Multi-decadal climate variability, New South Wales, Australia

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Abstract Traditional hydrological risk estimation has treated the observations of hydro-climatological extremes as being independent and identically distributed, implying a static climate risk. However, recent research has highlighted the persistence of multi-decadal epochs of distinct climate states across New South Wales (NSW), Australia. Climatological studies have also revealed multi-decadal variability in the magnitude and frequency of El Niño/Southern Oscillation (ENSO) impacts. In this paper, examples of multi-decadal variability are presented with regard to flood and drought risk. The causal mechanisms for the observed variability are then explored. Finally, it is argued that the insights into climate variability provide (a) useful lead time for forecasting seasonal hydrological risk, (b) a strong rationale for a new framework for hydrological design and (c) a strong example of natural climate variability for use in the testing of General Circulation Models of climate change.

Keywords Climate variability; drought; El Nino; ENSO; floods; interdecadal pacific oscillation; IPO; La Nina; pacific decadal oscillation; PDO

Introduction
Rainfall and streamflow are extremely variable across Australia. The quantification and understanding of climatological and hydrological variability is of considerable importance for the robust estimation of flood and drought risk. At present, traditional hydrological risk estimation methods are largely empirical in that observed histories of climate extremes are analysed under the assumption that individual events are independent and identically distributed (Franks and Kuczera, 2002). Traditionally, no account has been taken of the physical climatological mechanisms that actually deliver climate extremes.

Despite the development of rigorous Bayesian frameworks to assess the uncertainty of risk estimates, these techniques have not previously acknowledged the possibility of serial correlation within distinct periods of elevated or reduced risk. However, recent research has highlighted the existence of multi-decadal epochs of enhanced/reduced flood risk across New South Wales (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. Previous authors have noted that the mid-1940s corresponded to a change in both sea surface temperature anomalies as well as circulation patterns (Allan et al., 1995). Franks (2002a) 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.

In addition to hydrological observations of changing climate risk, climatological insights into the mechanisms of climate variability point to the invalidity of a purely empirical approach to risk estimation. Indeed, numerous previous studies have shown that a strong relationship exists between streamflow and the El Niño/Southern Oscillation (ENSO) phenomenon. In terms of New South Wales climate, the warm El Niño events are associated with marked reductions in rainfall and increased air temperatures and evaporative demand,
whereas the cool La Niña events typically deliver enhanced rainfall totals and cooler air temperatures. It is therefore clear that as individual drought and flood events are usually associated with ENSO extreme events, year-to-year flood and drought risk varies according to ENSO state.

Furthermore, recent climatological studies have also revealed multi-decadal variability in the modulation of the magnitude of El Niño/Southern Oscillation (ENSO) impacts. In particular, 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 (1920–1945 and 1975–2001) and cooling (1945–1975) in the Pacific Ocean. Power et al. (1999) showed how Australian ENSO correlations changed with the observed changes in persistent large-scale Pacific Ocean SST anomalies. Importantly, Power et al. (1999) demonstrated that individual ENSO events (i.e. El Niño, La Niña) had stronger impact across Australia during the negative phase of the IPO, implying that there exists a multi-decadal modulation of the magnitude of ENSO events.

In this paper, the role of ENSO and IPO processes in dictating flood and drought risk are assessed. The first sections detail the identification of the hydrological impacts of ENSO and IPO processes. The following section attempts to detail the climatological mechanisms by which this occurs. Finally, the implications of the climatological insights into hydrologic variability are discussed.

**Hydro-climatological observations of multi-scale variability**

To assess historic regional flood risk a state-wide index is derived and subsequently stratified according to ENSO classifications based on the NIÑO3 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. To assess historic variability of drought risk, a simulation model of a key water supply reservoir is constructed and its behaviour is subsequently assessed under different IPO states.

**ENSO-IPO controls on flood frequency**

To assess the role of ENSO extremes, Figure 1a 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. Given the clear role of La Niña events in flood risk identified in Figure 1a, to test

![Figure 1](https://iwaponline.com/wst/article-pdf/49/7/133/421146/133.pdf)

**Figure 1** Flood frequency curves for (a) El Niño and La Niña ENSO extremes, and (b) La Niña under negative IPO conditions and La Niña under non-negative IPO conditions.
the hypothesis that the IPO modulates the magnitude of La Niña events, as suggested by 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 and then according to La Niña events occurring under neutral and positive IPO phases. Figure 1b shows the resultant flood frequency curves. As can be seen, the frequency curve associated with La Niña events under negative IPO is markedly higher than the flood frequency associated with all other La Niña events.

