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Multi-decadal variability of rainfall and streamflow across eastern Australia

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Abstract This study investigates the influence of the El Niño/Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) on rainfall and streamflow regimes of eastern Australia. An analysis of historical rainfall and streamflow data for Queensland (QLD), New South Wales (NSW) and Victoria (VIC) reveals strong relationships between these indices and seasonal rainfall and streamflow totals. Rainfall and streamflow in NSW and QLD are shown to be significantly enhanced during the La Niña phase of ENSO, with La Niña impacts diminishing as one moves south into VIC. In addition, the study shows that on a multi-decadal time scale, the negative phase of the IPO is associated with "wetter" conditions than the positive phase. Importantly, the already enhanced La Niña rainfall and streamflow is demonstrated to be even further magnified during La Niña events that occur in the IPO negative phase. The results also indicate that some useful predictability of ENSO impacts can be achieved during the negative phase of the IPO for VIC.

Key words climate variability; El Niño/Southern Oscillation (ENSO); Inter-decadal Pacific Oscillation (IPO); Pacific Decadal Oscillation (PDO); rainfall; streamflow

INTRODUCTION

The rainfall and streamflow regimes of Australia are extremely variable. For example, multi-decadal epochs of enhanced/reduced flood risk across New South Wales have been identified (e.g. Erskine & Warner, 1988; Franks, 2002a; Franks & Kuczera, 2002). In particular, Franks & Kuczera (2002) demonstrated that a major shift in flood frequency occurred around 1945, whilst Franks (2002a) demonstrated that this step change could be objectively identified as corresponding to a change in both sea-surface temperature anomalies and circulation patterns (Allan *et al.*, 1995).

The high variability of rainfall and temperature in eastern Australian has been strongly associated with the regional influence of the El Niño/Southern Oscillation (ENSO) (e.g. Ropelewski & Halpert, 1987; Allan, 1988; Stone & Auliciems, 1992; Power *et al.*, 1998; Kiem & Franks, 2001). In particular, the warm El Niño phase of ENSO is associated with marked reductions in rainfall and increased air temperatures, whilst cool La Niña events are typically associated with enhanced rainfall totals and cooler air temperatures.

In addition to ENSO, recent studies have also revealed multi-decadal variability in the modulation of ENSO impacts (Power *et al.*, 1999; Kiem *et al.*, 2003; Kiem & Franks, 2004). The Inter-decadal Pacific Oscillation (IPO) is the coherent pattern of sea-surface temperature (SST) variability occurring on inter-decadal time scales over

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the Pacific Ocean. Similarly, recent studies by Mantua *et al.* (1997) and Nigam *et al.* (1999) have also shown how North Pacific SST can be correlated to weather patterns, streamflow and drought conditions throughout North America using the Pacific Decadal Oscillation or PDO. Power *et al.* (1999) showed that there is a close association between the decadal parts of the PDO index and the IPO index. Importantly, the IPO and PDO time series are highly correlated and represent variable epochs of warming and cooling in both hemispheres of the Pacific Ocean (Franks, 2002b).

Several studies have shown that the IPO influences both the strength and nature of the ENSO cycle. Power *et al.* (1999) suggested that individual ENSO events, El Niño and La Niña, had stronger, more predictable impacts across Australia during the negative phase of the IPO, implying that there exists a multi-decadal modulation of the magnitude of ENSO events. More recently, Kiem *et al.* (2003) and Kiem & Franks (2004) have demonstrated that the IPO also appears to modulate the frequency of individual La Niña events with marked consequences for multi-decadal flood and drought risk in eastern Australia and elsewhere. Across New Zealand, the IPO appears to have produced similar shifts in flood frequency (McKerchar & Henderson, 2003). Similarly, Verdon *et al.* (2004) demonstrated that meteorological fire risk was enhanced during IPO negative El Niño events for eastern Australia, again giving rise to variable epochs of elevated risk.

