The frequency of major flooding in coastal southeast Australia has significantly increased since the late 19th century

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(Manuscript received January 2016; accepted April 2016)

Millions of Australians live in a 1500 km stretch of coastal catchments in southeast Australia. Major flooding in this region causes death, economic loss and major disruptions to the lives of its inhabitants. Concerns have been raised that anthropogenic climate change might lead, or has already led, to an increased risk of extreme rainfall and associated flooding. Images of flooding commonly appear in the media, fuelling perceptions that flood frequency has already increased. Here we use a new dataset that allows us to estimate reliable trends over much longer periods than has previously been the case. The statistical significance of the trends is assessed using a method that is suitable for the non-Gaussian, serially correlated flood frequency data. We identify a statistically significant, increasing trend in the frequency of major floods since the late 19th century, which contributes to a 50% increase in frequency. While possible reasons for the increase are discussed (e.g. land use change, anthropogenic climate change, natural climate variability), further research is needed to clarify the relative importance of possible contributors.

1. Introduction

Concerns have been raised that anthropogenic climate change might increase—or might have already increased—the risk of flooding in some locations in Australia (Reisinger et al. 2014) and beyond (IPCC 2014). Concerns are further fuelled by an increased coverage of flooding in the media (Kundezewicz et al. 2012). Unfortunately, there is low confidence in the scientific community regarding even the sign of observed changes in flood frequency in many places, as flood records in many parts of the world are often sparse in space, and short or interrupted in time (Callaghan and Power 2014, Bates et al. 2008, Seneviratne et al. 2012, Kundzewicz et al. 2014). It is therefore important that flood records around the world be improved and extended back as far as possible using instrumental and other historical records (Kundzewicz et al. 2014).

Given the vulnerability of the region to flooding and the need to improve the documentation of flood trends, it is fortunate and timely that Callaghan and Power (2014) recently described a new uninterrupted record of major flood frequency for a continuous 1500 km stretch of coastal catchments in southeast Australia. The population in this region is growing rapidly and this growth is driving very strong urban development. Major flooding is a major hazard in this region. For example, floods in June 1852 caused at least 90 deaths, while 25 people died during the Brisbane River catchment floods in January 2011 (Callaghan and Power 2014).

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The database containing the flood records took many years to construct. Callaghan and Power (2014) used both instrumental and historical data, including newspapers, for the period 1860–2012. Their study region, which we adopt, extends from Brisbane (the largest city in Queensland) in the north, through Sydney (the largest city in Australia), to Eden (New South Wales; NSW) to the south (Figure 1).

Callaghan and Power (2014) considered a flood to be 'major' in two broad cases: (1) the inundation of a river within approximately 50 km of the coast. A river is regarded as 'inundated' if it causes extensive flooding in rural and/or urban areas. 'Extensive' flooding is characterised by the flooding of buildings above floor level, the isolation of properties and towns, and/or the closure of major rail and traffic routes; (2) non-riverine flooding inundates similar areas overland near the coast from the active part of a weather system, and extends at least 20 km along the coast. If major flooding occurred under (1) or (2) in more than one catchment, it is regarded as a single major flood.

Figure 1 The study region. Map created using the Interactive Data Language (IDL) 383 software, IDL Version 8.1 EULA http://www.exelisvis.com/Portals/0/pdfs/eula/IDL_81_EULA_2012.pdf

In an attempt to produce homogeneous records of major flood frequency, Callaghan and Power (2014) restricted attention to the period from 1860, when the region (i) is extensively populated, (ii) has extensive coverage of meteorological stations, (iii) is extensively connected by telecommunication, and (iv) has a busy coastal shipping offshore. In this paper we first extend the dataset described previously, to include more recent years, and we examine trends in the frequency of major floods.

Previous research indicates that there is a great deal of variability in eastern Australian streamflow, flooding and flood risk on interannual (Chiew et al. 1998, Power et al. 1999, Kiem et al. 2003, Verdon et al. 2004, Power and Callaghan 2016), and decadal/multidecadal timescales (Power et al. 1999, Franks 2002; Kiem et al. 2003, Power and Callaghan 2016). Much of the interannual variability is due to the El Niño–Southern Oscillation (Chiew et al. 1998, Power et al. 1999, Kiem et al. 2003, Verdon et al. 2004, Kiem et al. 2001, 2003, Pui et al. 2011, Power and Callaghan 2015). Much of the decadal/multidecadal variability is due to the Interdecadal Pacific Oscillation (IPO; Chiew et al. 1998, Power et al. 1999, Franks 2002, Kiem et al. 2003, Verdon et al. 2004, Franks and Kuczera 2002, Henley et al. 2015, Micevski et al. 2006, Christensen et al. 2013, Kiem and Verdon-Kidd 2013, Power and Callaghan 2016).

