Understanding and adapting to flood risk in a variable and changing climate

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Abstract Flooding over the last three years in various parts of eastern Australia, following more than a decade with very little flooding, has highlighted the fact that the risk of flooding is not the same from one time period (e.g. season, year, or decade) to the next and that traditional assumptions of hydroclimatic stationarity are invalid. Compounding this is the potential for non-stationarity in flood risk due to projected impacts of anthropogenic climate change. That is, under projected global warming the resulting changes to ocean–atmospheric circulation patterns are likely to lead to shifts in the location, magnitude and frequency of extreme precipitation events and the associated flooding. Therefore it is clear that "stationarity is dead" and that work is urgently required to: (a) re-evaluate current (or baseline) flood risk estimates to take into account the influences of natural climate variability, (b) develop estimations of future flood risk that take into account both the role of natural climate variability and the projected impacts of anthropogenic climate change, and (c) develop positive adaptation strategies and policy frameworks based on these re-evaluated (and more realistic) flood risk estimates. This study concentrates on the first task (re-evaluation of baseline flood risk estimates) by quantifying inter-annual to multi-decadal variability of flood risk in eastern Australia. Climate variability and climate change both play an important role in influencing flood risk but that role is not yet properly understood or quantified. In order to move towards a more resilient, well adapted world this paper addresses the fundamental, but as yet unanswerable, question of whether flood risk will increase or decrease by first understanding the mechanisms that cause flood risk to vary over time.

Key words non-stationarity; uncertainty; El Niño/Southern Oscillation (ENSO); Interdecadal Pacific Oscillation (IPO)

INTRODUCTION

Flooding is the most common natural hazard and third most damaging globally (after storms and earthquakes). For example, the average annual cost of flooding in Australia is estimated to be around $380 million (BITRE, 2008) with individual events responsible for billions of dollars worth of damage (e.g. the flooding associated with the 2008 Pasha Bulker storm in Newcastle caused $1.5 billion worth of insurance damages; the 2011 Brisbane flood had a damage bill exceeding $4 billion; early estimates suggest the January 2013 floods will cost at least $3 billion in Queensland alone). Furthermore, globally the value of infrastructure devoted to flood prevention or mitigation runs into the hundreds of billions of dollars, comprising stormwater drainage infrastructure, bridges, levees, coastal defence infrastructure, spillways, reservoirs devoted to flood detention, etc. However, for most locations, we do not really know what the true risk of flooding is and cannot answer the fundamental question of whether flood risk will increase or decrease in the future (let alone by how much). As a result most flood preparation and management strategies are inadequate – a point graphically demonstrated by the seriousness of the impacts associated with the flooding events seen recently (e.g. Australia over the last three years, North India (Uttarakhand) in June 2013, Norway in May 2013, Russia in 2012, Pakistan in 2010, Bangladesh in 2010, etc.).

Robustly estimating the risk of flooding is a major ongoing challenge due to the marked spatial and temporal variability of the hydro-climatic processes that drive flooding. 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 time period (e.g. year or season) to the next. That is, there is an assumption that hydro-climatic extremes are independent and identically distributed (IID) (also known as the stationarity assumption) and physical climate and hydrological mechanisms that actually deliver climate extremes are not taken into account. Despite the development of rigorous frameworks to assess the uncertainty of risk estimates, the assumptions of stationarity underlying these frameworks mean the resulting flood risk estimates are flawed (as are the resulting flood management, engineering design and infrastructure development) (e.g. Franks & Kuczera, 2002; Franks, 2002a,b; Kiem *et al.*, 2003, 2006; Milly *et al.*, 2008).

Existing flood risk estimation techniques do not acknowledge the possibility of distinct periods of elevated or reduced risk. This is despite the fact that numerous studies (e.g. Franks & Kuczera, 2002; Kiem *et al.*, 2003; Micevski *et al.*, 2006; Pui *et al.*, 2011) have established that flood risk does in fact change over time and that the existence of multi-decadal epochs of enhanced/reduced flood risk in historical records is strongly related to large-scale ocean-atmospheric circulation patterns such as the El Niño/Southern Oscillation (ENSO) and Interdecadal Pacific Oscillation (IPO, Power *et al.*, 1999). Compounding the issues associated with non-stationarity of flood risk due to natural climate variability are the potential changes to flood risk in the future due to:

