Aust. Met. Mag. 43 (1994) 73-80

Temporal variation of relations between tropical sea-surface temperatures and New South Wales rainfall

Ian Cordery and Yaw Opoku-Ankomah
School of Civil Engineering, University of New South Wales, Australia

(Manuscript received April 1993; revised November 1993)

Principal component analysis (PCA) of Pacific and Indian Ocean sea-surface temperatures (SSTs) revealed six dominant patterns in each season. PCA of New South Wales district rainfall with varimax rotation identified major patterns of rainfall variability. Each of the latter patterns characterised the rainfall variability of a subregion of the State. Correlations between the SST principal components (PCs) and rainfall PCs showed that some of the SST patterns were significantly related to the rainfall patterns. However, running correlations between the SST PCs and the rainfall PCs revealed instabilities in the relationships over the period 1933-87. Changes in the relationships were different for each season and also for each rainfall subregion. The SST patterns which were found to be related to the rainfalls were strongly related to the Southern Oscillation Index (SOI). The main features of the changes observed in the SST-rainfall relationships were similar to those in the SOI-rainfall relationships although the SST-rainfall relationships were generally weaker than the SOI-rainfall relations.

Introduction

A number of studies have examined the relationships between sea-surface temperatures (SSTs) and rainfall in New South Wales (NSW), Australia, with a view to identifying linkages which could be used for long-range rainfall and drought forecasting (Priestley 1964; Priestley and Troup 1966; Hirst and Linacre 1978; Angell 1981). O'Mahoney (1961), for example, suggested that fluctuations in Australian rainfalls might be associated with changes in sea temperatures and ocean currents. The latter in turn might be related to the amount of solar radiation received at the earth's surface. Some studies examined the relationships between SSTs and rainfall in the whole country (Streten 1981, 1983; Nicholls 1989; Drosdowsky 1993). Other studies looked at the associations between rainfall in other States and SSTs (e.g. Whetton 1990; Lough 1992). In all these studies, some significant correlations between SSTs and rainfall were found. The results also showed that wet years in Australia were associated with warm SSTs in the eastern Indian Ocean and the southwest Pacific. Conversely, very dry years were associated with low SSTs in these regions. Furthermore, the SST anomalies in the east Pacific were found to be frequently opposite to those in the Australian region.

The SST-rainfall relationships in Australia appear to have been well examined from the above-mentioned studies. However, the question of stability of the relationships over time, which is fundamental to forecasting, has not been addressed. In the literature, the possibility of significant relationships between SSTs and climatic indices not being stable over time has only been mentioned (e.g. Lough 1992), although SST is used as an important supporting indicator variable in producing forecasts of seasonal rainfall in Australia (Bureau of Meteorology, undated).

Investigations of the relationships between the Southern Oscillation Index (SOI) and Australian rainfall have also been relatively extensive (Troup 1965; Elliott and Angell 1988; McBride and Nicholls 1983; Nicholls 1984; Drosdowsky and Williams 1991). This is because SOI appears to be the most promising variable so far identified for possible long-range rainfall and drought forecasting, at least in eastern Australia. All these studies essentially agreed that the Southern Oscillation is strongly related to the rainfall in eastern Australia. However, there have been questions about the stability of the SOI-rainfall relationships (McBride and Nicholls 1983; Pittock 1984;

Corresponding author address: Professor I. Cordery, School of Civil Engineering, University of New South Wales, PO Box 1, Kensington, NSW 2033, Australia.

Nicholls 1984; Allan 1985). McBride and Nicholls (1983), for example, indicated that in general the SOI-rainfall relationships were stable over time, although they observed some instability. Nicholls (1984) also indicated some temporal instability in the SOI-rainfall relationship for a small region in Australia over the period 1913–80. However, this temporal instability has not been quantified. A recent study by Opoku-Ankomah and Cordery (1993) has clearly demonstrated that the relationships between NSW rainfalls and the SOI have not been stable in some regions and in some seasons over the period studied (1933 to 1988). Further work by Cordery et al. (1993) also demonstrated the instability of the SOI-rainfall relationship over a longer period (1882–1991). The Southern Oscillation is known to be associated with the ocean temperatures in the Pacific (Bjerknes 1969; Rasmusson and Carpenter 1982) and so the temporal instability of the SOI-rainfall relationship prompted the investigation of the stability of relationships between SSTs and NSW rainfalls in this study. Temporal variations in the relationships between SOI and rainfall cannot be assumed to be similar to those of the SST-rainfall relationships since the SSTs in the Pacific and the SO do not always act together (Deser and Wallace 1987).

