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Evaluating the non-stationarity of Australian annual maximum flood

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SUMMARY

Projections of future changes to flood risk resulting from the combined effects of natural climate variability and anthropogenic climate change typically have high uncertainty, due to uncertainty in both the atmospheric forcings and the processes by which rainfall is converted to runoff. In this paper we test for non-stationarity of the most extensive annual maximum (AM) streamflow database compiled in Australia to date, comprising records from 491 small to medium sized catchments with record lengths from 30 to 97 years, and with minimal regulation or land cover change. The data are analysed for trends using the Mann–Kendall (MK) test, for three study periods (1955–2004, 1965–2004, and 1975–2004). Three different approaches were used to account for the impact of serial correlation on the MK test, and a regional MK approach and a bootstrap resampling approach were used to account for the cross-correlation structure in the data. The outcome of the MK test indicates a significant downward trend in the AM flood data in the south-east and south-west regions of Australia. These downward trends are field significant at the 10% significance level, whereas any upward trends are not. In addition to the MK test, a partial MK analysis was performed to assess the influence of three indices representing large-scale climate variability: the Southern Annular Mode (SAM), El Niño Southern Oscillation (Niño 3.4) and the Interdecadal Pacific Oscillation (IPO). After accounting for these indices the total number of stations showing statistically significant trends is reduced, suggesting that much of the observed trend in AM floods may be associated with these climate modes. Given the significant covariability between these indices and the global warming trend, however, the extent to which observed changes are due to natural variability rather than anthropogenic climate change cannot yet be conclusively determined.

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1. Introduction

Some of the most notable impacts of climate variability and change are expected to be on the various components of the hydrological cycle. In particular, a change in the behaviour of the climate system can lead to changes in the magnitude and frequency of hydrological extremes, including the flood risk (Xu et al., 2006; Seneviratne et al., 2012). This challenges the assumption of stationarity which forms the basis for most flood estimation studies (Milly et al., 2008; Westra and Sisson, 2011). Furthermore, such changes can undermine the usefulness of the return period concept, and a failure to take non-stationarity into account can lead to the underestimation or overestimation of the design flood estimates (Khaliq et al., 2006).

Non-stationarity in flood risk can arise due to both natural and anthropogenic changes in atmospheric forcings, together with changes in catchment characteristics which can affect the translation of rainfall to runoff (IPCC, 2007). Here we define climate change as any change to atmospheric forcing resulting from human activities, including the emission of greenhouse gases as well as anthropogenic aerosols, whereas, climate variability is defined as changes resulting from 'natural' features of the climate, and may be due to internal dynamics of the climate system (such as El Niño-Southern Oscillation (ENSO) phenomenon) or external forcing (e.g. periodic fluctuations in solar radiation, and abrupt changes due to volcanic eruptions). Furthermore, changes in catchment characteristics such as land use (e.g. deforestation, urbanisation, major storages, farm dams), and forest fires can also have an important influence on catchment runoff, making it difficult to attribute changes to flood risk to any specific cause. Therefore, while the examination of changes in the observational records of floods represents an important field of study, such analyses must be undertaken with the understanding that a number of different forcings can yield similar changes in flood response, hampering efforts to attribute change to any single driver (Khaliq et al., 2008).

Many previous studies have focused on the identification and interpretation of temporal changes in river flow regimes, especially

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Table 1
Summary of previous studies that have assessed changes in Australian streamflow.

Authors	Data-set	Region	Index type	Findings
Chiew and McMahon (1993)	30 Stations	New South Wales (NSW)	Streamflow volumes	No clear evidence to suggest that the greenhouse effect had an impact on Australian streamflow volumes
Franks and Kuczera (2002)	41 Stations	NSW	Annual maximum flood peaks	Post-1945 20-year flood exceeds the pre-1945 20-year flood for 37 of the 41 sites
Kiem et al. (2003)	40 Stations	NSW	Regional flood index	Interdecadal Pacific Ocean (IPO) modulated both the magnitude and frequency of El Niño Southern Oscillation (ENSO) events resulting in multidecadal periods of elevated and reduced flood risk
Verdon et al. (2004)	152 Stations	Eastern Australia	Seasonal rainfall and streamflow totals	Both indices found to be significantly enhanced during the La Niña phase of ENSO
Micevski et al. (2006)	94 Stations	Queensland and NSW	Annual maximum flood data	IPO modulated the flood risk in New South Wales and southern Queensland, with flood quantiles being increased by a factor of approximately 1.7 during IPO negative periods
Murphy and Timbal (2008)	–	Southeastern Australia	Rainfall and temperatures indices	Combination of higher Temperature and lower rainfall has led to more severe droughts and extremely low streamflow for Victoria since the mid-1990s
Cai and Cowan (2008b)	9 Stations	Murray Darling Basin	Monthly total inflows	Decrease in annual and/or seasonal streamflow totals in could not be fully explained by the observed decrease in annual and/or seasonal rainfall totals
Kiem and Verdon-Kidd (2009)	9 Stations	Victoria in Australia	Monthly streamflow totals	Stratification of streamflow data according to multiple large scale climate drivers (e.g. ENSO, IPO, Indian Ocean Dipole (IOD) and Southern Annular Mode (SAM)), and antecedent catchment conditions, provides significantly different streamflow distributions
Pui et al. (2011)	128 Stations	NSW	Average daily streamflow data	Change in the annual maximum flood with change in IPO phase was mainly due to different antecedent wetness conditions preceding the annual maximum rainfall event

