Quantifying Drought Risk in a Nonstationary Climate

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ABSTRACT

Water management in Australia has traditionally been carried out on the assumption that the historical record of rainfall, evaporation, streamflow, and recharge is representative of current and future climatic conditions. However, in many circumstances, this does not adequately address the potential risks to supply security for towns, industry, irrigators, and the environment. This is because the Australian climate varies markedly due to natural cycles that operate over periods of several years to several decades. There is also serious concern about how anthropogenic climate change may exacerbate drought risk in the future. In this paper, the frequency and severity of droughts are analyzed during a range of "climate states" (e.g., different phases of the Pacific, Indian, and/or Southern Oceans) to demonstrate that drought risk varies markedly over interannual through to multidecadal time scales. Importantly, by accounting for climate variability and change on multitemporal scales (e.g., interdecadal, multidecadal, and the palaeo scale), it is demonstrated that the risk of failure of current drought management practices may be better assessed and more robust climate adaptation responses developed.

1. Introduction

Australia's vulnerability to climate variability has been highlighted by the current drought situation in southwest and southeast Australia (SEA). A step change in southwest Western Australia's climate since the mid-1970s has resulted in a severe decrease in inflows into storages, resulting in a complete restructure of water management in the region (IOCI 2002). Similarly, a persistent rainfall deficiency since the mid-1990s, known as the "Big Dry," has resulted in low inflows into SEA catchments and has seriously impeded agricultural production. In addition to agriculture losses there are also social and economic costs associated with urban water security issues, particularly as population increases. Further, the financial costs, and social and environmental consequences associated with major water infrastructure projects such as desalination facilities, dams, interconnecting pipelines, and water treatment plants are also significant, as is the stigma associated with the use of recycled water.

Current drought (and other extreme events) risk estimation methods are largely empirical. The observed history of climate extremes is analyzed under the assumption that the chance of an extreme event occurring is the same from one year to the next and that the future will look like the past (i.e., the stationary climate assumption). This assumption is flawed, given that the physical climatological mechanisms that actually deliver climate extremes have been ignored and also given that the impacts associated with anthropogenic climate change are not considered (e.g., Franks and Kuczera 2002; Kiem et al. 2003, 2006; Milly et al. 2008). Previous research has highlighted the existence of multiyear to multidecadal epochs of enhanced/reduced extreme event risk across eastern Australia (e.g., Erskine and Warner 1988; Franks and Kuczera 2002; Kiem et al. 2003, 2006; Kiem and Franks 2004; Verdon et al. 2004a,b). These studies clearly demonstrate that the first step in any drought (or flood, bushfire, or any other climate-driven extreme) risk assessment should be to understand the climate mechanisms that drive periods of elevated risk. For example, numerous studies [refer to Diaz and Markgraf (2000) and references therein] have shown that strong relationships exist between eastern Australian rainfall and streamflow, and the global-scale ocean–atmospheric circulation process known as the El Niño–Southern Oscillation (ENSO).

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ENSO refers to the anomalous warming [El Niño] and cooling [La Niña] that periodically occurs in the central and eastern tropical Pacific Ocean in combination with the Southern Oscillation. Previous work has also shown that, while ENSO is important, other climate phenomena also influence Australian climate on interannual to multidecadal time scales (e.g., Nicholls 1989; Power et al. 1999; Kiem et al. 2003, 2006; Kiem and Franks 2004; Verdon et al. 2004a,b; Verdon and Franks 2005; Hendon et al. 2007; Meneghini et al. 2007; Kiem and Verdon-Kidd 2009, 2010). More recently Verdon-Kidd and Kiem (2009a) showed that the three iconic droughts in Australia's history, the "Federation" drought (1895–1902), the "World War II" drought (1937–45) and the Big Dry (1994–present) are driven by a combination of different climate phenomena operating in the Pacific, Indian, and Southern Ocean regions. Based on this research, there is a clear need for an improved understanding into the multiple interactions between large- and local-scale climate drivers and their influence on drought risk.

It is also becoming increasingly apparent that the instrumental record is too short to capture multidecadal climate variability. Palaeoclimate records (e.g., coral fossils, tree rings, dust deposits, flood sediments, ice cores) can provide information about the climate system predating the instrumental record. While limited palaeodata exist for Australia, there are numerous reconstructions of the climate phenomena in the Pacific, Indian and Southern Oceans. Ocean–atmospheric interactions across these three oceans are known to modulate Australia's climate. Importantly, this information can be reconciled with the instrumental record (e.g., Verdon and Franks 2006, 2007) to provide insights into the occurrence and length of drought periods affecting Australia prior to observations, hence providing an improved understanding of "normal" and "extreme" Australian conditions (i.e., the baseline risk).

Compounding the influence of natural climate variability, and the problems associated with the brevity (in climatological terms) of instrumental hydroclimatological records, there is also serious concern about how human-induced climate change may increase the frequency and severity of extreme events, including droughts, in the future (e.g., Pittock 2003; Parry et al. 2007). However, the uncertainty associated with these future climate projections is significant – and magnified further when attempting to make inferences about drought risk at the regional scale (e.g., differentiating between coastal and inland processes). So much so that projections of future drought risk, on either the short (seasonal up to 5 years) or long (more than 10 years into the future) term, currently have limited practical usefulness for water resource managers and/or government policy makers (NCCARF 2009, unpublished manuscript). Water resource planning must account for both natural climate variation and human-induced climate change, since these factors will continue to influence Australia's climate, even if immediate action is taken to curtail greenhouse gas emissions. Such considerations are needed to avoid overallocation of water resources and to ensure economic activity based on utilization of water resources is not unnecessarily restricted. This paper aims to demonstrate that drought in Australia has historically been driven by large-scale climate phenomena and that drought risk is actually dependant on the underlying climate state; hence, it is crucial that this information underpins any drought risk assessment or management plan.

2. Data and methodology

a. Precipitable water data

In this study composite maps of precipitable water anomalies during different climate phases are generated using the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis global gridded dataset available from the U.S. National Oceanic and Atmospheric Administration (NOAA; available online at www.esrl.noaa.gov/psd/). The NCEP–NCAR reanalysis dataset, available for various atmospheric and hydrological variables, was developed using a state-of-the-art analysis/forecast system to perform data assimilation using past data from 1948 to the present. As with all reanalysis data, this dataset has various limitations, particularly in the Southern Hemisphere, where historical recorded data tends to be sparse. See Trenberth and Guillemot (1998) for a review of limitations associated with the NCEP–NCAR reanalysis data, in particular uncertainties inherent in the atmospheric moisture representation.

b. Rainfall data

Since the same amount of precipitable water can result in different amounts of surface rainfall (because moisture convergence can enhance the amount of moisture that has the potential to fall over an area), the Australian monthly gridded rainfall dataset (1900–2008) from the Australian Bureau of Meteorology (BOM) is also used to assess the relationship between surface rainfall and the various climate phenomena. The gridded data has been generated from observed data using an optimized Barnes successive correction technique (Barnes 1973) that applies a weighted averaging process to the station data.

