El-Nino/Southern Oscillation and Streamflow Patterns in South-East Australia

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SUMMARY The relationship between El-Nino/Southern-Oscillation (ENSO) and streamflow patterns in south-east Australia is investigated using an empirical method based on harmonic analysis and the detection of successive months with the same streamflow anomaly. The results indicate that below-normal streamflow in the southern parts of east Australia tends to be associated with ENSO. Further north, and east of the divide, the signal is poorly defined. The season of below-normal streamflow begins fairly early in the ENSO cycle around February during the ENSO year and extends for about one year. The signal is strongest around September. The association between ENSO and streamflow anomalies is stronger for Tasmania and catchments which drain inland into the Murray River compared to the coastal catchments which drain into the Pacific Ocean. The ENSO-streamflow relationship identified here has implications on the prediction of streamflow anomaly and on the management of water resources.

1 INTRODUCTION

El-Nino/Southern Oscillation (ENSO) is a warm event in the tropical Pacific Ocean and is considered a significant perturbation of the general atmospheric circulation. El-Nino is used to describe the appearance of warm surface water along the coasts of Peru and Ecuador while the Southern Oscillation is a see-saw of atmospheric pressure between the Pacific and Indo-Australian areas. The warm episodes (ENSO) have a typical life of about two years and affect climate patterns over many areas of the world (Yarnal, 1985; Hamilton, 1988; Philander, 1990). The time interval between successive ENSO events varies from two to ten years with a mean of about four years. A description of a typical ENSO episode morphology can be found in Rasmusson and Carpenter (1982). In Australia, significant correlations have been reported between ENSO and physical variables such as rainfall, temperature, wind, atmospheric pressure, sea level and cloudiness (Allan, 1988).

It is useful to examine streamflow behaviour to evaluate the potential influences of ENSO on water resources systems. The interannual variability in rainfall is usually enhanced in runoff and therefore it may be easier to identify ENSO signals from the analysis of streamflow patterns. The importance of the ENSO-streamflow relationship is emphasised in recent studies where Cayan and Peterson (1989) and Koch *et al.* (1991) pointed out that streamflow anomalies in certain parts of the United States may be predicted one or two seasons in advance by using the Southern Oscillation Index. Kuhnel *et al.* (1990) showed that the Southern Oscillation signal relating to rainfall and streamflow is stronger in south-east Australia than in south-east United States. Webb and Betancourt (1990) showed that the estimated 100-year flood associated with ENSO is double that for non-ENSO conditions and implied that standard methods of flood frequency (and other) analysis may have to take into account the time-variant climatic effects.

This study uses the empirical method described by Ropelewski and Halpert (1986) to investigate the relationship between ENSO and streamflow patterns in Australia. The method has been used by Ropelewski and Halpert (1987) to study global and regional precipitation patterns and by Kahya and Dracup (1993) to study United States streamflow patterns associated with ENSO. The method has two steps. First, a harmonic analysis is carried out to determine stations with similar seasonal ENSO signals. The regions with similar ENSO signals are labelled as candidate regions. Second, information from stations within a region is combined and analysed to identify successive months during the ENSO cycle with below or above normal streamflows. Streamflow information over the dry or wet period for all years of record is then analysed to determine the association between ENSO and streamflow anomalies in the region. The advantage of this methodology is that no assumption is made initially about the period and location of the ENSO-related responses in surface parameters.

2 STREAMFLOW DATA

The streamflow data are selected from the 69 'benchmark' catchments identified by the Australian Bureau of Meteorology (1991) as part of a project on "Monitoring Climate Change and Its Impact on Australia's Water Resources" for the Australian Water Resources Council. The rivers are unregulated and no significant land use change has occurred in the catchments. The stations are used only if they have 25 years of record from 1963 to 1987. They cover six ENSO years (1965, 1969, 1972, 1976, 1982 and 1986). The definition of the ENSO years is based on the studies of Quinn et al. (1978) and Rasmusson and Carpenter (1982).