Correlations of rainfall with SST in the oceans may be significant. However, significant correlations may occur by chance given the large number of correlations calculated, or the number of significant correlations may be inflated due to spatial autocorrelation. In statistical terms, this correlation may be referred to as being field insignificant. Livezey and Chen (1983) suggested a simulation approach to testing the field significance. Most of the preceding studies (e.g., Angel 1981) have examined the correlations of rainfall in NSW and SST in the Pacific region without testing for this field significance. The field significance of SST-rainfall relations is examined here indirectly by assessing the correlations of the major SST patterns with the major patterns of rainfalls, i.e. by reducing the dimensionality of the problem.

In this study, principal component analysis (PCA) is used to identify the major SST patterns in the Pacific and the Indian Oceans. Further, PCA with rotation is used to regionalise the rainfall characteristics in NSW. The PCs of rainfall and SSTs are then correlated. Running correlations are used to test the stability of the relationships over time.

Data

The SST data used in the analysis were extracted from the Comprehensive Ocean-Atmosphere Data Set (COADS) for the period 1933 to 1987. The data were mean monthly SSTs supplied in 2° longitude by 2° latitude grid cells. The SST data from the Pacific and Indian Oceans, between latitudes 60°N and 40°S, were sparse and unevenly spread. To increase the number of data values contributing to each monthly value used in the study, the values were averaged in 10° longitude by 10° latitude cells. The total number of 10° longitude by 10° latitude cells was 170. There were biases in the SST data collected because of changes in the measuring equipment and techniques (Folland and Parker 1990). Most of the changes occurred before the end of 1941. COADS has not been corrected (COADS Release 1 1985) and so the data between 1933 and 1941 were corrected here using values extracted from the Folland and Parker (1990) maps which present estimates of the biases.

Mean monthly rainfall for the 30 rainfall districts in NSW were obtained from the Australian Bureau of Meteorology. The Southern Oscillation Index (SOI) as defined by Troup (Pittock 1973), i.e. pressure difference between Tahiti and Darwin normalised to mean zero and standard deviation of 10, was also obtained from the Bureau.

Method

The monthly data sets were combined into four seasons: autumn consists of March, April and May, winter of June, July and August etc. PCA (S-mode) with Varimax rotation was used to regionalise the rainfall characteristics of NSW for each season. The correlation matrix was used in the extraction of the eigenvalues and eigenvectors (see Opoku-Ankomah and Cordery 1993). Studies by Richman (1986) and Kutzbach (1967) illustrate the application of PCs in many geophysical studies. The associations between SSTs (in each of the 170 10° by 10° cells) and the rotated rainfall PCs were examined by simple linear correlations. The SST region considered was between latitudes 60°N and 40°S.

PCA was also used to identify the most important SST patterns and regions. The correlations between the rainfall PCs and the SSTs indicated that the SST regions where significant correlations were found with the rainfall PCs were mainly in the tropical belt. Also the PCA with matrix approach assumes equal grid areas of the field from which the data were sampled (Buell 1975; 1979). However, the areas of the 10° by 10° SST cells in the higher latitudes are considerably smaller than those in the lower latitudes. Hence only SSTs in the Pacific and the Indian Oceans between latitudes 20°N and 20°S were used in the PC analysis. The number of SST cells in this region which were used for analysis was 82. The SSTs in the eastern Pacific have much higher variance than those in the rest of the study region, probably due to the occurrence of the El Niño events. In order not to concentrate the dominant patterns in the eastern Pacific region, the correlation matrix of the SSTs was computed and used for the eigen solution.

The scree test (Cattell 1966) and the log-eigenvalue (LEV) test (Craddock and Flood 1969) were used to determine the significant eigenvalues and corresponding PCs. Six dominant PC modes for SSTs were selected by the two approaches. The six retained PCs were also rotated for other sets of solutions.

The rotated and unrotated SST PCs were correlated with the rainfall PCs in each season. Further, to examine the stability of the relationships between the SST PCs and the rainfall PCs, running correlations between them were computed. Twenty-five-year data windows were used in the computations. This means that the first and the second correlation coefficients, for example, were computed for 1933–57 and 1934–58, respectively.

