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Multidecadal variability in coastal eastern Australian flood data

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Abstract
This study examines the applicability of the assumption in flood frequency analysis that flood peaks are independent and identically distributed. It investigates the effect and extent of multidecadal variability for mainly coastal, eastern Australian flood data. The Interdecadal Pacific Oscillation (IPO) is a climate index which describes this long-term variability. The flood data were stratified by IPO value and flood frequency analyses performed. Analysis of the stratified flood distributions revealed that the IPO modulated the flood risk in New South Wales and southern Queensland, with flood quantiles being increased by a factor of approximately 1.7 during IPO negative periods, whereas little effect was detected for sites in north-east Queensland located approximately north of the Tropic of Capricorn. This IPO modulation of flood risk may be explained by multidecadal movements of regional convergence zones. Neglect of the IPO dependence on flood risk can lead to significant bias in long-run flood risk.

Key words: flood frequency analysis, decadal variations, Interdecadal Pacific Oscillation (IPO), Pacific Decadal Oscillation (PDO), nonstationarity

1 Introduction
A basic assumption of flood frequency analysis (FFA) is that flood peaks are independent and identically distributed (iid). However, recent studies have questioned the validity of this assumption with evidence showing the existence of more than one distribution within Australian flood data, especially

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for New South Wales (NSW). Franks and Kuczera (2002) stratified the NSW flood record into pre- and post-1945 datasets and showed that the post-1945 dataset had an elevated 20-year flood risk over the pre-1945 dataset for 37 of the 41 sites analysed. Also, Erskine and Warner (1988) showed that coastal rivers of NSW exhibit alternating periods of high and low flood activity, which they denoted flood- and drought-dominated regimes respectively. The duration of these regimes varied between 30 and 50 years, with the flood regime being characterised by significantly more, and usually larger, floods than the intervening drought regime.

Power et al. (1999) showed that the association between El Niño/Southern Oscillation (ENSO) and Australian climate is modulated by the Interdecadal Pacific Oscillation (IPO), a climate index which uses a lowpass filter to high-light multidecadal sea surface temperature (SST) anomalies. A strong association was found between the magnitude of ENSO impacts during negative IPO phases, whilst positive IPO phases showed a weaker relationship. Kiem et al. (2003) analysed NSW flood data, using a regional flood index, stratifying the data based on IPO value. They found that the IPO modulated both the magnitude and frequency of ENSO events (El Niño and La Niña) resulting in multidecadal periods of elevated and reduced flood risk. In particular, they showed that La Niña events were the primary drivers of flood risk and that this was further enhanced under negative IPO phases. Furthermore, Verdon et al. (2004) examined the influence of ENSO and IPO on mean rainfall and streamflow in eastern Australia, using seasonal (September to January) totals. Both rainfall and streamflow were found to be significantly enhanced during the La Niña phase of ENSO. On multidecadal scales, the negative IPO phase was associated with ‘wetter’ conditions than the positive phase. Also, the magnitude of La Niña events was found to be further enhanced during the negative phase of the IPO.

This study will further examine the applicability of the iid assumption in FFA by investigation of the effect and extent of multidecadal variability — that is, the IPO modulation of flood risk — for eastern Australia flood data. Specifically, it investigates the evidence of IPO dependence at individual gauged sites and explores the northern, or tropical, extent of IPO dependence on flood risk. The IPO index is first described, and then the data and methodology are summarised. The results are then presented and discussed.

2 Interdecadal Pacific oscillation (IPO) index

The IPO is the coherent pattern of SST variability occurring on interdecadal time scales over the Pacific Ocean (Folland et al., 1999; Power et al., 1999; Allan, 2000). It is characterised by the third empirical orthogonal function of
Fig. 1. Annual IPO index time series.

13-year lowpass filtered global SSTs (Folland et al., 2002). Note that the IPO has a similar time series to that of the Pacific Decadal Oscillation (Mantua et al., 1997), which is derived using principal component analysis of North Pacific Ocean SSTs. In fact, both indices displayed marked multidecadal variability associated with the warming and cooling epochs exhibited in both Pacific and global temperature records (Franks, 2002, 2004).

The IPO annual time series is presented in Fig. 1 and represents an average of four seasonal values. Note that the time series reveals extended epochs above and below the long-term average. Also, due to the smoothing process, there is some ambiguity about the final few years of the IPO dataset.