Altogether, 25 stations which are mainly located in the south-east coast of Australia (see Figure 1) are used in this study. The catchment areas range from 15 to 1100 km2,

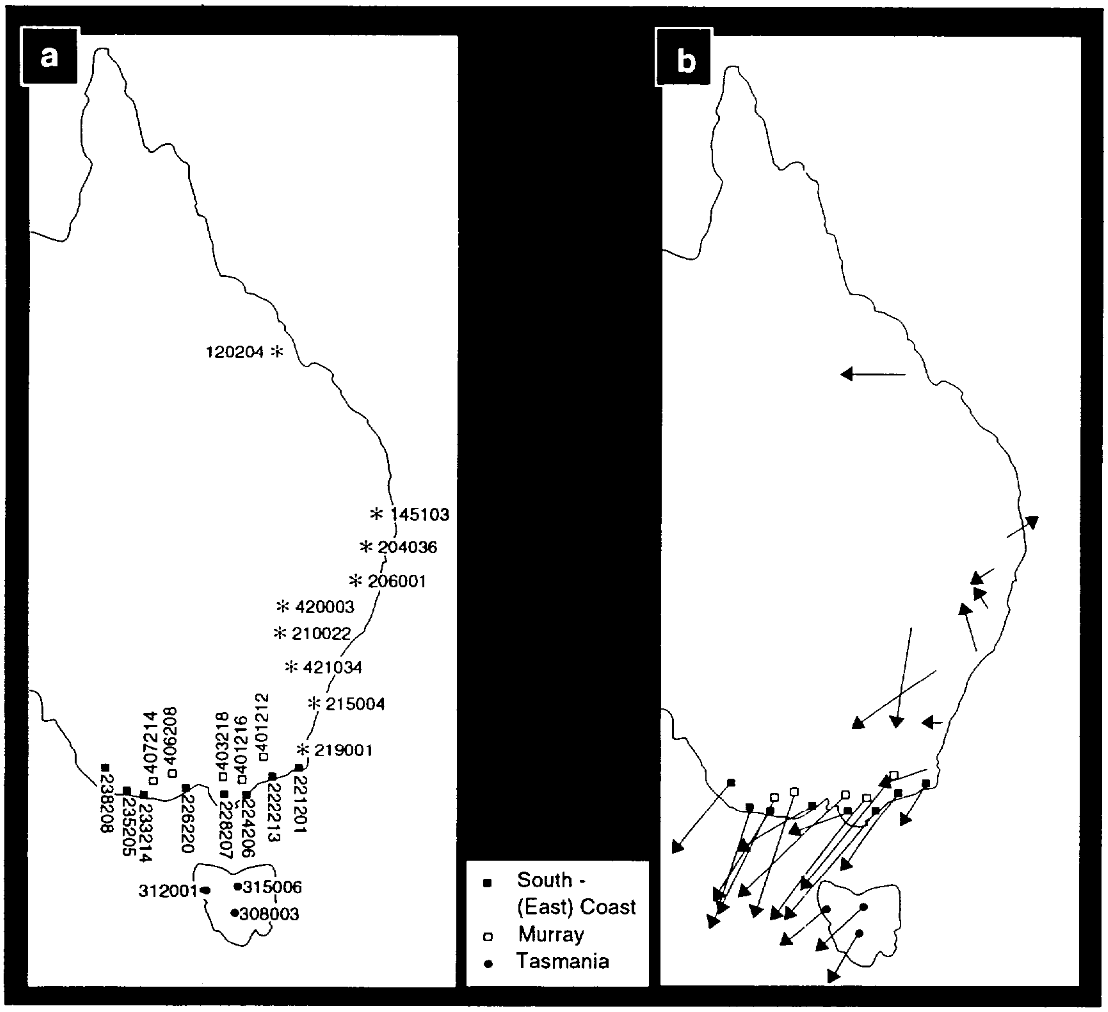

Figure 1 (a) Station locations and (b) streamflow vectors for the first harmonic fitted to 24-month ENSO composites

mean annual runoffs from 40 to 2000 mm, runoff coefficients from 0.05 to 0.9 and the coefficients of variation of annual flows from 0.15 to 1.2. Chiew and McMahon (1993) showed that, in general, there are no statistically significant trends in the streamflow records from these stations. A summary of the annual flow characteristics of these stations can also be found in Chiew and McMahon (1993).

3 ANALYSIS

3.1 Harmonic analysis and identification of candidate regions

The time series of raw monthly streamflows for each month is expressed as percentiles based on the lognormal distribution (LND). The cumulative density function (herein called lognormal percentile) of the LND can be approximated as (Yevjevich, 1972)

$$F(z) = \frac{1}{2}\left(1 + \mathrm{erf}(z/\sqrt{2})\right) \qquad (1)$$

The standardised variable, z, is computed as

$$z = (\ln x - \mu_n) / \sigma_n \qquad (2)$$

where x is the raw monthly streamflow, μ_n is the mean of ln x and σ_n is the standard deviation of ln x.

