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How and why are floods changing in Australia?

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One of the open questions about climate change is how future flood risk in Australia will change. Although changes to rainfall extremes are expected in most locations, it is not clear how these changes translate into flood risk due to the potential additional feedback of altered catchment characteristics (e.g., storage volumes, soil moisture, vegetation cover and fire disturbance) on runoff *due to the changing climate and/or direct human-led changes. Flood damages have increased over the instrumental period in Australia, but it is not known if this is due to changes in population densities, increased infrastructure in flood prone locations (the exposure), improved reporting or actual changes in the occurrence of flood-producing meteorological events (the hazard).*

This paper reviews the existing literature on historical and expected future flooding in Australia, focusing on the flood hazard. Trends and changes in flood-producing mechanisms are also reviewed. Three flood case studies, namely the 2007 Pasha Bulker storm, the flood characteristics of the Fortescue Marsh area in the Pilbara and the 1956 Murray River floods are used to highlight the complexities of flood behaviour and to illustrate remaining challenges.

We show that short instrumental records, large natural variability and the interrelated nature of other catchment changes limit our ability at this stage to understand how the flood hazard has changed in the historical period. Research efforts to both address this gap and continue to develop methods to best use projections from climate models are required to quantify future flood hazard. This information can then serve as an input to risk models that combine flood hazard with projections information, flood exposure and vulnerability.

1. INTRODUCTION

Floods are one of the most dangerous natural hazards, with thousands dying each year, millions affected and annual average costs into the hundreds of millions of dollars (Guha-Sapir et al., 2015). Australia experiences similar rates of disaster occurrence as other countries, but it experiences significantly fewer deaths when compared to developing countries (Kahn, 2005). Australia-wide, the overall death rate due to floods decreased from around 24 per 100,000 people per decade in the 1800s, to 0.04 per 100,000 per decade during the 1990s and the first decade of the 21st century (Attorney-General's Department, 2013). Estimates of the annualised total cost of floods in Australia are $US 300-400 million (Bureau of Transport Economics, 2001, Guha-Sapir et al., 2015) with variation due to event classification and methods for estimating indirect costs.

Analyses of flood damages find increases since 1960 in Australia (e.g. Guha-Sapir et al., 2015), but it is difficult to establish whether these are due to changes in reporting mechanisms, changes to the population and infrastructure and thus the community and assets exposed to floods, or to changes in the frequency and magnitude of the flood hazard. Schuster (2013) demonstrates that there are significant increases in the insurance losses from meteorological hazards whereas there is little increase in losses due to earthquakes over the same period. Assuming that exposure is similar for both, this suggests that there are changes to the frequency or magnitude of flood-causing mechanisms; however, the assumption of exposure similarity has been questioned by Bouwer (2011) and further investigation is warranted.

This paper reviews our understanding of historical flood risk and the current state of knowledge in potential future changes to flood risk. This work has been undertaken as part of the OzEWEX (www.wenfo.org/ozewex/) working group on Trends and Extremes with similar research occurring in a range of other natural hazards including bushfires, drought, coastal extremes, heatwaves, frost and storms. The aim of this series of work is to establish what is known and unknown about natural hazards in Australia so as to establish future research directions for the Australian science and engineering communities.

2. OBSERVED TRENDS IN FLOODS, RAINFALL AND CATCHMENTS

The most comprehensive study of flood trends in Australia to date was undertaken by Ishak et al. (2013) using a database of annual maximum flow compiled as part of the Australian Rainfall and Runoff revision projects (Engineers Australia, 1987). The stations were chosen based on the small amount of regulation and land use change as well as reasonably long records, giving a total database of 330 catchments. 20 to 30% of stations were found to have significant decreasing trends (depending on the length of record available for analysis). This was more than the number of stations with significant positive trends (2 to 5%). When the dry decade at the end of the analysis period was removed (i.e., analysis to 1995 instead of 2004) then the number of stations with negative trends was between 10 and 20% showing the important impact of interannual variability in such analyses. Modelling the association of the trends with large scale drivers of Australian climate such as the Southern Annular Mode (SAM), the El Niño Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) (Risbey et al., 2009) further reduced the number of statistically significant trends, showing that these drivers explain much of the variability in Australian flood records. This single study suggests that given there is minimal evidence for increasing trends in flooding, increases in flood related damages may be attributed to changes in reporting or exposure. Further work is needed to confirm this finding.