Finally, given the (multi-) decadal persistence of IPO phases, it is desirable to assess the variability of flood risk under the different IPO phases irrespective of inter-annual ENSO events. Figure 2 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.

IPO controls on drought risk

The reservoir used in this study is the Grahamstown Reservoir which has been operating since 1963 and is located within the Williams River catchment near Raymond Terrace, NSW, Australia. In order to simulate the reservoir’s performance in different climate states one thousand replicates of 1,000 year rainfall and streamflow sequences were created for the positive, negative and neutral IPO phases, based on the rainfall at Raymond Terrace and the streamflow at Glen Martin occurring within each phase. A stochastic modelling approach based on Monte Carlo sampling is then employed. A critical time for the local authority is when the storage level of Grahamstown Reservoir drops below 30% of capacity as this is when extreme and costly measures are undertaken in order to ensure drought security (HWC, 2000). Therefore, drought risk during the different IPO phases and also when using the different adaptive management procedures was assessed by analysing the total number of times the reservoir storage levels fell below the critical level of 30%.

Figure 3 shows the average probability, and 90% confidence interval, of a critical event during the different IPO phases using HWC’s current management procedures. When the IPO is positive the average probability of a “critical event” is 0.038 compared with 0.002 when the IPO is negative (a 95% decrease) and 0.020 during the neutral IPO phase (a 47% decrease). Therefore, the risk of falling below the critical level when IPO is positive is almost 20 times higher than it is during the negative IPO phase, indicating that the risk of drought is significantly higher when the IPO is positive. This is despite the fact that the positive IPO periods tend to be associated with only moderate ENSO impacts in Australia, and therefore only weak El Niño events (Power et al., 1999). The high drought risk in non-negative IPO states is due to the relatively low occurrence of recharging La Niña events. In IPO
negative conditions, the reservoir is large enough to ride out the occasional enhanced El Nino events and is significantly recharged due to enhanced and more frequent La Nina events (Kiem and Franks, 2004). The non-negative IPO conditions are therefore higher drought risk periods due to infrequent and low magnitude-impact La Nina events.

**Causes of variability**

Given the high degree of hydro-climatological variability explained by the combined ENSO and IPO indices, it is advantageous to develop a qualitative conceptual understanding of the physical mechanisms of ENSO and IPO processes. In particular, it is important to ask how IPO processes interact with ENSO to ultimately deliver the marked observations of variability.

**IPO modulation of ENSO event magnitude**

Whilst ENSO processes were initially identified using atmospheric pressure differences between Tahiti and Darwin, the most obvious indication of ENSO events is given by Eastern Equatorial Sea Surface Temperature (SST). The standard model of ENSO processes is given by the “delayed action oscillator”. Individual ENSO events are seen as preferred states arising from the internal interaction of oceanic and atmospheric processes in the Equatorial Pacific.

In essence, an anomalous perturbation in this coupled system, if sufficiently large, is magnified through the interaction of processes due to positive feedback reinforcing the anomalies in each. A longitudinal shift in equatorial circulation (i.e. Walker Cell) is developed which subsequently interferes with the Inter Tropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ). It has previously been demonstrated that relatively small shifts in the location of the SPCZ result in very large rainfall anomalies either side of the SPCZ (Salinger et al., 1995).

Though related, the SPCZ is most significant as it delivers rain-bearing cloud bands across Eastern Australia. The SPCZ is most active during November through to April (Folland et al., 2002) which in general terms coincides with the season of highest and most variable rainfall over Eastern Australia, and also corresponds to the period of greatest ENSO event impact (Kiem and Franks, 2001). Warm El Nino events disrupt the SPCZ, preventing its propagation to its usual southern latitude. Cold La Nina events represent an enhancement of the neutral ENSO state, with the effect that the SPCZ propagates further south than normal delivering more frequent rain-bearing cloud bands across South East Australia (Salinger et al., 1995).

In contrast to the equatorial nature of ENSO processes, the IPO processes are revealed in mid-latitude SST anomalies across the Pacific and Indian Oceans. Indeed the IPO index itself is derived from Principal Component Analysis of the modes of SST variability revealing the predominance of the low frequency component in the mid-latitudes (Power et al., 1999). A recent study by Folland et al. (2002) assessed the location of the SPCZ as a function of both ENSO and IPO. They demonstrated that the IPO SST anomalies affect the location of the SPCZ during the Austral Summer (Nov–Apr) in a manner similar to that induced by ENSO but on a multi-decadal timescale. Importantly, the results of Folland et al. (2002) showed that the SPCZ was at its southernmost during La Nina events under IPO negative conditions.