The logarithmic transformation is used to eliminate positive skewness in the frequency distribution of streamflow due to the occurrence of high flow events. To calculate the percentiles, the 12 months are considered separately, that is all January flows are considered as one time series, all February flows are considered as another time series, and so on (note that calendar years are used throughout). This effectively removes the annual cycle and other cycles in the time series because the 25-year LND percentile averages for all 12 months are almost the same. The use of LND percentiles also provides easy interpretation of streamflow patterns from the various stations with records of different magnitudes.

A 24-month period is used to define the ENSO cycle. The ENSO composite is formed for a 2-year period starting with July preceding the episode (designated as Jul(-)) and continuing through the June following the episode (Jun(+)). The months in year (0) refer to months during the ENSO year. The ENSO composite for each month is calculated as the average of the LND percentiles for the six ENSO events, that is the average of streamflow percentiles for all six Jul (-), all six Aug(-), and so on. The example in Figure 2 shows the composite lognormal percentiles for Station 401212.

A harmonic analysis is then carried out where the first harmonic is fitted to the 24-month ENSO composite. For simplicity, the equations presented here apply only to the fitting of the first harmonic to the 24-month composite from six ENSO events. The theory of harmonic analysis and generalised equations for higher order harmonic fits to different lengths of time series can be found in Brooks and Carruthers (1953), Rayner (1971) and Kahya and Dracup (1993).

The first harmonic fit for the 24-month composite can be written as

$$X = X_0 + C\cos\left(\frac{\pi}{12}(t - t_m)\right) \qquad (t=1,24) \qquad (3)$$

where X is the percentile value at time t, X_0 is the arithmetic mean of the percentiles and C is the amplitude of the first harmonic. The amplitude is the square root of the sum of squares of the two Fourier coefficients, A and B

$$C = \sqrt{A^2+B^2} \qquad (4)$$

$$A = \frac{1}{12}(X_1\cos 15° + X_2\cos 30° + X_3\cos 45° + ... + X_{24}\cos 360°) \qquad (5)$$

$$B = \frac{1}{12}(X_1\sin 15° + X_2\sin 30° + X_3\sin 45° + ... + X_{24}\sin 360°) \qquad (6)$$

The term t_m represents the phase shift of the first harmonic, expressed as the time (month) when the harmonic has a maximum, and is given by

$$t_m = 12/\pi \cos^{-1}(A/C) \qquad (7)$$

The first harmonic fit for Station 401212 is given in Figure 2.

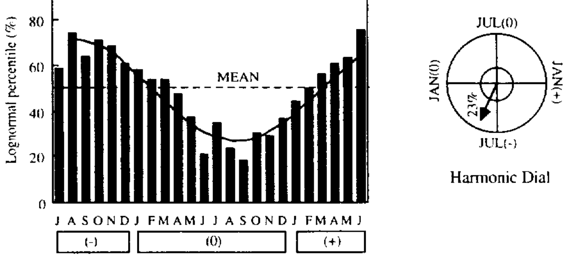

Figure 2 First harmonic fit to the 24-month ENSO composite for Station 401212. The harmonic dial refers to an amplitude of 22.7% and a phase shift of 37° (between Aug(-) and Sep(-))

The use of the first harmonic implies that streamflow fluctuations over the 24-month period can be approximated by a single sine curve with one maximum and one minimum corresponding to the hypothesised ENSO forcing. In general, low frequency variations (harmonics with a long period) in climatological time series represent large scale aspects of the atmospheric circulation, and high frequency variations (harmonics with a short period) refer to influences of local phenomena (Kirkyla and Hameed, 1989). The use of the first harmonic is therefore reasonable because ENSO is a slowly progressing large scale phenomenon.

Following Kahya and Dracup (1993), two methods are used in this study to assess the adequacy of the first harmonic fit. First, the variance reduction by the first harmonic ($C^2/2\sigma^2$) gives an indication of the goodness of fit of the first harmonic. The value of 0.86 for Station 401212 indicates that 86% of the variance in the 24-month composite is accounted for by the first harmonic. Second, the amplitude of the first harmonic fit for each of the six 24-month ENSO events is calculated and compared with the amplitude for the ENSO composite. Schuster's quantitative test of significance (Conrad and Pollak, 1950) is then applied to estimate the probability that the amplitude of the first harmonic is obtained by chance. The degree of significance (DOS) can be assessed from

$$\text{probability} = \exp(-\kappa^2) \qquad (8)$$

where for this study

$$\kappa = \frac{C}{\bar{C}/\sqrt{6}} \qquad (9)$$

$$\bar{C} = \sqrt{\frac{1}{6}(C_1^2 + C_2^2 + ... + C_6^2)} \qquad (10)$$

where C_1, C_2, ..., C_6 are the amplitudes of the first harmonic for the six ENSO events.