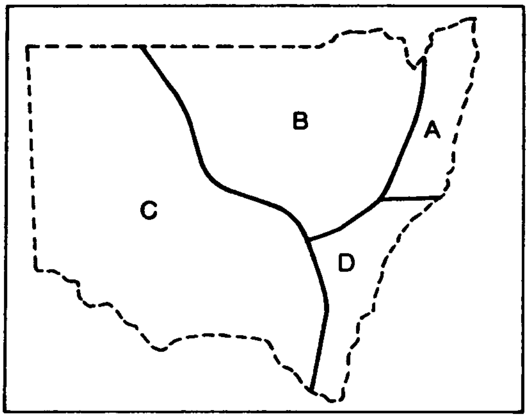
Results and discussion

Rainfall PCs

Principal component analysis of NSW seasonal rainfall revealed four major spatial patterns of rainfall in each season. These patterns were similar for all four seasons. In each season the rotated loadings of the patterns were high in one part of the State and very low or near zero elsewhere. Rainfall districts with PC loadings greater than 0.5 were classified into a subregion. This led to the regionalisation of NSW rainfall into four subregions (Fig. 1).

The division of the State into four rainfall subregions followed the topographic divide of the Great Dividing Range and the southerly and northerly wind systems. The range is about 100 km inland and is parallel to the NSW coast. The variance accounted for by the rainfall PCs changed with season. For example, the variance of the PC associated with subregion C was 10 per cent of the total in summer whereas in winter it was 20 per cent. This may be related to the variation in the wind system associated with the rain-producing mechanisms. Rainfall in the State is governed by the movement of the pressure systems. In summer, eastwards mobile anticyclones are far south of the State and rainfall is received from moist easterlies, either through convection or orographic lifting. In winter, the anticyclones are located north of the State and rainfall is received from prevailing westerlies and frontal activities. Rainfall is approximately uniform throughout the year in most parts of the State. However, areas like northeastern NSW have wet summers due to the strong influence of the easterlies in this season and relatively dry winters because the subtropical high is located near this latitude in winter.

Fig. 1 Subregions spanned by the rainfall principal components.



PC analysis of the SSTs

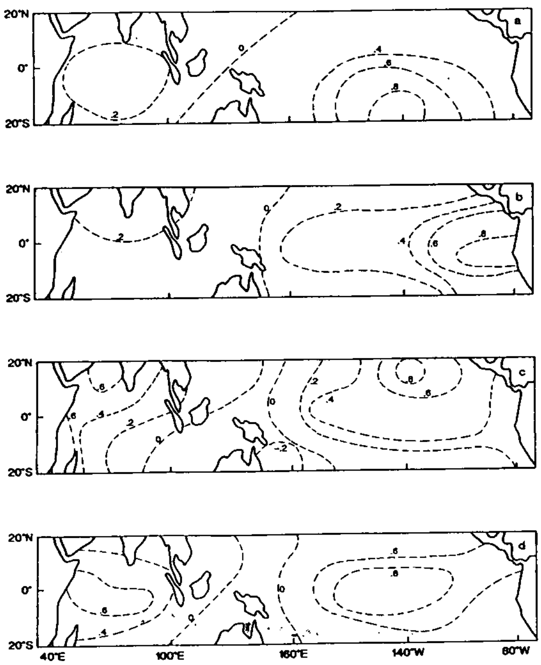
The variances explained by the retained PCs in each season are shown in Table 1. It may be seen from the Table that over 63 per cent of the variance of the SSTs in each season was retained.

The loadings of the first unrotated PCs in the four seasons are shown in Fig. 2. The high loadings identify the SST region with close similarity to the PC. With the unrotated PCs, the first PC has the highest variance and it tends to represent the average variation in the field concerned. In autumn, the unrotated PC has high loadings (0.8) in the central Pacific (Fig. 2(a)). However, in winter the high loadings are near the South American coast (Fig. 2(b)). As the seasons progress through winter, spring and summer, the SST region of high loadings near the South American coast stretches westwards to cover the central Pacific region. These features resemble the development of El Niño conditions where warming of the ocean starts at the South American coast and stretches westwards, as reported by Rasmusson and Carpenter (1982, 1983). The loadings of the first three rotated SST PCs in autumn and winter are shown in Figs 3(a–b) as examples. In almost all the plots, the high loadings were either localised in the central Pacific, as in Fig. 3(a)(i), or found along the South American coast, as can be seen in Fig. 3(b)(i). Some of the SST PCs also showed other centres of moderately high loadings in the Indian Ocean. This shows that there are synchronous variations in SSTs over wide regions of ocean. Figure 3(b)(iii) reveals another characteristic pattern in which SST PC loadings of opposite sign are observed between the central Pacific and northeastern Australia.

Table 1. The variances explained by the unrotated SST PCs in the four seasons.