Station-based monthly rainfall data was also obtained from the BOM for two stations located in New South Wales (NSW), Australia (Fig. 1). The first station is located

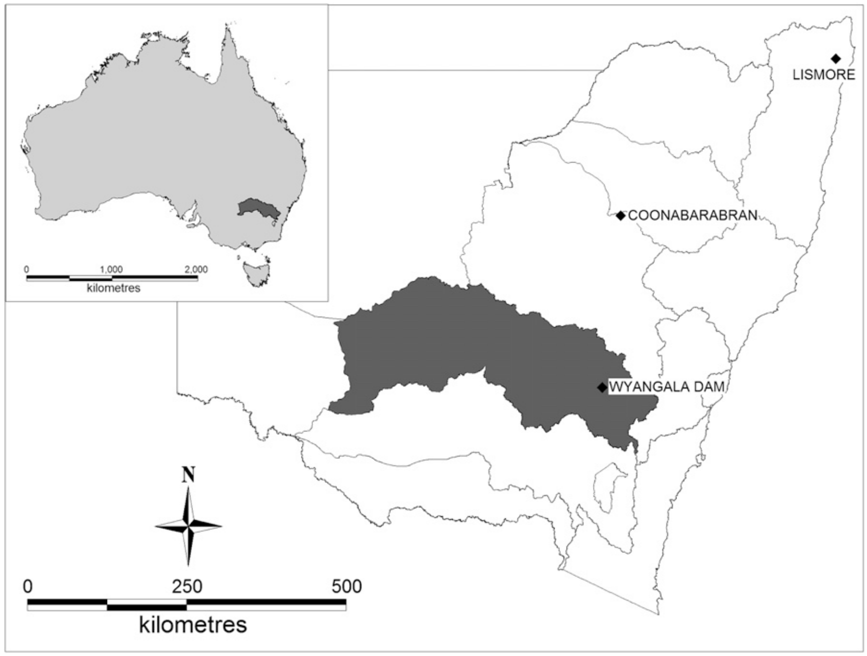

FIG. 1. Location of study sites used in this analysis (the Lachlan River valley shown in dark gray).

along the coastal fringe (Lismore), while the second is located west of the Great Dividing Range (Coonabarabran). This rainfall data is used in an analysis of agricultural drought risk, as described in section 2e.

c. *Wyangala Dam data*

Climatic influences on storage inflows are analyzed for the Wyangala Dam reservoir, located in the Lachlan River valley catchment in rural NSW (shown in Fig. 1). The Lachlan River valley, occupying an area of 85 000 km^2, is a complex regulated river system comprising numerous anabranches, several headwater storages, wetlands, and major irrigation developments (DLWC 2002). Wyangala Dam is the main reservoir in the Lachlan River system and has a storage capacity of 1217 gigaliters (GL). In this study storage inflows and storage volumes were simulated using the Integrated Quantity and Quality Model (IQQM). The model is designed to operate on a daily basis and to simulate a number of hydrological processes, including flow routing, reservoir operation, irrigation, urban water supply, and water accounting systems (DLWC 1998).

d. *Climate indices*

Numerous studies (e.g., Ropelewski and Halpert 1996; Chiew et al. 1998; Power et al. 1999; Thompson et al. 2000; Kiem and Franks 2001; Marshall et al. 2004; Verdon et al. 2004a,b; Verdon and Franks 2005) have shown that the four most influential climate modes on Australia's climate are as follows:

1) ENSO coupled ocean–atmosphere variability that manifests as abnormal warming (El Niño) and cooling (La Niña) of the tropical Pacific Ocean every 2–7 years. ENSO is represented by the Oceanic Niño index (ONI) from the U.S. NOAA Climate Prediction Center (CPC; available online at www.cpc.ncep.noaa.gov).
2) Interdecadal Pacific oscillation (IPO)—a low-frequency (15–35 yr) pattern of variability of the tropical and extratropical Pacific Ocean [refer to Power et al. (1999) for details]. Folland et al. (1999) derived an index of IPO variability using a low-pass filter of near-global sea surface temperature (SST), while Power et al. (1999) applied a spectral filter with a 13-yr cutoff to the raw IPO to generate a smoothed (or slowly varying) IPO time series. The smoothed time series of Power et al. (1999) is used in this study to identify epochs of positive and negative IPO.
3) Indian Ocean dipole (IOD)—a coupled ocean–atmosphere climate mode that occurs interannually in the tropical parts of the Indian Ocean (Saji et al. 1999). Typical of climate oscillations, the IOD experiences a "positive" phase and a "negative" phase. During a positive IOD event, the SST drops in the northeast Indian Ocean (i.e., northwest of Australia

SSTs) while the SST rises in the western equatorial Indian Ocean (near the east coast of Africa). Inverse conditions exist during a negative IOD event. Northwest of Australia SSTs (i.e., the eastern pole of the IOD) are used here to represent Indian Ocean influences on Australian rainfall, rather than the IOD, as previous studies have shown that warming in this region is most important for cloud band development and strongly related to above-average rainfall in SEA (e.g., Verdon and Franks 2005), while the need for an anomaly farther west has not been demonstrated.

4) Southern annular mode (SAM)—the leading mode of atmospheric variability over the southern extratropics. Also known as the Antarctic Oscillation and the high-latitude mode, the SAM represents an exchange of mass (sea level pressure seesaw) between the midlatitudes (~45°S) and the polar region (>60°S) (Thompson and Wallace 2000). SAM is represented by the monthly-mean Antarctic Oscillation (AAO) index, available from NOAA CPC (available online at http://www.cpc.ncep.noaa.gov/) from 1979 to present and from Thompson and Wallace (2000) from 1948 to 2002. In this study the NOAA CPC version of the AAO is used when it exists (i.e., from 1979) and the Thompson and Wallace (2000) AAO data are used prior to that. Overlapping periods of the two versions of the AAO were compared and the difference found to be negligible ($R^2 = 0.95$).

e. *Defining and measuring drought*

In general terms "drought" refers to a deficiency of water to meet needs (Redmond 2002); however, the definition of drought varies depending on the intended application. Rasmusson et al. (1993) identified four major categories of drought: meteorological, agricultural, hydrological, and economic drought. Meteorological drought occurs when there is a deficiency of precipitation, agricultural drought occurs when there is a deficit of soil moisture, and hydrological drought refers to a deficiency in the volume of the water supply (i.e., streamflow, reservoir storage, groundwater level). Therefore, the various categories of drought develop under different circumstances and operate over different time scales.

