9 Flood and Drought Risk in Eastern Australia

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INTRODUCTION

Eastern Australia experiences extreme climate variability at a range of time scales, from seasonal-interannual through to multi-decadal and longer. This variability of climate has a marked consequence on the subsequent hydrological variability and extremes. In this chapter, traditional methodologies for monitoring and estimation of current and future flood and drought are assessed in the light of the IAHS Predictions in Ungauged Basins (PUB) initiative. In the first section, climate variability in eastern Australia is characterized according to the time scales of different climate modes known to affect eastern Australia. The subsequent section presents insight into variability of drought and flood risk as a function of climate variability. The final sections review flood risk estimation and drought monitoring techniques as evaluated from a hydrological perspective, and aim to provide some suggestions for improved hydrological representation of drought and flood risk in ungauged basins.

CHARACTERIZING AUSTRALIAN CLIMATE VARIABILITY

Global circulation and climate is a combination of both chaotic and persistent (non-chaotic) factors. Climate variability is best characterized according to the time scale of that variability, as below:

- inter-annual variability,
- decadal to multi-decadal variability,
- longer-term variability.

Whilst inter-annual climate variability such as enhanced and depleted seasonal rainfalls induced by the El Nino-Southern Oscillation (ENSO) are largely predictable, longer-term trends in climate are the result of complex interacting physical processes that are not well understood. The predictability of climate at characteristic timescales is elaborated below.

Inter-annual variability

Despite being identified some 80 years ago, hydrological research has only recently begun implementing the predictability of seasonal rainfall and runoff as a function of ENSO. The development of the extreme phases of ENSO (the “warm” El Niño and “cold” La Niña) can be predicted with some accuracy from three to nine months in advance. Once an extreme phase is initiated, the predicted impacts on rainfall across Australia are well known and largely reliable (in terms of the seasons affected and the degree of rainfall enhancement/depletion) (Simpson *et al.*, 1993; Chiew *et al.*, 1998; Kiem & Franks, 2001).

The marked dependence of both flood and drought risk on ENSO states indicates substantial potential benefits for managing preparedness and infrastructure through simple ENSO monitoring. More recent research has identified a further control on ENSO behaviour which modulates the predictability of rainfall and runoff as well as flood and drought risk, and is discussed in the following section.

Decadal to multi-decadal variability

Recent research has identified longer-term persistent anomalies in the Pacific Ocean which affect the strength of ENSO impacts across Australia. Two indices have been developed, termed the Pacific Decadal Oscillation, or PDO (Mantua *et al.*, 1997) and the Inter-decadal Pacific Oscillation (or IPO; Power *et al.*, 1999). These indices represent persistent anomalous warming and cooling of the Pacific Ocean, which in turn is related to the global warming/cooling trends observed over the 20th century (Franks, 2002a).

The IPO/PDO phenomenon affects both the predictability and impact of extreme ENSO phases across Australia. There is also evidence that the IPO states may also affect ENSO behaviour through modulating the frequency of La Niña events; during the IPO negative epoch, corresponding to cooling conditions in the Pacific Ocean, a substantial increase in the number of cold La Niña events is observed (Kiem & Franks, 2004; Kiem *et al.*, 2003). The net effect of the IPO modulation of ENSO is to produce decadal to multi-decadal epochs of elevated flood and drought risk. The developed IPO and PDO indices reveal that the persistent states (warm and cool) exist for average periods of about 10–30 years. Whilst the causal factors of this variability remain unidentified, their persistent nature means that some insight can be gained into expected climate variability over periods of up to 10–30 years, if only based on current state.

IPO-PDO impacts have also recently been identified in a number of regional climates across the globe (Allan, 2000; Dettinger *et al.*, 2000). Recent research has indicated that this multi-decadal variability of Pacific and global trends may be the result of chaotic interactions between the oceans and atmosphere, whilst other observers have noted the coherence of this signal to changes in solar forcing (Reid, 1991; White *et al.*, 1997; Franks, 2002a). Whilst the causal mechanisms of this mode of variability remain undefined, the effects have been substantial. Irrespective of mechanism (internal variability *vs* external forcing), this mode of variability is a re-occurring aspect of natural climate variability which places significant uncertainty on attempts to predict future climate over longer periods.