3 Data and methodology

Annual maximum flood data from the Australian states of NSW and Queensland (Qld) were used in the study. The NSW data was obtained from the NSW Department of Land and Water Conservation Pineena database (Department of Land and Water Conservation, 2000), while the Qld data was provided directly by the Qld Department of Natural Resources and Mines (Hans Mulder, 2004, personal communication). Error checking was performed, including an independence check. The yearly peak flows were extracted using a water year from April to March, which corresponds to the typical ENSO cycle.

A total of 94 sites were analysed, with Qld having 52 sites and NSW 42 sites. The locations of the sites are shown in Fig. 2, along with the approximate location of the Great Dividing Range. Note that few sites are located to the west of the Great Dividing Range (see Fig. 2) due to the lower rainfall regime and consequent lower stream gauging density. The sites west of the Divide were selected such that they were not influenced by extensive floodplains — flood-
plain storage can attenuate flood peaks resulting in a decrease of discharge with **increasing catchment area**. The sites within Qld are minimally affected by regulation, while some of the NSW sites — mostly in western NSW — are situated on regulated rivers. A comparison (not shown) of analyses performed using both the regulated and unregulated sites and the unregulated sites only yielded similar results. Hence, the regulated sites were retained for this study, providing additional coverage within NSW. The spatial coverage of sites is considerable. Indeed, the latitudinal extent ranges from about 11° to 38° south, with the climate varying from tropical in northern Qld to alpine in the Snowy Mountains of southern NSW.

The flood frequency analysis was performed using the FLIKE software (Kuczera, 1999). FLIKE performs a Bayesian flood frequency analysis and provides accurate estimates of expected probability design floods and confidence limits. It supports many commonly used flood distributions — lognormal, log Pearson III, Gumbel, GEV, and generalised Pareto.

The Pinneena (NSW) data consists of a mixture of daily-read and true peak discharges (Micevski et al., 2005). A daily-read discharge is a discharge associated with a specific reading time — river levels, and thus discharges, were manually recorded at, typically, 9 am (Department of Land and Water Con-
Fig. 3. Histograms of record length for both IPO epochs.

Table 1
Summary of record lengths.

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Number of flows (years)</th>
<th>mean</th>
<th>sd</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPO-</td>
<td>23</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>IPO+</td>
<td>30</td>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>

This results in an underestimate of the true peak discharge because it is most unlikely that the true peak occurred at exactly 9 am. The true peak discharges were derived either from multiple observations during flood events or from continuous (fixed interval) readings. Note that most sites have had continuous readings since the early 1970s. In contrast, the Qld data consists almost entirely of true peak discharges and, so, contains few daily-read discharges. The magnitude of the errors associated with daily-read flows can be quite large. However, under normal circumstances, their impacts within flood frequency analysis have been shown to be minimal (Micevski et al., 2005). Thus, the daily-read discharges were treated as true peak discharges for this study.

The peak flows were stratified according to IPO value. The threshold used was an annual average IPO value of zero. Years that have an IPO > 0 belong to the IPO positive (IPO+) epoch. Likewise, years with IPO < 0 belong to the IPO negative (IPO-) epoch. Note that the ambiguity in IPO values would only result in the last few years possibly being misclassified into the wrong IPO epoch. This is considered to have minimal effect on the results. Fig. 3 presents a histogram of record length for each IPO epoch, while Table 1 presents statistics on the record lengths. The records lengths up to 25 years are dominated by Qld data, indicating that the Qld record length is, on average, shorter than that of NSW. Also, the IPO+ epoch has a longer record length than the IPO- epoch. Finally, note that a minimum record length of 10 years has been used in the analyses.
Fig. 4. A typically good lognormal fit to the IPO stratified data. Mean quantile and 90% probability limits are also shown.

Fig. 5. A poor lognormal fit to the IPO stratified data, with flattening in the right-hand tail.

4 Results

The datasets of peak flows, stratified according to IPO value, were fitted using the lognormal distribution. The majority of analyses demonstrated a good lognormal fit to the data — about 10% to 20% of analyses showed a poor fit with one or more observations lying outside the 90% limits and/or a flattening in the right hand tail of the distribution. Examples of good and poor fits are presented in Figs. 4 and 5 respectively. Overall, the lognormal distribution was deemed adequate. Note that when flood data are not stratified, the typical distribution used in Australia is the (three parameter) log Pearson 3.

The ratio of the fitted flood quantiles during IPO- periods to the fitted flood quantiles during IPO+ periods (‘flood ratio’) was calculated for several average recurrence intervals (ARIs), where the ARI is considered the reciprocal
Table 2
Summary of flood ratios.