However there are still very few long-term baselines that allow robust assessment of changes in flood magnitudes and frequency against the highly variable natural background for most of the continent, as well, or to integrate potential large-scale climatic drivers in future predictions (Frederiksen and Grainger, 2015, Frederiksen et al., 2014). In this regard, the database of floods on the southeastern coast of Australia prepared by Callaghan and Power (2014) should prove useful for examining flood trends due to its length (1860-2012) and because flood hazard is quantified through the number of deaths associated with each event.

In addition to trends in rainfall extremes, flood risk in Australia is influenced by the regional climatology and altered catchment characteristics (e.g., stored versus depleted volumes of soil moisture/groundwater, vegetation cover, disturbances of bushfires and landuse changes). Urbanisation is known to increase flood risk in a number of ways (Shuster et al., 2005), including through increases in impervious areas as well reduced infiltration in pervious areas. These lead to increases in the flood volume, higher peak flows and earlier time to peak. Flash flooding in particular is affected by urbanization, given the high and increasing proportion of the population in coastal catchments which tend to be small and have high rainfall intensities (National Sea Change Taskforce, 2011). Some local authorities are better at mitigating these urbanisation impacts than others and in some cases planning laws and development plans have been relaxed to allow for greater development (Gurran et al., 2013).

In rural areas changes in vegetation (e.g., land clearing, plantation growth, grazing and bushfires) can also affect flood risk via feedback mechanisms on catchment runoff. For instance, Pena-Arancibia et al. (2012) showed a small increase in catchment flood response after large-scale tree clearing in inland Queensland. Most other empirical analyses of this nature have considered mean catchment yield or low flows for water supply purposes (Brown et al., 2005) rather than peak flows. More research is needed to examine these issues in detail.

3. FUTURE CHANGES IN FLOODS, RAINFALL AND CATCHMENTS

General Circulation Models (GCMs) combined with statistical and dynamical downscaling are the most common way to consider the likely future changes in the hydrologic system (Fowler et al., 2007). However, when it comes to future flood risk there is a definite research gap for a number of reasons.
Assessing changes in flood risk is difficult because projections of rainfall extremes, particularly at sub-daily durations are considered "unreliable due to issues around model resolution and convection parameterization" (Westra et al., 2014). Australian catchments also range in size from small urban catchments to large multi-state basins and have varying degrees of regulation, urbanization and other modifications. It has been concluded that there is low confidence in GCM-based assessments of changes in flood risk (Kundzewicz et al., 2013).

As a starting point to overcome the catchment scale discrepancies, assessments of future flood risk have tended to be global scale studies and use daily rainfall with global river routing models or grid-based analyses. The Murray-Darling Basin has been modelled in some of these assessments but the limitations are the small number of climate models and scenarios adopted (e.g. Hirabayashi et al., 2008). More recent work has considered more models and scenarios to assess changes in the 1 in 100 year AEP event (Hirabayashi et al., 2013) but found considerable uncertainty in projections for the Murray-Darling system due to the differing future projections from the climate models used. There are also serious concerns with the representation of interannual variability in climate models (Johnson et al., 2011) which has implications for correctly modelling flood occurrence and magnitude in the future in Australia.

Arnell and Gosling (2014) also point out that these assessments do not consider small rivers or flash flooding in urban areas. With respect to the urban flood risk, increases in floods are generally expected because in these areas antecedent conditions have less relevance due to the relatively large proportion of impervious areas. However the gauging of small urban catchments has historically been relatively poor, making it more difficult to undertake any analyses on these areas.

The most recent synthesis of rainfall changes in Australia based on GCMs has shown increases in all regions in annual maximum rainfall even when median annual rainfall is projected to decrease (CSIRO and Bureau of Meteorology, 2015). Despite high confidence in such projections (due to good understanding of physical mechanisms) fine scale and high intensity events are unlikely to be well simulated by GCMs, as some important processes are not explicitly resolved. Westra et al. (2014) pointed out that fine resolution regional climate models are required for these sorts of assessments because these are capable of allowing convection to occur and may therefore more realistically represent the mechanisms that lead to sub-daily rainfall extremes and in particular flash flooding. Such conclusions are based on recent work by the UK Met office where a very fine (1.5 km) resolution simulation gave improved forecast skill in hourly rainfall characteristics relative to a coarser (12 km) regional climate model (Kendon et al., 2014). However, there has only been limited work in Australia (e.g. Argüeso et al., 2013), due to the computational burden of running such models. Recent advice from Engineers Australia (2014) suggests that a 5% increase in rainfall intensities per degree of local warming should be adopted for sensitivity analyses and/or design of engineering projects in Australia where cost benefit ratios suggest that climate change should be incorporated.