Longer-term climate

As noted earlier, climate at any given location is a singular result of the inter-play of many complex physical processes. Some of these processes are increasingly better understood. However, the causal physics behind the majority of climate processes are not. Attempts to predict the future climate are almost exclusively based on the use of General Circulation Models (GCMs), which purport to contain accurate descriptions of the physics of climate. These models do not accurately reproduce the modes of climate variability listed above. Furthermore, there are more fundamental deficiencies in GCMs that limit their utility as reliable predictors of future climate. These deficiencies include, but are not limited to, the descriptions of:

- the role of sea ice,
- cloud physics (formation, albedo effects, precipitation),
- land surface–atmospheric fluxes of energy and moisture,
- land surface–ocean fluxes (quantity, temperature, salinity),
- complex atmospheric photo-chemistry and solar–terrestrial interactions.

Given these and other uncertainties, contemporary GCM climate predictions are not reliable. GCMs should be viewed as interpretive and experimental tools, and not as predictive models. Whilst some uncertainties can be propagated through climate models, structural flaws (such as the absence of a key physical process) cannot be assessed, because GCMs are never rigorously tested as hypotheses. Contemporary GCMs cannot accurately reproduce the statistics of historic ENSO events; in a recent review, the GCMs simulated ENSO frequencies ranging from one per year to one every 15 years (Philander & Fedorov, 2003). Indeed the results from the CMIP (Coupled Model Intercomparison Project) indicated that the models could not provide realistic representation of historic ENSO variability. Moreover, the models did not show any robust change in ENSO behaviour under doubled CO_2 conditions associated with potential climate change scenarios (Collins, 2005). Given the strong dependence of the Australian climate on ENSO conditions and the observation of marked multi-decadal ENSO controls, it is clear that GCM-based scenarios for Australia and elsewhere are entirely uncertain.

ASSESSING THE ROLE OF ENSO AND IPO PROCESSES IN EASTERN AUSTRALIAN RAINFALL AND RUNOFF

Rainfall and streamflow are extremely variable across Australia. The quantification and understanding of climatological and hydrological variability is of considerable importance given the high degree of hydrological variability experienced in many parts of Australia as a function of ENSO. Furthermore, recent climatological studies have also revealed multi-decadal variability in the modulation of the magnitude of 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.

To evaluate the role of ENSO and IPO in hydrological variability, Verdon *et al.* (2004) analysed 182 raingauges and 152 streamflow gauges across Australia (Fig. 9.1). By simply stratifying the records according to standard El Niño/La Niña years, the enhancement of rainfall and streamflow under La Niña conditions could be assessed. Figure 9.2 shows the ratio of La Niña to El Niño summer season (Sep.–Jan.) rainfalls