Owing to the wide range of applications and the differences in the nature of the water deficiencies, a number of methods and indices have been developed that are specifically targeted at particular types of drought [e.g., standardized precipitation index (McKee et al. 1993), crop moisture index/Palmer drought severity index (PDSI) (Palmer 1965), surface water supply index (Shafer and Dezman 1982), among others]. In addition to this, a range of strategies has been adopted across the world to monitor and measure drought [e.g., the Drought Monitor for the United States and Rainfall Deciles (Gibbs and Maher 1967) in Australia]. However, the Rainfall Deciles method, in particular has a number of problems, including the following.

TABLE 1. Categories of the PDSI.

PDSI value	Classification
>4.0	Extremely wet
3.0 to 3.99	Very wet
2.0 to 2.99	Moderately wet
1.0 to 1.99	Slightly wet
0.5 to 0.99	Incipient wet spell
0.49 to −0.49	Near normal
−0.50 to −0.99	Incipient drought
−0.10 to −1.99	Mild drought
−2.0 to −2.99	Moderate drought
−3.0 to −3.99	Severe drought
<−4.0	Extreme drought

1) It only monitors meteorological drought (i.e., low precipitation) and does not monitor agricultural or hydrological drought (i.e., low runoff, soil moisture); yet, it is used for assessing agricultural assistance.
2) Small amounts of precipitation during periods in which little or no rainfall is routine can signal the end of a drought, even though the absolute quantity of precipitation is trivial and does not terminate the water deficit (Keyantash and Dracup 2002).
3) Rainfall records of sufficient quality and length are required to capture the full spectrum of natural variability of rainfall in the area. If the deciles are based on short records (common in most of Australia), or taken from a drought-rich epoch, then the system may incorrectly classify droughts.

Given the deficiencies identified for the rainfall deciles method, the PDSI (Palmer 1965) is used in this study to investigate agricultural drought. The PDSI is a supply and demand model used to estimate the amount of moisture in the soil at a particular location. The PDSI employs a two-layer model to provide an estimate of the soil moisture storage at any time, where moisture is first lost from the top layer when moisture demand exceeds supply, and is also the first to be recharged when there is surplus moisture. Although sometimes referred to as an index of meteorological drought, the method takes into account precipitation, evapotranspiration, and soil moisture conditions—all of which are determinants of agricultural drought (Alley 1984). Droughts are classified based on PDSI value (between −10 and +10) as shown in Table 1 [refer to Alley (1984) for a detailed description of how to calculate the PDSI].

In an effort to improve our understanding of drought in Australia, modeled soil moisture and all terrestrial water fluxes over the Australian continent have recently been produced at 5-km spatial resolution and daily temporal resolution for the last 109 years for the Australian Water Availability Project (AWAP). The soil moisture estimates have been produced using the WaterDyn model, developed by Raupach et al. (2009) to model the terrestrial water balance across continental Australia. Key inputs and constraints on the model are the meteorology (solar radiation, precipitation, minimum and maximum daily temperatures) and continental parameter maps (e.g., albedo, soil characteristics, seasonality of vegetation greenness). In this study output from AWAP is also used to demonstrate variability of agricultural drought risk (i.e., soil moisture).

3. Climatic drivers of drought risk

a. Variability of meteorological drought risk

The influence of ENSO, SSTs northwest (NW) of Australia, and the SAM on meteorological drought risk is shown in Fig. 2 (precipitable water) and Fig. 3 (surface precipitation). Note that, to be consistent with the analysis carried out using precipitable water data (which is available from 1948 onward), only rainfall data from the period 1948–2008 are used to generate Fig. 3. However, the same test was repeated using the full gridded rainfall dataset (1900–2008), resulting in almost identical maps.

Figures 2 and 3 show that meteorological drought is strongly related to each of the dominant climate modes (i.e., ENSO, NW of Australia SSTs, and SAM). During spring (September–November) and summer (December–February) of an El Niño event, precipitable water tends to be reduced over much of northern and eastern Australia (and parts of Tasmania), with decreased moisture derived from the Timor Sea to the northwest and the Coral Sea to the east, while the opposite conditions tend to occur during La Niña. As demonstrated by Fig. 3, the reduction in moisture availability is consistent with the observed surface precipitation patterns for El Niño and La Niña. The NW of Australia SSTs can also be seen to influence winter (June–August) rainfall over much of Australia, with anomalously cool SSTs in the region resulting in widespread decreases in rainfall, due to a reduction in moisture generated in the northeast Indian Ocean. As shown in Figs. 2 and 3, the opposite conditions arise when the NW of Australia SSTs are warm. The influence of the SAM on autumn rainfall is also clear, with positive events resulting in low rainfall across SEA but increases in northern Australia, due to an increase in moisture availability in the northeast Indian Ocean and a corresponding reduction over SEA.

It is important to note that the large-scale climate modes do not often influence rainfall in an independent manner, with the synchronization of the modes being of high importance to the resulting impact (Verdon–Kidd and Kiem 2009b). For example, La Niña events normally result in high rainfall across much of eastern Australia (as shown in Fig. 3). However, if the La Niña occurs in combination with a positive SAM event, rainfall does not tend to penetrate the southern regions (see Kiem and Verdon-Kidd 2009, 2010 for details). This has been the case during the last three La Niña events, which have coincided with a positive SAM, and therefore failed to break the severe drought that is currently being experienced in SEA.

b. Variability of agricultural drought risk

The climatic drivers of agricultural drought risk (PDSI) were investigated for two stations located in NSW, as shown in Fig. 4 (see section 2b for a description of the datasets used here and the PDSI methodology). ENSO clearly influences agricultural drought risk in the regions studied. For example, Fig. 4 shows that an El Niño results in dry conditions (ranging from incipient drought through to severe drought) at Lismore approximately 35% of the time, with very few wet spells. Conversely during a La Niña event wet conditions dominate, with a PDSI greater than 0.5 obtained approximately 75% of the time, with very few dry spells. The impact of El Niño on agricultural drought is even greater at Coonabarabran (according to PDSI) with monthly PDSI values <0.5 (i.e., dry) more than 50% of the time.