(i) Impacts of anthropogenic climate change (e.g. changes to the location, duration, magnitude, frequency, timing of extreme weather events) (e.g. Milly *et al.*, 2008; Westra, 2011; Westra *et al.*, 2012);

(ii) A return to some pre-instrumental (palaeo) climate epoch where the behaviour of large-scale climate drivers (e.g. ENSO etc.) that drive hydroclimatic variability is different to what is contained in the instrumental record (e.g. Verdon & Franks, 2006; Verdon-Kidd & Kiem, 2010; Vance *et al.*, 2012);

(iii) Changes to hydrological catchment conditions (e.g. land-use change, increased/decreased wetness, changes to topography due to, for example, erosion and mining);

(iv) Other human activities which increase exposure (e.g. population increase, development approvals in flood plains and construction of dams or levees).

Further complicating the issues listed above is the fact that current assessments of climate change impacts on flooding rely on hydrological models calibrated against historical conditions with stationary model parameters. Given the potential changes mentioned above, a false sense of precision (and accuracy) is associated with simulations of future hydrological conditions that emerge from such a modelling methodology. In short, the realisation that the risk profile of extreme events changes over time provides a fundamental challenge to decision makers across all levels of government and private industry (e.g. properties or assets which are currently not considered flood prone may become so in the future, or *vice versa*). Such realities require a change from current best practice that assumes flood risk is stationary (i.e. the same from one time period to another).

To address these challenges, a paradigm shift is required that accepts and accounts for the nonlinear and non-stationary nature of the hydroclimatic processes that drive flooding (e.g. Kiem *et al.*, 2003; Blöschl & Zehe, 2005; Wagener *et al.*, 2010; Kiem & Verdon-Kidd, 2011). Also needed is an increased awareness of the fact that while climate model projections can be useful they are also associated with significant uncertainties, some of which are likely to be irreducible (e.g. Stainforth *et al.*, 2007; Koutsoyiannis *et al.*, 2008, 2009), and all of which are amplified when used as inputs to hydrological modelling and other impact assessments (i.e. the concept of cascading uncertainty, e.g. Jones, 2000; Blöschl & Montanari, 2010). Hence, innovative methods are also required that robustly quantify the uncertainties involved and support decision making under uncertainty (e.g. Brown *et al.*, 2011; Brown & Wilby, 2012; Kiem *et al.*, 2013) as opposed to the current situation which sees many decision makers delaying action on adaptation and risk planning with the expectation that uncertainties in climate change information will be reduced (e.g. Risbey & O'Kane, 2011; Verdon-Kidd *et al.*, 2012) – a situation which may not happen or may occur only after the optimal time for action has passed.

This study, using eastern Australia as a case study (Fig. 1), concentrates on the fundamental first step of this paradigm shift, the re-evaluation of baseline flood risk estimates in the light of inter-annual to multi-decadal climate variability.

DATA AND METHOD

The streamflow data used in this study were obtained from the PINEENA database, developed and managed by the NSW Office of Water. Forty records spanning 1924 to 2009 were deemed

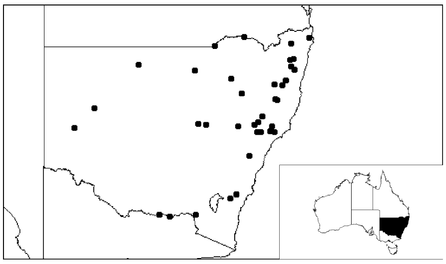

Fig. 1 Study area – eastern Australia.

suitable in terms of the length and continuity of record (see Fig. 1 for station locations and Kiem *et al.* (2003) for further details). Initially, to avoid the issue of spatial correlation, Kiem *et al.* (2003) collapsed the 40 flood records into a single annual maximum regional (i.e. NSW) flood index (RI) following Franks (2002b). The RI indicates the ratio of each annual maximum flood to the long-term mean annual maximum flood averaged across the NSW study region. Therefore an RI greater than one indicates a maximum flood event that is worse than the historical average. The RI was then stratified into El Niño, La Niña, and neutral categories based on the magnitude of the 6-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 and location being investigated (Kiem & Franks, 2001).