This study aims to assess the spatial influence of multi-temporal scale climate variability on rainfall and streamflow across eastern Australia. The influence of ENSO on seasonal rainfall and streamflow variability is investigated using historical data from a number of stations so as to ascertain not only the magnitude, but also the spatial extent of ENSO influence. Additionally, the modulation of ENSO induced rainfall and streamflow variability by the IPO is assessed. In this paper, rainfall and streamflow data from Queensland (QLD), New South Wales (NSW) and Victoria (VIC) are stratified according to ENSO classifications derived from the NINO3 index. The rainfall and streamflow data are then further stratified according to multi-decadal IPO classifications.

SITE SELECTION AND DATA

The rainfall and streamflow data used in this study were obtained from the Australian Bureau of Meteorology. A total of 182 rainfall records and 152 streamflow records across eastern Australia were deemed suitable for use in the study in terms of data length and continuity, as shown in Fig. 1. All rainfall gauges chosen for analysis contained complete data for the years 1924–1998 inclusive. Streamflow gauges were chosen with data records considered to be of sufficient length for the statistical analysis carried out in the study.

It can be seen from Fig. 1 that the locations of the rainfall stations provide a good spatial coverage of eastern Australia. However, most of the streamflow gauges used in the study are concentrated in coastal locations with the exception of VIC, due to the predominance of coastal rivers in eastern Australia.

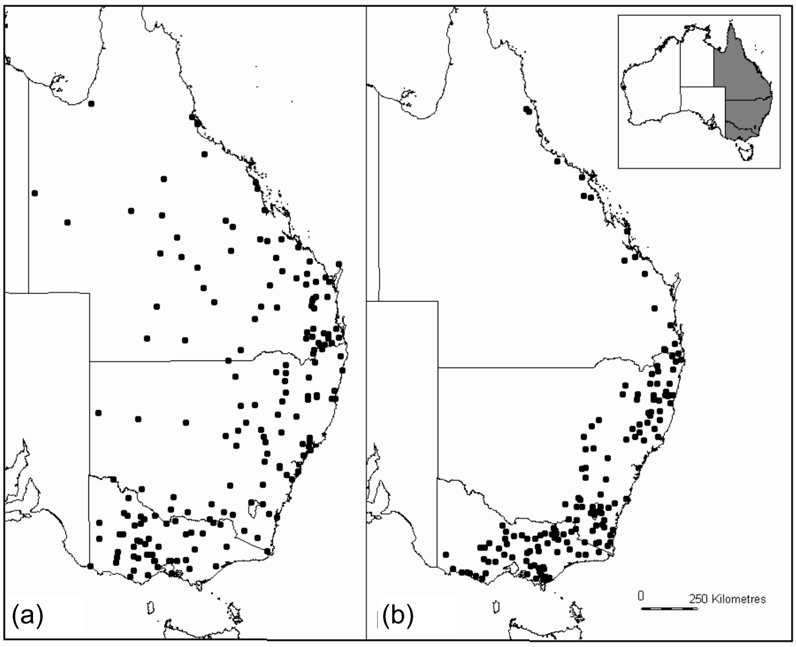

Fig. 1 Location of (a) rainfall gauges and (b) streamflow stations used in this study.

TEMPORAL STRATIFICATION ACCORDING TO ENSO AND IPO INDICES

The monthly NINO3 index of sea-surface temperature anomalies (Kaplan *et al.*, 1998) was used to stratify the rainfall and streamflow data. Each year was assigned an ENSO classification based on the six-month October–March average NINO3 value using a threshold of ±0.5. Whilst an entire range of ENSO indices, classification schemes and impact assessment methodologies have previously been employed by diverse authors, this method and ENSO index have been demonstrated to be the most robust for the time period being investigated (see for instance, Kiem & Franks, 2001).