PC	*Percentage of explained variance of each PC* *Autumn*	 *Winter*	 *Spring*	 *Summer*
1	27.1	27.9	37.3	40.6
2	12.2	10.6	9.2	6.9
3	8.1	7.9	6.3	6.1
4	6.5	6.2	5.5	5.9
5	5.9	5.4	4.3	4.7
6	4.4	5.1	4.1	3.8
Cumulative %	64.2	63.1	66.7	68.0

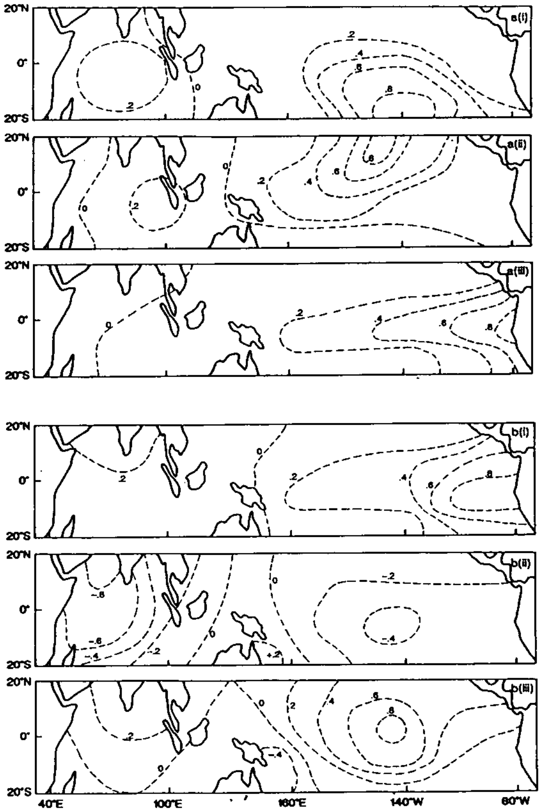
Fig. 2 Loadings of the first unrotated SST PCs. a) Autumn, b) winter, c) spring, d) summer.



Correlations of SST PCs and rainfall PCs

The correlation coefficients between the rainfall PCs and the rotated SST PCs were slightly higher than those between the rainfall PCs and the unrotated SST PCs. Hence, the results of the former are presented in Table 2. The correlation coefficients between the rainfall PCs and the SOI are also presented for further discussion. Relationships between the SST PCs and the rainfall PCs were significant in winter, spring and summer. The largest significant correlation values were, however, not much greater than 0.4. The

Fig. 3 Loadings of the first three rotated SST PCs. a) Autumn, b) winter; (i), (ii) and (iii) show the first, second and third rotated PCs respectively.



minimum useful value of the correlation coefficient for most practical purposes such as forecasting is 0.4 (Grant 1954). No significant relationships existed for autumn. The SOI-rainfall PC relations were slightly stronger than the SST PC-rainfall PC relations for winter and spring.

Comparing the SST-rainfall correlation coefficients with the corresponding SST-SOI correlation coefficients (Table 3), it is apparent that wherever the former relationships were significant, the latter were also significant. For example, in summer the correlation coefficient between the first rainfall PC and the first SST PC was −0.45 and the corresponding correlation coefficient between the SOI and the first SST PC was −0.83. Overall, the SST-SOI relationships were generally much stronger than the SST-rainfall relationships. This shows that both the SSTs and the SOI are strongly and jointly associated with the NSW rainfalls.

The rotated SST PC is a linear combination of the SSTs in the study area (latitudes 20°N to 20°S) where the SSTs are weighted by their loadings on the PC. Examination of the distribution of the

Table 2. Correlation coefficients between the first rainfall PCs and rotated PCs of SSTs and between first rainfall PCs and SOI in the same season, for the period 1933–1987. The first rainfall PC is denoted RPC1 in the table. $DSST_1$ is the difference between the SSTs off northeastern Australia and in the central Pacific. $DSST_2$ is the difference between the SSTs off northeastern Australia and in the Indian Ocean. The 1 per cent and 5 per cent significance levels are 0.35 and 0.27 and correlation coefficients at these levels of significance are marked ** and * respectively.

	Autumn RPC1	*Winter RPC1*	*Spring RPC1*	*Summer RPC1*
SST PC 1	−.13	−.27*	−.44**	−.45**
SST PC 2	.02	.35**	−.20	−.39**
SST PC 3	.04	−.50**	.47**	−.08
SST PC 4	−.05	.06	−.40**	−.01
SST PC 5	.03	−.06	.27*	−.46**
SST PC 6	−.21	.17	.50**	−.24
SOI	.29*	.61**	.59**	.34*
$DSST_1$	.07	.56**	.56**	.35**
$DSST_2$	.13	.56**	.45**	.22

Table 3. Correlation coefficients between the rotated SST PCs and SOI. The 1 per cent and 5 per cent significance levels are 0.35 and 0.27.