The importance of the IPO to flood variability means that even multidecadal data might not be long enough to estimate longer-term trends. The availability of the new dataset is therefore useful because it allows us to determine reliable flood trends over much longer periods than has been possible in Australia previously.

2. Methods

2.1 Updating the dataset

Callaghan and Power (2014) included a description of major coastal floods in the same study region from January 1860–December 2012. They identified 253 major floods. Three additional major floods occurred during the period January 2013–December 2014: Event Number 254 occurred on 27–28 January 2013 in the Brisbane creeks, Lockyer Valley and Grafton; Event Number 255 occurred on 23–24 February 2013 on the mid-North Coast of NSW, and Event Number 256 occurred on 1–3 March 2013 in the Hunter Valley.

2.2 ENSO years

In this paper we use 'ENSO years', defined here as the period May in one year to April in the following calendar year. This choice reflects the typical life-cycle of ENSO events (i.e. both El Niño and La Niña events), which tend to grow mature, erode and end within this period (Power and Smith 2007). We use the first year in the period to refer to that period, so that '1860', for example, is used to refer to the period April 1860–May 1861. The analysis described covers the period 1860–2013.

2.3 Assessing the statistical significance of trends

The statistical significance of trends is tested using two different methods. Both methods take serial correlation into account. The first method is described by Power et al. (1998). This method is ideally suited to red or white noise data that are normally distributed. The relative frequency of the major flood data (Figure 2a) deviates from this assumption and so an additional test on statistical significance is conducted. The second approach is a Monte Carlo method that incorporates information on both the relative frequency of the data, and its temporal persistence. The first datum (the randomly generated number of major floods in the first year, i.e., 1860) is generated by randomly selecting from the relative frequency distribution of the major flood data for the period 1860–2013 presented in Figure 2a. In order to incorporate persistence in the synthetic data, subsequent data is randomly selected from one of three additional relative frequency distributions (Figure 2b). These three distributions are also based on the observational data. However, each depends on the number of major floods in the previous year. The first distribution is based on the number of floods in years immediately preceded by years with zero or one floods. The second distribution is based on flood data in years immediately preceded by years with two or three floods. The third and final distribution is based on the number of floods in years immediately preceded by years with four or more floods. The (i) first, (ii) second, or (iii) third distribution is used to generate the number of major floods in a given year if the randomly generated number of major floods in the preceding year is (i) zero or one, (ii) two or three, or (iii) four or more, respectively.

Three thousand randomly selected artificial timeseries of major flooding for the period 1860–2012 are generated in this way. The average value of the autocorrelation coefficient of the simulated data at a one-year lag is 0.15, which compares favourably with the observational value of 0.14. The magnitude of the observed trend in major floods over the period 1860–2012 is only simulated in less than or equal to 2% of cases, giving a *p-value* of 0.02. This compares favourably with the *p-value* obtained using the 'first' method (i.e., 0.04, Table 1).

This entire approach, beginning with a re-calculation of all four of the relative frequency distributions, was repeated for the periods 1890–2013 and 1900–2013.

The significance of the results is expressed as a *p-value*. The *p-value* is equal to the estimated probability that the magnitude of the observed correlation coefficient can be exceeded in magnitude by chance, under the assumption that the data can be approximated as a red-noise process (Power et al. 1998). Trends with *p-values* less than or equal to 0.05 are referred to as 'statistically significant'.