Multi-decadal variability of flood risk is investigated by stratifying the RI according to the value of the IPO. The 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). In classifying the different IPO phases, the method of Power *et al.* (1999) was used. That is, thresholds of ±0.5 are used to distinguish positive, neutral and negative IPO phases. During the study period there have been three major IPO phases: two positive phases (IPO > 0.5) from *c.* 1920 to 1943 and *c.* 1977 to 2005 and a negative phase (IPO < –0.5) from *c.* 1945 to 1976.

RESULTS

To illustrate the relationship between floods in eastern Australia and inter-annual to multi-decadal variability, Fig. 2 shows, for the NSW RI, the historic flood frequency curves associated with: (a) the El Niño and La Niña extremes and (b) La Niña events that occur when the IPO is negative *versus* all other La Niña events. Figure 2(a) 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 across NSW) is approximately 17% (ARI between 5 and 6 years) if it is an El Niño year compared with >76% if it is La Niña (ARI approximately 1.3 years) – implying that nearly all La Niña events will be associated with an above average annual maximum flood event somewhere in NSW. Also strikingly apparent from Fig. 2(a) (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 almost five 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).

From Fig. 2(b) 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 (and illustrated in Fig. 2(a)) 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% greater than the average annual maximum flood) is approximately 4% (ARI approx.

25 years) during non-negative IPO La Niña compared with greater than 33% during IPO negative La Niña. Note that during El Niño events the PO for an annual maximum flood with RI equal to 1.1 is less than 0.3%. Figure 2(b) also 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 grey line) is more than 12 times greater than traditionally estimated during IPO negative La Niña events (ARI of 100 compared with ARI of approx. 8 years for the equivalent flood during IPO negative La Niña years) implying a significant underestimation of risk currently exists.

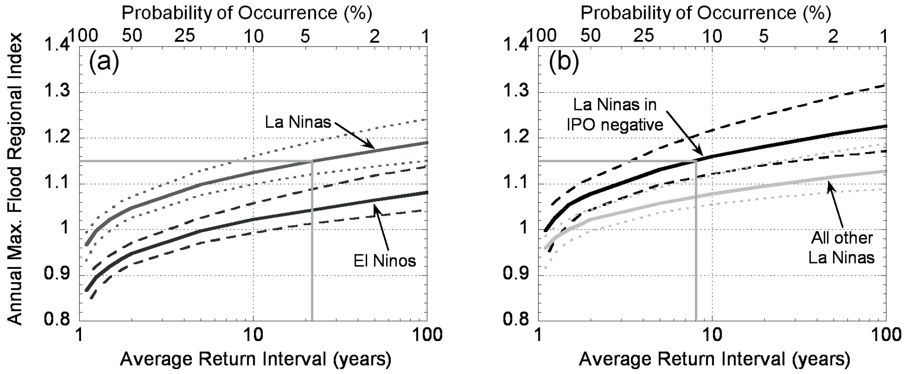

Fig. 2 Regional flood frequency curves under (a) El Niño and La Niña conditions and (b) La Nina events under IPO negative conditions and all other La Niña events. Dashed lines indicate 90% confidence intervals. Horizontal grey line indicates the magnitude of the "1 in 100 year flood" calculated using all years (i.e. under the traditional assumption that flood risk is the same from year to year – see Fig. 3).

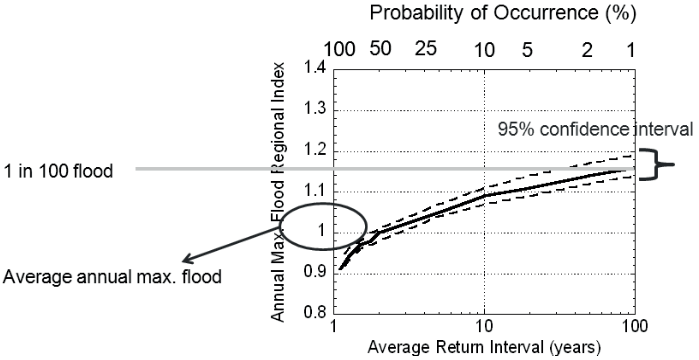

Fig. 3 Regional flood frequency curves based on NSW streamflow from 1924 to 2008 (i.e. using all years and a stationary climate assumption).

