932 to November 1974 have been calculated. Simultaneous correlations between the SO and rainfall show a clear annual cycle with the best relationship occurring in spring (September–November). The season with the weakest relationship is summer (December–February). In all seasons, seasonal rainfalls in some parts of Australia are significantly correlated with the SO in the preceding season. The strongest lag correlations occur with spring rainfall, which for some areas is also significantly correlated with the SO two seasons (six months) earlier.

Correlations were also calculated with the data divided into two subseries from 1932 to 1953 and from 1954 to 1974. These calculations suggest a westward shift with time of the correlation pattern, associated with substantial changes in the magnitude of the correlations in some areas.

Some speculations on the possible causes of certain aspects of the observed seasonal cycle in the correlations are advanced.

1. Introduction

This paper describes a study of the relationship between seasonal rainfall over Australia and the Southern Oscillation (SO). The SO is a planetary-scale phenomenon involving a negative correlation between pressure over Indonesia and pressure over the southeastern Pacific. The SO is related to fluctuations in the intensity of the Walker circulation, an east–west cell with its upward branch near Indonesia and downward branch over the tropical eastern Pacific. Associated with the SO are large interannual variations in sea surface temperature, rainfall and wind strength over much of the Pacific. The SO was described by G. T. Walker in the early decades of this century, and recent descriptions of many of its features have been given by Troup (1965), Trenberth (1976), Wright (1977), Julian and Chervin (1978) and Rasmusson and Carpenter (1982).

2. Background

It is common practice to describe the intensity of the SO in terms of a Southern Oscillation Index (SOI). Indices used in this paper are as follows:

1) The Troup Index, the mean sea-level pressure difference between Papeete and Darwin, normalized for each calendar month.

2) The Wright Index, derived from a principal component analysis of seasonal mean pressure at eight Southern Hemisphere or tropical stations.

3) Mean sea level pressure at Darwin (12°26′S, 130°52′E).

4) Mean sea level pressure at Papeete (17°33′S, 149°37′W).

The relationship between the SO and Australian rainfall has been investigated by Pittock (1975), using area-averaged rainfall for 107 Australian rainfall districts from 1941–70. Pittock demonstrated that annual rainfall over most of eastern Australia is well correlated with the Troup Index of the SO. His results are confirmed in Fig. 1 using data from 1933–74 for two other SOI's, the Wright Index (Fig. 1a) and Darwin pressure (Fig. 1b). Correlations exceeding 0.4 in magnitude are shaded in this figure and in the remainder of the diagrams in this paper.

3. Aims of the study

Rainfall over northern Australia is highly seasonal, with a summer-wet versus winter-dry cycle associated with variations in the latitude of the equatorial trough. It is thus of interest to determine the variation throughout the seasonal cycle of the relationship between the SO and Australian rainfall. This is the first aim of this paper. A number of earlier studies (Walker, 1923, 1924, 1928; Kidson, 1975; Wright, 1977) have studied this aspect of the SO but in each case with rainfall from only a few Australian stations.

The second aim is that of making a comprehensive examination of the lag correlations between the SO

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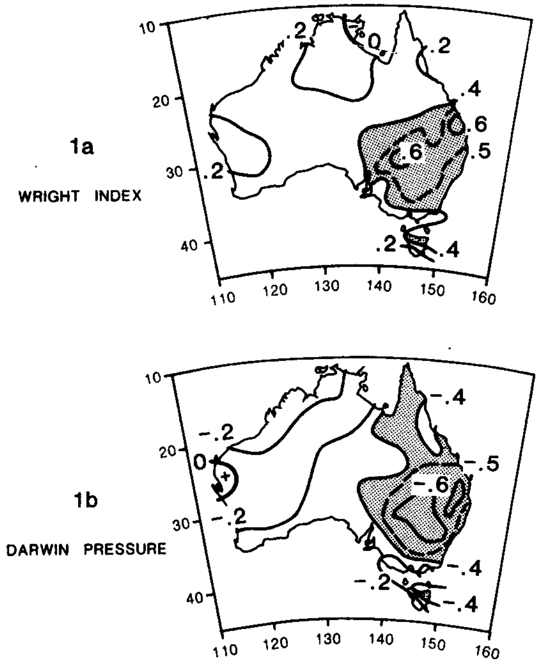

FIG. 1. Correlation between (a) annual mean value of the Wright SOI and Australian district mean annual rainfall; and (b)annual Darwin pressure and Australian district mean annual rainfall. Data from 1933–74.