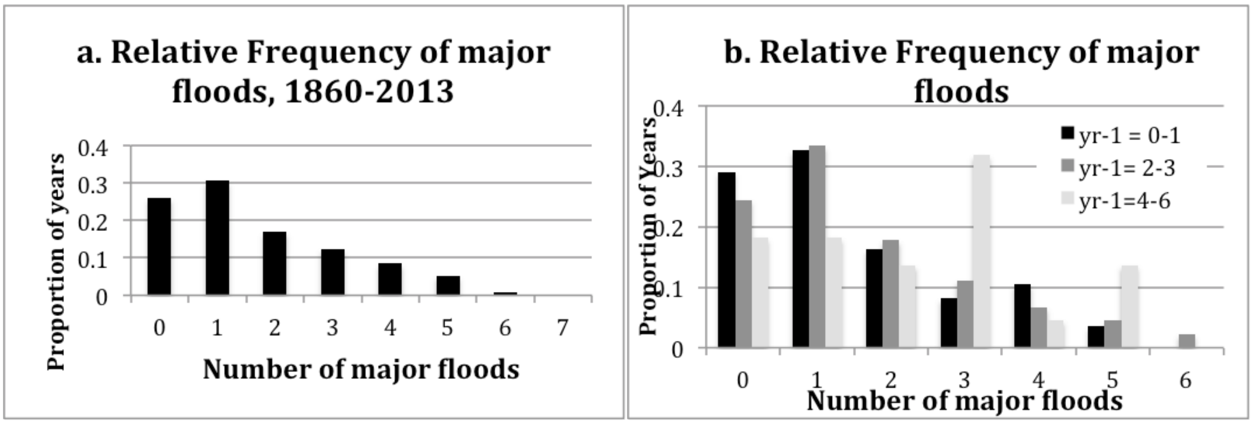

Figure 2 Relative frequency of major floods (proportion of years): (a), 1860–2013, (b) for three different subsets of the data. The three distributions in (b) are used in the Monte Carlo tests for statistical significance, to help incorporate observed temporal persistence. The first distribution (black) is based on the number of major floods in years immediately preceded by years with zero or one major floods. The second distribution (dark grey) is based on major flood data in years immediately preceded by years with two or three major floods. The third and final distribution (light grey) is based on the number of major floods in years immediately preceded by years with four or more major floods.

3. Results

The number of major floods per year (Figure 3) varies between a minimum of zero and a maximum of six. There is a good deal of variability from year-to-year, decade-to-decade and on longer timescales.

An increasing trend is also evident. The numerical value of linear trends in the number of major floods for three different periods—(a) 1860–2013, (b) 1890–2013, and (c) 1900–2013—are given in Table 1. These different periods are considered because they correspond to (a) the full length of the dataset, (b) a period for which we have confidence in the homogeneity of the dataset, and (c) a period for which we have high confidence in homogeneity, and extreme rainfall analyses are available for comparison.

There is a statistically significant (i.e. *p-value* $\leq$ 0.05) increasing trend in major flood frequency over the full period. This is true for two different estimates of statistical significance, both of which take serial correlation into account. The trends are large compared with the long-term average. For example, the 1860–2013 trend is *0.6 major floods/century*, while the long-term average over the same period is *1.6 major floods/year*. This trend contributes to a marked increase in the long-term average value from *1.3 major floods/year* in the first half of the record to *2.0 major floods/year* in the second half, a 50% increase.

Period	*Major floods/century*
1860–2013	0.60 (0.04, 0.02)
1890–2013	0.79 (0.05, 0.05)
1900–2013	1.0 (0.02, 0.03)

Table 1 Trends (per century) in the frequency of major floods, for three different periods. The *p-values* (given in brackets) are estimated using the two different techniques. The first figures in brackets are obtained using the technique described by Power et al. (1998), the second figures using the Monte Carlo technique outlined in Section 2. All trends are statistically significant.

Callaghan and Power (2014) used rainfall data to help identify many of the major floods. The spatial coverage of such data is more limited in the early part of the record, and this can lead to inhomogeneity in the ability to detect major floods. By 1890 the coverage of rainfall stations in the study region is much improved, and so trends for the period 1890–2013 are also shown. The sign of the trend remains the same, and the trend remains statistically significant (Table 1).

An increasing trend in the frequency of major flooding can occur if there is an increase in the frequency of extreme rainfall events. The trend in (a) 99th percentile daily rainfall amount (mm/century) at stations over Australia is presented in Figure 4a for the period 1900–2013. The stations used all have high quality daily rainfall records of sufficient quality, completeness and length to calculate reliable trends. The overwhelming majority of sites in the study region show increasing trends, and all but one of the sites closest to the coast show an increasing trend. Trends in the highest amount of daily rain received each year (Figure 4b) are also positive in the majority of sites in the study region.