Season	*SST PCs*					
	1	*2*	*3*	*4*	*5*	*6*
Winter SOI	−.60	.57	−.71	.31	−.36	.21
Summer SOI	−.83	−.74	.27	−.14	−.76	−.50

correlation coefficients which were initially computed (not shown) revealed that SSTs off northeastern Australia (10°S–20°S, 150°E–60°E), in the central Pacific (0°–10°N, 160°W–170°W) and in the Indian Ocean (0°–10°N, 70°E–80°E) were significantly related to the NSW rainfall. An attempt was made to improve the correlation by relating the difference between the SSTs off northeastern Australia and in the central Pacific ($DSST_1$) to the NSW rainfall. (The sign of the correlations of the rainfall and the SSTs in the two regions was opposite.) Similarly, the difference between the SSTs off northeastern Australia and the Indian Ocean ($DSST_2$) was also correlated with the NSW rainfalls. These relations in winter and spring were significant (Table 2); slightly stronger than the SST PC-rainfall relations and of similar strength to the SOI-rainfall relations.

These results demonstrate that over the period 1933–87, rainfall in NSW was closely linked to variations of SSTs in the tropical Pacific and Indian Oceans. However, examination of these relationships over 25-year subperiods showed important variations in the magnitudes of the correlations with time. Figures 4(a–d) show the temporal variations in the SST-rainfall relationships. The plots are the running correlation coefficients between the first SST PCs and the rainfall PCs in autumn, spring and summer and the third SST PC and rainfall PCs for winter. For winter and autumn, the relationships between the first SST PC and rainfall PCs were only marginally significant or non-significant as shown in Table 2. However for winter, relationships between the third SST component and the rainfalls were significant and were therefore examined. The third SST PC has high positive loadings off northeastern Australia and also high negative loadings in the central Pacific (Fig. 3b(iii)).

The plots in Fig. 4(a–d) show that the relationships between SSTs and NSW rainfall were not stable over time for some regions of the State. The variations were different for each season and to a

Fig. 4(a) Correlations of the amplitudes of the first autumn rotated SST PC and autumn rainfall PCs — 25-year data sets. The 1 per cent and 5 per cent significance levels are 0.51 and 0.40 respectively. A, B, C and D refer to rainfall regions shown in Fig. 1.

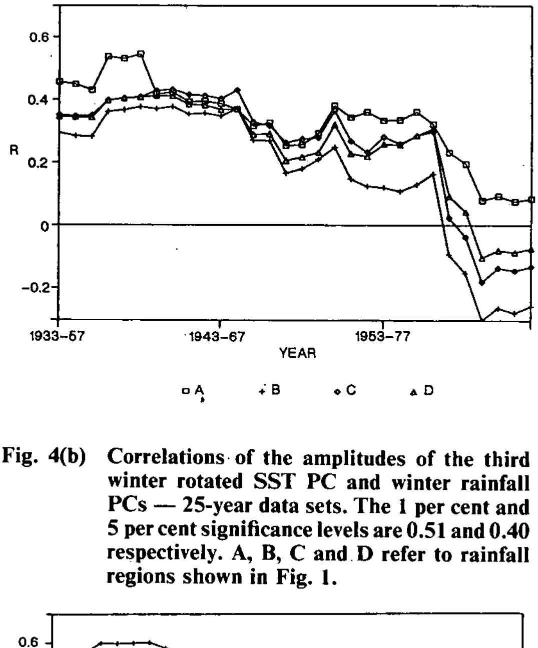


Fig. 4(b) Correlations of the amplitudes of the third winter rotated SST PC and winter rainfall PCs — 25-year data sets. The 1 per cent and 5 per cent significance levels are 0.51 and 0.40 respectively. A, B, C and D refer to rainfall regions shown in Fig. 1.

