Friday 1 April 2011

Submission to the Queensland Floods Commission of Inquiry

To The Commission,

I believe that some of our recent journal publications may be relevant to this Inquiry. I am a Hydroclimatologist from the University of Newcastle and our research (see attached publications) has shown that the risk of flooding for eastern Australia, and especially Queensland, is significantly increased during the La Niña phase of the El Niño/Southern Oscillation. La Niña conditions were predicted in April 2010 and were fully developed by at least September 2010 and yet the flooding that occurred was still seen as “unexpected” when it is actually consistent with the summer/autumn conditions that are typical of La Niña.

My colleagues and I have published several papers on this issue and it is my opinion that the findings and recommendations of these studies should be reviewed and considered as part of this Inquiry with a view to utilising climatic insights to improve preparation and planning for floods, emergency response to floods (and other climate-driven natural disasters), and legislation or policy associated with extreme climatic events.

Attached are the following papers:

- Kiem, A.S., Franks, S.W. and Verdon, D.C. (2006): Climate variability in the land of fire and flooding rain. Australian Journal of Emergency Management, 21(2), 52-56.
- Verdon, D.C., Wyatt, A.M., Kiem, A.S. and Franks, S.W. (2004): Multi-decadal variability of rainfall and streamflow - Eastern Australia. Water Resources Research, 40(10), W10201, doi:10.1029/2004WR003234.
- Kiem, A.S., Franks, S.W. and Kuczera, G. (2003): Multi-decadal variability of flood risk. Geophysical Research Letters, 30(2), 1035, doi:10.1029/2002GL015992.
- Verdon-Kidd, D.C. and Kiem, A.S. (2009): Nature and causes of protracted droughts in Southeast Australia - Comparison between the Federation, WWII and Big Dry droughts. Geophysical Research Letters, 36, L22707, doi:22710.21029/22009GL041067.

If you have any questions or require further information please let me know.

Thank you,

[redacted]

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Climate variability in the land of fire and flooding rain

Kiem, Franks and Verdon examine the relationship between multi-temporal climate variability and the risk of floods and bushfires

Abstract

Traditionally, the chance of climate related emergencies (e.g. floods, bushfires) occurring has been considered the same from one year to the next. However, recent research has highlighted the fact that this is definitely not the case. Analysis has revealed strong relationships between the El Niño/ Southern Oscillation (ENSO) and the occurrence of climate related emergencies, especially in eastern Australia. In addition, climatological studies have also revealed multi-decadal epochs of distinct climate states across eastern Australia. Within these multi-decadal epochs significant variability exists in the magnitude and frequency of ENSO impacts resulting in elevated (or reduced depending on the climate state) risk of extreme events such as floods, bushfires and droughts. Given that ENSO events can now be detected several months prior to their peak impact period, the opportunity exists to use climate variability insights to more accurately predict the chance of climate related emergencies occurring in the forthcoming season or year. Understanding of climate mechanisms that deliver high risk periods allows optimisation of emergency responses and effective management and mitigation of the disasters that occur as a result of the naturally occurring climate extremes for which Australia is renowned.

Introduction

It is well known that Australia displays marked climate variability ranging from long and destructive droughts to sudden and pervading flooding, interspersed with severe life and property threatening bushfires. Therefore, in order to minimise the impacts on the social and economic security and well-being of Australians, the quantification and understanding of climatological and hydrological variability is of considerable importance for properly estimating the risk of climate related emergencies (e.g. floods, bushfires) occurring in an upcoming season or year. At present, risk estimation methods are largely empirical in that observed histories of climate extremes are analysed under the assumption that the chance of an extreme event occurring is the same from one year to the next (Franks and Kuczera, 2002). Traditionally, physical climatological mechanisms that actually deliver climate extremes have not been taken into account.

Despite the development of rigorous frameworks to assess the uncertainty of risk estimates, these techniques have not previously acknowledged the possibility of distinct periods of elevated or reduced risk. However, recent research has highlighted the existence of multi-decadal epochs of enhanced/reduced flood risk across NSW (Franks, 2002a, b; Franks and Kuczera, 2002; Kiem et al., 2003). In particular, Franks and Kuczera (2002) demonstrated that a major shift in flood frequency (from low to high) occurred around 1945. Previous authors have noted that the mid-1940's also corresponded to a change in both sea surface temperature anomalies as well as atmospheric circulation patterns (Allan et al., 1995), suggesting large-scale ocean-atmospheric circulation patterns are linked to the Australian climate.

In addition to hydrological observations of changing climate risk, climatological insights into the mechanisms of climate variability point to the invalidity of purely empirical approaches to risk estimation. Indeed, numerous previous studies have shown that strong relationships exist between rainfall and streamflow and the global-scale ocean-atmospheric circulation process known as the El Niño/Southern Oscillation (ENSO). ENSO refers to the anomalous warming (El Niño) and cooling (La Niña) that periodically occurs in the central and eastern tropical Pacific Ocean as a result of the Southern Oscillation. For a comprehensive description of ENSO and a review of research into its causes and effects refer to Philander (1990) or Diaz and Markgraf (2000).

In terms of eastern Australian climate, the warm El Niño events are associated with below average rainfall and higher than average temperatures and evaporation, whereas the cool La Niña events typically deliver enhanced rainfall totals and cooler than normal conditions (e.g. Allan, 1988; Nicholls et al., 1996; Power et al., 1999; Verdon et al. 2004b). It is well known that the Australian climate varies markedly from year to year and these studies demonstrate that this variability is strongly related to ENSO, especially in eastern Australia. Kiem et al. (2003) demonstrate that year-to-year flood (and drought) risk also varies significantly and that this variability is also closely related to ENSO (Figure 1).

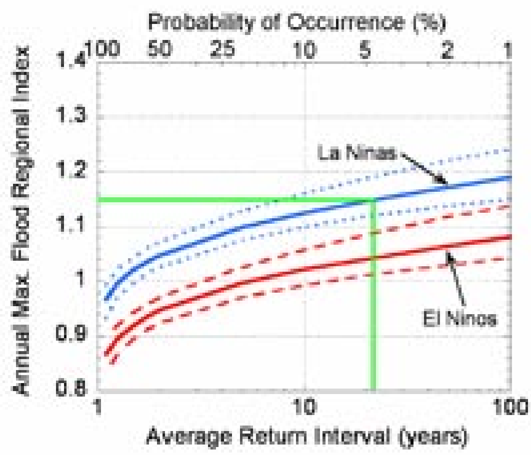
The other major climate related emergency affecting Australia is bushfires. The weather variables that generally increase the risk of bushfires are low precipitation and relative humidity combined with high temperature and wind speed. Since the high variability of rainfall and temperature in eastern Australia is strongly associated with the regional influences of ENSO (e.g. Allan, 1988; Nicholls et al., 1996; Power et al., 1999), it follows, and is demonstrated by Verdon et al. (2004a), that the ENSO also has a significant influence on eastern Australian bushfire risk (Figure 2).

Relationship between ENSO and climate related emergencies in eastern Australia

To illustrate the relationship between floods in eastern Australia and individual El Niño and La Niña events, Figure 1 shows the historic flood frequency curves associated with both El Niño and La Niña extremes. The annual maximum regional flood index (RI) shows the ratio of each annual maximum flood to the long-term mean annual maximum flood averaged across the NSW study region (Franks, 2002b). Therefore an RI greater than one indicates a maximum flood event that is worse than the historical average.

Figure 1 clearly shows that the Probability of Occurrence (PO), which is equal to the inverse of the Average Return Interval (ARI), for an annual maximum flood during a La Niña year is much higher than the PO for a flood of the same magnitude in El Niño events. For example, the PO for an annual maximum flood with RI equal to 1.0 (i.e. the average annual maximum flood) is approximately 17 per cent (ARI between five and six years) if it is an El Niño year compared with greater than 76 per cent if it is La Niña (ARI approximately 1.3 years). This implies that nearly all La Niña events will be associated with an above average annual maximum flood event. Also strikingly apparent from Figure 1 (illustrated by the green lines) is the inadequacy of the traditional '1 in 100 year flood' estimate. If the risk of flooding is assumed to be the same from year to year (i.e. the traditional and current assumption) then the chance of flood occurring during La Niña events is severely underestimated—with the PO for annual maximum flooding equivalent to the traditionally estimated '1 in 100 year flood' more than four times greater than traditionally estimated during La Niña events (ARI of 100 compared with ARI of ~23 years for the equivalent flood during La Niña years).

Figure 1. Regional flood frequency curves under El Niño (red) and La Niña (blue) conditions.



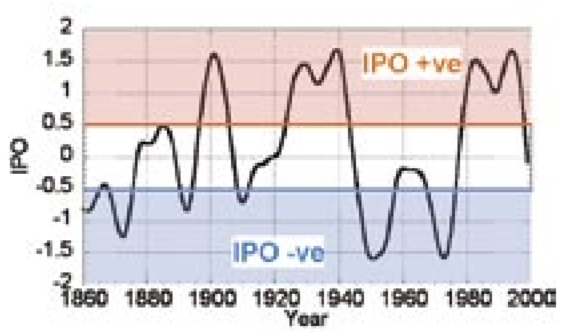
Dashed lines indicate 90 per cent confidence intervals. Horizontal green line indicates the magnitude of the '1 in 100 year flood' calculated using ALL years (i.e. under the traditional assumption that flood risk is the same from year to year). Vertical green line indicates that the probability (~4.3%) of the '1 in 100 year flood' occurring during a La Niña event is more than four times greater than traditionally estimated (see Kiem et al. (2003) for further details).

To illustrate the role of El Niño events in elevating bushfire risk, and the potential for predicting future high fire danger seasons, Figure 2 shows the percentage increase in the number of days with high (or greater than high) bushfire risk when El Niño years are compared to non-El Niño years. Daily bushfire risk is based on the Forest Fire Danger Index (FFDI; McArthur, 1967), with FFDI greater than 12 indicating a high (or greater than high) bushfire risk (Verdon et al.. 2004a). As can be seen, every station shows increases in bushfire risk with the south-east of NSW particularly elevated. This is significant given the devastating bushfires that occurred in this area in the summer of 2002/2003 and the fact that this period was also associated with El Niño conditions. While this does not mean that every El Niño will be associated with bushfires similar to those experienced in 2002/2003 (or vice versa), Figure 2 does suggest that the risk of bushfires occurring is significantly increased during El Niño events.

The results presented in Figures 1 and 2 clearly demonstrate that ENSO processes (El Niño and La Niña events) play a major role in determining flood and bushfire risk in eastern Australia. The fact that individual ENSO events can be detected at least six months prior to their consequent peak impact periods means that significant insight can be gained into the

Figure 2. Percentage increases in NSW bushfire risk under El Niño conditions compared to non-El Niño conditions.

Figure 3. Inter-decadal Pacific Oscillation index (1860-2000) – data supplied by the UK Meteorological Office.



forthcoming season or year. This enables adaptive management decisions to be made and damage minimisation procedures to be put in place before the period of elevated flood or bushfire risk. Such climate risk management strategies, based on insights gained through extensive research into ENSO and other climate processes, are now routinely applied in various domains (e.g. agriculture) in Australia and many other regions (see Meinke et al. (2005) for a useful overview).