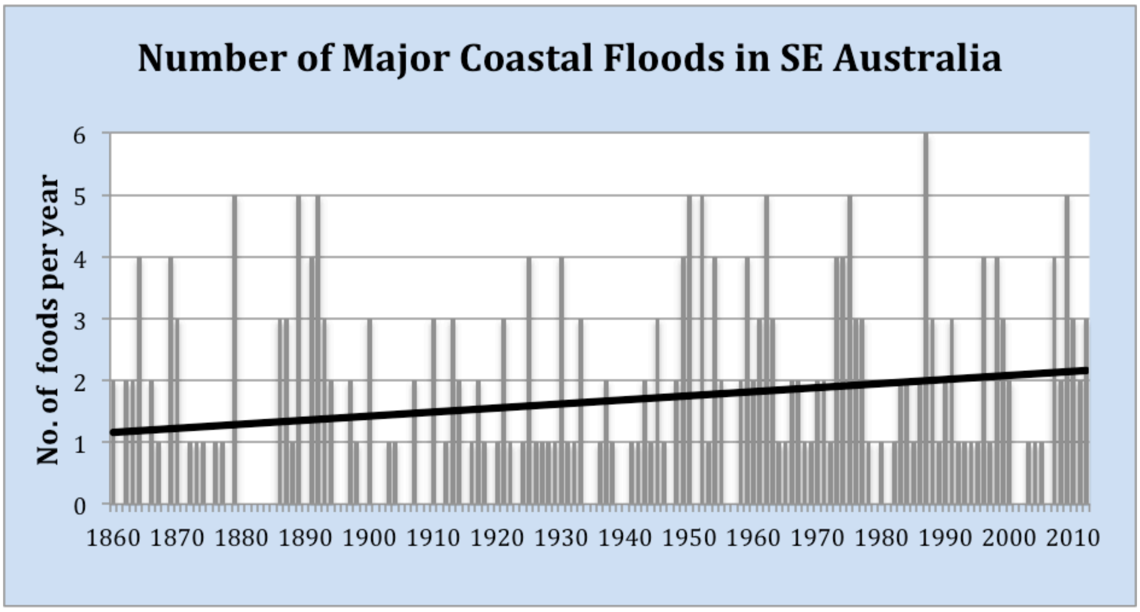

Figure 3 Number of major floods per year. The linear trend line is also shown.

Note that the rainfall records used in Figure 4 are relatively sparse, and both 99th percentile rainfall and highest daily rainfall in each year both occur much more often (i.e. are often less extreme) than the rainfall associated with the major floods we consider. The trends depicted in Figure 4 are nevertheless generally—though not entirely—consistent with the hypothesis that an increase in the amount of rain falling during extreme events contributed to the increasing trend in the frequency of major flooding. This is further supported by the fact that the trend in major flood frequency over the same period as the rainfall data (i.e. 1900–2013) is statistically significant (Table 1).

An increasing trend is consistent with the conclusion that extremes of intense precipitation, over various time intervals, are increasing in more places around the globe than not (e.g. Donat et al. 2013). An increase in the proportion of heavy rainfall has also been detected over Australia (Braganza et al. 2015). The fraction of Australia receiving a high proportion (greater than the 90th percentile) of annual rainfall from extreme rain days (greater than the 90th percentile for 24 hour rainfall) has been increasing since the 1970s (Gallant et al. 2013). However, significant regional variability exists (Braganza et al. 2015). For example, an eastern section of NSW and Queensland, with some overlap with the study region we use, experienced a significant decrease in extreme (99th percentile) rain events since 1950–2005 (Gallant et al. 2014).

These previous studies use shorter periods than we do. They also examine changes in events that occur more frequently than major flooding in a given region. For example, the most extreme index used in these previous studies (e.g. by Gallant et al. 2013), for example, is a 99th percentile. Thus on average approximately 3.6 such events occur each year at every location. So in 150 years—the approximate length of data we analysed—this gives 540 events at every location. On the other hand, the number of major floods that occurred in the Brisbane/Gold Coast/Tweed River region, for example, was approximately 65 over the same period. This is approximately an order of magnitude less frequent than a 99th percentile rainfall event. We are therefore examining events that are rarer, and very likely much rarer, than previous researchers.