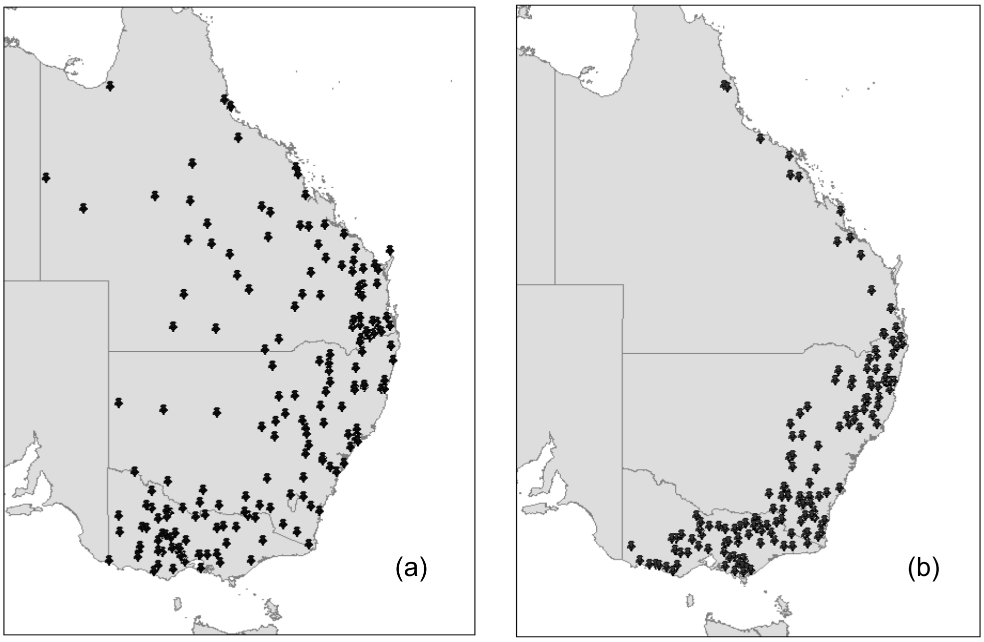

Fig. 9.1 *Long-term: (a) rainfall, and (b) runoff gauges, across eastern Australia.*

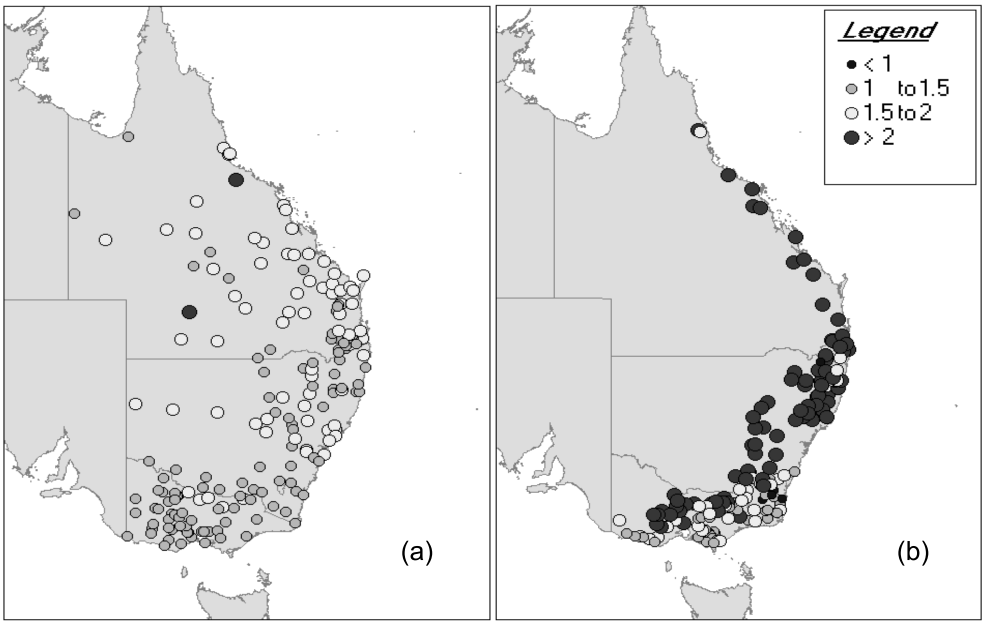

Fig. 9.2 *Spatial distribution of the ratio of La Niña to El Niño summer season (a) rainfall, and (b) runoff.*

and streamflow. Figure 9.2(a) shows that summer rainfall are consistently higher in La Niña events across all states. Figure 9.2(a) also shows that the greatest enhancement of rainfall occurs in the northern state of Queensland (with enhancement of 50–100%) whilst the southern states of New South Wales and Victoria show enhancement up to 50%. Figure 9.2(b) shows the corresponding enhancement of streamflow across eastern Australia. Importantly, the enhancement of streamflow is greater than that of rainfall due to the nonlinearity of runoff generating processes (typically >100% increase).

To evaluate the further enhancement of La Niña events due to the IPO negative state (1945–1975), the La Niña years where further stratified into negative and non-negative IPO categories. Figure 9.3 shows the ratio of IPO negative La Niña events to non-negative IPO events. Again, these figures show further enhancement of both rainfall and streamflow under negative IPO conditions. These results clearly demonstrate the key role of both ENSO and IPO processes in dictating summer season rainfall and runoff across eastern Australia. Such strong controls on hydrological variability imply potentially strong controls on extreme hydrological events such as floods and drought which are explored in the following section.