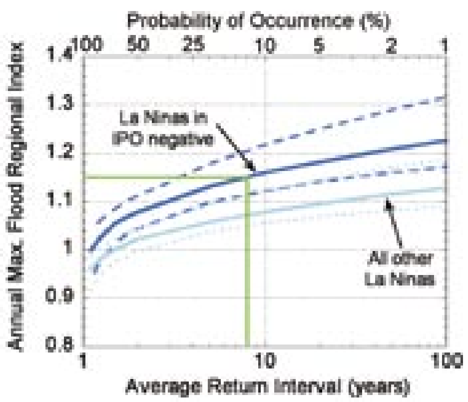
Multi-decadal variability of climate impacts in Eastern Australia

Recent climatological studies have also revealed multi-decadal variability in the modulation of the magnitude and frequency of ENSO impacts (Power et al., 1999; Kiem et al., 2003). In particular, Power et al. (1999) investigated marked temporal changes in ENSO correlations to Australian climate (i.e. rainfall and temperature) records. The temporal stratification of the climate sequences was achieved according to what has been termed the Inter-decadal Pacific Oscillation (IPO). The IPO is defined by low frequency (15 to 30 years) anomalous warming and cooling of Pacific-wide sea surface temperatures (Power et al., 1999; Folland et al., 1999; Allan, 2000), and is similar to the Pacific Decadal Oscillation (PDO; Mantua et al., 1997; Franks, 2002a). Power et al. (1999) showed how ENSO correlations with Australian rainfall and temperature changed with the observed changes in persistent large-scale Pacific Ocean sea surface temperature anomalies. Importantly, Power et al. (1999) and Verdon et al. (2004b) demonstrated that individual ENSO events (i.e. El Niño, La Niña) have stronger impact across Australia during the negative phase of the IPO, implying that there exists a multi-decadal modulation of the magnitude of ENSO impacts. Figure 3 shows the IPO index over the period 1860 to 1999.

Following Power et al. (1999) and Verdon et al. (2004b), Figure 3 indicates that persistent periods of enhanced ENSO impacts may exist at decadal and longer timescales, though it should be noted that part of this persistence is due to the smoothing algorithm chosen to produce the IPO index (see Power et al. (1999) for details). Anecdotal evidence also supports the idea of 'changes in climate' occurring during the mid 1940's and again in the mid-1970's over eastern Australia. To test the idea that El Niño and La Niña induced variability is enhanced under the IPO negative states, regional flood (Figure 4) and bushfire risk (Figure 5) data were stratified according to both the IPO and ENSO indices (Kiem et al., 2003; Verdon, et al. 2004a).

Figure 4 shows regional flood frequency curves for La Niña events under IPO negative and IPO non-negative conditions. It can be clearly seen that the PO for an annual maximum flood in an IPO negative La Niña event is even higher than the PO for a flood of the same magnitude in non-IPO negative La Niña events. As mentioned previously nearly all La Niña events are associated with above average annual maximum floods implying that flood risk in IPO negative La Niña events is *extremely* high. The PO for an annual maximum flood with RI equal to 1.1 (i.e. 10 per cent greater than the average annual maximum flood) is approximately four per cent (ARI ~25 years) during non-negative IPO La Niña compared with greater than 33 per vent during IPO negative La Niña. During El Niño events the PO for an annual maximum flood with RI equal to 1.1 is less than 0.3 per cent. Figure 4 further illustrates the inadequacy of the traditional '1 in 100 year flood' estimate. The PO for annual maximum flooding equivalent to the traditionally estimated '1 in 100 year flood' (illustrated by the horizontal green line) is more than twelve times greater than traditionally estimated during IPO negative La Niña events (ARI of 100 compared with ARI of ~8 years for the equivalent flood during IPO negative La Niña years) implying a significant underestimation of risk.

Figure 4. Regional flood frequency curves for La Nina events under IPO negative (dark blue) and IPO non-negative (light blue) conditions.

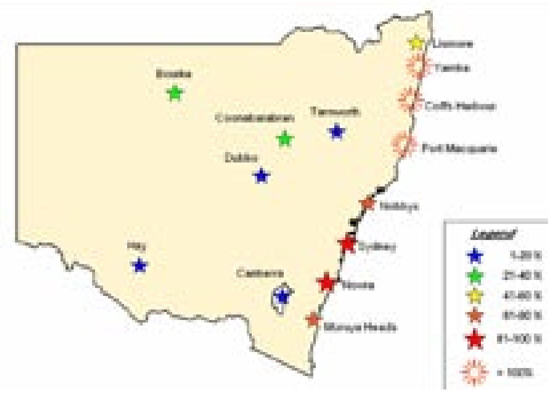


Dashed lines indicate 90 per cent confidence intervals. Horizontal green line indicates the magnitude of the '1 in 100 year flood' calculated using ALL years (i.e. under the traditional assumption that flood risk is the same from year to year). Vertical green line indicates that the probability (~12.5%) of the '1 in 100 year flood' occurring during a La Niña event is more than twelve times greater than traditionally estimated (see Kiem et al. (2003) for further details).

These results support the notion that the IPO enhances ENSO impacts. Importantly for flood management, it has been shown that in addition to modulating the magnitude of ENSO impacts there also tends to be a higher frequency of La Niña events during the IPO negative phase (Kiem et al., 2003). Therefore, contrary to the traditional assumption that flood risk is the same from one year to the next the results summarised here indicate that La Niña years are associated with enhanced flood risk (Figure 1) and that this risk is further elevated when the IPO is negative (Figure 4). Compounding the impact of the enhanced IPO negative La Niña type floods is the fact that La Niña events are much more likely to occur during the decadal/multi-decadal periods when the IPO is negative. This is supported by historical observation data where multi-year periods are associated with clusters of high magnitude floods (e.g. 1950s) for many regions of eastern Australia. Such non-stationarity of flood risk is statistically anomalous under traditional assumptions and therefore is not adequately accounted for in current flood risk management strategies. Nor are the links between climate variability and flooding currently used to predict and prepare for periods when emergency flood events are likely to occur despite the fact that such concepts are now routinely used to manage climate risk in agriculture and other domains (see Meinke et al. (2005) for an overview).

Figure 5 shows the percentage increase in bushfire risk when IPO negative El Niño events are compared with all other El Niño years. In comparison to Figure 3 (where all El Niño events were compared with non-El Niño events and it was shown that bushfire risk is elevated during El Niño events) it can be seen that IPO negative El Niño events are associated with an even greater risk of bushfire than the non-IPO negative El Niño events. This supports the notion that the magnitude of ENSO impacts is enhanced during periods when the IPO is negative and implying that bushfire risk is extremely high during IPO negative El Niño events when compared to all other years.

Figure 5. Percentage increases in NSW bushfire risk for El Niño events under IPO negative conditions compared to El Niño events occurring in non-negative IPO phases (see Verdon et al. (2004a) for further details).



Implications for emergency management

In this paper, the relationship between multi-temporal climate variability (e.g. ENSO and IPO) and the risk of floods and bushfires across NSW has been demonstrated. These results also confirm the observation that IPO negative conditions tend to be associated with enhanced impacts of individual ENSO events (Power et al., 1999; Verdon et al., 2004b) and increased frequency of La Niña events (Kiem et al., 2003), resulting in the risk of climate related emergencies occurring being distinctly non-stationary. This is at odds with current assumptions that each year is associated with the same risk of flood or bushfire. Accordingly, there are a number of implications for optimal management of emergency services.

Year to year variability of extreme climate impacts is marked in eastern Australia and is primarily the result of individual ENSO events. While individual flood and bushfire events are impossible to predict the good news is that simple detection methodologies based on indices of ENSO activity provide at least six months lead time prior to the annual period of peak ENSO impacts (i.e. the time when bushfires and floods are most likely), usually September to April for eastern Australia (e.g. Stone et al., 1996). Furthermore, understanding of other non-ENSO processes, such as the IPO, that alter the magnitude and frequency of ENSO impacts (e.g. Power et al., 1999; Kiem et al., 2003; Verdon et al., 2004a, 2004b), has the potential to greatly improve our ability to forecast climate anomalies, and therefore high risk periods with respect to flood and bushfires. However, whether or not low frequency oscillations like the IPO (and other non-ENSO processes) can be measured in real time, or forecast months in advance, to enable improved seasonal and annual forecasts is the subject of current research. In any case, it is currently possible to use at least the ENSO related insights presented in this study to more accurately determine the chance of climate related emergencies occurring in the forthcoming season or year. The lead time provided via insights into climate processes enables adaptive planning for emergency management services in anticipation of elevated climate risk periods—a concept that is already routinely being applied to manage climate risk in other domains (e.g. agriculture).

Floods and bushfires are, and always will be, part of the Australian climate and it is impossible to prevent these natural disasters from occurring. Therefore, adequate understanding of the mechanisms that cause enhanced risk periods, and the recognition that enhanced risk periods exist but are predictable, is essential to effectively manage and minimise the damage associated with floods and bushfires when they do occur.

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Multidecadal variability of rainfall and streamflow: Eastern Australia

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[1] 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 multidecadal timescale 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. This result is of particular importance as the influence of ENSO in VIC appears to be weak; however, the results indicate that some useful predictability of ENSO impacts can be achieved during the negative phase of the IPO for VIC. *INDEX TERMS:* 4215 Oceanography: General: Climate and interannual variability (3309); 4522 Oceanography: Physical: El Nino; 1854 Hydrology: Precipitation (3354); 1860 Hydrology: Runoff and streamflow; *KEYWORDS:* El Niño–Southern Oscillation (ENSO), Interdecadal Pacific Oscillation (IPO), Pacific Decadal Oscillation (PDO), rainfall, streamflow, climate variability

Citation: Verdon, D. C., A. M. Wyatt, A. S. Kiem, and S. W. Franks (2004), Multidecadal variability of rainfall and streamflow: Eastern Australia, *Water Resour. Res.*, *40*, W10201, doi:10.1029/2004WR003234.

1. Introduction

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

[3] The high variability of rainfall and temperature in eastern Australian has been strongly associated with the regional influence of the El Niño–Southern Oscillation [e.g., *Ropelewski and Halpert*, 1987; *Allan*, 1988; *Stone and Auliciems*, 1992; *Power et al.*, 1998; *Kiem and Franks*, 2001]. In particular, the warm El Niño phase of ENSO are associated with marked reductions in rainfall and increased air temperatures, while cool La Niña events are typically associated with enhanced rainfall totals and cooler air temperatures. Previous research has also shown that ENSO influences streamflow volumes around the world [e.g., *Kahya and Dracup*, 1993; *Moss et al.*, 1994; *Piechota and Dracup*, 1996; *Piechota et al.*, 1998; *Chiew et al.*, 1998; *Dettinger et al.*, 2000; *Kiem and Franks*, 2001; *Wooldridge et al.*, 2001].