The rainfall and streamflow data were also stratified into the three phases of the IPO. In classifying the different IPO phases, Power *et al.* (1999) used the thresholds of ±0.5 to distinguish positive, neutral and negative phases. Figure 2 displays the oscillations of the IPO from 1920 to 1999. During this period there have been three major phases of the IPO: two positive phases (IPO > 0.5) between 1924 and 1943, and

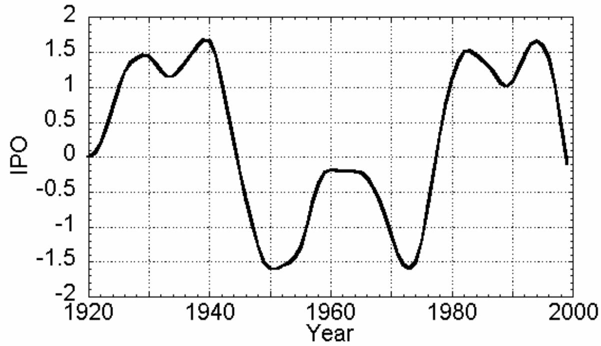

Fig. 2 The Inter-decadal Pacific Oscillation (IPO) from 1920 to 1999.

1979 and 1997, and a negative phase (IPO <–0.5) from 1946 to 1976. These phases exclude the 10 years from 1958 to 1967 when the absolute value of the IPO index was <0.5.

Determination of the ENSO impact period

A typical ENSO cycle usually initiates in April/May of the first year and concludes in March/April of the following year. However, the timing of ENSO impacts on rainfall varies spatially across the Australian continent (Ropelewski & Halpert, 1987). This study aims to investigate the magnitude of the impact of ENSO on eastern Australia; therefore, it is important to determine the critical period at which these impacts occur. The period of maximum impact is assessed by determining the influence of ENSO on rainfall on a monthly basis for each State (NSW, QLD and VIC). The two ENSO extremes, El Niño and La Niña, are compared so as to determine the period of greatest variability across eastern Australia. A Student's t test is used to determine the probability that the mean of the El Niño rainfall distribution is equal to the mean of the La Niña rainfall distribution (Benjamin & Cornell, 1970). The number of stations that show a significant difference ($p < 0.1$) in rainfall during La Niña years compared to El Niño years is then determined for each month and state. Table 1 displays the results of the ENSO impact period analysis.

Whilst the period of impact varies from station to station, a general impact period is chosen so as to best represent the interval where the greatest number of stations display a significant ENSO influence. It is possible that each state could be assigned an individual impact period, however state boarders are relatively arbitrary. Indeed, each station studied could be assigned an individual impact period; however, this would have provided further complications in a comparative study between gauges. With this in mind a common impact period is used, over which ENSO and IPO impacts are assessed and directly compared. Table 1 demonstrates that all states show ENSO impacts during September and these impacts fade by February of the following year. Whilst some states display an earlier onset of ENSO influence on rainfall (for example QLD) this is not consistent until September. In addition, VIC displays no ENSO impacts during the winter months. Therefore, in this study, the ENSO impact period for eastern Australia is defined as the months September–January inclusive.

Table 1 Number of stations where La Niña rainfall is significantly higher than El Niño rainfall.

	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
QLD	0	3	46	10	48	25	16	26	36	5	11	2
NSW	0	0	16	1	40	17	36	3	41	2	0	1
VIC	0	0	0	0	4	9	24	4	4	0	0	2

VARIABILITY OF RAINFALL AND STREAMFLOW DUE TO ENSO IMPACTS

The variation in rainfall and streamflow totals between the two extreme ENSO phases (El Niño and La Niña) is examined in order to determine the magnitude of ENSO-