Also important to note is that despite rigorous frameworks to assess the uncertainty of risk estimates (e.g. FLIKE as per Kuczera, 1999), if climate variability (and change) is not taken into account the bounds of uncertainty do not accurately capture the true risk in certain climate epochs. For example, if stationarity is assumed and the regional flood frequency curves are calculated using all data (see Fig. 3) a 1-in-100 year flood equal to 1.2 on the y-axis (i.e. 20% greater in magnitude than the average annual maximum flood) would be considered statistically unlikely (i.e. outside the 95% confidence interval on Fig. 1). However, during a La Niña event a 1-in-100 year flood equal to or greater than 1.2 is definitely within the realms of possibility (Fig. 2(b)) and a large flood (beyond what was considered possible under the assumption of stationarity) is more likely than not if it is an IPO negative La Niña (Fig. 2(b)) – this is very much in line with recent experiences where both the 2010/2011 and 2011/2012 eastern Australian floods were associated with IPO negative La Niñas (as were other major floods before that in 1974 and 1893).

DISCUSSION

Climate variability and climate change both play an important role in influencing flood risk but that role is not yet properly understood or quantified. In order to move towards a more resilient, well adapted world this paper addresses the fundamental, but as yet unanswerable, question of whether flood risk will increase or decrease by first demonstrating that flood risk has varied and will continue to vary over time and second, by attempting to better understanding the mechanisms that cause this non-stationarity in flood risk.

The results demonstrate that natural climate variability plays a major role in determining flood risk, at least for eastern Australia. The fact that individual ENSO events can be detected at least 6 months prior to their consequent peak impact periods and that IPO epochs generally persist for at least a decade means that significant insight can be gained into the forthcoming season or year, enabling adaptive management decisions to be made, and damage minimization procedures to be put in place, before the period of elevated flood risk. Such climate risk management strategies, based on insights gained through extensive research into ENSO and other climate processes, are routinely applied in, for example, agriculture (see Meinke *et al*., 2005, for a useful overview).

These results also 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 indicate that for eastern Australia, La Niña years are associated with enhanced flood risk and that this risk is further elevated when the IPO is negative. 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 observations where multi-year periods of high magnitude flooding exist (e.g. for eastern Australia: 1890s, 1950s, 1970s, 2010/2011, 2011/2012) and coincide with La Niña and/or IPO negative conditions. Such non-stationarity of flood risk is statistically anomalous under traditional assumptions and therefore is not adequately accounted for in current flood risk management – nor are links between climate variability and flooding currently utilized to predict and prepare for periods when emergency flood events are likely to occur.

Floods are, and always will be, experienced in most countries and it is impossible to prevent these natural disasters from occurring or predict exactly where and when they will occur. However, adequate understanding of the mechanisms that cause enhanced risk periods, and the recognition that enhanced risk periods: (a) do and always will exist and (b) might be predictable up to 6 months in advance based on improved ENSO forecasting schemes, is essential to effectively manage and minimize the damage associated with floods when they do occur.

Finally, much focus has been (and is being) given to the issue of quantifying the impacts of anthropogenic climate change on flood risk and large amounts of time and money are being spent on developing adaptation plans to cope with future flood risk. Undoubtedly this is an important issue. However, it must be realized that a large proportion of flood risk is, and will continue to be, driven by natural phenomena and that a revision of flood risk estimates is urgently required that takes into account the results presented here and in previous work (e.g. Kiem *et al*., 2003, 2006; Micevski *et al*., 2006). Until baseline (i.e. existing) flood risk is robustly quantified to account for non-stationarity due to natural climate variability and until projections of the impact of anthropogenic climate change on future flood risk are put within the context of this existing risk, all work looking to develop adaptation strategies and policy to cope with flooding at some point in the future, based on projections from climate models that are extremely uncertain about future impacts on hydrological extremes (e.g. Kiem & Verdon-Kidd, 2011), is premature. Indeed, unless existing flood risk can be robustly quantified (i.e. to account for natural hydroclimatic variability) and adequately managed then it is questionable whether the tools even exist to deal with flood risk in a future that is projected to be associated with enhanced hydroclimatic variability (including increased frequency of extremes), higher tidal anomalies (due to increased sea-level rise and storm surge), and (in some coastal areas) continued land subsidence.

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