As previously discussed, the synchronization of climate modes tends to modulate the resulting impact, particularly in regions where no single mode is dominant (Kiem and Verdon-Kidd 2009, 2010). For example, during the year 1982 ENSO was in an El Niño state, while the SAM and NW of Australia SSTs were also in a dry phase. The resulting impact on agricultural drought is shown in Fig. 5.

In terms of short-term rainfall deficiencies and their overall effect, the 1982–83 drought was perhaps Australia's most severe in the twentieth century—though the Federation, World War II, and Big Dry droughts are considered to be worse due to their protracted nature (e.g., Verdon-Kidd and Kiem 2009a). Figure 5 illustrates just how widespread the rainfall and upper soil moisture deficiencies were, with only the far northwest of Australia escaping the disaster. The rainfall and soil moisture deficiencies affected discharge across much of the Murray–Darling Basin, southwest Western Australia, and Tasmania. This was a year that resulted in severe dust storms, total fire bans, heavy water restrictions, and devastating bushfires in NSW, Queensland, Tasmania, South Australia, and Victoria, including the infamous Ash Wednesday bushfires.

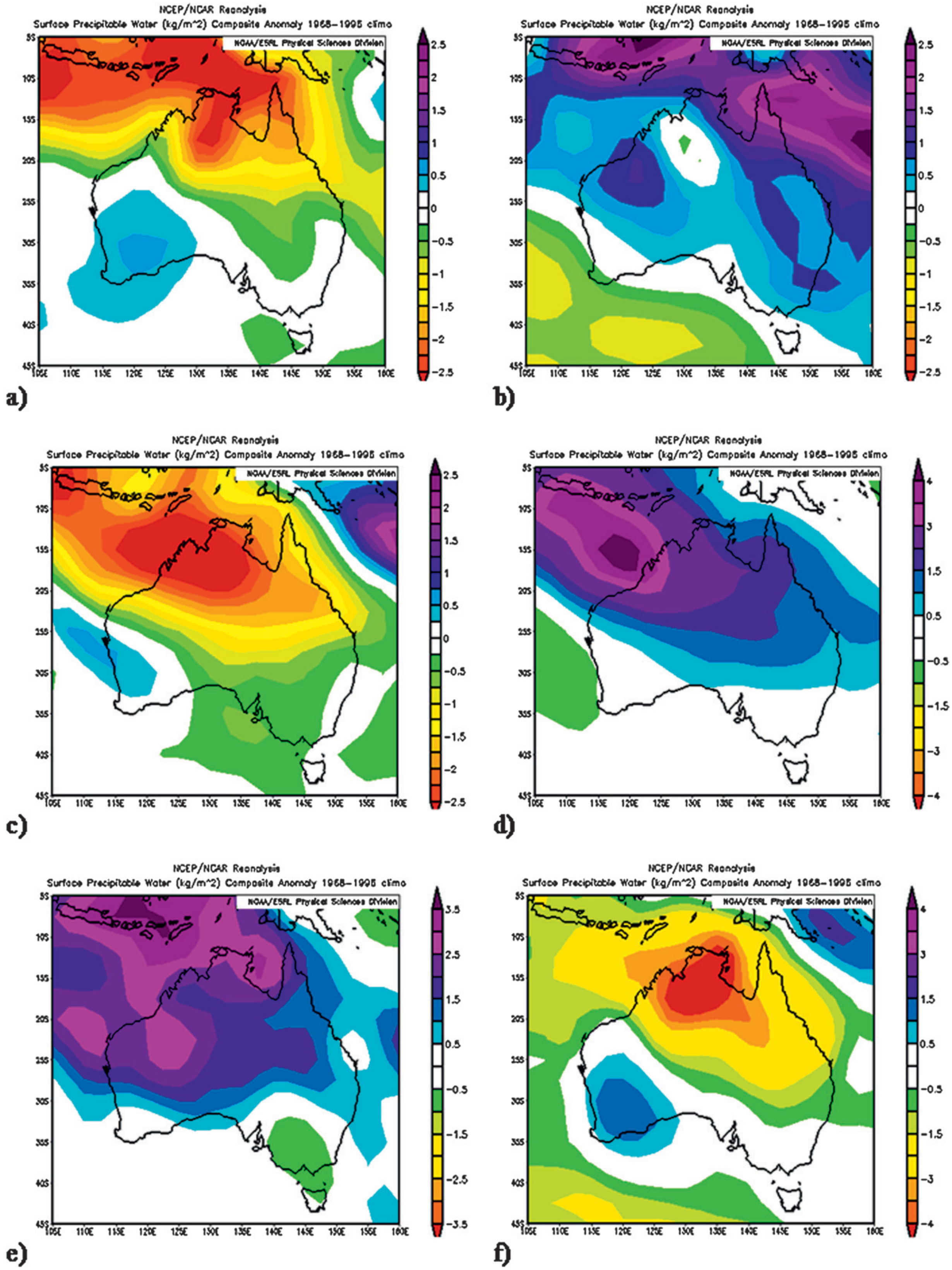

FIG. 2. Precipitable water anomalies during (a) spring/summer (September–February) and El Niño, (b) spring/summer (September–February) and La Niña, (c) winter (June–August) and cool NW of Australia SST, (d) winter (June–August) and warm NW of Australia SST, (e) autumn (March–May) and SAM positive, (f) autumn (March–May) and SAM negative.