TABLE 1. Autocorrelations of four Southern Oscillation Indices for each season. Data from 1932–74.

Seasons	Troup SOI	Wright SOI	Darwin pressure	Papeete pressure
Dec–Feb with following Mar–May	0.53	0.64	0.30	0.35
Mar–May with following Jun–Aug	0.62	0.71	0.70	0.45
Jun–Aug with following Sep–Nov	0.77	0.81	0.69	0.61
Sep–Nov with following Dec–Feb	0.76	0.76	0.64	0.58

and Australian rainfall, with a view to establishing the SO's use in seasonal rainfall prediction. The possibility of using the SO in seasonal prediction arises from its well-known tendency to persist. This persistence is demonstrated in Table 1 which shows autocorrelations, at a lag of one season, for each of the SOI's, for each season of the year.

The persistence of the SO, and its simultaneous relationship with Australian rainfall has resulted in several authors examining the use of the SO in Australian seasonal rainfall prediction (e.g., Quayle, 1929; Grant, 1954; Priestley, 1962; Nicholls and Woodcock, 1981; Nicholls *et al.*, 1982). These earlier studies, however, have again concentrated on limited areas, rather than examining the relationship over the entire continent.

The final aim of the study is to compare the relative performance of the four versions of the SOI, both as indices of rain-producing anomalies over Australia and as possible predictors of seasonal rainfall. Comparisons of indices of the SO have also been reported by Trenberth (1976, 1977) and Chen (1982). Trenberth and Chen considered spectral and cross-spectral analyses of time-series of surface pressure at a number of stations in the SO region of influence. Their studies provided information about which indices best represent the strength and temporal variations of the planetary-scale oscillation. The comparisons in the current paper are concerned with a different aspect, specifically which indices have the closest simultaneous and lag associations with rainfall in a localized region.

4. Data and treatment

Rainfall data used are district averages of seasonal totals from December–February 1932 to September–November 1974, for the 107 Australian rainfall districts. The locations of the districts are shown in Pittock (1975) and Coughlan (1979). As noted earlier, throughout the paper areas with correlations greater than 0.4 are shaded on the diagrams. For a 42-year series (applicable for all figures except Fig. 8) a correlation of this magnitude is significant at the 1% level under the assumption of independence between years and a normal distribution. Lag one-year autocorrelations for both annual and seasonal values of the four indices are shown in Table 2. These values are generally small, suggesting that serial correlation does not seriously affect the interpretation of the correlations between the SOI's and rainfall.

Inspection of the data reveals, however, that seasonal rainfalls in some seasons and regions, e.g., northern Australia during the dry season, are not normally distributed. Cube roots of the seasonal rainfall were therefore calculated in an endeavor to produce distributions closer to the normal. As correlations between the SOI's and these transformed rainfalls were found to be very similar to the correlations

TABLE 2. Lag one-year autocorrelations for seasonal and annual mean values of four Southern Oscillation indices. Data from 1932–74.

Index	Seasons Dec–Feb	Mar–May	Jun–Aug	Sep–Nov	Annual
Troup SOI	0.12	0.02	−0.15	−0.10	0.00
Wright SOI	0.03	0.37	−0.03	0.08	0.21
Darwin pressure	0.17	0.11	−0.06	−0.16	0.06
Papeete pressure	0.11	−0.16	−0.18	−0.04	0.03