[4] In addition to ENSO, recent studies have also revealed multidecadal variability in the modulation of ENSO impacts [*Power et al.*, 1999; *Kiem et al.*, 2003; *Kiem and Franks*, 2004]. The Interdecadal Pacific Oscillation (IPO) is the coherent pattern of sea surface temperature (SST) variability occurring on interdecadal timescales over the Pacific Ocean. Similarly, recent studies by *Mantua et al.* [1997] and *Nigam et al.* [1999] have also shown how North Pacific sea surface temperatures (SST) can be correlated to weather patterns, streamflow and drought conditions throughout North America using the Pacific Decadal Oscillation or PDO [*Mantua et al.*, 1997]. *Power et al.* [1999] showed that there is a close association between the decadal part of the PDO index and the IPO index. Importantly, the IPO and PDO time series are highly correlated and represent

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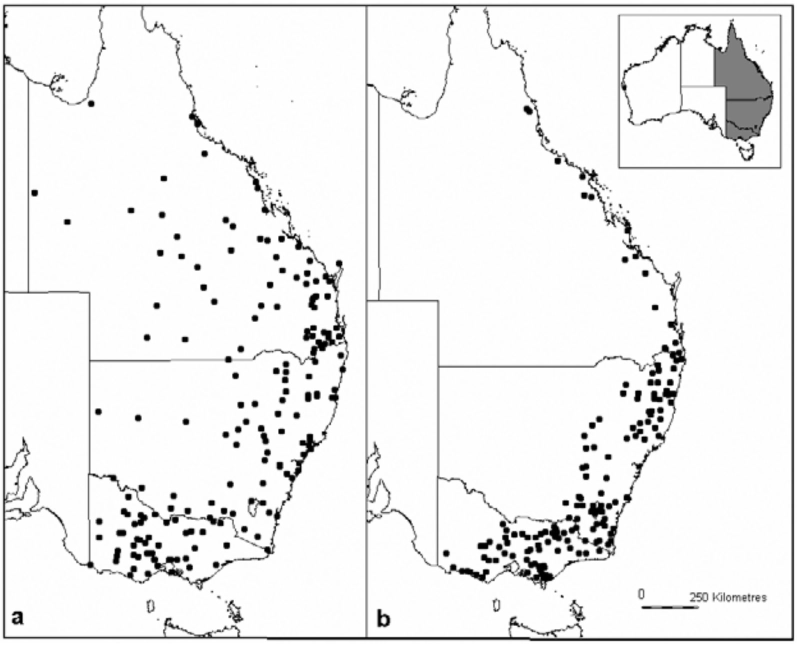

Figure 1. Location of (a) rainfall gauges and (b) streamflow stations used in this study.

variable epochs of warming and cooling in both hemispheres of the Pacific Ocean [*Franks*, 2002b].

[5] A number of 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 multidecadal modulation of the magnitude of ENSO events. More recently, *Kiem et al.* [2003] and *Kiem and Franks* [2004] have demonstrated that the IPO also appears to modulate the frequency of individual La Niña events with marked consequences for multidecadal flood and drought risk in eastern Australia and elsewhere. Across New Zealand, the IPO appears to have produced similar shifts in flood frequency [*McKerchar and 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.

[6] This study aims to assess the spatial influence of multitemporal-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) is stratified according to ENSO classifications derived from the NINO3 index. The rainfall and streamflow data is then further stratified according to multidecadal IPO classifications.

2. Site Selection and Data

[7] The rainfall and streamflow data used in this study were obtained from the 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 Figure 1. All rainfall gauges chosen for analysis contained complete data for the years 1924 to 1998 inclusive. Streamflow gauges were chosen with data records considered to be of sufficient length for the statistical analysis carried out in the study.

[8] It can be seen from Figure 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.

3. Temporal Stratification According to ENSO and IPO Indices

[9] 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 6-month October to March average NINO3 value using a threshold of ±0.5. While 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, e.g., *Kiem and Franks*, 2001].

[10] 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 1924–1943 and 1979–1997 and a negative phase (IPO < −0.5) from 1946–1976. These phases exclude the

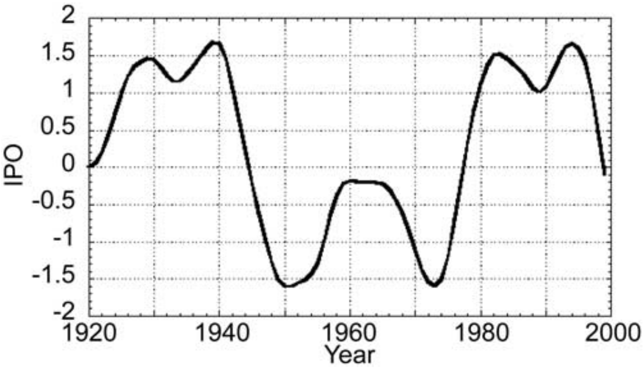

Figure 2. The Interdecadal Pacific Oscillation (IPO) from 1920 to 1999.

ten years from 1958–1967 when the absolute value of the IPO index was less than 0.5.

4. Determination of the ENSO Impact Period

[11] 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 and 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 Students 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 and Cornell*, 1970]. The number of stations that show a significant difference (p value of less than 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.

[12] While 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. While 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 to January inclusive.

5. Variability of Rainfall and Streamflow Due to ENSO Impacts

[13] 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 related variability. The ratio of September to January mean rainfall and streamflow during La Niña years compared to El Niño years is displayed in Figure 3. A Students t test is also applied to determine if the rainfall and streamflow in La Niña years is statistically different to El Niño rainfall and streamflow. Figure 4 highlights which stations display a statistically significant difference.

[14] 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 Figure 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.

6. Multidecadal Variability of Rainfall and Streamflow

6.1. IPO Modulation of Rainfall and Streamflow Variability

[15] 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 multidecadal timescale. Figure 5 shows the ratio of September to January rainfall and streamflow during years classified as IPO negative compared to the IPO positive years.

[16] 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

Table 1. Number of Stations Where La Niña Rainfall Is Significantly Higher Than El Niño Rainfall

	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April
Queensland	0	3	46	10	48	25	16	26	36	5	11	2
New South Wales	0	0	16	1	40	17	36	3	41	2	0	1
Victoria	0	0	0	0	4	9	24	4	4	0	0	2

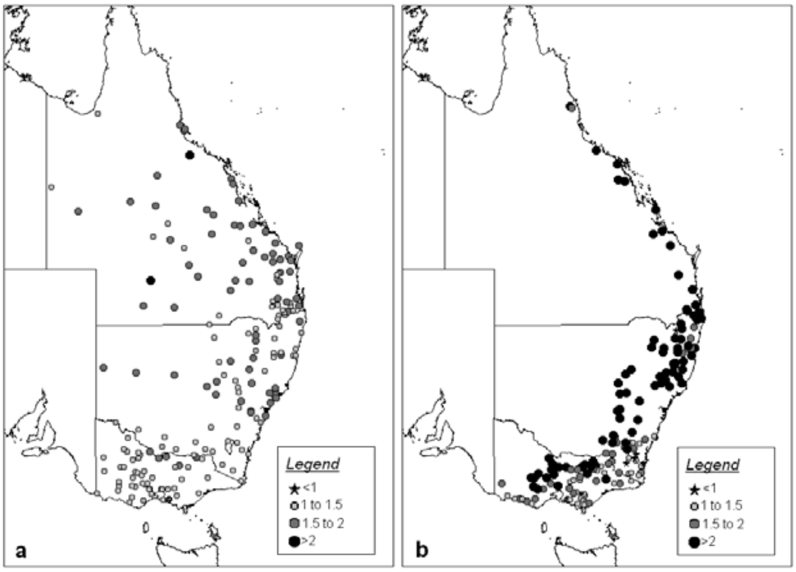

Figure 3. Increase in (a) rainfall and (b) streamflow during La Niña years compared to El Niño years.

that streamflow is considerably enhanced during IPO negative. 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.

[17] 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 Figure 6.

[18] 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.

6.2. Modulation of La Niña–Related Rainfall and Streamflow Variability by the IPO

[19] To determine if La Niña rainfall and runoff is further enhanced during the negative phase of the IPO, the rainfall and streamflow (Figure 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 nonnegative phase of the IPO, within the time period being investigated. A Students t test is used to determine if the difference in

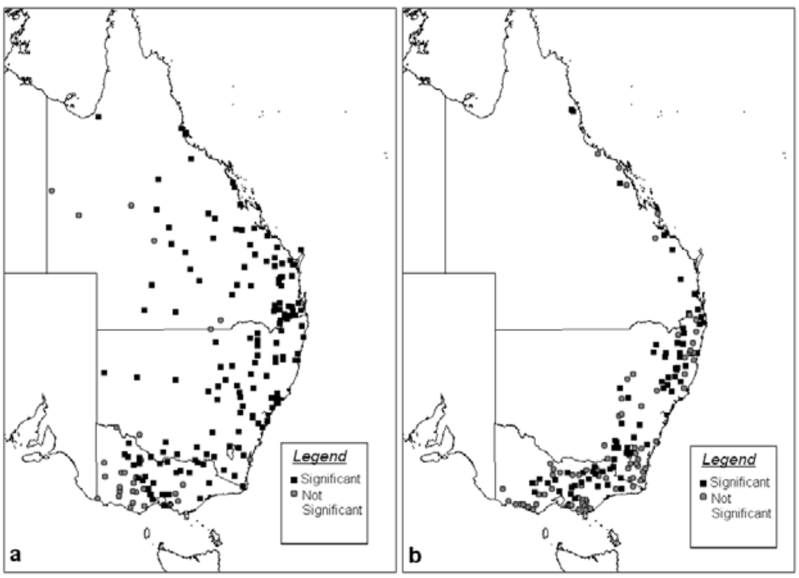

Figure 4. Results of significance test showing stations where the (a) rainfall and (b) streamflow in La Niña years is significantly higher than El Niño years.

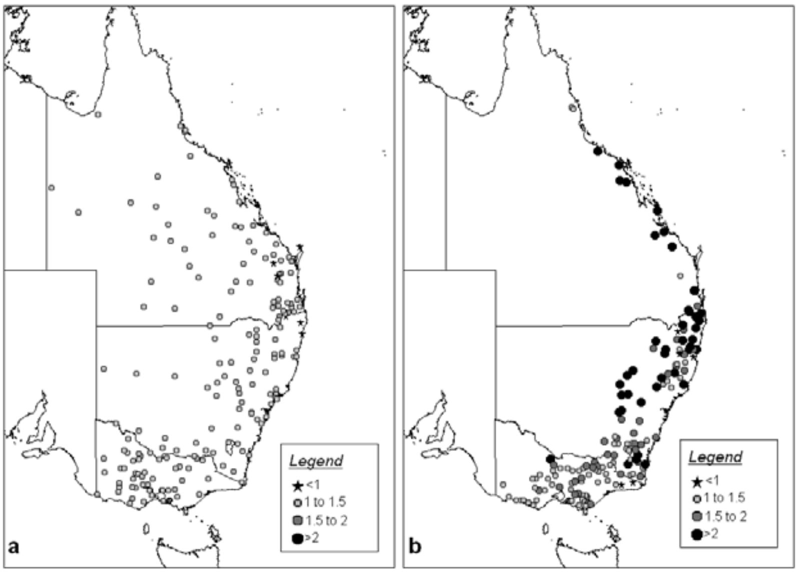

Figure 5. Increase in (a) rainfall and (b) streamflow during IPO negative years compared to IPO positive years.

rainfall and streamflow is statistically significant, as shown in Figure 8.