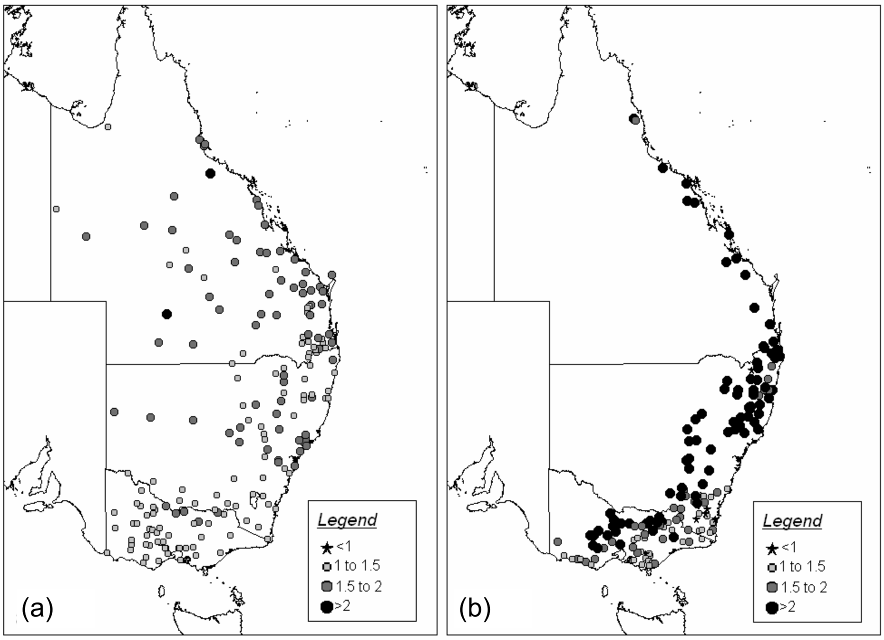

Fig. 3 Increase in (a) rainfall and (b) streamflow during La Niña years compared to El Niño years.

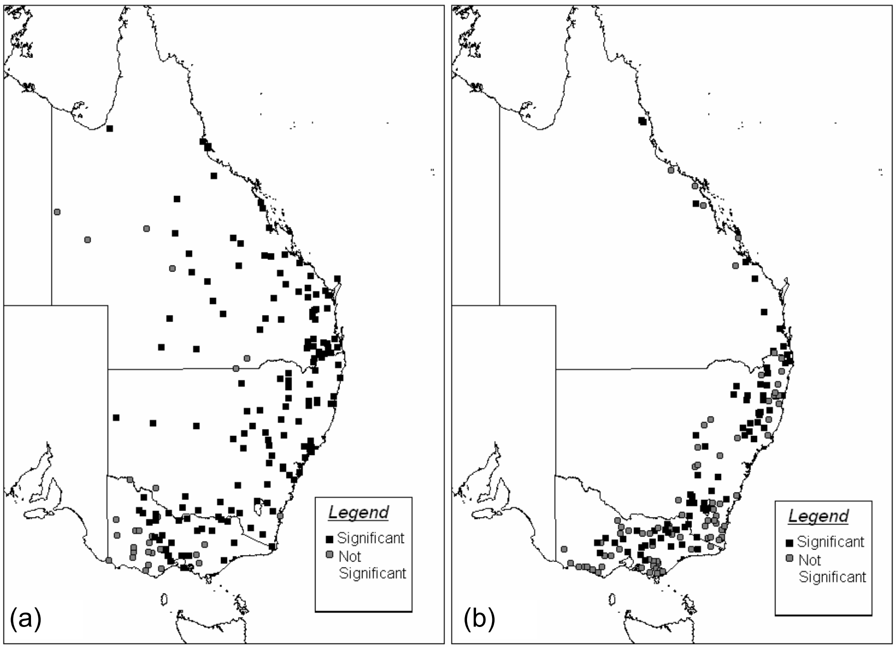

Fig. 4 Results of significance test showing stations where the (a) rainfall and (b) streamflow in La Niña years is significantly higher than in El Niño years.

related variability. The ratio of September–January mean rainfall and streamflow during La Niña years compared to El Niño years is displayed in Fig. 3. A Student's *t* test is also applied to determine whether the rainfall and streamflow in La Niña years is statistically different from El Niño rainfall and streamflow. Figure 4 highlights which stations display a statistically significant difference.