<table>
<thead>
<tr>
<th>ARI</th>
<th>Flood ratio</th>
<th>mean</th>
<th>sd</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.49</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.46</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.47</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1.50</td>
<td>0.67</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6. Histograms of flood ratios for several ARIs.

of the annual exceedance probability. The flood ratios are summarised in Table 2 and histograms of the flood ratios are presented in Fig. 6.

Fig. 6 shows that the flood ratio is below one for between 11% and 27% of sites, depending upon the ARI selected; that is, between 73% and 89% of sites have a flood ratio > 1. Also, approximately 40% of sites have a flood ratio > 1.5. This indicates a significant difference between the IPO+ and IPO- epochs because these differences would not likely come about by chance alone. Indeed, Monte Carlo studies have shown that if the two IPO epochs were identically distributed, then about 50% of sites would have a ratio < 1. Moreover, the probability of a ratio > 1.5 at any site is approximately 0.1 (Franks and Kuczera, 2002, Fig. 7). Using the binomial distribution, the probability of 38 or more sites out of 94 having a ratio > 1.5 is well below the 0.1% level (about $10^{-14}$), under the iid assumption. This result assumes that the sites are not spatially correlated, which is not the case. Nonetheless, it still provides strong evidence that the flood distributions are not identically distributed between the two IPO epochs, especially after consideration of Table 2 which shows that the mean ratio is about 1.5.

The analysis was repeated with the minimum record lengths ranging from 15 to 25 years, with the results summarised in Table 3. Similar results to Table
Table 3
Summary of results for varied minimum record lengths (averaged over ARIs 2, 5, 10, and 20 years).

<table>
<thead>
<tr>
<th>Min. record length</th>
<th>No. of sites</th>
<th>Proportion of sites ratio &lt; 1</th>
<th>Proportion of sites ratio &gt; 1.5</th>
<th>No. of sites with ratio &gt; 1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>64</td>
<td>0.15</td>
<td>0.4</td>
<td>26</td>
</tr>
<tr>
<td>20</td>
<td>39</td>
<td>0.10</td>
<td>0.5</td>
<td>20</td>
</tr>
<tr>
<td>25</td>
<td>31</td>
<td>0.05</td>
<td>0.5</td>
<td>16</td>
</tr>
</tbody>
</table>

![Graph showing relationship between 10-year flood ratio and catchment area.](image)

Fig. 7. Relationship between 10-year flood ratio and catchment area.

2 and Fig. 6 were found, with the varied minimum record lengths yielding binomial probabilities of about $10^{-10}$ for encountering the number of observed sites having a ratio $> 1.5$. This suggests it is highly unlikely that sampling error is responsible for the observed IPO effect.

The graph of the 10-year flood ratio against catchment area is presented in Fig. 7. There appears to be no relationship present, with quite a large amount of scatter being displayed. This absence of scale dependence suggests that the IPO dependence of flood risk is a regional phenomenon independent of catchment area.

In contrast, a strong relationship is uncovered upon examination of the spatial distribution of the flood ratios. Fig. 8 presents a plot of the 10-year flood ratio as a function of latitude, while Fig. 9 shows the spatial distribution of the flood ratios. The figures show that the flood ratio increases when moving southward through Queensland, with the largest flood ratios occurring in southeast Queensland and northeastern New South Wales. The flood ratio is relatively constant throughout New South Wales. An interesting feature is the apparent clustering of ratios in Fig. 8. The majority of the flood ratios $< 1$ occur north of latitude $22^\circ$ south, while all but two flood ratios $> 1.5$ occur south of this latitude. Additionally, as shown in Fig. 8, the mean flood ratios for sites north and south of this latitude are 1.0 and 1.7 respectively.
Fig. 8. Relationship between 10-year flood ratio and latitude.

Fig. 9. Spatial distribution of the 10-year flood ratio.

Coincidently, this latitude is similar to that of the Tropic of Capricorn (23.5 degrees).
The effects of the IPO on eastern Australian rainfall and climate are poorly understood. Arblaster et al. (2002) have offered some physical reasons for the effects of the IPO on Australian rainfall, based on the results of a single climate model. The interdecadal SST variations may affect convection in the equatorial Pacific Ocean leading to shifts in the rising branch of the Walker circulation, which may then influence ENSO’s effect on Australian rainfall. Also, there may be increased (atmospheric) subsidence over Australia, i.e. lower rainfall, resulting from an anomalous regional Hadley circulation that may form above the warmer, western Pacific SSTs.