[20] 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. While it can be seen from Figure 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 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.

7. Conclusions

[21] This study has aimed to establish how observed multitemporal-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 multidecadal sea surface temperature variability as represented by the IPO.

[22] The results confirm that a strong relationship exists between ENSO and seasonal rainfall variability in eastern

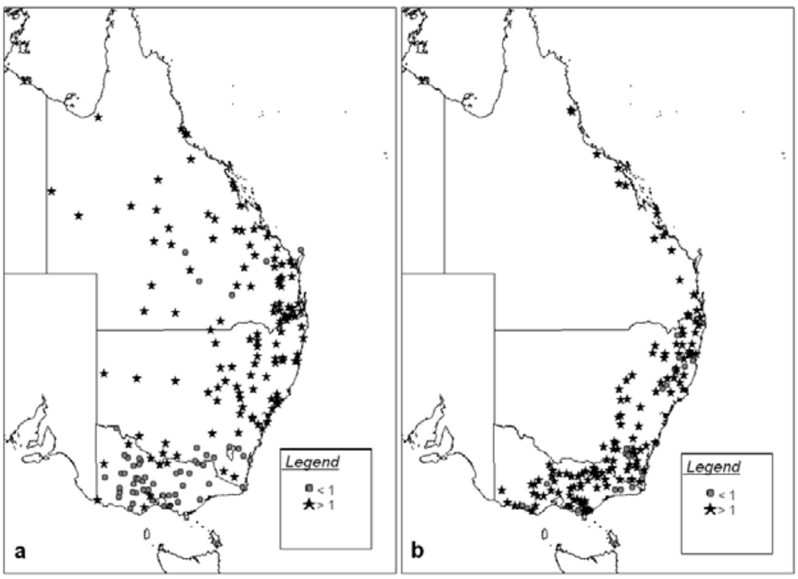

Figure 6. Ratio of the IPO negative standard deviation to IPO positive standard deviation for (a) rainfall and (b) streamflow distributions.

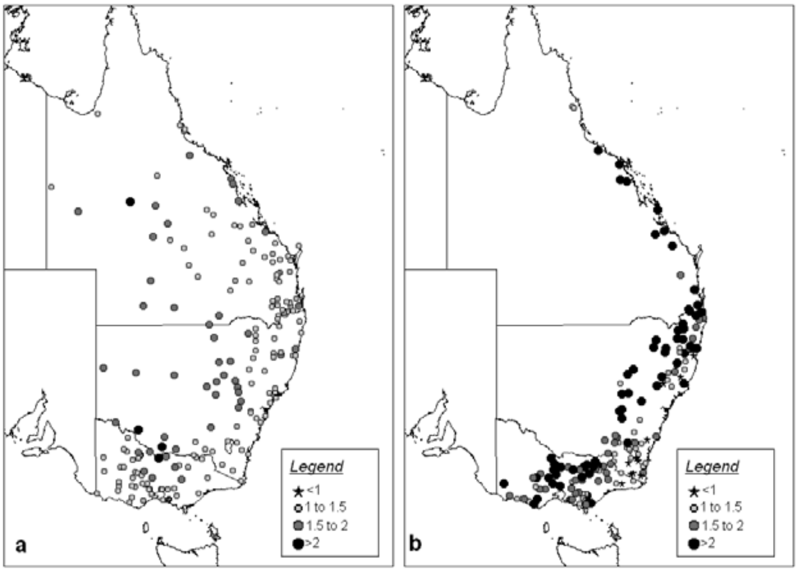

Figure 7. Increase in (a) rainfall and (b) streamflow during IPO negative La Niña years compared to all other La Niña years.

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% to 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.

[23] An investigation into how multidecadal 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 and *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 streamflow. While 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.

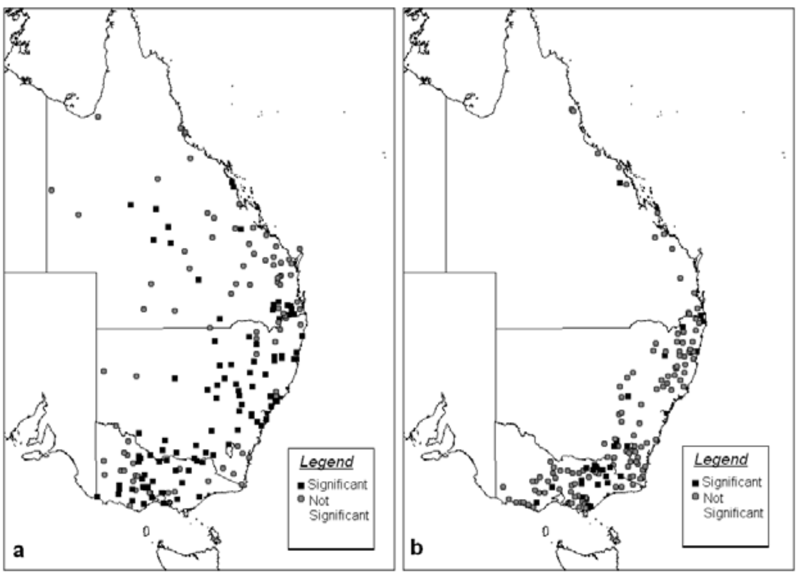

Figure 8. Results of significance test showing stations where the (a) rainfall and (b) streamflow in IPO negative La Niña years is significantly higher than all other La Niña years.

[24] The combined ENSO and IPO indices explain a high degree of the hydroclimatological variability observed in eastern Australia. Recent research by *Folland et al.* [2002] demonstrated how ENSO and IPO processes influences 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, while 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 multidecadal timescale. 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.

[25] While 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 multidecadal shifts in sea surface temperatures is unclear [*Franks*, 2002b, 2004]. At present it is uncertain whether multidecadal variability is an internal artifact 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 timescales.

[26] 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 impacts QLD and NSW rainfall and streamflow, but also that the influence extends to as far south as VIC. While 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 just ENSO indices alone.

[27] **Acknowledgments.** DCV and AMW would like to thank the University of Newcastle Research Scholarship Scheme and Australian Research Council. ASK is supported by the Australian Academy of Science - Japan Society for the Promotion of Science Post-doctoral Fellowship Scheme. Partial funding for this study was provided by the Sydney Catchment Authority. The authors wish to acknowledge Francis Chiew and Tom McMahon for providing the streamflow data used in the study and the UK Meteorological Office for kindly making the IPO data used in this study available.

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Multi-decadal variability of flood risk

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[1] Recent research has highlighted the persistence of multi-decadal epochs of enhanced/reduced flood risk across New South Wales (NSW), Australia. Recent climatological studies have also revealed multi-decadal variability in the modulation of the magnitude of El Niño/Southern Oscillation (ENSO) impacts. In this paper, the variability of flood risk across NSW is analysed with respect to the observed modulation of ENSO event magnitude. This is achieved through the use of a simple index of regional flood risk. The results indicate that cold ENSO events (La Niña) are the dominant drivers of elevated flood risk. An analysis of multidecadal modulation of flood risk is achieved using the interdecadal Pacific Oscillation (IPO) index. The analysis reveals that IPO modulation of ENSO events leads to multi-decadal epochs of elevated flood risk, however this modulation appears to affect not only the magnitude of individual ENSO events, but also the frequency of their occurrence. This dual modulation of ENSO processes has the effect of reducing and elevating flood risk on multi-decadal timescales. These results have marked implications for achieving robust flood frequency analysis as well as providing a strong example of the role of natural climate variability. *INDEX TERMS:* 1821 Hydrology: Floods; 4215 Oceanography: General: Climate and interannual variability (3309); 4522 Oceanography: Physical: El Niño; KEYWORDS: Climate variability, El Niño/Southern Oscillation (ENSO), flood frequency, Inter-decadal Pacific Oscillation (IPO), Pacific Decadal Oscillation (PDO), multidecadal. **Citation:** Kiem, A. S., S. W. Franks, and G. Kuczera, Multi-decadal variability of flood risk, *Geophys. Res. Lett.*, *30*(2), 1035, doi:10.1029/2002GL015992, 2003.

1. Introduction

[2] The quantification and understanding of hydrological variability is of considerable importance for the estimation of flood risk. At present, traditional methods are largely empirical in that annual maximum floods are assumed to be independently and identically distributed [*Franks and Kuczera*, 2002]. Despite the development of rigorous Bayesian frameworks to assess the uncertainty of flood risk estimates, these techniques have not acknowledged the possibility of serial correlation within periods of elevated or reduced flood risk [cf. *Kuczera*, 1999]. However, recent research has highlighted the persistence of multi-decadal epochs of enhanced/reduced flood risk across New South Wales [*Erskine and Warner*, 1988; *Franks*, 2002a, 2002b; *Franks and Kuczera*, 2002]. In particular, *Franks and Kuczera* [2002] demonstrated that a major shift in flood frequency occurred around 1945. Previous authors have noted that the mid-1940's corresponded to a change in both sea surface temperature anomalies as well as circulation patterns [*Allan et al*., 1995]. *Franks* [2002b] showed that the observed change in flood frequency could be objectively identified as corresponding to this shift in climate parameters. Furthermore, it was shown through the use of a simple index of regional flood risk that the observed shift in flood frequency was statistically significant at the <1% level.

[3] In addition to hydrological observations of changing flood risk, recent climatological studies have also revealed multi-decadal variability in the modulation of the magnitude of El Niño/Southern Oscillation (ENSO) impacts. *Power et al*. [1999] have investigated marked temporal changes in ENSO correlations to Australian rainfall records. The temporal stratification of the rainfall sequences was achieved according to what has been termed the Inter-decadal Pacific Oscillation (IPO). The IPO was defined by anomalous warming and cooling in the Pacific Ocean and is similar to the Pacific Decadal Oscillation or PDO [*Mantua et al.*, 1997; *Franks*, 2002a]. Importantly, *Power et al*. [1999] demonstrated that individual ENSO events (ie. El Niño, La Niña) had stronger impact across Australia during the negative phase of the IPO, implying that there exists a multidecadal modulation of the magnitude of ENSO events.

[4] The study aims to extend the analysis of *Franks* [2002b] to assess the role of ENSO processes and their multi-decadal modulation, in dictating flood risk across New South Wales (NSW), Australia. In this paper, a derived regional index of flood risk [*Franks*, 2002b] stratified according to ENSO classifications based on the NINO3 index. The index is then further stratified according to the multi-decadal IPO classifications. The stratified flood frequency data are analysed using Bayesian flood frequency analysis to quantify uncertainty on quantiles and thus elucidate the key controls on NSW flood risk.