The DOS for Station 401212 is 0.03 indicating that the probability that the amplitude of the first harmonic is produced by chance is less than 0.03.

The parameters of the first harmonic (amplitude and phase shift) and the statistics which describe the goodness of fit for the 25 stations are given in Table 1. For easy comparison of the streamflow patterns of the different stations, the parameters of the first harmonic are condensed in a vector and presented as a harmonic dial. The vector has a length equal to the amplitude and a direction equal to the phase shift expressed in degrees (see Table 1 and Figure 2).

The harmonic fits of the 24-month ENSO composite for the 25 stations are plotted as vectors in Figure 1(b). The plots indicate that streamflow records from stations in the southern part of east Australia show similar phase shifts. Further north, and east of the divide, the signal is poorly defined. This agrees with Ropelewski and Halpert's (1987) analysis of Australian precipitation records.

A closer investigation of Figure 1(b) and Table 1 indicates that the stations can be grouped into three regions (called candidate regions), namely the South-(East) Coast (the south coast of east Australia), Murray and Tasmania. The catchments in the Murray Region drain inland into the Murray River while catchments in the South-(East) Coast drain into the Pacific Ocean.

Table 1
Parameters of the first harmonic fit for 24-month ENSO composite

Station number	Amplitude	Phase shift (angle)*	Phase shift (month of maximum)#	$C^2/2\sigma^2$	Schuster's DOS
120204	9.2	86	5.7	0.33	0.34
145103	5.1	234	15.6	0.07	0.56
204036	4.1	53	3.6	0.09	0.72
206001	3.0	163	10.9	0.05	0.89
210022	8.1	165	11.0	0.19	0.41
215004	1.7	96	6.4	0.01	0.95
219001	8.0	69	4.6	0.31	0.42
420003	15.1	12	0.8	0.52	0.07
421034	12.9	56	3.8	0.54	0.17
South-(East) Coast					
221201	6.8	31	2.0	0.24	0.41
222213	14.8	35	2.3	0.67	0.06
224206	22.0	38	2.5	0.81	0.01
226220	13.2	58	3.9	0.67	0.06
228207	8.9	68	4.6	0.34	0.28
233214	16.3	24	1.6	0.58	0.04
235205	16.8	18	1.2	0.68	0.07
238208	14.5	39	2.6	0.65	0.11
Murray					
401212	22.7	37	2.5	0.86	0.03
401216	22.9	34	2.2	0.83	0.03
403218	21.9	44	2.9	0.83	0.04
406208	21.1	18	1.2	0.62	0.02
407214	21.0	25	1.7	0.75	0.04
Tasmania					
308003	8.1	30	2.0	0.31	0.36
312001	11.3	49	3.3	0.53	0.19
315006	10.9	44	2.9	0.44	0.24

* 0^o indicates that the maximum of the first harmonic occurs in Jul(-), 90^o indicates that the maximum occurs in Jan(0), ... , and 270^o in Jan(+) (see harmonic dial in Figure 2)

\# 1.0 indicates that the maximum occurs in Jul(-), 2.0 in Aug(-), ..., and 24.0 in Jun(+)

The goodness of choice of the candidate regions can be assessed by calculating the coherence

$$\text{coherence} = \frac{\sqrt{\left(\sum_{i=1}^{n} C_i \sin\theta_i\right)^2 + \left(\sum_{i=1}^{n} C_i \cos\theta_i\right)^2}}{\sum_{i=1}^{n} C_i} \qquad (11)$$

where C_i and θ_i are the amplitude and phase angle of station i respectively and n is the number of stations in the candidate region. Although the three candidate regions are subjectively chosen, the coherences are extremely high (0.97 for the South-(East) Coast and 0.99 for the Murray and Tasmania regions). The stations in the Murray and Tasmania regions show remarkable similarities (see amplitude and phase shift in Table 1), while the first harmonic parameters for stations in the South-(East) Coast vary over a bigger range.

The statistics indicate that the first harmonic fits for these stations, particularly those in the Murray Region, are relatively good. The percentage of variance reduction by the first harmonic is generally greater than 0.5 and Schuster's DOS is generally less than 0.15. The ENSO signals for the Murray Region are greater than the signals for the other two regions as indicated by the higher amplitude of the first harmonic for the Murray Region compared to the other two regions.