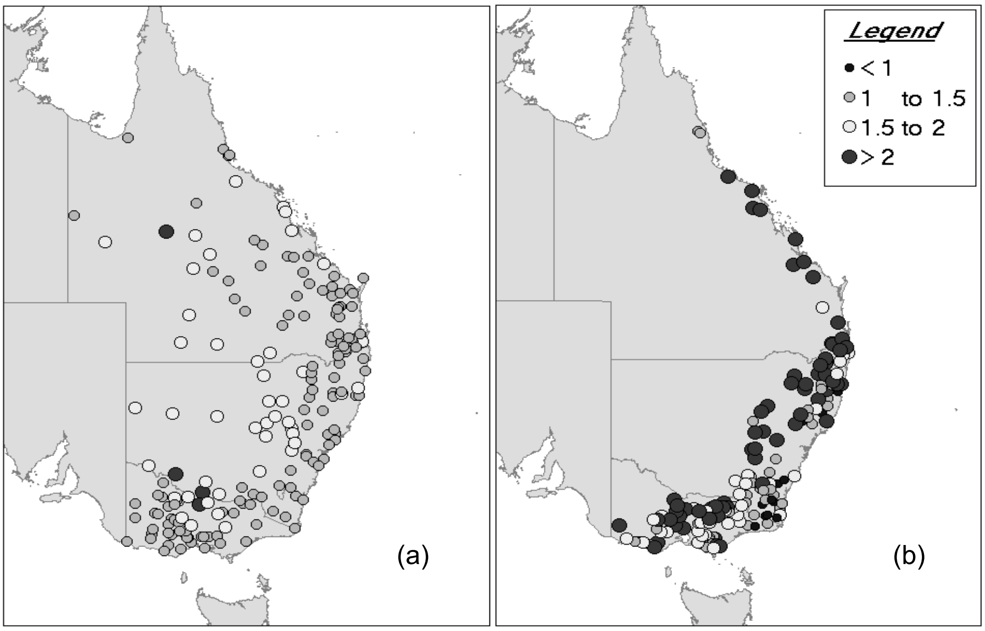

Fig. 9.3 *Spatial distributions of the ratio of IPO negative La Niña to all other La Niña summer season: (a) rainfall and (b) runoff.*

ENSO–IPO controls on 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 & 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 & Warner, 1988; Franks, 2002a; 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 (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 (Franks, 2002b). 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 ENSO phenomenon—given such teleconnections, extreme events are not independent but linked more or less directly to ENSO and other climate phenomena.

In terms of the 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 should vary according to ENSO state.

Assessing ENSO-IPO controls on flood frequency

To assess the role of ENSO and IPO extremes in dictating flood variability, a study by Kiem *et al*. (2003) stratified historic flood records according to ENSO-IPO climate states. Figure 9.4 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 Fig. 9.4, 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 and then according to La Niña events occurring under neutral and positive IPO phases. Figure 9.5 shows the resultant flood frequency curves; 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 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 9.6 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 clear, therefore, 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.

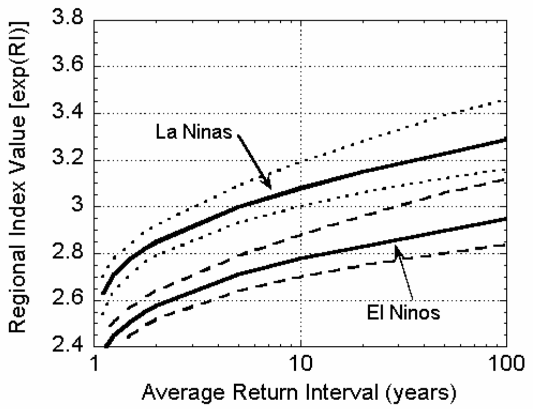

Fig. 9.4 *New South Wales regional flood frequency curves for El Niño and La Niña years.*