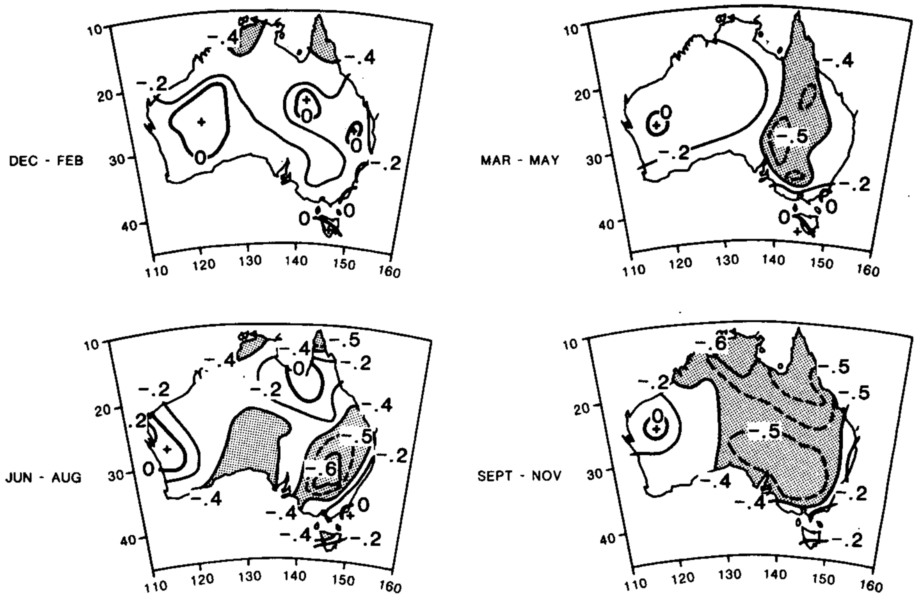

FIG. 2. Simultaneous correlations between Darwin pressure and district rainfall for the four seasons, December–February, March–May, June–August, September–November. Data from 1932–74.

with untransformed rainfall, only the latter are presented and it is concluded that any deviation from normality does not markedly affect their interpretation.

5. Simultaneous correlations

Figure 2 shows simultaneous correlations between Darwin pressure and rainfall for each season. A substantial seasonal variation in the magnitude and the areal extent of significant correlation is evident, with the strongest relationship occurring in spring (September–November). Winter (June–August) and autumn (March–May) also show substantial areas of significant correlations. The areas of significant correlations are generally located in the east and north of the continent.

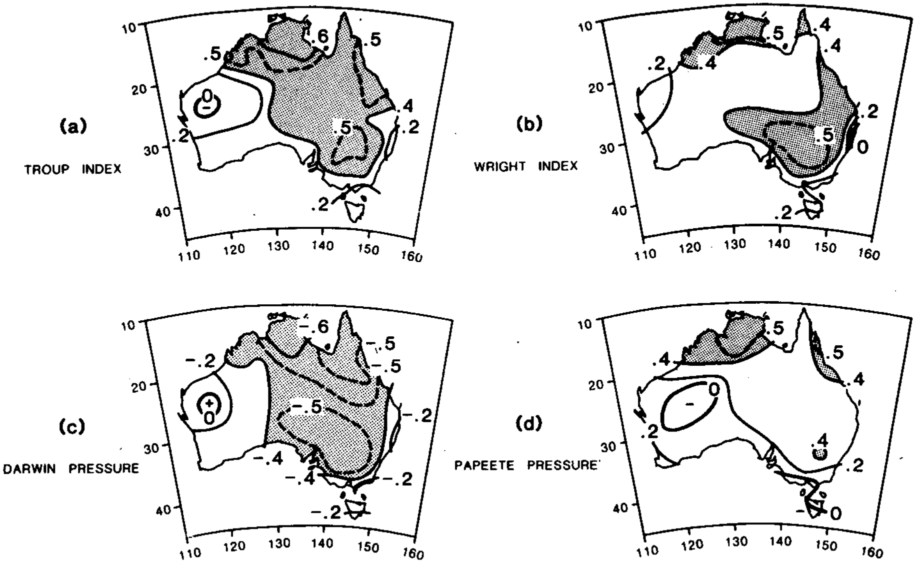

FIG. 3. Correlations between September–November average value of the Southern Oscillation Index and September–November district mean rainfall. Correlations have been calculated for four Southern Oscillation Indices (a) Troup Index, (b) Wright Index, (c) Darwin pressure, (d) Papeete pressure. Data from 1932–74.

The summer season (December–February), on the other hand, exhibits generally small, non-significant correlations except for the far north. This season is the peak of the north Australian wet season and the summer monsoon. Thus, there seems to be only a weak relationship between the SO and monsoon rainfall over Australia.

Correlations of the other SOI's with seasonal rainfall show similar behavior to that illustrated in Fig. 2. The correlations for each index with spring rainfall are shown in Fig. 3. Some differences in the correlation patterns are discernible, with the Troup Index and Darwin pressure producing the strongest relationships and Papeete the weakest. Even for Papeete, however, areas of significant correlations are found. Inspection of correlations for the other three seasons (not shown) reveals similar results, with Papeete producing the weakest correlations and all four indices showing the same seasonal variation in the strength of their correlations with rainfall. This is hardly surprising since the four indices are strongly related, and indeed all except Papeete pressure explicitly include Darwin pressure as part of the index. Indeed, the correlations between Australian rainfall and Papeete pressure, 55° longitude distant, are perhaps the most physically significant as they attest to the planetary-scale nature of the mechanisms affecting the interannual variations in Australian rainfall.