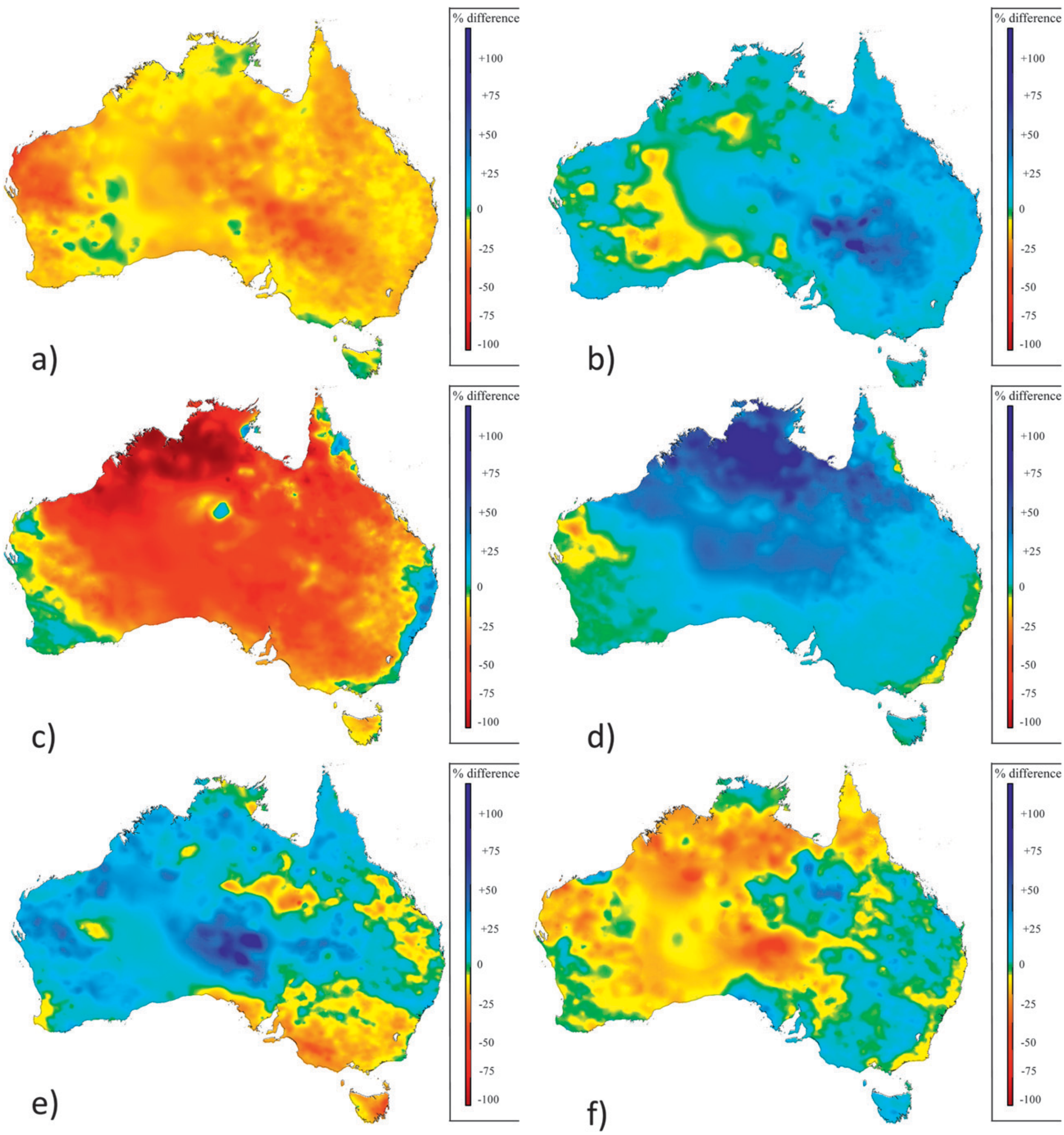

FIG. 3. Percentage change in rainfall at the surface compared to the long-term mean during (a) spring/summer (September–February) and El Niño, (b) spring/summer (September–February) and La Niña, (c) winter (June–August) and cool NW of Australia SST, (d) winter (June–August) and warm NW of Australia SST, and (e) autumn (March–May) and SAM positive, (f) autumn (March–May) and SAM negative. Note that a value of −50% indicates that the average rainfall received during the particular climate phase is only half of the long-term average (based on the period 1900–2008).

c. *Multidecadal variability of hydrological drought risk*

A hydrological drought occurs when there is a long persistent period of low rainfall, such as the recent drought conditions in SEA, which in turn affects inflows and storage volumes. Therefore, a single climate event (e.g., ENSO, NW of Australia SSTs, or SAM) is unlikely to result in a hydrological drought—unless the storage has very little carryover reserve and is therefore highly

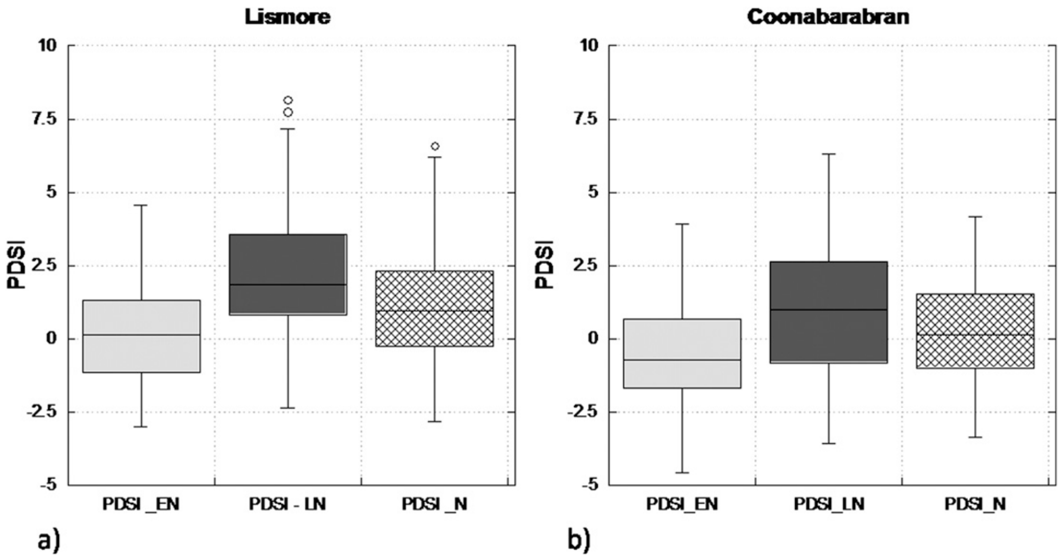

FIG. 4. Monthly PDSI values stratified according to ENSO phase for (a) Lismore and (b) Coonabarabran (EN: El Niño, LN: La Niña, and N: Neutral).

sensitive to annual rainfall changes. Rather, hydrological drought (i.e., persistent dry conditions) is brought about when multiple ‘‘dry’’ climate events occur in sequence (e.g., a run of El Niño events or a period of sustained positive SAM). The climate phenomena linked to persistent ENSO activity is known as the interdecadal Pacific oscillation (IPO; Power et al. 1999). During the positive phase of the IPO there is a tendency for a higher proportion of El Niño events, whereas La Niña events tend to be more frequent during periods of the negative