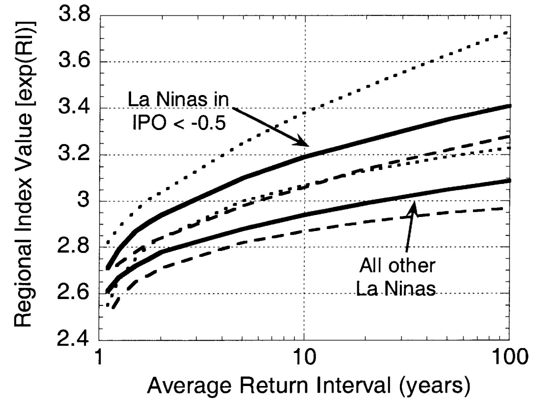

Fig. 9.5 *New South Wales regional flood frequency curves for IPO negative La Niña events compared to all La Niña.*

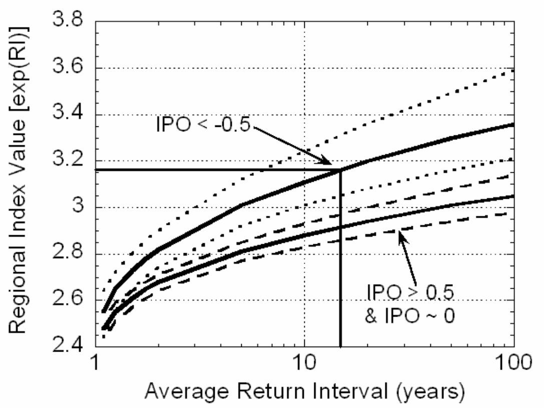

Fig. 9.6 *New South Wales regional flood frequency curves for negative and non-negative IPO epochs. Note that the solid line represents the 1-in-100 year flood as derived by traditional analysis.*

IPO controls on drought risk

The reservoir used here is the Grahamstown Reservoir which has been operating since 1963 and is located within the Williams River catchment near Raymond Terrace, New South Wales, Australia. In order to simulate the reservoir's performance in different climate states, one thousand replicates of 1000-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. 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 9.7 shows the average probability, and 90% confidence interval, of a critical event during the different IPO phases using the Hunter Water Corporation's (HWC) 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 Niño events and is significantly recharged due to enhanced and more frequent La Niña events. The non-negative IPO conditions are therefore higher drought risk periods due to infrequent and low magnitude-impact La Niña events. For more details, the reader is referred to Kiem & Franks (2004).

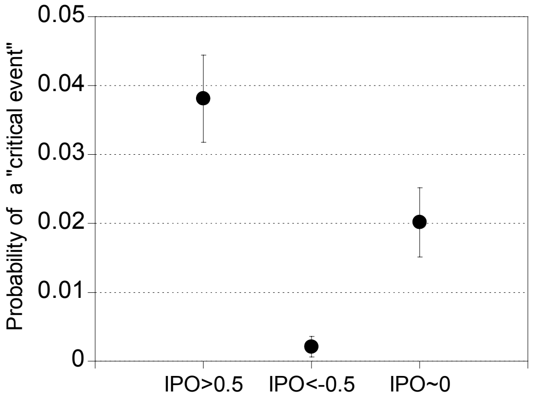

Fig. 9.7 *The probability of reaching a critical (<30%) event in Grahamstown Dam reservoir under different IPO states.*

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 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. the 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).

The ITCZ and SPCZ are most significant as they deliver rain-bearing cloud bands across eastern Australia. The ITCZ 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 & Franks, 2001). Warm El Niño events disrupt the ITCZ/SPCZ, preventing its propagation to its usual southern latitude. Cold La Niña events represent an enhancement of the neutral ENSO state, with the effect that the ITCZ/SPCZ propagates further south than normal, delivering more frequent rain-bearing cloud bands across southeast 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 time scale. Importantly, the results of Folland *et al*. (2002) showed that the SPCZ was at its southernmost during La Niña events under IPO negative conditions.

This provides strong corroborative evidence of the enhancement of La Niña 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 *et al*., 2003; Kiem & Franks, 2004).