There is limited research into the other changes in catchments and society that may affect future flood hazards. Increases in overall population and changes in population density in coastal areas (National Sea Change Taskforce, 2011) are likely to increase the number of people exposed to floods and in particular flash flooding in small urban catchments. Potential future changes in rural areas include forest plantations and changes in agriculture and irrigation practices. However the impacts of these on flood risk have not been investigated and should be an area of future research. For example the Murray-Darling Basin Plan does not explicitly consider climate change, only climate variability, even though changes to management of the Basin have impacts over decadal timeframes (Murray Darling Basin Authority, 2015).

4. CASE STUDIES

The relationships between the catchment characteristics and changes in the amount, frequency, timing and intensity of rainfall are complicated. Short records and spatially sparse gauging densities do not help in exploring the temporal and spatial patterns of flood risk. The following three case studies have been chosen to illustrate the interactions between these features in greater detail and to highlight the open research questions that are presented in the final section of this paper.

4.1. 2007 Pasha Bulker storm

The 2007 Pasha Bulker storm illustrates some of the complicated interactions that can lead to serious flooding. The overall cause of the flood event was an East Coast Low (ECL) system that developed off the NSW central coast in June 2007. There were three main impacts of the event including:

1. Flash flooding in Newcastle and the Central Coast
2. High winds and large wave heights
3. Hunter River flooding

ECLs occur relatively frequently off the New South Wales coast (Pepler et al., 2014) and the 2007 event was not particularly severe (Verdon-Kidd et al., 2010), however there were 9 deaths and over $1.5 billion damage (Mills et al., 2010). The severity of the event was influenced by the interaction of a number of factors. There were five ECLs in June 2007 which is rare but not unprecedented (Verdon-Kidd et al., 2010). It has been conjectured that the ECLs developed due to favourable conditions in the upper atmosphere and high sea surface temperatures as a result of the La Niña event (Verdon-Kidd et al., 2010). However, Pepler et al. (2014) found that there was little relationship between ENSO and

ECLs and showed a stronger relationship between the SAM and ECL-driven rainfall in cool season months. The flash flooding in the urban areas of Newcastle and the Central coast was caused by a band of convective clouds within the ECL, leading to several hours of very intense rainfall (Mills et al., 2010). The flash flooding was found to have an annual exceedance probability of around 1% (Verdon-Kidd et al., 2010). The impacts associated with the extreme rainfall event were exacerbated by blockage from debris as well as features of the urban environment such as embankments and property fences.

The Hunter River flood impacts from the event were a result of widespread areas with rainfall totals in some locations of over 400 mm (Mills et al., 2010, Verdon-Kidd et al., 2010) over a period of 3 days. For context, the mean June rainfall at Nobbys Head (Bureau of Meteorology Stn 061055) in Newcastle is 116 mm. Verdon-Kidd et al. (2010) note that the high flows were a result of the area of maximum rainfall being centred on a highly developed part of the coast. However the damages and hazards to human populations were not as severe from this part of the event due to the Hunter River Flood Protection System, which is a series of 170 km of levees and control structures. The forecast peak for the event was higher than the recorded peak. One of the reasons for this discrepancy was changes in streambank vegetation levels (Verdon-Kidd et al., 2010), demonstrating the impacts of catchment changes on flood hazard.

4.2. North-western Australia floods

In contrast to the heavily populated south east coast of Australia, floods in north western Australia (specifically the Fortescue Marsh area) have traditionally been perceived as a promise of a bountiful season more than a hazard because they drive plant production and the boom and bust ecology (McGrath et al., 2012). The ecological dynamics of this large wetland and its catchment rely on strongly episodic annual summer floods that most often are generated by 1-2 day intense rainfall events. Human occupation prior to European settlement would also have been drawn to the area during wet years. In the semi-arid landscapes of the Pilbara, large and at least partially persistent waterbodies like the Fortescue Marsh are to this day of significant heritage value (Barber and Jackson, 2011). Yet, negative impacts from flooding can also be significant and have historically included submerged roads and airstrips, loss of stock and delays in communication resulting in prolonged isolation of early settlers communities. More recently the extensive iron ore mining industry faced impacts such as multiple-day interruptions of operations and dewatering costs. Large wet years in this area are usually marked by several, cumulative large floods and result in inundations that may extend into the following year (Rouillard et al., 2015).