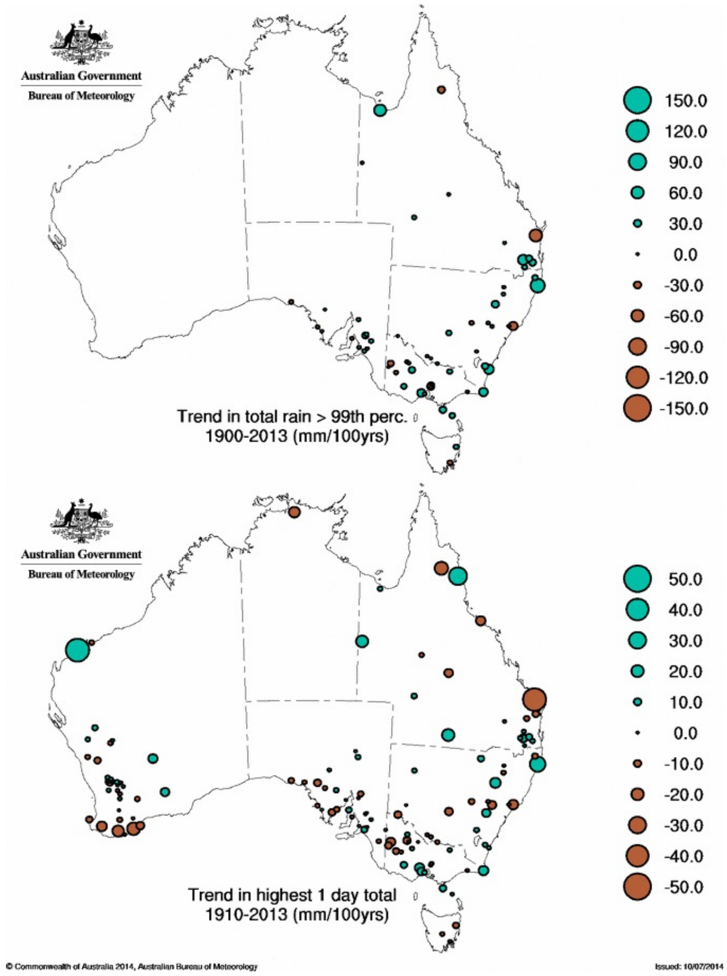

Figure 4 Trend in (a) total rainfall above the 99th percentile in each year, and (b) highest one day total in each year. 1900–2013. Source: Bureau of Meteorology http://www.bom.gov.au/climate/change/index.shtml#tabs=Tracker&tracker=extremes-trend-maps&tQ(map)=R99p&tQ(period)=1910 and http://www.bom.gov.au/climate/change/index.shtml#tabs=Tracker&tracker=extremes-trend-maps&tQ(map)=RX1d&tQ(period)=1910.

4. Discussion

Various factors can contribute to long-term trends in flood records (Bates et al. 2008, Kundzewicz et al. 2014, Sereviratne et al. 2012). For example: (1) changes in our ability to detect major floods over time; (2) naturally occurring climatic variability on multidecadal and longer timescales; (3) a possible increase in the intensity and frequency of rainfall extremes in response to anthropogenic warming of the planet (IPCC 2013, IPCC 2014); (4) urbanisation giving rise to greater runoff; and (5) from dams and engineering activity specifically aimed at reducing flood risk. Other factors that can potentially affect major flooding include (6) bushfire, (7) deforestation, (8) afforestation and (9) other land-use change in catchments. We will now consider the contributions these factors might have made to the observed, statistically significant increase in the frequency of major floods over 1860–2013, 1890–2013, and 1900–2013, beginning with (1), that is, changes in our ability to detect major floods over time.

The availability of the National Library of Australia newspaper archive provides an efficient and effective mechanism to identify major floods that occurred from 1860. However, inhomogeneity could arise if major floods were not reported in the newspapers. These days, major floods are always reported in newspapers. Major floods in the early years were also highly newsworthy because they tended to have a greater impact than in more recent years for several reasons. First, roads and bridges were far inferior to roads and bridges today, and they were more often located at lower levels near riverbanks. They were consequently more likely to be cut, and to be cut earlier on, when major floods occurred, causing disruption. Second, settlers resided near riverbanks because water was plentiful and the alluvial soil was good for cropping. This resulted in large numbers of drownings when major floods occurred (Callaghan and Power 2014). This continued through to the Depression, when poor families moved to riverbanks and lived in tents. These impacts and their newsworthiness increased the likelihood that the major floods were reported in newspapers at the time.

Callaghan and Power (2014) also went to a great deal of trouble to maximise the homogeneity of the record of major floods. They increased the likelihood that the major floods were reported by restricting attention to a period and location (i) that is extensively populated, (ii) has an extensive coverage of meteorological stations, (iii) is extensively connected by telecommunication, and (iv) when there is busy coastal shipping offshore (as noted above). They located all available river height records and augmented this with additional events identified in newspaper reports.