2. Derivation of a Regional Index

[5] The streamflow data used in this study were obtained from the PINEENA database, developed and managed by the NSW Department of Land and Water Conservation. 40 records spanning 1924 to 1999 were deemed suitable in terms of the length and continuity of record. If the flood gauges were perfectly correlated, treating them as entirely uncorrelated would imply 40 independent records with any inferred change having unwarranted statistical support. To avoid the issue of spatial correlation, the 40 flood records were collapsed into a regional flood index following *Franks* [2002b].

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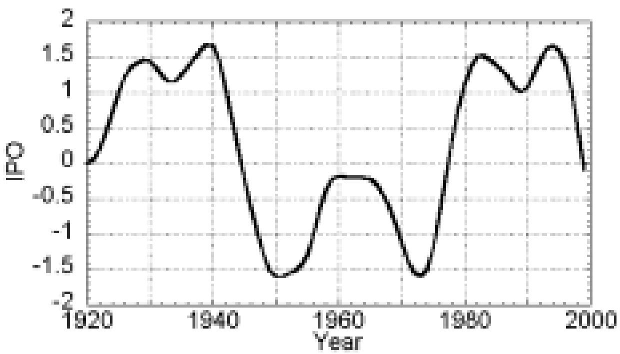

Figure 1. The Inter-decadal Pacific Oscillation (IPO) from 1920 to 1999.

3. Temporal Stratification According to ENSO and IPO Indices

[6] Stratification of the regional flood index record according to ENSO classifications was made using the monthly NINO3 index. Every year from 1924 to 1999 was given an ENSO classification based on the six-month October to March average NINO3 value. This method and index combination has previously been demonstrated to be the most robust for the time period being investigated [*Kiem and Franks*, 2001].

[7] The Inter-decadal Pacific Oscillation (IPO) is the coherent pattern of sea surface temperature (SST) variability occurring on inter-decadal time scales over the Pacific Ocean [*Folland et al.*, 1999; *Power et al.*, 1998, 1999; *Allan*, 2000]. In classifying the different IPO phases, *Power et al.* [1999] used the thresholds of ±0.5 to distinguish positive, neutral and negative phases. Figure 1 shows the time series of the IPO over the period of flood data employed in this study. As can be seen, during this period there have been three major phases of the IPO: Two positive phases (IPO > 0.5) and a negative phase (IPO < -0.5).

4. Results

[8] The regional flood index was stratified according to El Niño and La Niña extremes, as defined by the NINO3 index. The stratified data were then subjected to a Bayesian flood frequency analysis in order to properly account for parameter uncertainty [*Kuczera*, 1999].

[9] To assess the role of ENSO extremes Figure 2 presents the flood frequency under El Niño and La Niña conditions along with the associated 90% confidence limits. From this plot it can be readily seen that much higher flood risk must be associated with La Niña events as opposed to El Niño. Also immediately apparent is the degree of separation of the confidence limits indicating a highly statistically significant difference between the two ENSO extremes. Although not shown in Figure 2 for the sake of clarity, the flood frequency distribution associated with neutral ENSO events lies between the two extremes.

[10] Given the clear role of La Niña events in flood risk identified in Figure 2, to test the hypothesis that the IPO modulates the magnitude of La Niña events, as suggested by

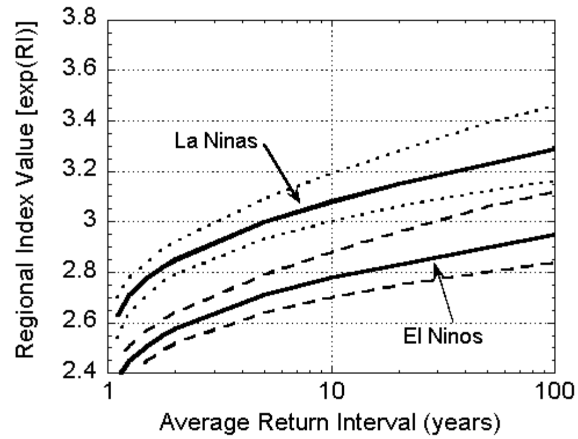

Figure 2. Log-normal expected quantiles and their 90% probability limits (dashed lines) for the regional index under El Niño and La Niña conditions.

Power et al. [1999], a stratification on La Niña under different IPO phases is required. To achieve this test, the regional index is stratified according to La Niña events occurring under negative IPO phase (<-0.5) and then according to La Niña events occurring under neutral and positive IPO phases (>-0.5). Figure 3 shows the resultant flood frequency curves. As can be seen, the frequency curve associated with La Niña events under IPO negative (<-0.5) is markedly higher than the flood frequency associated with all other La Niña events. The 90% quantiles marginally overlap suggesting significant difference between the conditioned distributions.

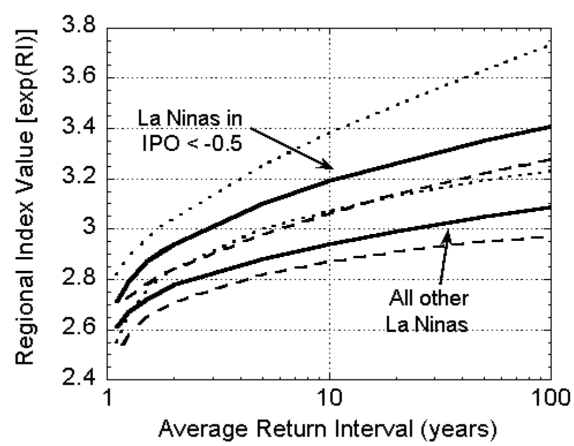

Figure 3. Log-normal expected quantiles and their 90% probability limits (dashed lines) for the regional index under La Niña conditions during the negative IPO phase and La Niña conditions during non-negative IPO phases.

[11] Finally, given the observed persistence of IPO phases, it is desirable to assess the variability of flood risk under the different IPO phases irrespective of interannual ENSO events. Figure 4 shows the flood frequency curves for IPO negative (<-0.5) against non-negative IPO phases. Again, it can be seen that IPO negative phase corresponds to a much increased flood risk when compared to the non-negative phases of IPO. It is therefore clear that monitoring of the

multi-decadal IPO phase may provide valuable insight into flood risk on multi-decadal scales, whilst the joint occurrence of inter-annual La Niña events within the IPO negative phase represents further elevated flood risk.

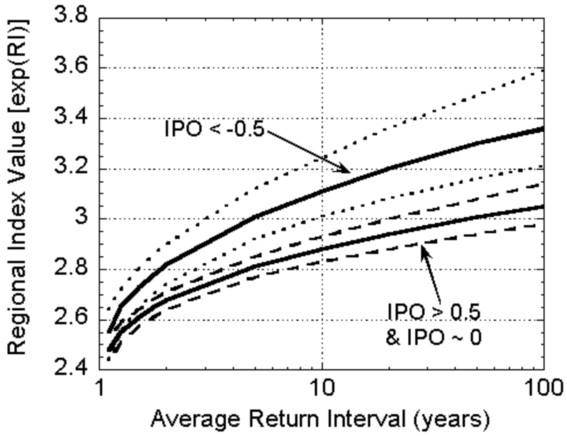

Figure 4. Log-normal expected quantiles and their 90% probability limits (dashed lines) for the regional index under the positive and negative IPO phases.

5. Analysis of ENSO Event Frequency Under Different Multi-Decadal IPO Phases

[12] Given the strong control on flood risk exerted by La Niña events and modulated in their magnitude by multidecadal IPO processes, it is intuitive to examine the frequency of occurrence of such high magnitude events. Table 1 shows the IPO phases that have occurred between 1924 to 1999, and the frequency of ENSO events under each of these phases. Note that the IPO phases are as defined earlier in this paper (with 1924–43 denoted IPO > 0.5(1) and 1979–97 denoted IPO > 0.5(2)).

Table 1. Number of El Niño, La Niña and Neutral Events Occurring Within Each of the IPO Phases.

	IPO > 0.5(1)	IPO > 0.5(2)	IPO < -0.5	IPO ~ 0
El Niño	4	6	4	3
La Niña	4	1	10	7
Neutral	12	12	7	6
Total	20	19	21	16

[13] Immediately apparent from Table 1, it can be seen that IPO negative phases tend to be biased towards an increased frequency of La Niña events. It therefore appears that the multi-decadal processes as represented by the IPO may modulate the frequency of ENSO events as well as the magnitude of their impact.

[14] To test the statistical significance of the dependence of ENSO event frequency on IPO phase a simple test of proportions was applied [*Hogg and Tanis*, 1988]. It is assumed that the sampling distribution of the proportion of El Niño events occurring within any IPO phase can be approximated by a normal distribution with a mean of p and a variance of $p(1-p)/n$, where p is the proportion of El Niño events that have occurred within each IPO phase, calculated using $p = y/n$, where y is the number of El Niño events that have occurred and n is the total number of years in the IPO phase being investigated. This was repeated for La Niña and Neutral events.

[15] In order to determine whether the probability (P1) of a given ENSO event occurring during one IPO phase was significantly different to the probability (P2) of the same ENSO event occurring during a different IPO phase the following statistical test was used. Let y_1 represent the number of El Niño events, for example, that occurred in the n_1 years when IPO was positive and y_2 the number of El Niños that occurred in the n_2 years when IPO was negative. A test statistic used to test the hypothesis that P1 equals P2 is:

$$z = \frac{|p_1 - p_2|}{\sqrt{p(1-p)(1/n_1 + 1/n_2)}}$$

where $p_1=y_1/n_1$, $p_2=y_2/n_2$, $p=(y_1+y_2)/(n_1+n_2)$ and $z \sim N(0,1)$.

Table 2. Results Obtained When the Frequency at Which El Niño, La Niña and Neutral Events Occur in the Different IPO Phases are Compared. Significance at the <5% and <1% level is represented by * and ** respectively.

Period being tested		y_1	n_1	p_1	y_2	n_2	p_2	z	p-value
EL NIÑO									
Period 1	Period 2								
IPO > 0.5 (1)	IPO > 0.5 (2)	4	20	0.20	6	19	0.32	0.828	0.204
IPO > 0.5 (1)	IPO < -0.5	4	20	0.20	4	21	0.19	0.077	0.469
IPO < -0.5	IPO > 0.5 (2)	4	21	0.19	6	19	0.32	0.914	0.180
IPO > 0.5 ALL	IPO < -0.5	10	39	0.26	4	21	0.19	0.576	0.282
LA NIÑA									
Period 1	Period 2								
IPO > 0.5 (1)	IPO > 0.5 (2)	4	20	0.20	1	19	0.05	1.376	0.084
IPO > 0.5 (1)	IPO < -0.5	4	20	0.20	10	21	0.48	1.864	0.031*
IPO < -0.5	IPO > 0.5 (2)	10	21	0.48	1	19	0.05	2.996	0.001**
IPO > 0.5 ALL	IPO < -0.5	5	39	0.13	10	21	0.48	2.969	0.001**
NEUTRAL									
Period 1	Period 2								
IPO > 0.5 (1)	IPO > 0.5 (2)	12	20	0.60	12	19	0.63	0.203	0.420
IPO > 0.5 (1)	IPO < -0.5	12	20	0.60	7	21	0.33	1.712	0.043*
IPO < -0.5	IPO > 0.5 (2)	7	21	0.33	12	19	0.63	1.886	0.030*
IPO > 0.5 ALL	IPO < -0.5	24	39	0.62	7	21	0.33	2.085	0.019*

[16] Table 2 shows the results obtained when the probability of El Niño, La Niña and Neutral events occurring in different IPO phases were compared. The p-value in Table 2 indicates the probability that the frequency at which a given ENSO event occurs in one IPO phase is equal to the frequency at which the same ENSO event occurs at in a different IPO phase.