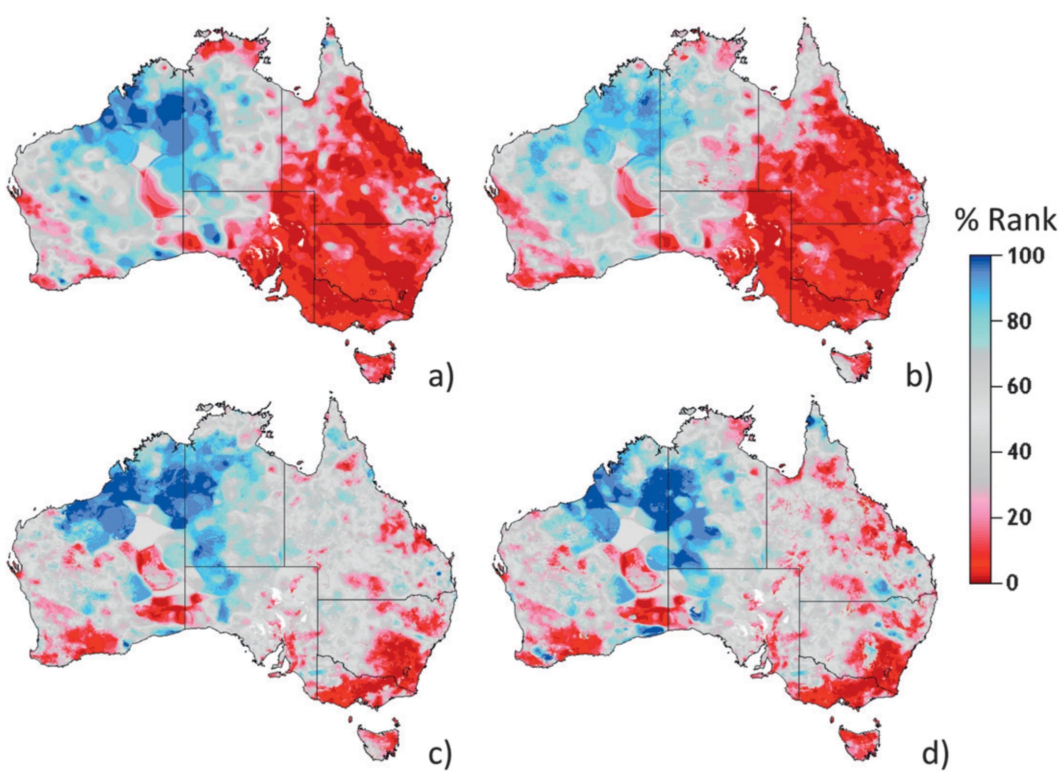

FIG. 5. Percent rank (a) rainfall, (b) upper-level soil moisture, (c) deep soil moisture, and (d) discharge (runoff + drainage) during 1982 (annual time series available online at http://www.csiro.au/awap/).

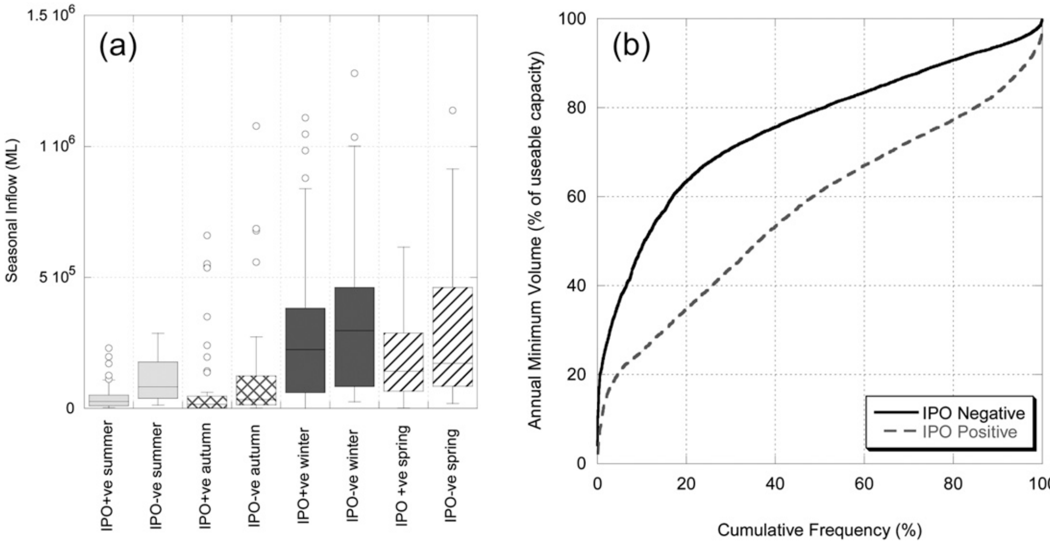

FIG. 6. (a) Seasonal inflows into the Wyangala Dam reservoir and (b) cumulative frequency plot of annual minimum volume for Wyangala Dam, during the two phases of the IPO.

phase (Kiem et al. 2003). This multidecadal clustering of ENSO events has a large effect on the risk of hydrological drought (and flooding) for at least Queensland and NSW (Kiem and Franks 2004). Persistency in the SAM or NW of Australia SSTs also results in sustained droughts for other regions (Samuel et al. 2006; Kiem and Verdon-Kidd 2009, 2010).

The impact of multidecadal phasing of climate on hydrological drought is investigated for Wyangala Dam, located in NSW (see Fig. 1 for location). Figure 6 shows the seasonal inflows and the minimum annual volume of water in Wyangala Dam during the two phases of the IPO.

Figure 6a demonstrates that inflows into Wyangala Dam are strongly related to the phase of the IPO, with effects extending across all seasons, although summer and autumn tend to be more significantly affected. The modulation of inflows in turn influences storage levels in the Wyangala Dam, as demonstrated by Fig. 6b. For example, the probability of storages being above 50% capacity during the IPO negative period is approximately 90%, whereas during the IPO positive period the probability is only 60%. These results demonstrate that hydrological drought risk is clearly variable (i.e., nonstationary) and noticeably dependant on persistent climate events. Therefore, this information needs to be taken into account to robustly quantify drought risk and develop appropriate water resource management procedures.