3.2 Season detection, index time series and ENSO-streamflow association

In this section, the ENSO composites (LND percentiles) for stations in a candidate region are averaged to give the aggregate composite for the region. However, a 36-month cycle is considered here instead of the 24-month cycle used in the previous section. A 36-month cycle is consistent with Kahya and Dracup (1993) and is used to avoid the identification of the complementary La Nina signal. Figure 3(a) shows the aggregate composite for the Murray Region. A dry or wet season is defined here as a period of several successive months with same sign anomalies (percentiles greater than or below 50%). From Figure 3(a), a dry season which extends for 13 months from Feb(0) to Feb(+) is identified for the Murray Region. Figure 3(a) also indicates that the aggregate composite contains a 'complementary' wet season. This is expected because the first harmonic yields single-valued maximum and minimum percentiles which correspond to a group of positive and negative streamflow anomalies. Only one of the two seasons is selected as the seasonal ENSO signals because the other is the counterpart extreme to the one selected (see Figure 2).

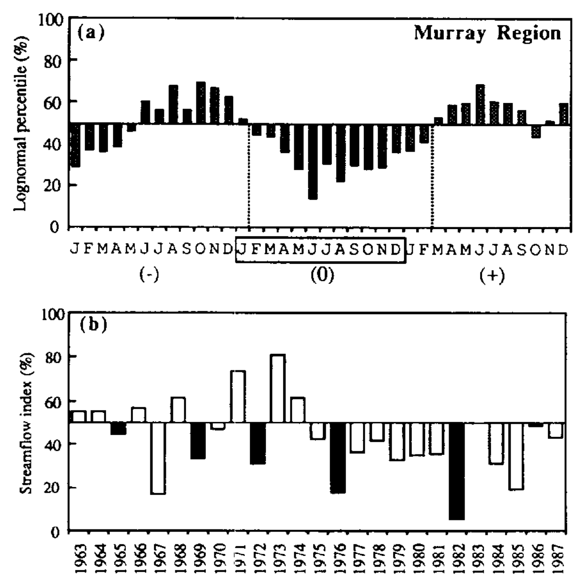

Figure 3 (a) 36-month ENSO aggregate composite for the candidate Murray Region and (b) index time series for the season delineated by the dashed lines in (a)

A time series of the lognormal percentiles, averaged over the signal season, for all years of record is then used to examine the strength of the ENSO-streamflow association. The 'index time series' (ITS) for the Murray Region is given in Figure 3(b). As an example, the streamflow index for 1970 in Figure 3(b) is the average of the percentiles over the 13 months from February 1970 to February 1971. The aggregate composites, season detection and ITS for the Tasmania and South-(East) Coast regions are given in Figures 4 and 5 respectively. The analysis is carried out using aggregate composites for candidate regions so that consistent ENSO signals can be detected over a geographical region. The analysis can also be carried out for individual stations, but the anomalies detected may only represent a local phenomenon associated with that single catchment.

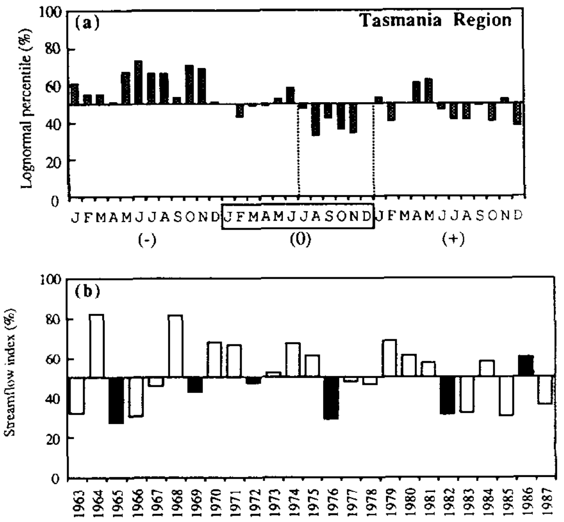

Figure 4 (a) 36-month ENSO aggregate composite for the candidate Tasmania Region and (b) index time series for the season delineated by the dashed lines in (a)