[17] Table 2 shows that when the negative IPO phase is compared with the positive IPO phases, the frequency at which La Niña events occur is significantly higher when the IPO is negative. Table 2 also demonstrates that the number of Neutral events that occur when the IPO is positive is significantly higher than when the IPO is negative, indicating a higher rate of occurrence of the ENSO extremes (El Niño or La Niña) when the IPO is negative. Table 2 also shows that no significant difference is observed between the two positive IPO phases in either El Niño, La Niña or Neutral events.

[18] It is therefore apparent from these results that the IPO negative phase, representing cool anomalies in the midlatitude Pacific Ocean SST, contain a statistically significant proportion of La Niña events. This indicates a predisposition of the negative (cool) IPO phase towards increased frequency of cool La Niña events. Thus the IPO modulation of flood risk across NSW appears due to its modulation of the magnitude and frequency of strong La Niña events.

[19] This dual modulation has the effect of reducing and elevating flood risk on multi-decadal timescales. Indeed, the 100 year average return interval derived by traditional empirical analysis returns a value of 3.17 for the regional index. However, within the IPO negative phase the regional flood of this magnitude occurs with a return period of 15 years. Given the observed persistence of IPO phases beyond this period, it seems that the '100 year flood' is most likely to occur during this period. Instrumental evidence bears testament to this in the occurrence of clusters of high magnitude floods. This apparent clustering, statistically anomalous under the traditional paradigm, is entirely intuitive within the concept of multi-decadal modulation of ENSO-induced flood extremes.

6. Conclusions

[20] This paper has sought to explain the temporal changes previously observed in NSW flood risk over the period 1924–99. This has been attempted through an analysis of ENSO processes and their modulation via multi-decadal SST as represented through the IPO index. The results have shown that La Niña events predominate the long-term flood risk. Moreover, multi-decadal modulation of ENSO processes result in extended periods of elevated flood risk. This paper has demonstrated that these multidecadal processes may modulate the frequency of ENSO extremes as well as the magnitude of their impact.

[21] There are a number of important implications associated with these insights;

1. Traditional flood risk where the climate is effectively assumed static is inadequate. Long term flood risk will be under- or over-estimated if the data used for analysis are drawn from a single or unknown combinations of IPO climate state.

2. Persistent periods of IPO negative phases are associated with much elevated flood risk. Given their persistent nature, these high risk periods can be identified through monitoring the IPO index, potentially providing useful guidance for operational flood management and infrastructure maintenance.

3. The observation of the modulation of ENSO extremes also has implications for reservoir management. The observation of increased La Niña events under IPO negative conditions will have significance for recharge of surface reservoirs with preliminary results indicating similar multi-decadal variability in drought risk [*Kiem and Franks*, 2003].

[22] Finally, it is worthwhile to note that the results shown here represent one manifestation of natural climate variability. The quantification of hydrological variability represents an integrated measure of natural climate variability. Flood risk is a key hydrological variable in terms of social and economic importance. At present it is unclear whether the multi-decadal modes of sea surface temperature variability are an internal artifact of the ocean-atmosphere system, or forced by external variations in ultraviolet irradiance [*Latif and Barnett*, 1994; *White et al*., 1997; *Reid*, 2000; *Franks*, 2002a]. In either case, the data presented here might be used as a performance indicator for General Circulation Models that attempt to project the influence of anthropogenic factors on climate. If these models can successfully represent such historic variability in a key hydrological variable, then increased confidence might be placed in the simulation of future, anthropogenically forced climate.

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Nature and causes of protracted droughts in southeast Australia: Comparison between the Federation, WWII, and Big Dry droughts

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[1] Three protracted droughts have occurred during the instrumental history of Southeast Australia (SEA) – the "Federation" (∼1895–1902), "World War II" (∼1937–1945) and the "Big Dry" (∼1997–present). This paper compares the nature and causes of these droughts in order to better inform drought management strategies in SEA. It is shown that the three droughts differ in terms of severity, spatial footprint, seasonality and seasonal rainfall make-up. This diversity arises due to the fact that the droughts are driven by different climatic teleconnections with the Pacific, Indian and Southern Oceans. Importantly, this study highlights potential flaws with drought forecasting and management in SEA and emphasises the need for further research into understanding and representing hydroclimatic drivers of drought. **Citation:** Verdon-Kidd, D. C., and A. S. Kiem (2009), Nature and causes of protracted droughts in southeast Australia: Comparison between the Federation, WWII, and Big Dry droughts, *Geophys. Res. Lett.*, *36*, L22707, doi:10.1029/2009GL041067.

1. Introduction

[2] A prolonged drought has affected Southeast Australia (SEA) since the mid-1990s. Known as the "Big Dry", this drought has had serious impacts on agricultural production (due to decreased irrigation allocations), biodiversity (due to prolonged changes in habitats), bushfire regimes and water availability for industrial and consumptive use. Not surprisingly, the Big Dry has attracted a great deal of media attention, along with labels such as "worst drought on record". However Australia, with its highly variable climate, is no stranger to such drought conditions. For example, the "Federation drought" (∼1895–1902) was associated with drought conditions covering the majority of the eastern two thirds of Australia. From 1937—1945 SEA was subjected to yet another multi-year drought, known as the "World War II (WWII) drought". In addition to the three multi-year droughts mentioned, a number of shorter, equally intense droughts have also occurred during Australia's instrumental history (e.g., 1914–1915, 1965–1968 and 1982–1983).

[3] Despite the regular occurrence of prolonged droughts in SEA, a comparative study has not been carried out to determine how the Big Dry compares, in terms of nature and causal processes, to other multi-year droughts. Furthermore, research to date has focused on identifying a single climate phenomena/process to explain the Big Dry [e.g., *Ummenhofer et al.*, 2009; *Larsen and Nicholls*, 2009; *Taschetto and England*, 2009]. This has lead to conflicting opinion as to the cause of the Big Dry with candidates currently including the Indian Ocean Dipole (IOD), Subtropical Ridge (STR), El Niño/Southern Oscillation (ENSO), ENSO Modoki and various anthropogenic influences.

[4] *Risbey et al.* [2009] showed that individual drivers, when treated as a single process, account for less than 20% of monthly rainfall variability for most Australian regions. Therefore it is unlikely that a single climate phenomenon was responsible for all drought events in SEA, rather, different dry epochs are likely to be driven by different and/or multiple climate processes [e.g., *Nicholls*, 2009; *Kiem and Verdon-Kidd*, 2009]. Therefore, this paper aims to provide a comparative analysis of the nature (in terms of rainfall deficiencies) and causes (in terms of remote climate drivers) of the three major protracted droughts that have occurred during the instrumental record in SEA - the Federation drought, WWII drought and the Big Dry.

2. Data

[5] This analysis is focused on rainfall rather than streamflow, or any other drought related variable. This is because streamflow is impacted by additional mechanisms (e.g., soil moisture, seasonality and intensity of rainfall, land cover change, extractions, loss to groundwater etc.) which are unlikely to be constant during the three periods of interest (i.e., 1895–2002, 1937–1945, 1997–present). The Australian Monthly Gridded Rainfall Dataset from the Australian Bureau of Meteorology (BoM) is used to assess the spatial extent of the three droughts. The gridded data spans the period 1900–2008, providing limited information on the Federation drought. To overcome this, along with gridded data issues relating to interpolation and smoothing of extreme events, additional point source data from 12 stations located in SEA is used to characterise the droughts. The stations chosen for analysis (Figure 1a) have sufficiently long records (i.e., spanning all three droughts) and minimal missing data (i.e., at least 99% complete).

3. Results

3.1. Comparison of Annual Rainfall

[6] The average annual rainfall deficiency across SEA during the three major multi-year droughts compared to the long term mean (based on the period 1900–2008) is shown in Figure 1, while Table 1 displays the results for the 12 individual rainfall stations. Note that in this study the Big Dry is defined as the period 1997–2008, however there is some evidence the drought may have initiated as early as 1994 [*Kiem and Verdon-Kidd*, 2009].

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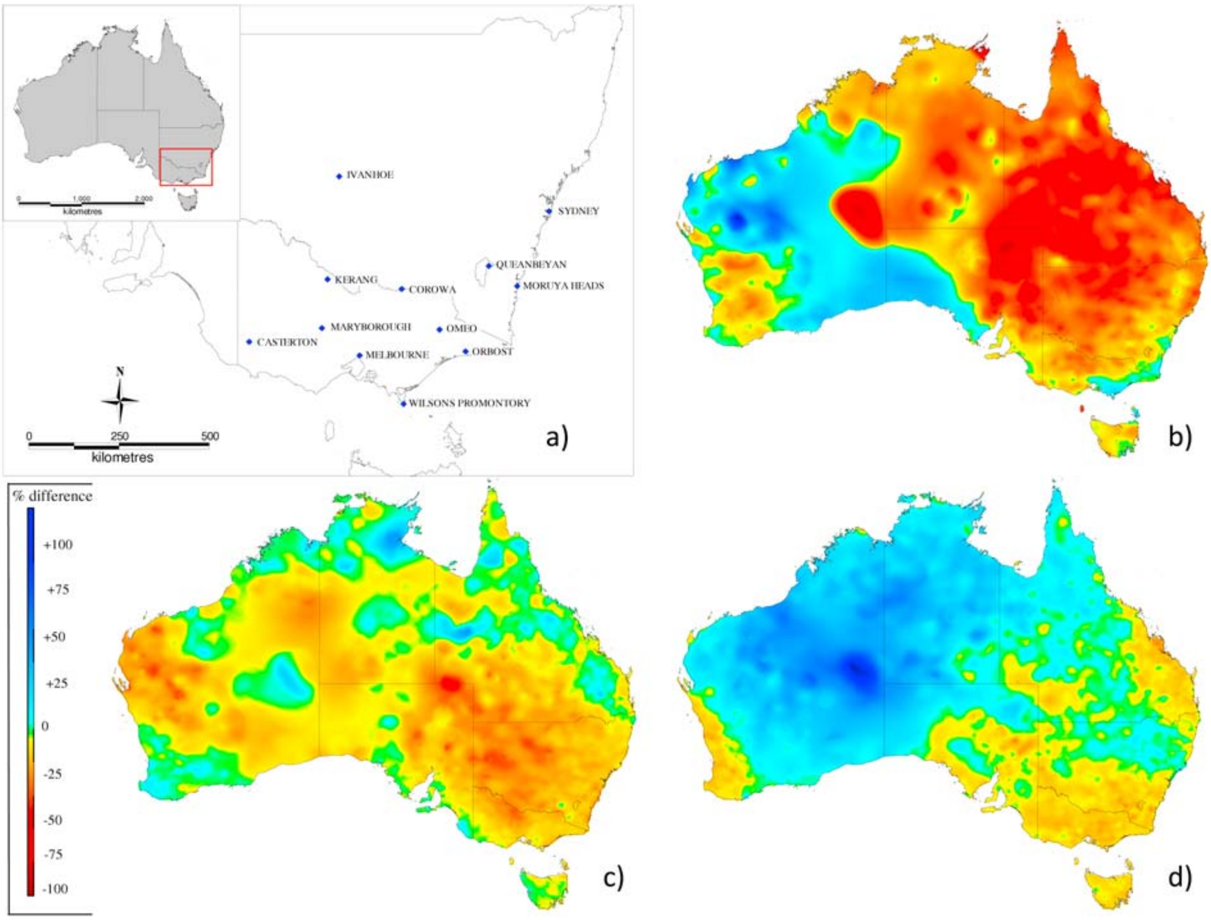

Figure 1. (a) Location of 12 rainfall stations in SEA, annual average rainfall deficiencies during (b) Federation, (c) WWII, and (d) Big Dry droughts. Note that a decrease of 50% indicates that the rainfall received during the drought was only half the long term average.