6. Lag correlations

Correlations have also been calculated between each SOI and district rainfall in the following season. Fig. 4 shows the correlations between autumn SOI and winter rainfall. All indices show areas of significant correlation over eastern Australia, suggesting that seasonal prediction may be feasible. Again the relationship with Papeete is the weakest.

The correlations between spring rainfall and the SOI's in winter are shown in Fig. 5. Significant correlations occur over much of northern Australia for each index and also, with the exception of Papeete, in an area in the southeast.

Autumn and summer rainfalls are less strongly correlated with the SOI's in the preceding season. Fig. 6 shows the lag correlations for the Wright index for these seasons. Again the other indices produce similar behavior.

Correlations have also been calculated for two-season lags. Strong correlations at this lag were found only for spring. The correlations of autumn Darwin pressure with rainfall in this season are shown in Fig. 7.

7. Discussion

a. Stability of correlations with time

The results discussed in the two previous sections indicate that over the period 1932–74, Australian rainfall in some seasons and areas was significantly correlated with the SOI in the same or preceding seasons. The results are consistent with work carried out earlier this century (e.g., Quayle, 1929) suggesting that a degree of stability exists in the relationships. The extent of this stability has been examined further by separating the data into two sub-sets (1933–53 and 1954–74) and recalculating the correlations. The si-

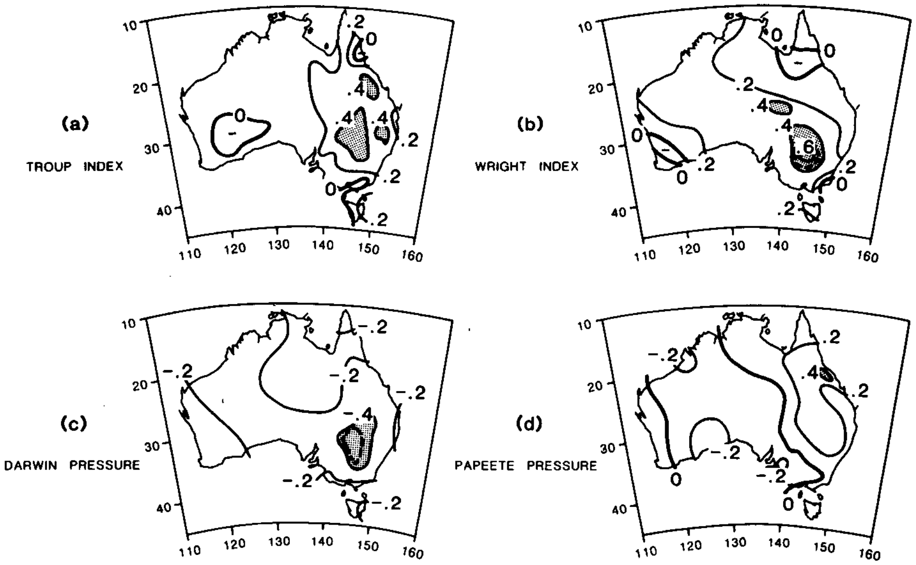

FIG. 4. Lag correlations between March–May mean value of the Southern Oscillation Index and June–August mean rainfall. The SOI used is the Troup Index (a), the Wright SOI (b), the Darwin pressure (c) and the Papeete pressure (d). Data from 1932–74.