FLOOD AND DROUGHT RISK ESTIMATION – IMPLICATIONS FOR CURRENT PRACTICE AND A ROLE FOR PUB?

The previous sections have elucidated the key climatological drivers of both flood and drought risk from seasonal-interannual timescales (as a function of individual ENSO events) through to multi-decadal time scales (as a function of the modulation of ENSO through the IPO). The key insight developed is that hydrological risk, on any timescale, is not the same from one year to the next—climatological variability at a range of time scales suggests that the traditional risk estimation practices, where annual maxima are assumed to be independent and identically distributed, are invalid in such cases. More significantly, the results indicate that if risk estimates are based purely on the available historic data without reference to the prevailing climate state, then the data may bias our risk estimates through inadequate sampling of long-term variability.

There is therefore a key question about current practice and the bias induced by available data as a function of when they were collected. This can be viewed as a key PUB question. In the majority of cases, data are not available for the quantification of flood and drought risk. Ungauged catchments obviously require some form of regionalization or transfer of risk estimates. However, the observation that long-term climate variability dominates the historic data where they are available indicates that even in gauged catchments, the data typically spanning 80–90 years at best, are not long enough to incorporate the full variety of climate variability. Indeed, most gauged catchments contain data that span just one IPO negative epoch and two IPO positive epochs, and hence represent just three samples of IPO state!

Clearly instrumental data need to be augmented with proxy series from palaeo-reconstructions if the substantial uncertainty associated with the IPO climate states is to be reduced. The necessity of seeking to augment existing instrumental records also necessitates a greater dialogue with hydro-geomorphologists who may be able to provide some historic measures of pre-instrumental flood history. An alternative approach would be to seek other measures of hydrological variability from the pre-instrumental period. One particularly interesting approach is to seek chemical signatures of catchment recharge fluxes within speleothems (stalagmites). Working in the Wombeyan caves underlying a key Sydney water supply catchment, McDonald *et al*. (2004) demonstrated that the dripwater in the caves could be directly related to recharge rates. This opens up the possibility of utilizing measured ratios of Mg and Ca, recorded through the growth of stalagmites, to provide an integrated measure of catchment recharge fluxes well beyond the instrumental record. PUB as an integrating initiative in hydrological research is ideally placed to facilitate the development of long-term records of hydrological variability, as well as providing a rationale basis for the regionalization of instrumental variability in space and time.

In addition to providing a framework for the integration and regionalization of alternative long-term measures of hydro-climatic variability, the PUB mission may also usefully contribute to the practical assessment of flood and drought assessment through the development of robustly regionalized hydrological models. In the following sections, contemporary practice in flood and drought assessment are reviewed, with the aim of identifying how PUB may improve practice in the future.

Drought assessment – a role for PUB

The definition of drought is inherently subjective and has therefore been defined in a wide variety of ways utilizing different indicators and parameters. Perhaps the simplest definition of drought is as insufficient water to meet needs. This definition is naturally vague in the sense that a drought is defined with an explicit recognition of the needs for water in a particular activity. Traditionally, as numerous scientific groups have been concerned with drought monitoring and estimation, there are consequently a range of drought definitions. In particular, four major types of drought can be defined as:

- meteorological
- agricultural
- hydrological
- economic

Consequently, we can define all droughts as a physical deficiency of moisture for a specific need. However, the nature and location of the moisture may vary. For example, a meteorological drought can be defined as a deficiency of precipitation measured over a period; an agricultural drought can be defined as a deficiency of soil moisture (root zone) throughout a soil profile for the purpose of agricultural productivity; a hydrological drought can be defined as a deficiency in the volume of water available for water supply or irrigation; and an economic drought might be defined as a deficiency of water such that severe economic consequences might be felt beyond the immediate users of deficient water.

Given the wide range of users of moisture and the differences in the nature or location of the deficient moisture, it should not be a surprise that a wide range of monitors and indices have been developed and refined for a variety of applications.