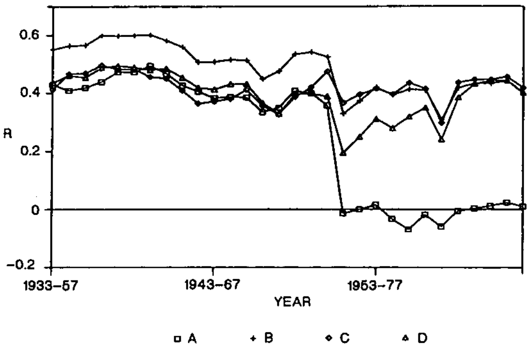


Fig. 4(c) **Correlations of the amplitudes of the first spring rotated SST PC and spring rainfall PCs — 25-year data sets. The 1 per cent and 5 per cent significance levels are 0.51 and 0.40 respectively. A, B, C and D refer to rainfall regions shown in Fig. 1.**

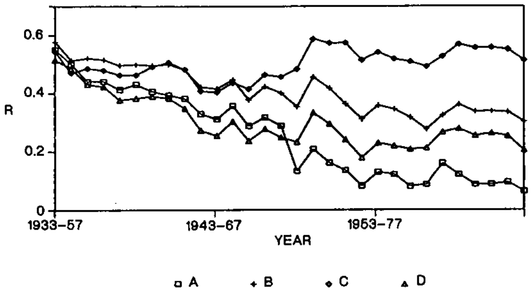
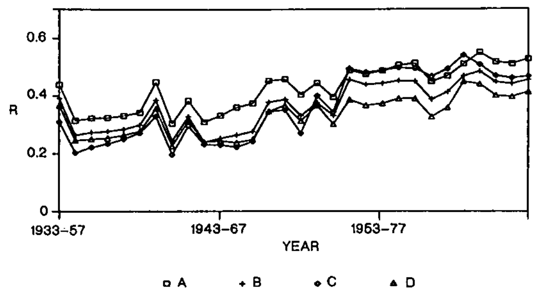


Fig. 4(d) **Correlations of the amplitudes of the first summer rotated SST PC and summer rainfall PCs — 25-year data sets. The 1 per cent and 5 per cent significance levels are 0.51 and 0.40 respectively. A, B, C and D refer to rainfall regions shown in Fig. 1.**



lesser extent for each rainfall region. These results are important since SSTs in the Pacific and Indian Oceans are known to be related to rainfall in Australia (e.g. Drosdowsky 1993) and are used as a subsidiary variable with SOI for preparation of climate outlooks (Australian Bureau of Meteorology, undated). The tropical SSTs appear to be the second most important indicator (after SOI) for the preparation of these outlooks. The stability of the relationships over time is fundamental to any expectation of reliability for such a forecasting scheme.

The plots of SST-rainfall running correlations also show striking similarity to the SOI-rainfall plots reported in Opoku-Ankomah and Cordery (1993) for the same period of time and to those reported by Cordery and Yao (1993) for 1882–1991. The major difference is that the SOI-rainfall relationships are stronger than the SST-rainfall relationships. However no clear reasons for the changes in the relationships over time can be provided at this stage.

The changes in the correlation coefficients do not only indicate strengthening or weakening of the relationships between SSTs and rainfall but, as in the case of SOI-rainfall relationships reported by Cordery et al. (1993), they also indicate that the regressions themselves (both slope and intercept) change quite dramatically. The individual series of seasonal rainfall and SOI data have been shown to be stationary, not only for the period considered here, but for 1882–1991 (Cordery et al. 1993). Since the SST-rainfall relations are similar to the SOI-rainfall relations it can be inferred that non-stationarity of any of the individual data series is not the cause of the non-stationary of the SST-rainfall relations shown in Fig. 4.

It can be seen that for some seasons there are large discontinuities in the plots of correlation coefficients between one 25-year window and those following. For example, this occurs in Fig. 4(a) in three of the rainfall regions between the 1956–80 and 1959–83 correlation windows. In each case these changes are produced by the removal of data points close to the respective regressions and their replacement by points some distance from the regression (e.g. the difference between the 1956–80 and 1957–81 regressions is that the data point for 1956 is removed from the former relation and the 1981 data point is added). Between 1956–80 and 1959–83 the regressions for all four regions change character completely. Similarly, in summer the SST-rainfall correlations improve steadily over time, as shown in Fig. 4(d). At this stage of the research there is no apparent physical cause for these very definite changes in the relationships