In general most of the annual rainfall across the Australian northwest falls in the hot summer months. Tropical cyclones and other lows contribute up to 50% of the total annual rainfall in the region, one of the highest contributions globally (Jiang and Zipser, 2010, Lavender and Abbs, 2013). The extreme rainfall (intra-seasonal and inter-annual) variability across much of northern Australia has been attributed to the interaction between tropical cyclogenesis, the seasonal position of the Intertropical Convergence Zone, the Indo-Australian monsoon, ENSO as well as intra-seasonal variability in the Madden Julian Oscillation (MJO) and the SAM (Leroy and Wheeler, 2008, Frederiksen et al., 2014, Risbey et al., 2009, Evans et al., 2014). For example the MJO may push cyclonic rains away from the northwest of Australia to the southeast of the continent (Leroy and Wheeler, 2008). Similarly, La Niña years are associated with more frequent TCs in the Coral Sea (Bureau of Meteorology, 2011).

4.3. 1956 Murray River floods and human induced changes on flood behaviour

The 1956 Murray River floods were the largest flood events in the instrumental record for many parts of the Murray-Darling basin (Overton, 2005), with major floods in both the Darling River and the Murray River. The floods followed months of above average rainfall in New South Wales along the Murrumbidgee and Lachlan Rivers and in western Queensland. The peak of the flooding at the lower end of the river system was experienced in August. Both 1955 and 1956 were strong La Niña years. Many parts of the Murray-Darling basin experienced the highest rainfall totals on record during this period. The IPO was also in a negative phase during this period, which has been shown to enhance both the tendency for and strength of La Niña impacts (Power et al., 1999, Kiem and Verdon-Kidd, 2013, Kiem et al., 2003).

Regulation of the Murray River has changed the nature of flood events significantly. Prior to regulation, flows below bankfull were common with minor floods every 1 to 2 years (Walker and Thoms, 1993). The regulated regime maintains flows near bankfull capacity and water level changes from minor floods are reduced. This is important because floods are not only a natural hazard but also the lifeblood of ecosystems and agricultural production in floodplains and wetland. For example, the lack of major flooding along the Murray River between around 1997 and 2010 had severe impacts on river system health. While the Millennium Drought was the primary cause for the lack of major flood events, the retention of floodwaters and subsequent diversion for irrigation was primarily responsible for the reduction in minor flood events, exacerbating the impacts of the drought on riverine ecosystems (Van Dijk et al., 2013). Similar causative links have been suggested between the diversion of floodwaters in unmanaged inland water systems in New South Wales and Queensland and the concurrent decline in migratory water bird populations (Kingsford and Porter, 2009), but such a link is inherently harder to substantiate.

5. CONCLUSIONS

Flooding events are rarely the result of a single factor. In the case of the Pasha Bulker storm the East Coast Low was the primary driver but the largest hazards came from embedded convective systems. Conditions for ECL formation may have been more favourable due to La Niña whilst the hazards on the ground were intensified by urban development (blockage and embankments) in the Newcastle CBD and mitigated by vegetation changes in the case of the Hunter River mainstream flooding at Maitland. In general, very little research has been conducted on whether the intensity and/or severity of ECLs will be affected by climate change, the interaction between ECLs and climate modes such as the SAM and ENSO, or whether the behavior of small-scale features such as convection embedded in ECL events may change as the atmosphere warms. Research underway in the Eastern Seaboard Climate Change Initiative and the NSW/ACT Regional Climate Modelling Project (NARCliM) is starting to address these gaps but further work is needed.

Although the mechanisms and hazards for floods in the Fortescue Marsh are very different from the eastern seaboard of Australia, there are a few parallels in terms of considering flood hazard. Firstly individual tropical cyclones can be identified as the primary drivers of flooding but it is the combination of the timing and number of cyclones in a season that leads to an overall wet season due to the 'system memory' in the catchment. Secondly tropical cyclones can be affected on intra-seasonal scales by large scale modes e.g. the MJO and enhanced on interannual scales by the occurrence of La Niña events.

The impacts of large scale drivers was evident from the 1956 Murray River flooding with widespread flooding due to months of heavy rainfall over the entire Murray-Darling basin, a result of both the negative IPO and 1955 and 1956 La Niña events. The link between Murray River floods and rainfall at seasonal and annual timescales suggests that the meteorological processes that would produce these floods are likely to be very different to those for small catchments. Furthermore, regulation of the Murray River has changed the nature of flood behavior significantly with important ecological impacts.

In conclusion, although there are some uncertainties in future extreme rainfall trends, the picture is much clearer than for future flood occurrence, magnitude and the overall hazard, due to the combined influences of changes to the local climate as well as those of the surface environment. Significant advances are required to improve our understanding of future interannual variability, in particular its influence on catchment wetness, and how this will combine with rainfall for changes in the overall future flood risk.

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