Figure 3 shows that rainfall is considerably enhanced during the La Niña phase of ENSO compared to El Niño. This difference is also statistically significant for the majority of stations, as shown in Fig. 4. The influence of La Niña on rainfall tends to be greater for northern NSW and QLD, where this increase in rainfall is generally between 50 and 100% for the majority of stations. The relationship is weaker, though still evident, in VIC. The magnitude of the enhancement of streamflow under La Niña conditions is also shown to be substantial, with approximately half of these stations showing the difference to be statistically significant. The vast majority of stations located within NSW and QLD, and many of the northern VIC stations, show an increase in streamflow of greater than 100% during La Niña years compared to El Niño years.

MULTI-DECADAL VARIABILITY OF RAINFALL AND STREAMFLOW

IPO modulation of rainfall and streamflow variability

The variability of rainfall and streamflow during the different phases of the IPO is examined to determine if there is any difference in rainfall and streamflow totals on a multi-decadal time scale. Figure 5 shows the ratio of September–January rainfall and streamflow during years classified as IPO negative compared to the IPO positive years.

Figure 5 demonstrates that rainfall tends to be higher during the negative period of the IPO compared to the positive period. Additionally, nearly all of the stations show that streamflow is considerably enhanced during IPO negative years. The streamflow during the IPO negative years is shown to be more than twice that during IPO positive years for the majority of QLD and NSW stations.

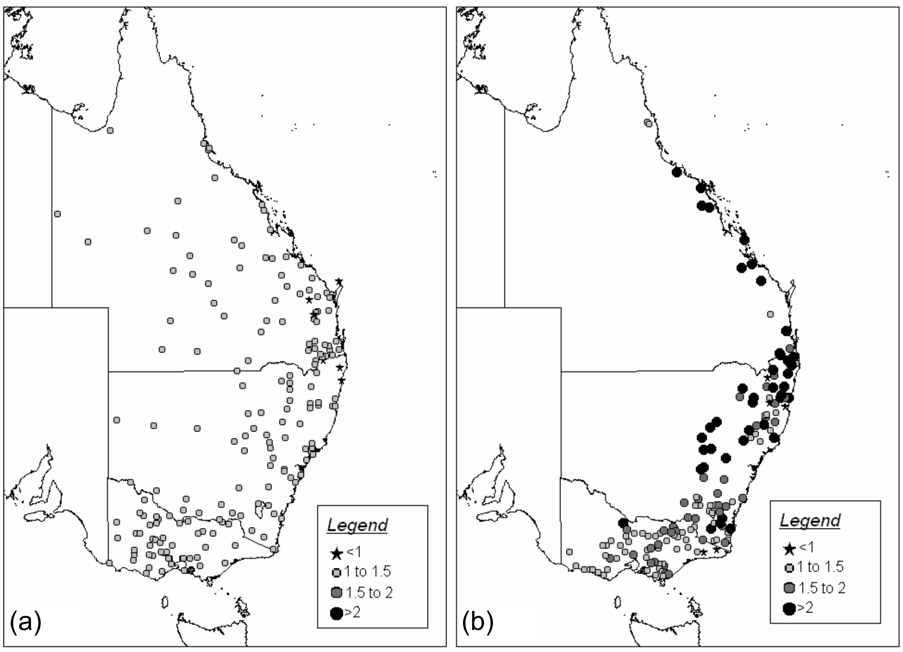

Fig. 5 Increase in (a) rainfall and (b) streamflow during IPO negative years compared to IPO positive years.

