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The impact of climate variability on flood risk

ANTHONY S. KIEM & STEWART W. FRANKS

School of Engineering, University of Newcastle, Callaghan, New South Wales 2308, Australia
a.kiem@studentmail.newcastle.edu.au

Abstract The variability of flood risk across New South Wales, Australia, is analysed with respect to the observed modulation of El Niño/Southern Oscillation (ENSO) impacts. 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 multi-decadal modulation of flood risk is achieved using the Inter-decadal 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 analyses as well as providing a strong example of the role of natural climate variability.

Key words Australia; climate variability; El Niño/Southern Oscillation (ENSO); flood frequency; Inter-decadal Pacific Oscillation (IPO); multi-decadal; Pacific Decadal Oscillation (PDO)

INTRODUCTION

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 & 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 (NSW; Erskine & Warner, 1988; Franks, 2002a,b; Franks & Kuczera, 2002). In particular, Franks & 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 (2002b) showed that the observed change in flood frequency could be objectively identified as corresponding to this shift in climate parameters.

In addition to hydrological observations of changing flood risk, recent climatological studies have 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 is 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 (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, a derived regional index of flood risk (Franks, 2002b) is 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.

DERIVATION OF A REGIONAL INDEX

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. Forty 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). First, the individual records are scaled by the mean of the log annual flood maximum discharge. For example:

$$x_t^j = \frac{\ln Q_t^j}{\sum_{i=1}^{N} \ln Q_i^j / N} \qquad \text{for } j = 1, \ldots\ldots, M \tag{1}$$

where x_t^j is the normalized index for gauge j, at year t, N is the total length of the flood record (1924 to 1999) and M is the total number of gauges. For each year, the resultant 40 scaled time series are then averaged to provide the regional flood index:

$$RI_t = \sum_{j=1}^{M} x_t^j / M \qquad \text{for } t = 1, \ldots, N \tag{2}$$

TEMPORAL STRATIFICATION ACCORDING TO ENSO AND IPO INDICES

Stratification of the regional flood index record according to ENSO classifications was made using the six-month October to March average of the Niño3 index (Kiem & Franks, 2001). 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.*, 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. Fig. 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) between

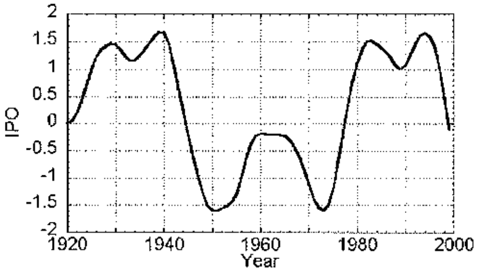

Fig. 1 The Inter-decadal Pacific Oscillation (IPO) from 1920 to 1999.

1924–1943 and 1979–1997, and a negative phase (IPO < –0.5) from 1946–1976. These phases exclude the 10 years from 1958–1967 when the absolute value of the IPO index was less than 0.5.

RESULTS

The stratified data were then subjected to a Bayesian flood frequency analysis in order to properly account for parameter uncertainty (Kuczera, 1999). To assess the role of ENSO extremes Fig. 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 significant statistical difference between the two ENSO extremes. Although not shown in Fig. 2 for the sake of clarity, the flood frequency distribution associated with neutral ENSO events lies between the two extremes.

Given the clear role of La Niña events in flood risk identified in Fig. 2, to test 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 (< –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 in the negative under IPO phase is markedly higher than the flood frequency associated with all other La Niña events.

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 inter-annual ENSO events. Figure 4 shows the flood frequency curves for IPO negative 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.

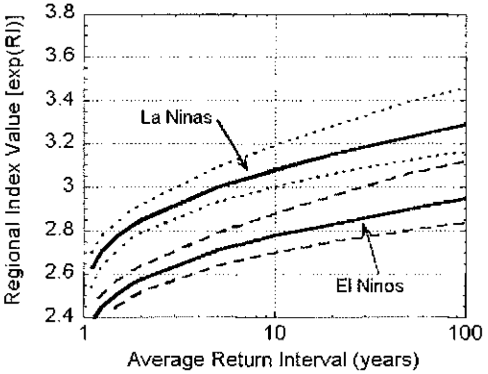

Fig. 2 Log-normal expected quantiles and their 90% probability limits (dashed lines) for the regional index under El Niño and La Niña conditions.

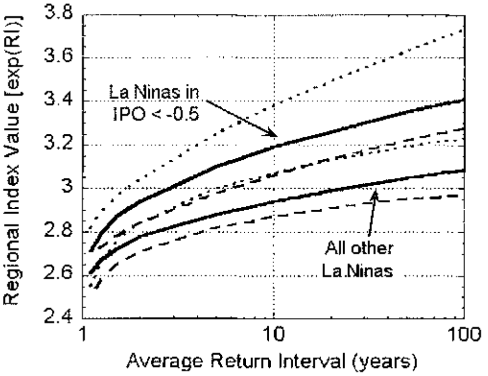

Fig. 3 Log-normal expected quantiles and their 90% probability limits (dashed lines) for the regional index under La Niña conditions during the negative IPO phase and La Niña conditions during non-negative IPO phases.

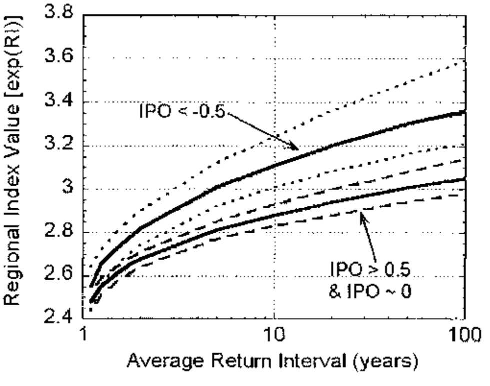

Fig. 4 Log-normal expected quantiles and their 90% probability limits (dashed lines) for the regional index under the negative and non-negative IPO phases.

Analysis of ENSO event frequency under different multi-decadal IPO phases

Given the strong control on flood risk exerted by La Niña events and modulated in their magnitude by multi-decadal 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 and 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 1924–1943 denoted IPO > 0.5 (1) and 1979–1997 denoted IPO > 0.5 (2)).

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. Kiem *et al.* (2003) tested the statistical significance of the dependence of ENSO event frequency on IPO phase using a simple test of proportions with Table 2 showing the results obtained when the probabilities 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 in a different IPO phase. It was found that when the

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

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*

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. No significant difference was found between the two positive IPO phases for the rate at which either El Nino, La Nina or Neutral events occur.

It is therefore apparent from these results that the IPO negative phase, representing cool anomalies in the mid-latitude 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.

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.

CONCLUSIONS

This paper has sought to explain the temporal changes previously observed in NSW flood risk over the period 1924–1999. 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 multi-decadal processes may modulate the frequency of ENSO extremes as well as the magnitude of their impact. There are a number of important implications associated with these insights:

- 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.
- 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.
- 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. Indeed, preliminary results indicate similar multi-decadal variability in drought risk (Kiem & Franks, 2003).

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 artefact of the ocean–atmosphere system, or forced by external variations in ultraviolet irradiance (Latif & 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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