A critique of the State of the Art

The wide variety of different drought indices available for drought assessment and monitoring may induce a lack of consistency in drought assessment for the diverse range of impacts. Evidently, a purely meteorological approach to drought definition does not capture the hydrological processes that vary spatially. Water yields under meteorological droughts cannot therefore be assessed through such approaches. Similarly, different agricultural activities suffer a wide range of impacts from a single drought. Consequently, if one requires the formal distinction of drought, for instance for the purpose of providing exceptional circumstances (or natural disaster) financial assistance, the adoption of a single method of drought assessment ignores the variety of impacts within the range of water users.

A good example of this lack of consistency is the drought declaration process adopted during the 2002–current eastern Australian drought. This drought was induced by an El Nino event that initiated in late 2001, re-emerged and strengthened during 2002 and finally waned around April 2003. The consequences of this drought are still being felt due to the lack of significant recharge despite the end of the El Nino event itself. The drought has led to the declaration of up to 92% of New South Wales being "drought-affected".

The formal definition of drought in this case is based on the Bureau of Meteorology rainfall decile method. This method of drought assessment is based purely on rainfall anomalies, and hence is classified as a meteorological drought index, and yet is used for agricultural assistance packages. A formal drought is declared when three consecutive months display rainfall that is in the lowest 10% of previous monthly totals from the last 30-year period. There are a number of problems with this approach:

1. The method utilizes rainfall alone and therefore does not account for soil profile moisture more useful for agricultural assessment, nor does it assess consequent available water for water supply.
2. The method is applied according to rainfall districts (presumably centred on reliable, long-term raingauge locations). These rainfall districts may not correspond to hydrological catchments which can be viewed as the natural units of integrated hydrological drought. Consequently boundaries of rainfall districts cut through individual paddocks and properties, irrespective of the hydrological context of these boundaries.
3. The method requires three consecutive months of <10% rainfall deficient occurrences. One might observe two such months that record the lowest ever observed rainfalls for those months, but then experience a month that is deficient but not under the <10% threshold.
4. As the method utilizes the previous 30 years of observed rainfall anomalies, a major question as to the stationarity of the climate is apparent. There is plenty of evidence for multi-decadal epochs of elevated/reduced rainfalls as a function of variable ENSO and IPO behaviour (see above). Consequently, the method is highly vulnerable to the climate epoch from which the available data are utilized.

Towards an integrated, hydrological model of drought – a role for PUB

The diversity of indices and monitors used for drought assessment induces inconsistencies and inaccuracies in the representation of drought impacts and assessments. A more rational approach to drought monitoring, assessment and definition would be to provide a consistent basis for drought assessment. In this light, it is worthwhile to note that many of the indices and monitors of drought assessment are actually crude forms of hydrological moisture accounting models, albeit applied one-dimensionally and highly simplified. If a consistent hydrological model were to be used, it would provide a consistent platform for drought impact assessment. One obvious advantage to the current state of the art would be the improvement of the representation of land surface processes that affect the partitioning of rainfall into soil moisture and runoff. Simple conceptual rainfall–runoff models may be ideally suited for this task. An additional advantage of these models is that they include multiple outputs of different moisture variables. Consequently, different drought impacts for different societal/agriculture activities could be assessed through consistent definitions of drought thresholds and utilizing the relevant variables. For instance, hydrological drought can be defined according to streamflow levels whilst agricultural activities might be based on the level of the catchment soil moisture store. Again, differentiation of diverse agricultural activities can also be incorporated, e.g. graziers who require certain minimum levels of soil moisture to maintain a grazing cover that are quite different from soil profile levels required for seasonal crop production. Consequently, different thresholds for the soil moisture store and dynamics could be set.

A major step toward an integrated hydrologically-based drought assessment technique would be the development of appropriate regionalization techniques of appropriately selected conceptual rainfall–runoff models. This would enable a more robust drought assessment procedure for ungauged basins—clearly a key aim of the IAHS Predictions in Ungauged Basins (PUB) initiative. If successful, I argue that the following advantages for drought estimation would include:

- robust process-oriented differentiation of soil moisture status and available surface water for diverse impact assessment;
- consistent assessment between different regions;
- consistent assessment between different activities/impacts;
- assessment at the natural units of drought (catchment or sub-catchments);
- regionalization to ungauged basins.