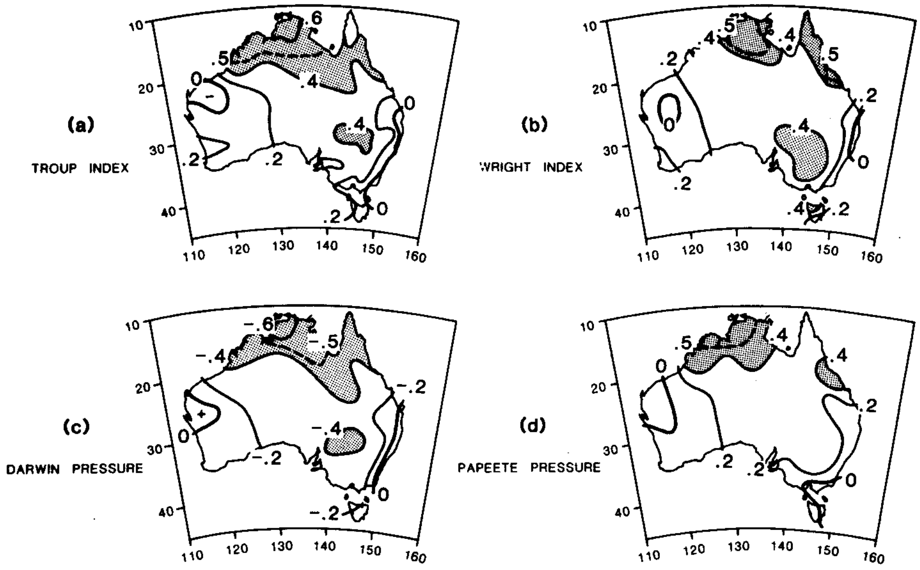

FIG. 5. Lag correlations between June–August SOI and September–November rainfall for four Southern Oscillation Indices. (a) Troup SOI, (b) Wright SOI, (c) Darwin pressure, (d) Papeete pressure.

multaneous correlations between Darwin pressure and spring rainfall are shown in Fig. 8, and can be compared with the correlations calculated on the complete data set (Fig. 2). It should be noted, however, that due to the shorter time series the shaded areas in Fig. 8 are of lower statistical significance than those in the earlier figures.

The correlations in Fig. 8 provide further evidence that, in general, the rainfall–SOI relationships have remained stable. There does appear, however, to have been a westward shift in the region of large correlations between the two periods. This shift has a pronounced effect on the association between the SO and rainfall in some areas. Along the central east coast, for example, a region that exhibited strong negative correlations in the earlier subseries, small positive correlations are evident in the later period. This suggests that some care needs to be taken in the use of these correlations for forecasting purposes. The shift might be the result of changes in observing practices or possibly a change in climate. If so, predictive relationships based on relatively short periods of recent

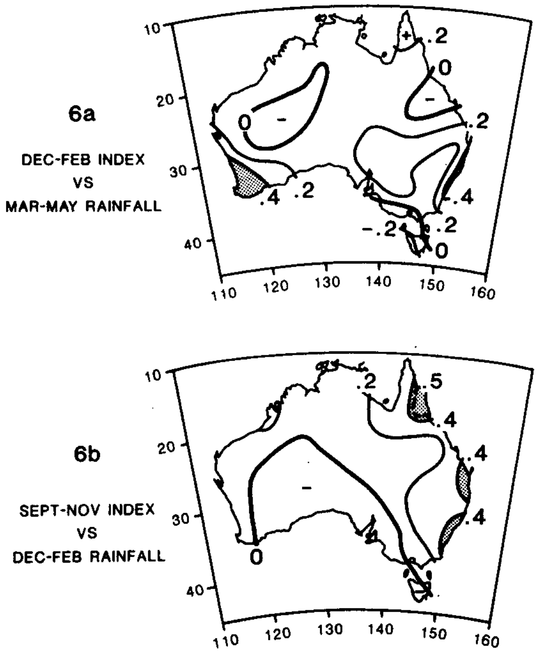

FIG. 6. Lag correlations between the (a) December–February mean Wright SOI and March–May mean rainfall; and the (b) September–November mean Wright SOI and December–February mean rainfall.

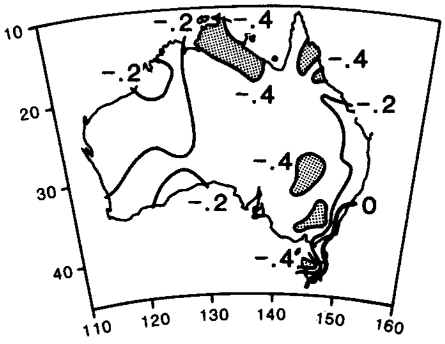

FIG. 7. Lag correlations between March–May mean Darwin pressure and September–November district mean rainfall. Data from 1932–74.