An interpretation of the results may also be offered in terms of the movement of the regional convergence zones. Salinger et al. (1995) demonstrated that changes in the location of the South Pacific Convergence Zone (SPCZ) are responsible for relatively large changes in rainfall in the Southwest Pacific, about its mean position. The SPCZ is disrupted by El Niño (warm) events that prevent it from reaching its normal southerly position. La Niña (cool) events enhance the SPCZ, allowing it to move further south than normal (Salinger et al., 1995), delivering more rain-bearing cloud bands across eastern Australia. The IPO has been shown (Folland et al., 2002) to be associated with the location of the SPCZ in a similar manner to ENSO, except on multidecadal timescales. Whilst the SPCZ does not directly affect rainfalls in NSW, the SPCZ is related to the Intertropical Convergence Zone (ITCZ), which influences eastern Australian rainfalls. It is therefore expected that the IPO will have a marked effect on the location of the ITCZ, similar to that on the SPCZ, and thus explaining how New South Wales and the southern parts of Queensland generally experience greater rainfall (and discharge) during IPO- periods. Note, however, that the northern part of Queensland is not affected by this multidecadal variability because, despite changes in the location of the ITCZ, it nonetheless remains under the ITCZ’s influence.

The results show that the flood risk can be increased quite significantly during IPO- periods, except for sites in northern Queensland. Fig. 10 shows two flood series stratified into IPO+ and IPO- epochs, along with the average annual peak discharge during each IPO epoch. The top panel shows a site in northern Queensland with a flood ratio of about 1.1. The IPO epochs have mean flows of 10.9, 11.7, and 9.3 GL/day, which indicates a fairly homogeneous time series. In contrast, the bottom panel presents a site in northeastern NSW that has a flood ratio of about 1.6. The IPO epochs have mean flows of 73.0, 143.7, and
Fig. 10. Flood series showing IPO stratifications and average discharges. Top panel is site 110003A (flood ratio $\approx 1.1$) and bottom panel is site 204001 (flood ratio $\approx 1.6$).

80.2 GL/day, which illustrates a strong influence on flood risk related to the IPO phase.

A similar pattern of modulation of flood risk would be expected to continue further south into the state of Victoria. However, the effect of this modulation (ie. the flood ratio) would be smaller than that observed in NSW due to the reduced ENSO impacts within Victoria. In general, the IPO modulation of flood risk should be expected in ENSO-affected areas because the IPO modulates both the magnitude and the frequency of ENSO events (Kiem et al., 2003; Kiem and Franks, 2004).

It is important to recognise the practical significance of IPO modulation of flood risk. The use of at-site flood data with an inadequate coverage of both IPO epochs may result in biased estimates of long-run flood risk. For example, Table 4 shows that using flood data from an IPO+ period would likely lead to a large underestimate of the long-run (marginal) flood risk for the bottom site in Fig. 10; whereas a relatively unbiased estimate should be obtainable for the top site in Fig. 10 using just IPO+ data. In cases with inadequate coverage of one of the IPO epochs, the prospect of significant bias in long-run flood risk is high. It therefore may be necessary to use a regional flood frequency distribution that has been obtained from a dataset containing sufficient samples from both IPO positive and negative periods to augment the limited at-site data — this
Table 4
Discharges corresponding to various ARIs for both IPO epochs.

<table>
<thead>
<tr>
<th>Site</th>
<th>ARI (years)</th>
<th>Discharge</th>
<th>IPO-</th>
<th>IPO+</th>
</tr>
</thead>
<tbody>
<tr>
<td>110003A</td>
<td>2</td>
<td>74</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>188</td>
<td>178</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>306</td>
<td>280</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>458</td>
<td>408</td>
<td></td>
</tr>
<tr>
<td>204001</td>
<td>2</td>
<td>77</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>176</td>
<td>117</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>271</td>
<td>171</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>387</td>
<td>234</td>
<td></td>
</tr>
</tbody>
</table>

is the focus of current research and will be reported elsewhere.

6 Conclusion

It has been shown that the IPO modulates the flood risk within parts of eastern Australia. Sites in eastern New South Wales and southeastern Queensland have a flood quantile about 1.7 times greater during IPO negative periods than during IPO positive periods (for ARIs ranging from 2 to 20 years). Northeast Queensland sites show little IPO modulation of flood risk. Decadal-scale movements of regional convergence zones may explain this IPO modulation of flood risk.

Though this study is somewhat limited by the geographic coverage of the data, its findings are, nonetheless, of considerable practical importance because the study area encompasses a significant proportion of the Australian population and associated infrastructure. If long-term flood risk is estimated using at-site data with poor coverage of one of the IPO epochs, then it is likely that flood risk will be significantly biased.

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