Flood risk estimation – event-based and continuous simulation models

Current Australian practice in flood risk estimation is characterized by empirical flood frequency analysis, if gauged data are available at a site, or by the application of event-based models if long-term flood data are not available. As has been demonstrated above, flood frequency data in eastern Australia display marked multi-decadal variability as a result of ENSO and IPO processes. This observation invalidates the traditional assumption that annual maxima floods are independent and identically distributed. The consequence of applying such techniques to Australian sites is that the resultant flood risk estimates will be biased by the epoch from which the data are available. Consequently, empirical flood frequency analysis must be viewed as subject to unacceptable uncertainty when applied in the Australian context.

The more typical approach to flood risk assessment does not, however, employ empirical flood frequency analysis if only because most sites are not gauged. In the case of ungauged basins, practicing engineers tend to use event-based or continuous simulation hydrological models and design storm estimates developed within the Australian Rainfall and Runoff manual. In its favour, the ARR manual provides an informal standard to which different practitioners can adhere. The downside of the methods typically employed are that the models used (particularly the event-based models) may be physically crude with respect to actual hydrological processes. For instance, event-based models often contain parameters such as “initial loss” and “continuing loss” to represent initial catchment storage deficits and evapotranspiration losses. An advantage of the continuous simulation models is that such losses should be explicitly linked to processes and may evolve as a function of actual or stochastically-derived forcing data (rainfall, PET). However, continuous simulation of flood risk requires the specification of a hydrological model that ideally should be well regionalized for robust application to ungauged basins. Whilst numerous previous studies have attempted to develop regionalization schemes for Australian catchments, it is not untypical for only approximately 40% of the variance of model parameters to be explained by the identified regionalization relationships. This is in part due to the lack of universal applicability of a single hydrological model as well as due to errors in input/calibration data leading to significantly biased model parameters (e.g. Kavetski *et al.*, 2002).

A significant role for PUB in this light would be to develop new techniques toward the regionalization of hydrological models. A number of new approaches could be beneficially explored. Given the model dependence of many previous regionalization schemes, perhaps one should not attempt the regionalization of a model but of the observed flow characteristics themselves. This may have the effect of reducing the role of the model structural error in derived parameter values. A second beneficial approach would be to employ input error-sensitive calibration schemes, such as BATEA (Bayesian Total Error Analysis; Kavetski *et al.*, 2002) which offers the ability to assess the potential role of errors in the forcing (rainfall) data that may unduly bias the calibrated model parameters, thus confounding regionalization. Another opportunity lies in the observation that regionalization schemes will always be subject to error and uncertainty at some level. Application of robust uncertainty estimation approaches may at least indicate the degree of confidence that should be placed in applying regionalization approaches to specific, ungauged catchments.

SUMMARY

This chapter has aimed to provide some context to climate variability in eastern Australia as well as demonstrating the marked role of El Nino/Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) in dictating flood and drought risk on seasonal-interannual through to multi-decadal time scales. This chapter has also sought to demonstrate that there are key PUB issues that are required to be addressed before robust flood and drought risk estimation and assessment is achieved. These can be summarized as follows:

- IPO modulation of ENSO event magnitude and frequency controls multi-decadal flood and drought risk. This invalidates the application of traditional flood and drought risk estimation techniques—available data must be viewed as conditional on the climate state from which they are collected.
- Spatial variability of ENSO and IPO impacts indicates that there is a need to develop a regionalized model of climate impacts to provide robust estimation of their effects in ungauged basins.
- Given short instrumental records relative to the persistence of IPO, the instrumental record requires augmentation with proxy measures of pre-instrumental climate variability. Again, spatial variability must be quantified.
- Current drought assessment techniques are many and varied. However, all in essence are simplified hydrological models. The development of regionalized conceptual hydrological models would provide a consistent drought monitoring framework at the catchment scale—the natural unit for drought assessment.
- Current flood risk estimation practice typically utilizes event-based modelling approaches which are weak in terms of hydrological process. Again, a regionalized hydrological model coupled with robust stochastic generation of rainfall that recognizes ENSO/IPO effects would provide a consistent framework for robust long-term flood risk estimation.

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