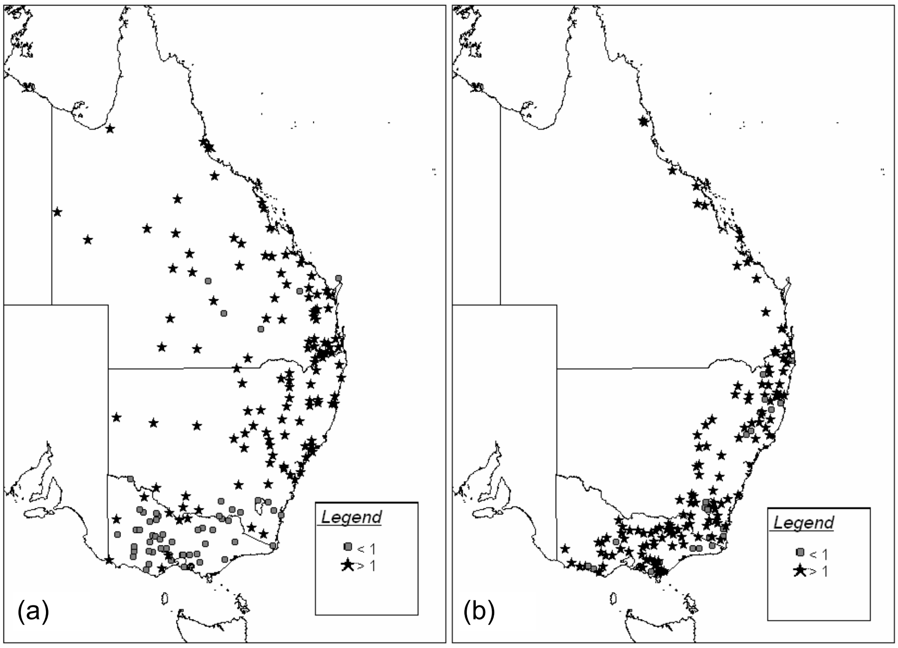

Fig. 6 Ratio of the IPO negative standard deviation to IPO positive standard deviation for (a) rainfall and (b) streamflow distributions.

The standard deviations of the distributions are compared to test whether the variability of rainfall and runoff is different in the two phases of the IPO. Stations where the standard deviation is higher for the IPO negative distributions compared to the IPO positive distributions are highlighted in Fig. 6.

The variability of rainfall and streamflow is shown to differ between the two phases of the IPO. Figure 6 demonstrates that, during the negative phase of the IPO, rainfall tends to be more variable than during the positive phase of the IPO for much of NSW and QLD. This effect is amplified in the streamflow, where the influence of the IPO also extends to VIC.

Modulation of La Niña related rainfall and streamflow variability by the IPO

To determine if La Niña rainfall and runoff is further enhanced during the negative phase of the IPO, the rainfall and streamflow (Fig. 7) in La Niña years occurring in the IPO negative phase are compared to all other La Niña years. Seven La Niña years (1949, 1954, 1955, 1970, 1971, 1973, 1975) occur during the IPO negative phase, with 11 other La Niña years (1924, 1933, 1938, 1942, 1944, 1964, 1967, 1984, 1988, 1995, 1998) occurring in the non-negative phase of the IPO, within the time period being investigated. A Student's *t* test is used to determine if the difference in rainfall and streamflow is statistically significant, as shown in Fig. 8.

The results show that the magnitude of La Niña impacts is modulated by the IPO. Figure 7 clearly demonstrates that the negative phase of the IPO substantially magnifies the already enhanced La Niña rainfall and streamflow. Whilst it can be seen from Fig. 8 that the difference in streamflow is not statistically significant for the majority of stations, the relationship is consistent throughout eastern Australia with all states