In order to identify major floods over and above those in official river height records they conducted a search and analysis of other information sources. They first noted the occurrence of major weather systems in the study region identified previously (Public Works Department 1985, Callaghan and Helman 2008). They then examined rainfall records, as well as newspaper reports archived in the Australian National Library. The latter included official reports from the Chief Astronomer and Chief Meteorologist or official government observers in remote areas at the time. This allowed Callaghan and Power (2014) to ascertain whether or not major flooding occurred in association with these weather events, or if major floods might have occurred in cases where corresponding river height information was incomplete or unavailable. They also identified additional major weather events not listed previously. Callaghan and Power (2014) were therefore able to develop a record of the occurrence of major weather for every day impacting the region back to 1860. They then examined rainfall records for each of these days and then newspapers for all of these days they found to have extremely high and widespread rainfall.

This process revealed floods associated with extremely high rainfall over a broad area and/or widespread flood damage. Callaghan and Power (2014) therefore included these events in their list of major floods. They identified a total of 253 major floods between 1860 and 2012. Of these 191 have river height records while the remaining 62 were ‘proxies’. While great care was taken, the partially subjective nature of the process means that there is no guarantee that all major floods have been included or that all of the events included were actually major floods. In fact Callaghan and Power (2014) identified additional events in which major flood events might have occurred, but as the evidence was not as strong they did not include them in their analysis. It is interesting to note that the frequency of such events increased markedly over time. In fact there were only 17 such events during 1860–1950, but 62 events during 1951–2012. So if such events were included in our analysis they would actually strengthen the increasing trend, not weaken it.

Information in the last two paragraphs increases confidence (i) in the detection of major floods by Callaghan and Power (2014), and (ii) that the increasing trends across the region over 1890–2013 (and 1900–2013) are genuine and do not merely reflect an increase in our ability to detect major floods.

The increase in flood frequency will have a contribution from (2) naturally occurring climate variability and possibly from (3) increases in the frequency and intensity of rainfall extremes in response to anthropogenic warming (Reisinger et al. 2014, IPCC 2013, IPCC 2014, Whetton et al. 2014). Projected increases in extreme rainfall over Australia (and elsewhere) tend to be larger and more robust the more extreme the rainfall index used (Whetton et al. 2015). Given that we are examining events that only occur once every two-to-three years or so on average in a particular region, we are looking at events that are certainly extreme in the context described previously by Whetton et al. (2015). For comparison, a 99th percentile event would occur approximately *3.6 times per year*, i.e., about an order of magnitude more frequently. We would therefore expect the anthropogenic influence on such events to be greater than less extreme events.

Further evidence for an anthropogenic role in the observed increase in the frequency of major flooding is provided by the latest IPCC report (2014) which concluded that '*Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent by the end of this century, as global mean surface temperature increases*'. More recently Dowdy et al. (2015) concluded that there is high confidence in a projected increase in the frequency of extreme rainfall throughout the eastern seaboard of Australia. These and other consistent conclusions (Reisinger et al. 2014) relate to future changes. However, we know that the world has already warmed up in response to past increases in greenhouse gases (IPCC 2013, IPCC 2014), as has Australia (Braganza et al. 2015). This implies that anthropogenic climate change might already be partially responsible for the observed increase in the frequency of heavy rainfall in some—though not all—of the locations the study region (see Figure 4). We therefore conclude that anthropogenic climate change might have contributed to the observed increases in extreme rainfall amounts and that this might, in turn, have contributed to the increase in major flood frequency as discussed above. However, further research is needed to confirm the extent of this influence.

As noted previously (Callaghan and Power 2014), river floods in the study region have been mitigated in some places by increasing discharge rates through dredging and removing rock outcrops etc., and by building dams to store floodwaters. This mitigation has been offset to some extent by an increase in urban runoff, caused by growth in urban areas, especially during the last 40 years. Dams have been constructed throughout the study region. For example, the Warragamba Dam on the Nepean-Hawkesbury River System was opened in 1960. The Warragamba Dam slows the release of flood waters into downstream areas. In 1961, floodwaters coming from the Warragamba River were reduced by a quarter and delayed by several hours. Other large dams in the study region in the Brisbane River System include Somerset Dam (opened in 1953) and Wivenhoe Dam (opened in 1985). It is therefore likely that human interventions of this kind have offset the increasing trend in major flooding identified in this study to an extent. However, major floods often occur simultaneously in more than one river system and some rivers have not been dammed. As simultaneous flooding across different river systems is counted as a single event, the impact of damming on the trend in the frequency of major flooding is likely small. Moreover, contribution (5) will reduce the number of major floods over time, not increase it, and so (5) is certainly not responsible for the increasing trend in major floods we identify.