4. Palaeoclimate informed drought risk

It is becoming increasingly apparent that the instrumental record (in Australia ~100 years for rainfall and less for streamflow) is not long enough to capture the true nature of climate variability occurring over multidecadal time scales or longer. In an attempt to overcome some of these limitations, recent studies have used palaeoclimate information, such as tree-ring chronologies and coral fossils, as proxy environmental records of the various climate phenomena (e.g., ENSO, IPO, SAM, and NW of Australia SSTs). Figure 7 displays the relative frequency of El Niño to La Niña events within a 15-yr moving window during the last 600 years. In this figure higher ratios indicate more frequent El Niño events during the 15-yr period and therefore highlight likely periods of drought in Australia. This time series is based on an annual ENSO reconstruction by D'Arrigo et al. (2005), which is derived from 175 tree-ring chronologies from the southwestern United States and Mexico.

A number of peaks in El Niño frequency are shown in Fig. 7, including the well-known trend toward a higher incidence of El Niño events during the early 1900s and from 1975 to 2000. However, it is also clear that epochs of even greater El Niño activity have occurred in the past. For example, a significantly high proportion of El Niño events are shown to have occurred during the 1820s through to the 1830s, during which eight El Niño events occurred and only one La Niña within a 15-yr period. Anecdotal evidence of the resulting impact of this run of El Niño events on the Australian climate is compelling—a severe drought in NSW during the period 1826–29 caused Lake George to dry up and the Darling River ceased flowing, crops burned, livestock died, and, despite their familiarity with the land's natural resources, many Aboriginals were also reported to have perished

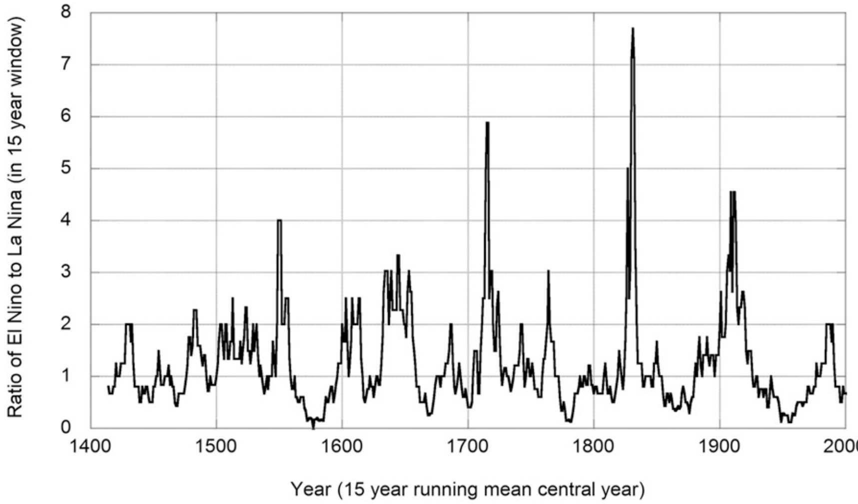

FIG. 7. Fifteen-year moving window of relative El Niño to La Niña event frequency.

through starvation (Shaw 1984). Ominously, the 1820s–30s and early 1700s were both associated with higher proportions of El Niño events than we have observed over the period for which we have instrumental rainfall/streamflow records, which clearly indicates that the "worst drought on record" is unlikely to be the "worst drought possible," irrespective of the potential effects of anthropogenic climate change.

A reconstruction of the time series of changes in the IPO was developed by Verdon and Franks (2006) using a multiproxy dataset to study the long-term behavior of persistent climate events linked to prolonged hydrological drought in parts of Australia. They found that the duration of IPO epochs has varied over the past 350 years, with the shortest IPO epoch persisting for just 13 yr, while the longest duration was 34 yr. In addition, consistent with the last 100 years and the work of D'Arrigo et al. (2005), periods of intense El Niño activity such as the 1720s and 1830s (identified in Fig. 7) have occurred during positive IPO epochs (Verdon and Franks 2006). How this information can be used in assessing (and managing) drought risk is further explored in section 5.

5. Accounting for variability of drought risk in water resource modeling

Water resource managers in NSW (and many other parts of the world) typically use an estimate of the "worst drought in 100 years" for drought risk assessment. This estimate is based on the lowest cumulative inflow sequences that have been recorded during the instrumental record, spanning approximately 100 years for NSW. The problem with this system is that "records" are continually broken owing to the short nature of the data on which the estimates are based and the extreme nature of climate variability in Australia. For example, inflows during the recent drought were lower than the previous historical minimums for some of the catchments in SEA, resulting in an overestimate of expected inflows and critically low storage volumes (i.e., failure of the system). In some cases the inflows were equal to or lower than those projected by 2030 under climate change (e.g., Jones and Durack 2005). This clearly demonstrates that water management procedures based on the short instrumental record are at risk of failure. In addition, it is clear that current climate change scenarios provide limited information on extreme events—particularly when the baseline on which these scenarios are founded is incorrectly assessed. As a step toward overcoming this issue, Verdon and Franks (2007) developed a simple stochastic framework for use in long-term drought risk assessment that specifically incorporates multidecadal persistence of rainfall, brought about by changes in the primary climate drivers. The framework consists of a first-order autoregressive [AR(1)] stochastic simulation model forced to replicate the wet and dry cycles of the IPO to simulate a range of statistically viable climate scenarios [see McMahon et al. (2008) for other examples of a recently developed climate-informed stochastic simulation (CISS) approach designed to realistically simulate nonstationarity inherent in hydroclimatic time series].

The methodology developed by Verdon and Franks (2007) was employed to generate 100 replicates consisting of 100-yr inflow time series to Wyangala Dam (refer to Fig. 1 for location) to assess a range of plausible inflow scenarios. Rainfall replicates were produced using the CISS method and then converted to flows using the Lachlan River Valley Integrated Quantity and Quality Model (IQQM). Figure 8 shows the flow duration curve