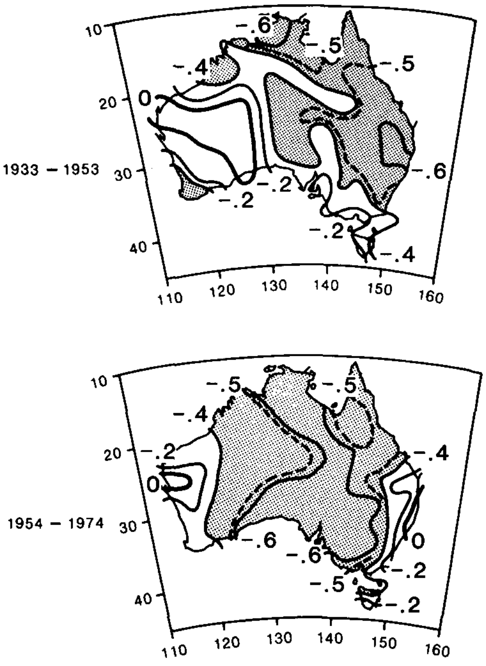

FIG. 8. Simultaneous correlations for September–November between Darwin pressure and district rainfall: (top) data from 1933–53, (bottom) data from 1954–74.

data may produce better forecasts than those based on all available historical data. In relation to this point, the temporal variations in the characteristics of the SOI's over periods of decades (Troup, 1965; Trenberth 1976) should be noted. Pittock (1975) has documented the occurrence of a significant change in mean precipitation over parts of Australia between 1914–45 and 1946–78. The latter period experienced considerably greater precipitation over the southeast of the continent. This change in rainfall may be related to the above-noted shift in correlation patterns.

b. Relationship between the SO and the Australian monsoon

Rainfall over northern Australia is highly seasonal, with more than 90% occurring between November and April. This summer–wet versus winter–dry variation is associated with the seasonal movement of the equatorial trough (Troup, 1961). This phenomenon is the Australian northwest monsoon. One result of this study is that rainfall during the peak monsoon months (December–February) is only weakly related to the SOI's, compared with the relationship during the pre-monsoon season (September–November).

The reason for the large drop in the magnitude of the correlations from spring to summer is not obvious. In an attempt to gain some insight, an empirical orthogonal function (EOF) analysis has been carried out on the 1932–74 time-series of normalized seasonal rainfalls for the 14 districts located equatorward of 20° latitude.

The first eigenvector may be interpreted as the dominant large-scale pattern of interannual variability for each season. The percentage of the total variance accounted for by this eigenvector is much lower in summer (43%) than in spring (60%). It is this first eigenvector which in both seasons is related to the SOI. This is demonstrated in Table 3 which lists the correlations between the Troup Index and the amplitudes of the first four rainfall eigenvectors. In both spring and summer the first eigenvector, and only the first, is significantly correlated with the SOI.

The lower two rows in Table 3 show lag correlations between the Troup Index and the magnitudes of the rainfall eigenvectors in the following season. The first eigenvector of spring rainfall is closely linked to the winter SOI but the equivalent relationship for summer rainfall is much weaker and not statistically significant. This is puzzling since the SOI's show strong persistence from spring to summer (Table 1). Notwithstanding, Table 3 does indicate that a link exists between the dominant pattern (first eigenvector) of interannual rainfall variations and the SO.

Thus the principal mode of interannual variations of rainfall is related to the SOI in both seasons but this mode is more dominant in spring than in summer. Two possible causes of this behavior suggest themselves. First, there may be some independent large-scale feature of the atmosphere contributing more to the control of summer rainfall than of spring rainfall. Alternatively, it could be that small-scale effects, possibly random, play a greater role in summer.

8. Concluding remarks

This study has examined the simultaneous and lag correlations between four indices of the Southern Oscillation and areal averaged seasonal rainfall in Australia, using data from 1932–74. The main results are as follows:

1) A distinct seasonal cycle exists in the correlations.

TABLE 3. Correlations between the Troup Index and magnitudes of eigenvectors of tropical Australian rainfall: Data from 1932–74. Correlations significant at 5% are italicized.

Correlations between		Rainfall eigenvector			
Troup Index in	Eigenvector in	1	2	3	4
Sep–Nov	Sep–Nov	*0.68*	0.08	0.29	0.14
Dec–Feb	Dec–Feb	*0.57*	0.09	−0.07	0.17
Jun–Aug	Sep–Nov	*0.60*	0.14	0.19	0.14
Sep–Nov	Dec–Feb	0.34	0.33	−0.26	0.15

2) Spring (September–November) is the season with the strongest relationships.

3) Summer (December–February) shows the weakest relationships.