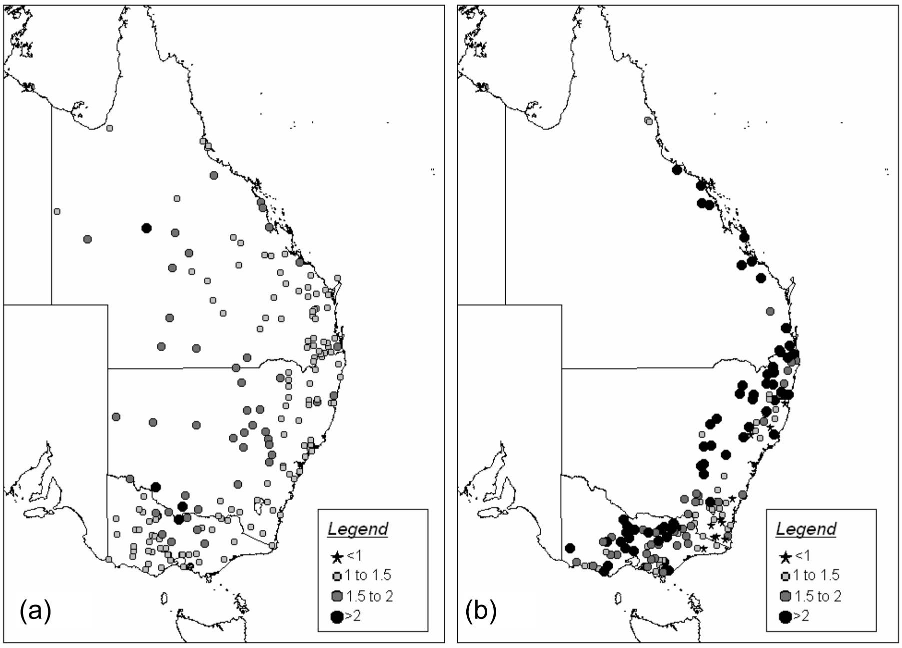

Fig. 7 Increase in (a) rainfall and (b) streamflow during IPO negative La Niña years compared to all other La Niña years.

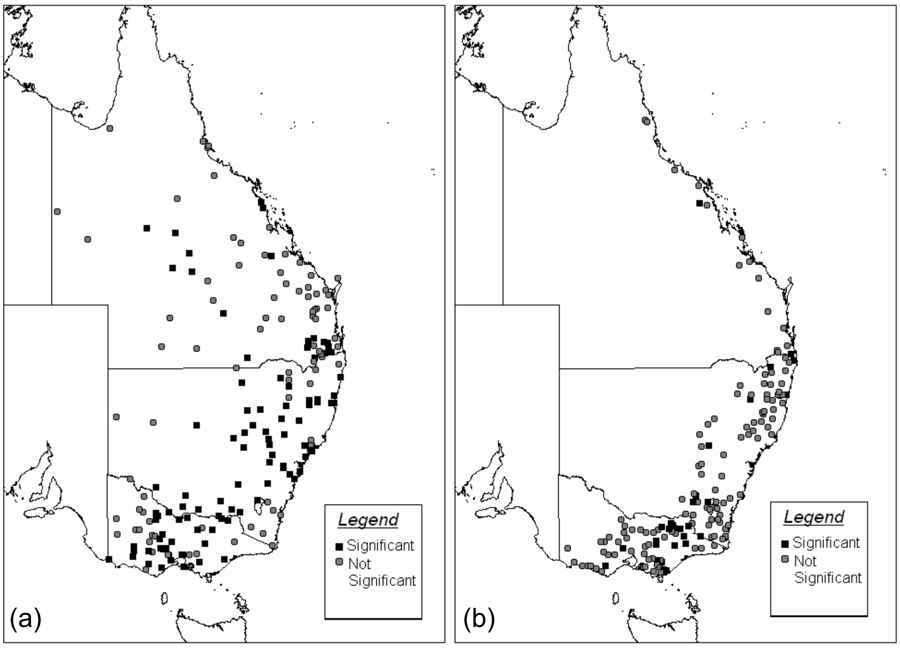

Fig. 8 Results of significance test showing stations where the (a) rainfall and (b) streamflow in IPO negative La Niña years is significantly higher than in all other La Niña years.

displaying evidence of IPO negative La Niña years being substantially "wetter" than all other La Niña years. It is also appears that the modulation of La Niña impacts is stronger in the south, with southern NSW and VIC having the highest concentration of stations showing a significant increase in rainfall and streamflow during IPO negative La Niña years.

CONCLUSIONS

This study has aimed to establish how observed multi-temporal scale climate variability influences rainfall and streamflow across eastern Australia. This has been achieved through an analysis of the impact of ENSO on rainfall and streamflow regimes and their modulation via multi-decadal SST variability as represented by the IPO.