The extent to which (4), urbanisation giving rise to greater runoff, contributed to the increasing trend is unclear. Nor is it possible for us to quantify the possible contribution of (6) bushfire, (7) deforestation, (8) afforestation and (9) other land-use change in catchments to the trend in the frequency of major floods identified.

5. Conclusions

In summary, we have established that there is an increasing trend in the frequency of major flooding in the study region since the late 19th century. Given the importance of major flooding to the region and its growing population, additional research to further clarify the cause of the increasing trend, including the extent to which anthropogenic climate change might have contributed, is therefore a priority.

Acknowledgements

We wish to thank Anthony Kiem and Allie Gallant for reviewing an earlier draft. The data used are in this investigation are comprised of the data presented by Callaghan and Power (2014) and the data described in Section 2.

References

Bates, B.C., Kundzewicz, Z.W., Wu, S. and Palutikof J.P. (eds.) *Climate Change and Water*. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp., 2008.

Braganza, K., Murphy, B., Timbal, B., Hope, P., Dowdy, A., Hennessy, K., Bhend J., and Kirono, D. 2015. Chapter 4—Understanding Australian climate. In: CSIRO and Bureau of Meteorology 2015, *Climate Change in Australia Infor-*

mation for Australia's Natural Resource Management Regions: Technical Report, CSIRO and Bureau of Meteorology, Australia, 216 pp.

Callaghan, J. and Helman, P. 2008. *Major Storms on the East Coast of Australia 1770–2008,* Griffith Centre for Coastal Management, Griffith University, Gold Coast Queensland.

Callaghan, J. and Power, S.B. 2014. Major coastal flooding in southeastern Australia 1860–2012, associated deaths and weather systems. *Aust. Meterol. Oceanogr. J.*, 64, 183–213.

Chiew, F.H.S., Piechota, T.C., Dracup, J.A. and McMahon, T.A. 1998. ENSO and Australian rainfall, streamflow and drought: Links and potential for forecasting. *J. Hydrol*., 204, 138–149.

Christensen, J.H. Kanikicharla, K.K. Aldrian, E., An, S.-I., Cavalcanti, I.F.A., de Castro, M., Dong, W., Goswami, P., Hall, A., Kanyanga, J.K., Kitoh, A., Kossin, J., Lau, N.-C., Renwick, J., Stephenson, D.B., Xie, S.-P. and Zhou, T. 2013. Climate Phenomena and their Relevance for Future Regional Climate Change. In Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. (eds.): *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Donat, M., Alexander, L.V., Yang, H., Durre, I., Vose, R., Dunn, R.J.H., Willett, K.M., Aguilar, E., Brunet, M., Caesar, J. and Hewitso, B. 2013. Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset. *J. Geophys. Res. – Atmospheres*, 118, 2098–2118.

Dowdy, A.J., Grose, M.R., Timbal, B., Moise, A. and Ekström, M. 2015. Rainfall in Australia's eastern seaboard: a review of confidence in projections based on observations and physical processes. *Australian Meteorol. Oceanogr. J*., 65, 107–126.

Franks, S.W. 2002. Identification of a change in climate state using regional flood data. *Hydrol. Earth System Sci.*, 6, 11–16.

Franks, S.W. and Kuczera, G. 2002. Flood frequency analysis: Evidence and implications of secular climate variability, New South Wales. *Water Resources Research,* 38, 10.1029/2001WR000232.

Gallant, A.J.E., Reeder, M.J., Risbey J.S. and Hennessy, K.J. 2013. The characteristics of seasonal-scale droughts in Australia. *I. J. Climatol*., 33, 1658–1672.

Gallant, A.J.E., Karoly, D., and Gleason, K. 2014. Consistent trends in a modified climate extremes index in the United States, Europe, and Australia. *J. Climate*, 27, 1379–1394.

Henley, B.J., Gergis, J., Karoly, D.J., Power, S., Kennedy J. and Folland, C.K. 2015. A tripole index for the Interdecadal Pacific Oscillation. *Climate Dynamics*, 45, 3077–3090.