This provides strong corroborative evidence of the enhancement of La Nina events under IPO negative conditions as originally suggested by Power et al. (1999), and as inferred from flood and water supply drought analyses above (see also Kiem and Franks, 2004; Kiem et al., 2003). However, Folland et al. (2002) also demonstrate that the SPCZ is at its northernmost location during El Nino events under IPO positive conditions. If the
observed climate variability across Eastern Australia is viewed as solely due to the presence or otherwise of the SPCZ, then this result would appear to conflict with the observations of enhanced El Nino events under IPO negative conditions (Power et al., 1999; Verdon et al., 2004). One would expect greatest impacts of El Nino under IPO positive conditions.

Again, consideration of rain-bearing circulation patterns may assist in the interpretation of the empirical observations and correlation. During “normal” El Nino events, the northerly location of the SPCZ moves the corresponding rain-bearing cloud bands north. However, southern areas of Eastern Australia do not display marked reductions in rainfall due to the dominance of Southern Ocean cold fronts in delivering rainfalls across southern parts of eastern Australia. For this reason, areas south of New South Wales display progressively less impact from the majority of El Nino events. It is likely that under IPO positive El Nino conditions, when the SPCZ is at its most extreme northern limit, greater opportunity for the propagation of these southern cold fronts into New South Wales is possible. The effect would be to mitigate the impact of the extreme north location of the SPCZ by delivery of rainfall not associated with the SPCZ but translocated due to the SPCZ migration. Thus, the marked rainfall deficiency associated with IPO negative El Nino may be due to the lack of both SPCZ and Southern Ocean influences across New South Wales.

Figure 4 shows a schematic diagram of the key features of ENSO-IPO impacts. Whilst the role of Southern Ocean cold fronts remains speculative, it may be easily tested through analysis of historic synoptic meteorological data, and is the subject of current research.

### IPO modulation of ENSO frequency

Whilst recent climatological research points to the explanation of IPO modulation of the magnitude of individual ENSO events, the issue of the IPO modulation of ENSO frequency is less clear. A number of previous studies have observed and evaluated changes in the relative frequencies of El Nino and La Nina events using historical or long-term proxy data, although these studies did have the advantage of IPO processes in their considerations. When IPO stratification of an ENSO timeseries is considered, it is immediately apparent that the IPO negative phase appears to be associated with a higher frequency of La Nina events (Kiem and Franks, 2004; Kiem et al., 2003). Indeed between 1945 and 1976 almost 50% of all years in IPO negative states are classified as La Nina according to the NINO3 classification (Kaplan et al., 1998). Whilst La Nina events appear to be highly dependent upon IPO state, El Nino events showed limited but insignificant differences between IPO states.

![Figure 4](https://iwaponline.com/wst/article-pdf/49/7/133/421146/133.pdf)

**Figure 4** Schematic diagram of SPCZ and indicative changes in its location under IPO and ENSO states, after Folland et al. (2002). Also indicated is the possible role of Southern Ocean cold fronts which, it is speculated, may mitigate the effects of extreme NE location of the SPCZ under simultaneous El Nino and IPO+ conditions.
To elucidate how IPO processes may affect La Nina frequency, consideration of the nature of the IPO signal and long-term changes in SST may be of some use. Recent climatological research has attempted to explain the observations of long-term change in equatorial SST anomalies.

Kleeman and Power (2000) note that there are two key mechanisms by which equatorial SST anomalies may arise; (a) stochastic forcing by atmospheric transients or chaotic climate dynamics within the equatorial zone, and (b) extra-tropical/mid-latitude forcing due to gyres or thermohaline circulations, external to the equatorial zone. Of these two possibilities, Kleeman and Power (2000) suggest that observations of sub-tropic subduction and consequent upwelling in the equatorial Pacific point to an influence of the mid-latitude SST anomalies (and hence IPO) interacting with ENSO.

In terms of IPO, the negative state is associated with cooling mid-latitude SST anomalies. This water is subducted and transported to the equatorial Pacific where upwelling permits the anomalously cool water to return to the surface and influence the development of La Nina conditions. This circulation, known as a Sub Tropic Cell (STC) or gyre, provides a mechanism by which long-term anomalies represented by the IPO may prejudice equatorial SST and hence predispose ENSO processes towards a particular ENSO state.

This oceanographic mechanism indicates the possibility of IPO SST anomalies influencing ENSO SST anomalies. As noted earlier, the instrumental record indicates a clear increased frequency of La Nina events under IPO negative conditions, however no statistically significant difference was observed for El Nino events. Nonetheless, the possibility of IPO modulation of ENSO through subtropical cells may have substantial basis.