4) In some seasons, especially spring, the lag correlations are strong enough to suggest the possibility of seasonal rainfall prediction.

5) The strongest correlations are found in eastern and northern Australia.

6) The correlation patterns have remained reasonably stable over time although there is evidence of a westward shift of the area with the strongest correlations.

7) In both spring and summer the Troup SOI is significantly correlated with the coefficient of the first principal component of tropical Australian rainfall. In spring, however, this component accounts for a much greater proportion of the variance.

Some of these conclusions confirm earlier studies of the Southern Oscillation and Australian rainfall (e.g., Quayle, 1929) but the present study has extended and clarified the seasonal relationships, as well as providing further evidence of the general stability of these relationships, and thus of their use in seasonal prediction.

A number of questions raised in this study deserve further attention. Thus the apparent westward shift of the region of largest correlations has ramifications for the derivation of seasonal prediction techniques. It could mean that the use of relatively short periods of recent data might provide better forecasts than the use of all available historical data. Work on determining the optimum data period for the derivation of seasonal prediction techniques is warranted, as is further work on the causes of the apparent westward shift and of the weakening of the relationship between rainfall and the Southern Oscillation in summer.

Acknowledgments. The calculations were performed by making minor modifications to a computer program provided by M. J. Coughlan who also provided the rainfall data tape. Southern Oscillation Index time series were provided by A. J. Troup. Considerable improvements to the manuscript resulted from suggestions by P. B. Wright, K. E. Trenberth, and an anonymous reviewer.

REFERENCES

Chen, W. Y., 1982: Assessment of Southern Oscillation sea-level pressure indices. *Mon. Wea. Rev.*, **110**, 800–807.

Coughlan, M. J., 1979: Recent variations in annual-mean maximum temperatures over Australia. *Quart. J. Roy. Meteor. Soc.*, **105**, 707–719.

Grant, A. M., 1954: The application of correlation and regression to forecasting. Meteor. Study No. 7, Bureau of Meteorology, Melbourne, Australia, 14 pp.

Julian, P. R., and R. M. Chervin, 1978: A study of the Southern Oscillation and Walker Circulation phenomenon. *Mon. Wea. Rev.*, **106**, 1433–1451.

Kidson, J. W., 1975: Tropical eigenvector analysis and the Southern Oscillation. *Mon. Wea. Rev.*, **103**, 187–196.

Nicholls, N., and F. Woodcock, 1981: Verification of an empirical long-range weather forecasting technique. *Quart. J. Roy. Meteor. Soc.*, **107**, 973–976.

——, J. L. McBride and R. J. Ormerod, 1982: On predicting the onset of the Australian wet season at Darwin. *Mon. Wea. Rev.*, **110**, 14–17.

Pittock, A. B., 1975: Climatic change and the patterns of variation in Australian rainfall. *Search*, **6**, 498–504.

Priestley, C. H. B., 1962: Some lag associations in Darwin pressure and rainfall. *Aust. Meteor. Mag.*, **38**, 32–42.

Quayle, E. T., 1929: Long-range rainfall forecasting from tropical (Darwin) air pressure. *Proc. Roy. Soc. Victoria*, **41**, 160–164.

Rasmusson, E. A., and T. H. Carpenter, 1982: Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Mon. Wea. Rev.*, **110**, 354–384.

Trenberth, K. E., 1976: Spatial and temporal variations of the Southern Oscillation. *Quart. J. Roy. Meteor. Soc.*, **102**, 639–653.

——, 1977: Southern Oscillation index and atmospheric carbon dioxide. *Nature*, **267**, 650.

Troup, A. J., 1961: Variations in upper tropospheric flow associated with the onset of the Australian summer monsoon. *Indian J. Meteor.Geophys.*, **12**, 217–230.

——, 1965: The Southern Oscillation. *Quart. J. Roy. Meteor. Soc.*, **91**, 490–506.

Walker, G. T., 1923: Correlation in seasonal variations of weather, VIII. *Mem. Indian Meteor. Dept.*, **24**, 75–131.

——, 1924: World weather IX. *Mem. Indian Meteor. Dept.*, **24**, 275–332.

——, 1928: World weather II. *Mem. Roy. Meteor. Soc.*, **11**, No. 17, 97–106.

Wright, P. B., 1977: The Southern Oscillation—Patterns and mechanisms of the teleconnections and the persistence. HIG-77-13, Hawaii Inst. Geophys., University of Hawaii, 107 pp.