On occasion a large change in the SST-rainfall relationship is produced by one apparently anomalous data point. For example in winter, as shown in Fig. 4(b), the large change in region A correlation between the 1950–74 and 1951–75 windows results from the inclusion of 1950 rainfall in the former and its exclusion from the latter. The 1950 winter rainfall was two and a half times higher than the next highest winter rainfall. The resulting outlier through which the regression line must pass produced an anomalous correlation coefficient of about 0.4, whereas in fact for all correlation windows in which the 1950 data point was included, the other 24 data points suggest the correlation coefficient was close to zero, as it was for those windows in which 1950 did not feature. The same result occurs with SOI-rainfall correlations for the period 1882–1991 where the winter correlation is about 0.4 for all windows in which the 1950 data point features, but is quite different before and after those windows (Cordery et al. 1993). This single point dominance of the correlation coefficients did not occur for any of the other data shown in Fig. 4. For example, for the other districts shown in Fig. 4(b), no single exchange of data points produces inordinately large changes in correlation coefficients. However, the real concern of this paper is the long-term changes in the relationships as shown in Figs 4(a), (c) and (d). These changes are large for all regions in autumn (Fig. 4(a)), large for the coastal regions A and D in spring (Fig. 4(c)) and show a steady, consistent trend for all regions in summer (Fig. 4(d)). Examination of Figs 4(a) to (d) shows that large changes in the SST-rainfall relationships occur at different times for each season, sometimes affecting relationships for all rainfall regions at the same time and sometimes affecting the relationship for only one of the rainfall regions. This range of different effects suggests that changes in relationships are sometimes produced by changes in only one of the variables at a single location, but more often they are caused by either a widespread SST change or a widespread change in rainfall. However, since the relations discussed here are between PCs of SSTs and rainfalls, errors in individual data observations (which are always a possibility) could not be the cause of the general non-stationarities presented.

The similarities between the SST-rainfall and SOI-rainfall relationships and the strong correlations between the SSTs and the SOI as shown in Table 3 confirm that the ocean and the atmosphere are integral parts of the SO phenomenon. This view is also held by others such as Rasmusson and Carpenter (1982) who suggested that the ocean provides a memory mechanism for the SO. However, the linking mechanisms between these phenomena are not understood, but the temporal instability of the relationships between them and rainfall demonstrated here may provide indicators of other avenues to which investigations of these phenomena should perhaps be directed.

Conclusion

This study has shown that the dominant patterns of SSTs in the Pacific and the Indian Oceans are related to NSW rainfalls. The relationships are, however, weaker than the SOI-rainfall relationships.

The relationships are observed to be generally unstable over the period studied. Further, the degree of instability is different for each season and subregion of the State. The dominant SST patterns which are related to rainfall are also strongly related to the SOI, reflecting the coupling of the ocean and the atmosphere in the SO phenomenon. The patterns of correlations of SST-rainfall and SOI-rainfall are also similar.

The factors affecting the changes in the relationships over time are unknown. The changes are particularly puzzling because the individual phenomena are stationary. The changes may be associated with some other as yet unidentified phenomenon which influences either SST and SOI or the rainfall system itself. These changes may give rise to the variations in the influence of the SO and non-SO factors on NSW rainfall.

References

Allan, R.J. 1985. The Australasian summer monsoon, teleconnections, and flooding in the Lake Eyre basin. *South Australian Geographical Papers, No. 2*, Roy. Geog. Soc., Australasia.

Angell, J.K. 1981. Comparison of variations in atmospheric quantities with sea surface temperature variations in the equatorial eastern Pacific. *Mon. Weath. Rev.*, *109*, 230–43.

Bjerknes, J. 1969. Atmospheric teleconnections from the equatorial Pacific. *Mon. Weath. Rev.*, *97*, 163–72.

Buell, C.E. 1975. The topography of empirical orthogonal functions. *Preprints Fourth Conf. on Prob. and Stats in Atmos. Sci.*, Tallahassee, FL, Amer. Met. Soc., 188–93.

Buell, C.E. 1979. On the physical interpretation of empirical orthogonal functions. *Preprints Sixth Conf. on Prob. and Stats in Atmos. Sci.*, Banff, Alta., Amer. Met. Soc., 112–17.

Bureau of Meteorology. Undated. *Seasonal outlook service, What it is and how to use it.* Bur. Met., Australia, 1–9.

Cattell, R.B. 1966. The scree test for the number of factors. *J. Multiv. Behav. Res.*, *1*, 245–76.

COADS (Comprehensive Ocean-Atmosphere Data Set) Release 1, NOAA/ERL, April 1985, Boulder, Colorado.

Cordery, I. and Yao, S.L. 1993. Non stationarity of phenomena related to drought. *Publ. No. 213*, Intern. Assn Hydrological Sciences, 87–93.

Cordery, I., Yao, S.L. and Opoku-Ankomah, Y. 1993. Forecasting drought — Is it possible? Hydrology and Water Resources Symposium. *Nat. Conf. Publ. 93/14*, Inst. Engrs, Aust., 387–91.