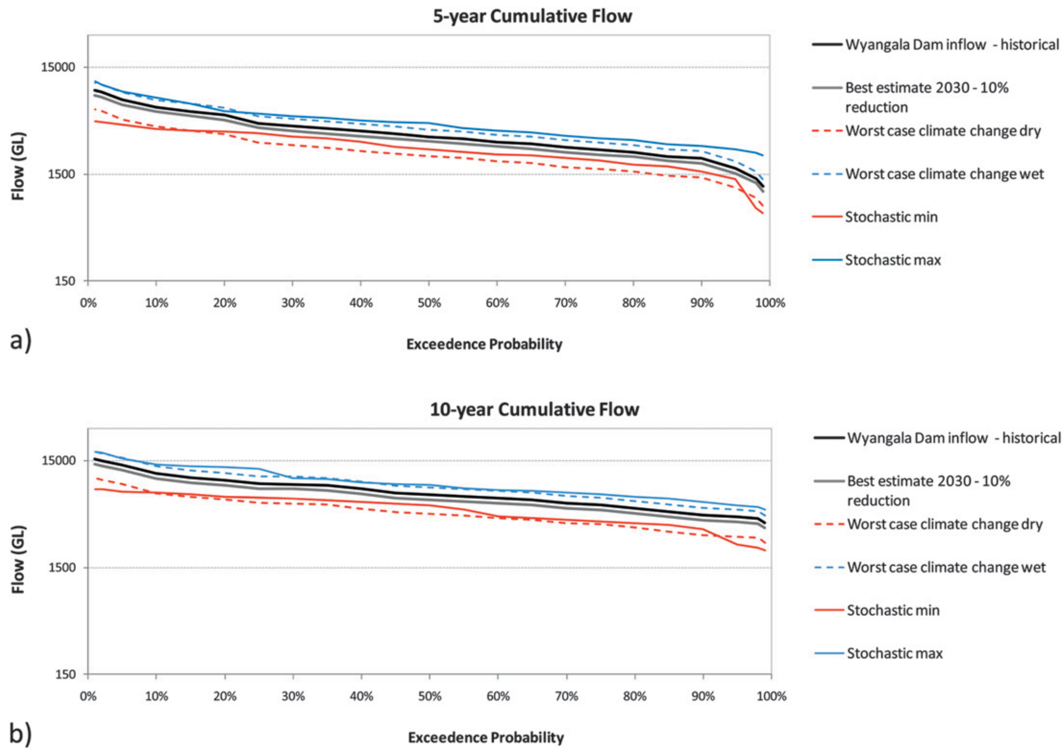

FIG. 8. Flow duration curve for the Wyangala Dam based on historical flow, climate change impacted flow, and flows derived from the climate informed stochastic simulation for (a) 5–yr and (b) 10-yr cumulative flows.

for inflows to Wyangala Dam derived from the CISS approach, along with the instrumental record and also a 2030 climate change scenario. According to the findings of the Murray–Darling Sustainable Yields project (CSIRO 2008), inflows in the Lachlan River valley are projected to decrease by 10% (for the "best estimate"). The extreme estimates, which come from the high global warming scenario, range from a 34% reduction to a 17% increase in mean annual runoff. The instrumental inflow time series (1898–2006) has been used as the baseline for the climate change scenarios shown in Fig. 8. The 5-yr and 10-yr cumulative inflows are shown here since most reservoirs are designed with carryover storage that is sufficient to last through a 2–3-yr drought. It is the longer droughts (5–10 yr) that have the greatest impact on water availability and hence agriculture, environment, economy, and society.

Figure 8 clearly highlights the fact that the instrumental record alone is not a particularly good guide on which to base water management procedures, nor should it alone be used to determine the likelihood of a drought occurring. The stochastic simulation demonstrates that it is statistically possible to receive lower (and also higher) inflows than have been recorded in the last 110 years—even lower than the recent drought. Figure 8 also highlights the danger of using the limited instrumental record as a baseline for future climate change risk assessment, without properly assessing the underlying variability (i.e., the upper and lowers bounds of the stochastic simulation). The results presented here demonstrate a false sense of security that may be derived from applying climate change factors to the instrumental inflow record (which is common practice in Australia and elsewhere) and expecting this to guard against future extremes, particularly if the best-estimate climate change scenario is used. Importantly, these results highlight the fact that water resource management must account for the full range of natural climate variability (instrumental and preinstrumental), in addition to future effects of anthropogenic climate change, if climate sensitive industry (and/or infrastructure) is to become sustainable in the long term.

6. Discussion

This paper highlights the fact that drought risk is not stationary in Australia, rather it varies on a range of time scales (e.g., seasonal, annual, interdecadal, multidecadal, and the palaeo scale) and is strongly influenced by the underlying climate state. Therefore, drought management strategies based on the "stationary climate assumption," particularly those based on relatively short (in climate terms) instrumental data, are likely to fail—even if potential impacts of climate change are factored in.

To effectively manage drought risk the following issues should be addressed:

1) Reassessment of baseline risk—how dry can it get and for how long? This requires an understanding of the drivers of regional drought risk and long-term variability of the system. An example of how this may be achieved has been outlined in this paper.
2) Improved forecasting of periods of elevated drought risk (seasonal through to multidecadal). Reliable forecasts are required at temporal and spatial scales useful to decision makers. Improved seasonal forecasts will enhance the effectiveness of ''short term'' drought management strategies (i.e., seasonal water allocations, reservoir restrictions, crop planting decisions, among others). To date seasonal forecasting schemes in Australia have focused on predicting ENSO alone, with some effort now being directed toward forecasting IOD. However, as this paper demonstrates, even a perfect ENSO forecast will not suffice in predicting droughts in SEA since not all droughts affecting SEA are ENSO driven (also see Verdon-Kidd and Kiem 2009a). As Barros and Bowden (2008) demonstrated, there is considerable opportunity to improve seasonal forecast skill in SEA using multiple climate indicators (indeed, climate forecasting systems will need to account for all climate modes, and their interactions, to be successful). Furthermore, to increase drought resilience in the ''long term'' (i.e., decades into the future), skillful multidecadal forecasts are required to aid decision making surrounding major drought management infrastructure projects (e.g., new or enlarged reservoirs, desalinization plants, new pipelines, etc) and/or longer-term drought management policy (e.g., water allocation buy-back schemes, environmental flow allowances, drought relief assistance funding, etc).
3) Implications of climate change—how is drought risk likely to change in the future due to human-induced global warming? This will require an analysis of how well global climate models simulate the large-scale drivers of drought risk in Australia. In addition, detailed analysis is also required of how well global climate model outputs can be downscaled to catchment or farm scale, and how well those downscaled meteorological forcings can be translated into hydrologic impacts with localized hydrological models.

The occurrence of drought in eastern Australia impacts negatively on the agricultural and water resource management sectors (among others). Clearly, the economic and social losses are enhanced during times when those involved are unprepared. Therefore, incorporating climate insights (such as those highlighted in this paper) into water management practices is an important step toward minimizing the negative effects of drought—and perhaps maximizing benefits during nondrought years.

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