IPCC, 2013. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.* In Field, C.B. et al. (eds.): A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

IPCC, 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Core Writing Team, R. K. Pachauri and L .A. Meyer (eds.)). IPCC, Geneva, Switzerland, 151 pp.

Kiem, A.S., Franks S.W. and Kuczera, G. 2003. Multi-decadal variability of flood risk. *Geophys. Res. Lett*., 30, doi:10.1029/2002GL015992.

Kiem, A.S. and Franks, S.W. 2001. On the identification of ENSO-induced rainfall and runoff variability: a comparison of methods and indices. *Hydrol. Sci. J.*, 46(5), 715–728.

Kiem, A.S. and Verdon-Kidd, D.C. 2013. The importance of understanding drivers of hydroclimatic variability for robust flood risk planning in the coastal zone. *Australian J. Water Resources*, 17, 126-134.

Kundzewicz, Z.W., Plate, E.J., Rodda, H.J.E., Rodda, J.C., Schellnhuber, H.J. and Strupczewski, W.G. 2012. F, Flood risk in Europe—setting the stage. In: Z.W. Kundezewicz, ed. *Changes in flood risk in Europe*. Wallingford: IAHS Press, 11–26.

Kundzewicz, Z.W., Kanae, S., Seneviratne, S.I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L.M., Arnell, N., Mach, K. and Muir-Wood, R. 2014. Flood risk and climate change: global and regional perspectives, *Hydrological Sciences Journal*, 59, 1–28, DOI: 10.1080/02626667.2013.857411.

Micevski, T., Franks S.W. and Kuczera, G. 2006: Multidecadal variability in coastal eastern Australian flood data. *J. Hydrology*, 327, 219–225.

Power, S.B. and Smith, I.N. 2007. Weakening of the Walker Circulation and apparent dominance of El Niño both reach record levels, but has ENSO really changed? *Geophys. Res. Lett*, 34, doi: 10.129/2007/GL30854.

Power, S.B. and Callaghan, J. 2016: Variability in severe coastal flooding in south-eastern Australia since the mid-19th century, associated storms and death tolls. *J. Applied Meteorol. Climatol*., 55, 1139–1149. doi: 10.1175/JAMC-D-15-0146.1

Power, S., Casey, T., Folland, C., Colman A., and Mehta, V. 1999. Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dynamics*, 15, 319–324.

Power, S., Tseitkin, F., Torok, S., Lavery, B. and McAvaney, B. 1998. Australian temperature, Australian rainfall, and the Southern Oscillation, 1910-1996: Coherent variability and recent changes. *Aust. Meteorol. Mag*., 47, 85–101.

Public Works Department, 1985. Elevated ocean levels and storms affecting the New South Wales coast 1880 to 1980, *Report 85041*, Coastal Section, Public Works Department NSW, Sydney, Blain Bremner and Williams Pty Ltd.

Pui, A., Lala, A. and Sharma, A. 2011: How does the Interdecadal Pacific Oscillation affect design floods in Australia? *Water Resources Research*, 47, doi:10.1029/2010WR009420.

Reisinger, A., Kitching, R.L., Chiew, F., Hughes, L., Newton, P.C.D., Schuster, S.S., Tait, A. and Whetton, P. 2014. Australasia. In Barros, V.R. et al. (eds.): *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects*. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1371–1438.

Seneviratne, S.I., Nicholls, N., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M. and Reichstein, M. 2012. Changes in climate extremes and their impacts on the natural physical environment. In Field, C.B. et al. (eds.): *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. A Special Report of WGs I and II of the IPCC. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 109–230.

Verdon, D.C., Wyatt, A.M., Kiem A.S. and Franks, S.W. 2004. Multidecadal variability of rainfall and streamflow: Eastern Australia. *Water Resources Research*, 40, doi:10.1029/2004WR003234.

Whetton, P., Moise, A., Kirono, D., Rafter, T., Wilson, L., Hennessy, K., Bhend, J., Hope, P., Timbal, B., Dowdy, A., Watterson, I., Grose, M., Narsey S. and Bathols, J. 2015. *Rainfall*, in: Chapter 7, *Projections: Atmosphere and the Land*, In Ekström, M. et al. (eds.): CSIRO and Bureau of Meteorology 2015: *Climate Change in Australia. Information for Australia's Natural Resource Management Regions: Technical Report*, CSIRO and Bureau of Meteorology, Australia, 216 pp.