Craddock, J.M. and Food, C.R. 1969. Eigenvectors for representing the 500 mb geopotential surface over the northern hemisphere, *Q. Jl R. met. Soc.*, *95*, 576–93.

Deser, C. and Wallace, J.M. 1987. El Niño events and their relation to the southern oscillation: 1925–86. *J. geophys. Res.*, *92*, 14189–96.

Drosdowsky, W. 1993. An analysis of Australian seasonal rainfall anomalies: 1950–1987. II: Temporal variability and teleconnection patterns. *Int. J. Climatol.*, *13*, 111–49.

Drosdowsky, W. and Williams, M. 1991. The southern oscillation in the Australian region. Part I: anomalies at the extremes of the oscillation. *Jnl climate*, *4*, 619–38.

Elliot, W.P. and Angell, J.K. 1988. Evidence for changes in southern oscillation relationships during the last 100 years. *Jnl climate*, *1*, 729–37.

Folland, C.K. and Parker, D.E. 1990. Observed variations of sea surface temperature. In *Climate Ocean Interaction.* Proceedings of a Workshop jointly organised by NATO and Commission of the European Communities, UK, 26–30 September 1988. M.E. Schlesinger (ed.), Kluwer Academic Publishers, 21–52.

Grant, A.M. 1954. The application of correlation and regression to forecasting. *Meteorological Study No. 7.* AGPS, Canberra.

Hirst, A. and Linacre, E.T. 1978. Associations between coastal sea-surface temperatures, onshore winds and rainfall in the Sydney Area. *Search*, *9*, 325–7.

Kutzbach, J.E. 1967. Empirical eigenvectors of sea-leavel pressure, surface temperature, and precipitation complexes over North America. *Jnl appl. Met.*, *6*, 791–802.

Livezey, R.E. and Chen, W.Y. 1983. Statistical field significance and its determination by Monte Carlo Techniques. *Mon. Weath. Rev.*, *111*, 46–59.

Lough, J.M. 1992. Variations of sea-surface temperatures off North-Eastern Australia and associations with rainfall in Queensland: 1956–1987. *Int. J. Climatol.*, *12*, 765–82.

McBride, J.L. and Nicholls, N. 1983. Seasonal relationships between Australian rainfall and the Southern Oscillation. *Mon. Weath. Rev., 111*, 1998-2004.

Nicholls, N. 1984. The stability of empirical long-range forecast techniques: a case study. *Jnl Clim. appl. Met., 23*, 143–7.

Nicholls, N. 1989. Sea surface temperatures and Australian winter rainfall. *Jnl climate, 2*, 965–73.

O'Mahony, G. 1961. Investigation of periodicities in rainfall in the Australian region. *Aust. Met. Mag., No. 33*, 1–36.

Opoku-Ankomah, Y. and Cordery, I. 1993. Temporal variation between New South Wales rainfall and the southern oscillation. *Int. J. Climatol., 13*, 51–64.

Pittock, A.B. 1973. Global meridional interaction in stratosphere and troposphere. *Q. Jl R. met. Soc., 99*, 424–37.

Pittock, A.B. 1984. On the reality, stability, and usefulness of southern hemisphere teleconnections. *Aust. Met. Mag., 32*, 75–82.

Priestley, C.H.B. 1964. Rainfall-sea surface temperature association of the New South Wales Coast. *Aust. Met. Mag., No. 47*, 15–25.

Priestley, C.H.B. and Troup, A.J. 1966. Droughts and wet periods and their association with sea surface temperature. *Aust. J. Sci., 29*, 56–7.

Rasmusson, E.M. and Carpenter, T.H. 1982. Variations in tropical sea surface wind fields associated with the southern oscillation/El Niño. *Mon. Weath. Rev., 110*, 354–84.

Rasmusson, E.M. and Carpenter, T.H. 1983. The relationship between eastern equatorial pacific sea surface temperatures and rainfall over India and Sri Lanka. *Mon. Weath. Rev., 111*, 517–28.

Richman, M.B. 1986. Rotation of principal components. *J. Climatol., 6*, 293–335.

Streten, N.A. 1981. Southern hemisphere sea surface temperature variability and apparent associations with Australian rainfall. *J. geophys. Res., 86, No. C1 (April-June)*, 485–97.

Streten, N.A. 1983. Extreme distribution of Australian annual rainfall in relation to sea surface temperatures. *J. Climatol., 3*, 143–53.

Whetton, P.H. 1990. Relationships between monthly anomalies of Australian region sea-surface temperature and Victorian rainfall. *Aust. Met. Mag., 38*, 31–41.