with the recognition that streamflow represents an integrated response to different atmospheric inputs to a catchment (Khaliq et al., 2008). Examples include studies by Lettenmaier et al. (1994), Zhang et al. (2001), Burn and Hag Elnur (2002), Birsan et al. (2005), Novotny and Stefan (2007), and Petrow and Merz (2009), among many others. The basis of the above mentioned research was the detection of temporal changes in hydrological time series by employing a range of parametric and non-parametric approaches. Khaliq et al. (2009) presented a comprehensive review of the methodologies adopted for the identification of hydrological trends, while Kundzewicz and Robson (2004) provided general guidance for the detection of trends in hydrological data.

In Australia, analyses of trends in rainfall, temperature and evapotranspiration data have been undertaken by many researchers (e.g. Plummer et al., 1999; Smith et al., 2000; Griffiths et al., 2005; Gallant et al., 2007; Alexander et al., 2007; Pook et al., 2008; Cai and Cowan, 2008a; Taschetto and England, 2009 and Johnson and Sharma, 2010). Most of these studies have found trends in Australian rainfall and temperature data, the common findings being that the northwest has experienced an increase in rainfall over the last 50 years, while much of eastern Australia and the far southwest have experienced a decrease. Furthermore, Hardwick-Jones et al. (2010), Jacob et al. (2011) and Westra and Sisson (2011) have evaluated changes in sub-daily extreme precipitation, and found that changes in fine-time scale rainfall are of greater magnitude than in longer duration rainfall, with possible implications on the types of catchments which would be most susceptible to increases in flood risk.

There also have been a number of studies on detecting trends in Australian streamflow data, and these have been summarised in Table 1. Many of these studies, including Kiem et al. (2003), Micevski et al. (2006), Kiem and Verdon-Kidd (2009) and Pui et al. (2011), have focused on the role of natural climate drivers such as ENSO and the Interdecadal Pacific oscillation (IPO) on flood frequency, and found that flood risk is conditionally dependent on both these climate indices and on the catchment antecedent wetness conditions. In contrast, studies by Murphy and Timbal (2008) and Cai and Cowan (2008b) have focused on explaining the recent droughts, and found that the combination of high temperature and low rainfall has contributed to the recent severe droughts but it could not fully explain the observed low flow.

In summary, most of the previous studies on trends in Australian streamflow data have focused only on a few rivers or on a particular region of Australia, with an emphasis on the existence of inter-annual to inter-decadal climate variability and its impact on long term flood risks at local scales. Furthermore, none of the previous studies looked at trends in Australian flood data considering the serial and inter-station correlation covering all of Australia as a study domain. This study fills this gap by focusing on the trend identification in Australian flood data using the most extensive and comprehensive database currently available in Australia (as detailed in Section 2.1). The study also assesses the temporal trends in the Australian AM flood data when the impact of the fluctuations in various modes of climate variability (represented by three large-scale climate indices) has been removed.

2. Data

2.1. Selection of study catchments

Availability of a quality controlled dataset is essential for a meaningful trend analysis (Kundzewicz and Robson, 2004). The annual maximum (AM) flood data series used in this study have been prepared as part of the on-going revision of the regional flood estimation methods in Australian Rainfall and Runoff (I.E. Aust., 2001). The dataset represents the most comprehensive quality-controlled flood series dataset (in terms of temporal and spatial coverage) that is currently available in Australia. In preparing the study dataset, the following criteria were developed to ensure that the study catchments are minimally affected by the land use change and artificial storage, and have a relatively long period of quality-controlled streamflow record.

2.1.1. Data quality

Most statistical analyses of flood data assume that the available data is error free; however, at some stations this assumption may be grossly violated. Stations graded as 'poor quality' or with specific comments by the gauging authority regarding quality of the data were assessed in greater detail, and stations deemed 'low quality' were excluded.

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