Summary
The previous sections have attempted to place the recent hydrological insights into the role of ENSO and IPO in dictating climate risks within the context of the current understanding of the interaction of these processes from recent climatological studies. The development of this understanding is an essential pre-requisite to developing robust estimation methodologies for hydro-climatological risk estimation. From both the hydrological and climatological observations, it is clear that IPO and ENSO processes are related and, in tandem, may dictate variability across Eastern Australia on multiple timescales. Despite increasing attention and understanding of both ENSO and IPO processes, there are still many remaining questions regarding their interaction, the spatial variability of their impact and most importantly the nature of future climate variability under their regime.

Future climate variability
Increased understanding of historic variability through increased understanding of climate processes should enable a more realistic model of climate risk and may be used to mitigate future climate extremes at a range of temporal scales. Indeed, the 2002–3 El Nino event that ultimately produced the most extensive drought across New South Wales, occurred following a return to IPO negative conditions in 2001. As suggested by Power et al. (1999), IPO negative states are be associated with enhanced ENSO event impacts across Australia. This has also been demonstrated with respect to flood, drought and forest fire data across New South Wales. These insights point to increased predictability of ENSO and IPO impacts across New South Wales.

At present, it remains unclear whether multi-decadal IPO variability is an internal artefact of the ocean-atmosphere system or externally forced by long-term solar variability (Franks, 2002b). It should be noted that in the third assessment, the Intergovernmental Panel on Climate Change acknowledged the significant role of solar variability in climate (IPCC, 2002). Figure 5 shows the variable periods of warming and cooling in the global
temperature record observed over the last century. From Figure 5, it can be seen that the
transitions between warming/cooling periods occur in the mid-1940s and the mid-1970s,
matching the IPO transitions over the same period.

This coherence between the IPO and global temperature record should be expected as
the IPO is derived from large-scale low-frequency sea surface temperature anomalies
across the Pacific Ocean. Figure 5 also demonstrates the global SST timeseries in compar-
sion to an index of historic solar variability. As can be seen, the distinctive period of global
cooling observed between 1945 and 1975 (corresponding to IPO-ve and increased frequen-
cy of cold La Nina events) is matched by a decline in solar variability. Whilst such results
cannot be taken as definitive, they are nonetheless highly suggestive of a causal link
between solar behaviour and multi-decadal climate variability.

Whether the multi-decadal IPO processes are internal to the ocean-atmosphere system
or forced by external solar variability, it is clear that both mechanisms are likely to be
subject to chaotic effects. This will hinder deterministic prediction via complex ocean-
atmosphere models. Irrespective of causal mechanism, the observed persistence of IPO
may itself be used to define the likely IPO state over decadal timescales. As IPO state
appears to modulate interannual ENSO impacts over New South Wales, it is expected that
this will enable a new degree of insight into climate over a range of useful timescales.

However, the implied assumption of using historic relationships to predict future cli-
mate risk is that future IPO and ENSO controls on climate variability will behave similarly
to those observed over the relatively limited instrumental records available for long-term
climate assessment. It is entirely possible that much longer-term mechanisms and modes of
climate variability may exist and that current concern over anthropogenic effects on
climate may mean that the past is not necessarily a robust indication of things to come.
Nonetheless, a simple conceptual model of climate variability according to historical
ENSO-IPO impacts would be at least complementary to coupled ocean-atmosphere models
approaches that suffer from their reductionist nature and their very complexity (Franks,
2002b). The conceptual ENSO-IPO model of hydrological variability is more easily
facilitated in terms of its implementation and more directly relevant to the prediction of the
hydrological variables as they can be directly derived from networks of hydrological
observations themselves, where they are available.

Implications
There are numerous implications of the work presented. It is clear that flood and drought
risk estimation methodologies that do not account for the observed multi-decadal variabili-
ty will be in substantial error when applied within New South Wales. Given quasi-global
impacts of ENSO and IPO processes, it is likely that many other regions will display similar
variability. The results presented here also demonstrate additional predictive insight for

Figure 5 Time series of global SST anomalies and estimated solar irradiance (1900–2000) after Franks
(2002b)
seasonal-interannual ENSO forecasts using just two simple indices of climate. Finally, the observation of IPO and ENSO controls on multi-decadal epochs of elevated or reduced climate risks also presents a unique opportunity to assess the simulation of historic natural climate variability within complex coupled ocean-atmosphere models. Given their use in the projection of anthropogenic impacts on climate, it is crucial that these models be evaluated with regard to observed natural changes in key hydrological variables such as flood and drought risk if confidence is to be placed in their use.

References