The results confirm that a strong relationship exists between ENSO and seasonal rainfall variability in eastern Australia. The magnitude of seasonal rainfall variability was shown to be forced by the extreme phases of ENSO, with almost all stations displaying an increase in rainfall of 50–100% in La Niña years compared to El Niño years. In addition to rainfall variability, the paper investigated the influence of ENSO on streamflow variability. It was shown that the La Niña phase of ENSO substantially increases streamflow totals with most stations displaying an increase of more than 100% during La Niña years. The influence of ENSO on rainfall and streamflow was shown to extend to all states (NSW, QLD and VIC); however, the effects were found to be greater in NSW and QLD.

An investigation into how multi-decadal climate variability influences the streamflow and rainfall regimes of eastern Australia revealed that the IPO plays an important role in modulating these regimes. Power *et al.* (1999) found that the IPO negative phase modulates the magnitude of individual ENSO events. Kiem & Franks (2004) showed that the IPO also appears to modulate the frequency of ENSO events (in particular the occurrence of La Niña events). This study shows that the negative phase of the IPO, irrespective of ENSO, is associated with an increase in the magnitude of rainfall and runoff as well as greater variability of rainfall and runoff compared to the IPO positive phase. Additionally, this study demonstrates that the negative phase of the IPO magnifies the already enhanced La Niña rainfall and stream–flow. Whilst the IPO was found to modulate ENSO impacts consistently across eastern Australia, the difference was found to be statistically significant for a greater number of stations in southern NSW and VIC. This is most likely due to the relatively weak impact of ENSO during the non-IPO negative phases.

The combined ENSO and IPO indices explain a high degree of the hydro-climatological variability observed in eastern Australia. Recent research by Folland *et al*. (2002) demonstrated how ENSO and IPO processes influence the location of the South Pacific Convergence Zone (SPCZ). The SPCZ is responsible for delivering rain-bearing cloud bands across eastern Australia in summer months. Salinger *et al*. (1995) showed that El Niño events disrupt the location of the SPZC, preventing its propagation to its usual southern latitude, whilst during La Niña events the SPCZ propagates further south than normal delivering more frequent rain-bearing cloud bands across south east Australia. Folland *et al*. (2002) demonstrated that the IPO SST anomalies also influence the location of the SPCZ during the Austral Summer in a manner similar to that induced by ENSO, but on a multi-decadal time scale. Importantly, the results of Folland *et al*. (2002) show that the SPCZ is at its southernmost during La Niña events that occur during the negative phase of the IPO, in line with previous empirical results of ENSO-IPO impacts on flood and drought risk (Franks, 2004). This present study shows that the combined effects of La Niña and IPO negative enhance rainfall and streamflow in eastern Australia and the research by

Folland *et al*. (2002) provides a possible mechanistic justification by which these processes operate.

Whilst the research by Folland *et al*. (2002) provides a likely mechanism of how the IPO may influence rainfall in Australia, the actual cause of the multi-decadal shifts in SSTs is unclear (Franks, 2002b, 2004). At present it is uncertain whether multi-decadal variability is an internal artefact of the ocean–atmosphere system or externally forced by long-term solar variability. The forcing of SST variability via an external solar control has previously been suggested by Reid (1991). Using nonlinear time series analysis, Franks (2002b) demonstrated marked coherence between solar variability, global SST data and the IPO-PDO indices. This study demonstrated that the temperature trends over the 20th century and, hence, the IPO are at least potentially forced by solar irradiance. Whether the IPO and PDO processes are internal to the Earth climate system or forced by external variability, both processes are subject to chaotic effects, hindering the possibility of deterministic prediction (Franks, 2004). However, irrespective of the causal factors behind this variability, the observed persistence of the IPO may itself be used to define the likely state over decadal time scales.

A unique aspect of the results presented here is the analysis of the spatial extent of ENSO and IPO impacts for eastern Australia. The results confirm that ENSO and IPO strongly impact on QLD and NSW rainfall and streamflow, but also that the influence extends to as far south as VIC. Whilst the influence of ENSO may be weaker for VIC, these impacts are significantly enhanced during the negative phase of the IPO. This result is of particular significance as it implies that some useful predictability of ENSO impacts in VIC can be achieved during future IPO negative phases, whereas only weak relationships have previously been found using ENSO indices alone.

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