[7] It is clear from Figure 1 and Table 1 that the three droughts have a very different spatial signature and magnitude of impact. The Federation drought was concentrated in northern and eastern Australia (and parts of SW Western Australia) and is the most severe of the three droughts for much of New South Wales (NSW) and Queensland (QLD), however the SE coastal regions appear to have escaped severe drought. The WWII drought extended across much of the country and is the only drought of the three studied to have affected NW and SE Australia simultaneously. Figure 1c shows that the Big Dry is confined to SEA, SE QLD and SW Western Australia, with above average rainfall observed elsewhere, particularly NW Western Australia.

3.2. Comparison of Seasonal Rainfall

[8] Numerous studies have demonstrated that, rather than a decline in rainfall across all seasons, the main reason for extremely low runoff in SEA during the Big Dry is the disproportionately large decline in autumn/early-winter rainfall [e.g., *Murphy and Timbal*, 2008; *Pook et al.*, 2008; *Kiem and Verdon-Kidd*, 2009]. This raises the question – did the Federation and WWII droughts also exhibit seasonality in the rainfall decline? This is investigated in Figure 2, where seasonal rainfall reduction compared to the long term mean is shown for each station.

[9] In Figure 2 the dominant autumn rainfall decline during the Big Dry is evident for most stations (particularly those located in the north of the study region), consistent with previous findings. Generally, the Federation and WWII droughts do not follow the same seasonal trend as the Big Dry. For example, Figure 2 shows that the Federation drought was predominantly due to rainfall reductions in spring/summer. During the WWII drought, rainfall was

Table 1. Annual Average Rainfall Deficiency Compared With Long Term (1900–2008) Mean During the Federation, WWII, and the Big Dry Droughts for Selected High Quality Stations

Station Location	Federation Drought (1895–1902)	WWII Drought (1937–1945)	Big Dry (1997–Present)
Ivanhoe	−18%	−41%	−12%
Sydney	−6%	−14%	−7%
Queanbeyan	−17%	1%	−5%
Kerang	−29%	−35%	−3%
Moruya	−2%	−4%	−12%
Corowa	−19%	−18%	−14%
Maryborough	−16%	−29%	−19%
Omeo	−7%	−9%	−11%
Casterton	−11%	−9%	−12%
Orbost	−8%	−10%	−9%
Melbourne	1%	−16%	−23%
Wilsons Prom	2%	0%	−16%

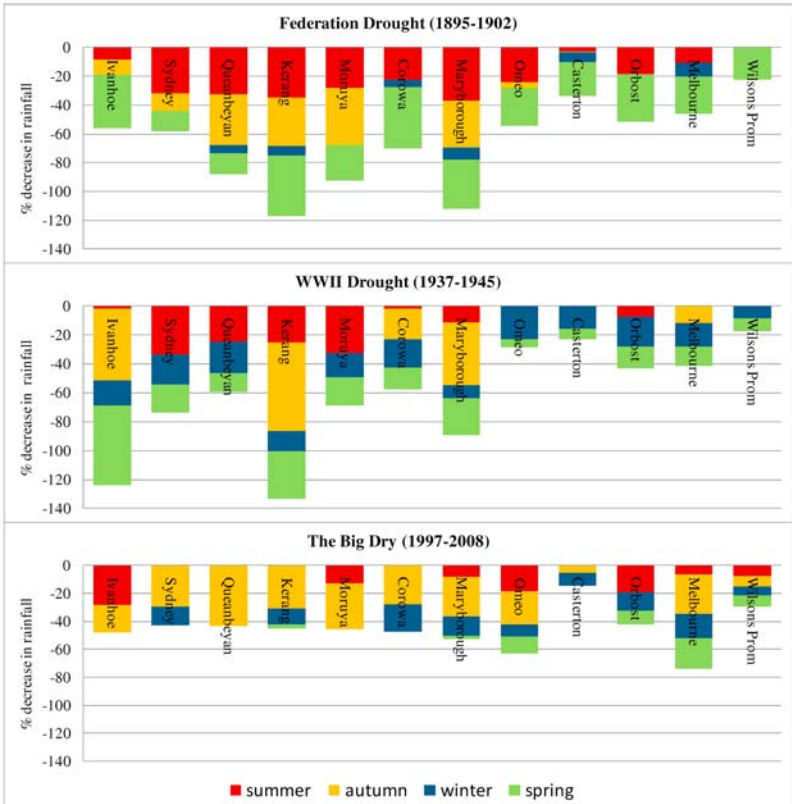

Figure 2. Seasonal average rainfall deficiencies during the Federation, WWII, and Big Dry droughts.

reduced across all seasons, however there does appear to be some spatial variability – with stations located in the NW of the study region displaying a larger autumn rainfall decline, stations located along the coastal fringe of NSW exhibit a summer decline, while the SE displays marked winter/spring rainfall deficiencies.

3.3. Comparison of Daily Rainfall

[10] Changes in daily rainfall statistics (i.e., changes to the frequency, intensity, duration and/or sequencing of rainfall events) have important hydrological implications, as this will influence soil moisture and runoff generated [e.g., *Kiem and Verdon-Kidd*, 2009]. The average number of wet days per year (defined as any day with rainfall greater than 1 mm) and the average daily rainfall intensity during the three droughts is shown in Table 2. The results are presented as a percent difference compared to long term average.

[11] Table 2 shows the Federation drought was primarily caused by a decrease in the number of rain days rather than a change in the rainfall intensity. During spring this decrease is striking (∼25% on average). The opposite is true for the Big Dry, where a decrease in the rainfall intensity, rather than number of rain days, appears to be the primary driver – particularly during autumn (∼25% decrease in intensity on average). This result is consistent with recent work by *Pook et al.* [2008] and *Verdon-Kidd and Kiem* [2009] who showed that the frequency of synoptic patterns associated with intense rainfall across SEA has reduced markedly during autumn since 1994. Both the average daily intensity and number of rain days was reduced during the WWII drought and again there appears to be strong spatial variability in the impacts.

3.4. Causal Mechanisms

[12] Numerous studies have demonstrated that the four most influential climate modes on SEA's climate are:

[13] 1. El Niño/Southern Oscillation (ENSO) – coupled ocean-atmosphere variability that manifests as abnormal warming (El Niño) and cooling (La Niña) of the tropical Pacific Ocean. El Niño tends to result in warm dry conditions in SEA, while the reverse is true for La Niña [e.g., *Chiew et al.*, 1998; *Kiem and Franks*, 2001; *Verdon et al.*, 2004].

[14] 2. Inter-decadal Pacific Oscillation (IPO) – a low frequency (15–35 years) pattern of variability of the tropical and extra-tropical Pacific ocean (refer to the work of *Power et al.* [1999] for details). The IPO appears to modulate the strength and frequency of ENSO events, whereby the positive (negative) phase is associated with a higher frequency of El Niño (La Niña) events and suppressed (enhanced) impacts of La Niña [*Power et al.*, 1999; *Kiem et al.*, 2003; *Verdon et al.*, 2004]. Also see *Power and Colman* [2006] regarding the origins of the IPO and issues with reliability pre-1950.

[15] 3. Indian Ocean Dipole (IOD) – a coupled ocean-atmosphere climate mode that occurs inter-annually in the tropical parts of the Indian Ocean. During a positive IOD event, the sea-surface temperature (SST) drops in the northeast Indian Ocean (near the NW coast of Australia)

Table 2. Comparison of the Number of Wet Days Per Year and Average Daily Rainfall Intensity for Each of the Three Droughts[a]

Station	Federation				WWII				Big Dry			
	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
% Difference in Number of Wet Days Per Year												
Ivanhoe	**−14**	**−26**	**3**	**−30**	−38	**−36**	**−22**	**−40**	4	**−13**	6	0
Sydney	−10	**−13**	25	**−11**	−27	−2	6	0	−4	−7	−3	−1
Queanbeyan	**−35**	**−30**	**−22**	**−19**	−20	−8	**−12**	**−7**	28	**−23**	29	2
Kerang	**−34**	**−32**	**−17**	**−43**	−17	**−33**	**−20**	**−27**	16	**−16**	−8	−4
Moruya	**−16**	**−15**	24	**−19**	−5	0	3	−1	−1	**−14**	−2	−8
Corowa	**−31**	**−17**	**−16**	**−38**	−26	**−16**	**−16**	**−16**	−4	**−20**	**−13**	−8
Maryborough	47	58	−8	**−29**	−13	−6	**−14**	**−17**	−4	**−21**	**−15**	−4
Omeo	**−16**	8	5	**−22**	−5	5	**−11**	**−7**	−2	**−15**	−5	−3
Casterton	−9	10	**−11**	**−12**	21	−4	−3	**−11**	−6	−8	−5	3
Orbost	**−24**	**−13**	24	**−32**	0	12	−4	**−5**	11	−1	−5	5
Melbourne	0	2	−4	**−21**	−4	0	−1	**−11**	−12	**−20**	**−21**	**−17**
Wilsons Promontory	−10	−6	−6	**−14**	12	8	6	3	−5	**−13**	**−11**	**−5**
% Difference in Average Daily Rainfall Intensity												
Ivanhoe	**−19**	**−14**	**−5**	**−22**	−4	4	**−11**	**−8**	−34	**−41**	**−18**	**−12**
Sydney	**−26**	**−18**	5	−7	**−21**	**−3**	**−21**	**−14**	−3	1	15	−1
Queanbeyan	11	12	38	13	**−15**	**−20**	**−30**	**−19**	−13	**−29**	−5	**−15**
Kerang	24	37	41	20	**−21**	**−27**	−7	**−10**	−22	**−34**	**−21**	**−9**
Moruya	9	−3	41	**−19**	0	32	**−18**	5	**−13**	**−30**	18	−6
Corowa	18	19	23	−1	−9	15	−3	**−11**	−5	**−15**	**−11**	−10
Maryborough	−2	−5	17	0	**−19**	**−22**	−4	**−13**	−12	**−36**	**−29**	**−18**
Omeo	8	5	4	**−7**	7	13	3	12	**−23**	**−36**	**−18**	**−17**
Casterton	11	−5	14	**−14**	12	−8	−7	−10	−8	**−16**	**−16**	1
Orbost	55	50	58	51	**−17**	5	**−24**	2	**−29**	**−31**	**−15**	**−26**
Melbourne	2	21	0	**−18**	−4	**−11**	−9	−5	−9	**−10**	−2	**−10**
Wilsons Promontory	24	19	4	**−12**	−7	3	−8	−10	**−19**	**−16**	−5	**−13**

[a]Percentage difference is in reference to the long term mean and decreases of more than 10% are in bold.

while the SST rises in the western equatorial Indian Ocean. Inverse conditions exist during a negative IOD event. Positive (negative) IOD events tend to result in reduced (enhanced) winter and spring rainfall in SEA [e.g., *Verdon and Franks*, 2005].