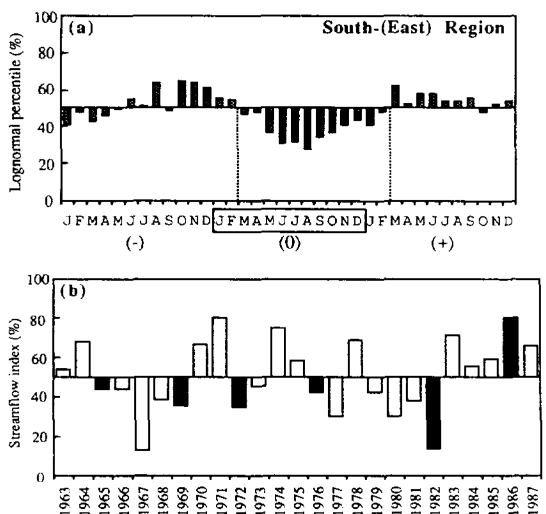

Figure 5 (a) 36-month ENSO aggregate composite for the candidate South-(East) Coast Region and (b) index time series for the season delineated by the dashed lines in (a)

4 DISCUSSION

The analysis suggests that dry conditions in the southern coast of east Australia tend to be associated with ENSO. In the Murray Region, low streamflow begins fairly early in the ENSO cycle in Feb(0) and extends over a long 13-month period to Feb(+). The signal is strongest in Aug(0) and Sep(0). Note that the strongest signal corresponds to the maximum or minimum in the harmonic fit (see Figure 2 and phase shift in Table 1) and not to the maximum 'anomaly' of the aggregate composite (as in Figures 3(a), 4(a) and 5(a)). The signal for Tasmania is similar to the Murray Region, although it is weaker and has a shorter period. Below 'normal' streamflow extends only over a six-month period from Jul(0) to Dec(0) (see Figure 4(a)), with the signal being strongest around Oct(0). In the South-(East) Coast, the low streamflow anomalies extend for 12 months from Mar(0) to Feb(+) (see Figure 5(a)), with the signal being strongest around Sep(0). The season and timing of below-normal streamflow is similar to the below-normal precipitation anomalies found by Ropelewski and Halpert (1987). Although this confirms the findings of Ropelewski and Halpert, it is interesting to note that there appears to be no delay in the streamflow response to precipitation anomalies despite the nonlinear rainfall-runoff relationship.

The index time series for the Murray Region (Figure 3(b)) suggests that the association between ENSO and streamflow anomaly for the region is fairly strong. For all the six ENSO years, streamflow is below-normal, and two of the three strongest negative streamflow anomalies occurred during ENSO years. The signal for Tasmania is weaker with below-normal streamflow occurring in only five of the six ENSO years. In addition, there are many strong negative streamflow anomalies during non-ENSO years (see Figure 4(b)). The ENSO-streamflow association for the South-(East) Coast is the weakest of the three regions. Like Tasmania, there is below-normal streamflow during five of the six ENSO years. However, the strongest positive streamflow anomaly also occurred during the ENSO year of 1986 (see Figure 5(b)). It is therefore interesting to note that the ENSO signals become weaker as we proceed south across the divide from the Murray Region to the coast, but becomes strong again as we move further south into Tasmania.

5 SUMMARY AND CONCLUSIONS

The first harmonic fit over a 24-month composite ENSO cycle indicates that stations in the southern parts of east Australia show similar phase shifts in the ENSO-streamflow relationship. Further north, and east of the divide, the signal is poorly defined. The analysis of aggregate composites for candidate regions indicates that below-normal streamflows tend to be associated with ENSO. The season of below-normal streamflow begins fairly early in the ENSO cycle around Feb(0) and extends for about one year. The signal is strongest around Sep(0). The association between ENSO and streamflow anomalies is stronger for Tasmania and catchments which drain inland into the Murray River compared to the coastal catchments which drain into the Pacific Ocean.

There are three limitations in the approach used here. First, the results may be dominated by the strong 1982 ENSO episode (see Figures 3(b), 4(b) and 5(b)). Second, the analysis is very much at the mercy of available station data, and for this reason, this study is limited to catchments in south-east Australia. Third, it is difficult to establish the statistical significance of the ENSO-streamflow relationships in a meaningful way.

However, the results here are sufficient to suggest a possible teleconnection between ENSO and streamflow anomaly in south-east Australia. The identification of ENSO-streamflow association for core regions has implications on the long-range prediction of climate and streamflow and on the management of water resources. For example, the catchments used in this study are dominated by winter rainfall with dry conditions extending over long periods of summer. Low streamflows associated with ENSO during the summer months therefore have, at the very least, direct implications on irrigation water management.

6 ACKNOWLEDGEMENTS

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