[16] 4. Southern Annular Mode (SAM) – the leading mode of atmospheric variability over the southern extratropics. The SAM represents an exchange of mass between the mid latitudes and the polar region [*Thompson and Wallace*, 2000] which modulates westerly winds over the southern extratropics and embedded frontal weather systems. The positive phase of SAM has been associated with reduced autumn rainfall in SEA via a reduction in frontal systems [e.g., *Verdon-Kidd and Kiem*, 2009; *Nicholls*, 2009].

[17] Figure 3 shows the timeseries of ENSO (represented by the Niño3.4), IPO, NW of Australia SSTs (eastern pole of the IOD) and SAM, along with the three protracted drought epochs. See *Verdon-Kidd and Kiem* [2009] for a description of these indices. NW of Australia SSTs are used here rather than the IOD as previous studies have shown that warming to the NW of Australia (i.e. the eastern pole of the IOD) is most important for cloud band development and strongly related to above average rainfall in SEA [e.g., *Verdon and Franks*, 2005], while the need for an anomaly further west has not been demonstrated. In fact the poles of the IOD are not negatively correlated as one would expect [*Dommenget and Latif*, 2002] and intermittent decoupling of the east and west pole of the IOD can lead to false classification of events. It should also be noted that the STR is suggested to have played a significant role in the recent drought [e.g., *Larsen and Nicholls*, 2009], however data is not available for the STR prior to 1950 and therefore STR was not included in this analysis. The instrumental record of the SAM (available from 1957 to present [*Marshall*, 2003]) has been extended using *Jones et al.*'s [2009] reconstruction.

[18] It is evident that the Federation drought occurred during a period of sustained El Niño activity (as indicated in Figure 3 by the warm SSTs in the Niño3.4 region), with only 1898 reaching the La Niña threshold. Furthermore, the impacts of this lone La Niña might have been suppressed since it occurred during an IPO positive epoch [e.g., *Verdon et al.*, 2004]. SSTs off the NW of Australia (eastern pole of IOD) were warm during the Federation drought suggesting that the Indian Ocean variability was not a major contributor to this drought. Likewise the SAM index was predominantly negative and, taking this result at face value (ignoring concerns over its reliability prior to the 1950s), suggests that SAM was unlikely to have contributed to the rainfall decline. These results (i.e., ENSO and IPO being primary drivers of Federation drought) are consistent with the observed spatial footprint and seasonality of the Federation drought (Section 3) given the greatest impact of El Niño on rainfall in SEA is during the spring/summer months and the magnitude of impact is greater in NE Australia than SE. Further, *Verdon-Kidd and Kiem* [2009] found that El Niño events were associated with a weakening and northward retraction of the easterly trough, also consistent with the observed reduction in the number of rain days.

[19] Figure 3 demonstrates that ENSO switched between El Niño and La Niña conditions during the WWII drought (with slightly more El Niño years) and the SAM alternated between its positive and negative phase, indicating that neither persistent El Niño conditions nor positive SAM caused the WWII drought. However, SSTs off the NW coast of Australia (the eastern pole of the IOD) were cooler than average for six out of the nine years during the WWII drought, suggesting that the Indian Ocean is a likely contributor to this drought. This finding is consistent with

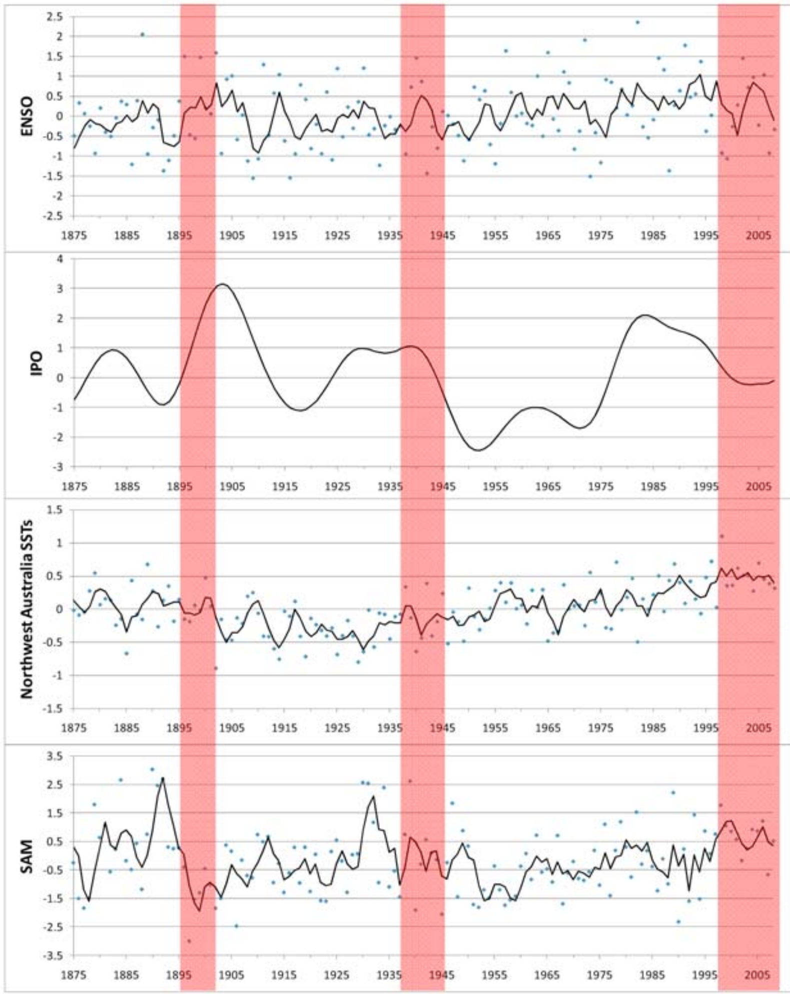

Figure 3. Historical timeseries of ENSO, IPO, NW of Australia SSTs and SAM. Dots represent the mean 'annual' value for each index, solid line is the 3 yr moving average, red shaded regions indicate the three major droughts.

observed reductions in winter/spring rainfall (which is when the IOD is dominant) and the clear NW-SE signature of the drought across the country (Figure 1c). However, Figure 3 also exhibits other periods of persistently negative SSTs off NW Australia in the last 100 years – in fact the whole period from 1910–1945 was predominately below average. So why wasn't this entire period dry? The key is the sequencing of the years during the drought. Of the three La Niña events that occurred during the WWII drought, two occurred in combination with a positive SAM. *Kiem and Verdon-Kidd* [2009] have shown that SAM acts to block the propagation of La Niña rainfall into SEA (indeed La Niña can be as dry as El Niño in SEA when the SAM is positive). In addition, the IPO was positive during this period which might have also acted to suppress the impact of La Niña.

[20] Figure 3 suggests that SAM is a major causal factor of the Big Dry, with a sustained positive epoch occurring from 1997–present. In addition, there were three consecutive El Niño events (2002–2004) during the peak of the drought and a complete lack of La Niña from 2000–2006. The La Niña events of 2007/2008 did not result in drought breaking rain for SEA because the SAM was strongly positive during this time. Although, in areas to the north of SAM's reach (i.e., QLD and northern NSW) the 2007/2008 La Niña did in fact break the drought. NW Australian SSTs have been warmer than usual since 1985, suggesting that Indian Ocean variability is unlikely to have been a major driver of the Big Dry (contrary to the findings of *Ummenhofer et al.* [2009]). The dominance of the SAM in the current drought is consistent with autumn rainfall decline observed during the Big Dry, since this is the season where SAM has been most consistently positive since the mid-1990s [*Kiem and Verdon-Kidd*, 2009]. Further, the fact that the spatial signature of the Big Dry (Figure 1d) shows drought being focused on SEA and southwest WA is consistent with a reduction in pre-frontal systems, which in turn is symptomatic of a positive SAM phase [e.g., *Verdon-Kidd and Kiem*, 2009].

[21] It is also worth noting from Figure 3 that the short but intense 1982–1983 drought (worst on record in terms of short-term rainfall deficiencies) occurred when the Pacific was in an El Niño IPO positive state, the waters off NW Australia were cool and the SAM was positive (i.e., all four modes locked into their dry phase).

4. Discussion

[22] The Federation, WWII and Big Dry droughts are the three longest droughts on instrumental record in

SEA – though similarities between them end there. Each drought is quite dissimilar in terms of severity, spatial signature, seasonality and seasonal rainfall make-up. Results presented here suggest this is because each drought was driven by a different climate process (or combination of processes). Importantly, these results highlight some major issues with drought management and forecasting in SEA, in particular:

[23] 1. It is now understood that droughts in SEA are associated with at least four major climate phenomena (ENSO, IPO, IOD and SAM). This raises the questions – have we experienced the worst drought possible in SEA? What if we were to experience a situation identical to the 1982/1983 event (when all four modes were locked into their dry phase) sustained over a longer period of time? How likely is this situation to occur? Answers to these questions require study of the pre-instrumental history combined with utilisation of stochastic frameworks to more robustly quantify the risk of drought. Climate model projections should also satisfactorily account for the natural variability mentioned above and then be interrogated to provide insight into the degree to which anthropogenic climate change contributes to the current drought (the Big Dry) and if/how the risk of drought may change in the future.

[24] 2. To date forecasting schemes have focussed on predicting ENSO (with some effort now being directed towards forecasting IOD). However, even a perfect ENSO forecast will not suffice in predicting protracted droughts in SEA. Indeed, climate forecasting systems will need to account for all climate modes, and their interactions, in order to be successful.

[25] Further understanding into how multiple physical mechanisms, including anthropogenic climate change, interact to drive SEA climate, and improved conceptualisation and representation of these interactions in dynamical climate models (both regional and global models), is required if we are to satisfactorily predict onset and conclusion of drought. Failure to address these issues will result in drought management strategies continuing to be largely ineffective in reducing Australia's vulnerability to drought.

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