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EDITORIAL

Introduction to the special issue: historical and projected climatic changes to Australian natural hazards

Seth Westra[1] · **Christopher J. White**[2] · **Anthony S. Kiem**[3]

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1 Introduction

Australia's size and varied climates mean that it is affected by a range of weather-related natural hazards, including tropical and extra-tropical storms and associated extreme wind and hail, coastal and inland floods, heatwaves and bushfires. These hazards cause multiple human and environmental impacts, and collectively account for 93 % of Australian insured losses (Schuster 2013). In addition, drought—often treated distinctly from other hazards due to its more gradual onset—can cause substantial reductions in agricultural productivity, and places stress on municipal and industrial water resources and natural ecosystems.

Evidence is building that the frequency and cost of natural hazards are increasing both in Australia (Insurance Council of Australia 2013; Schuster 2013) and globally (Munich Re 2014). However, understanding the cause of these changes has proved to be difficult, with increases in reporting rates (Munich Re 2014), changes in societal exposure and vulnerability (Bouwer 2011; Neumayer and Barthel 2011) and anthropogenic climate change (IPCC 2013) all potentially playing a role in explaining the observed changes. Yet although the potential causes are many, correct attribution of the observed changes is necessary in order to identify appropriate policy responses, and to predict how the frequency and severity of natural hazards might change in the future.

This Special Issue focuses on the specific role of large-scale climatic changes on the observed and future incidence of Australian natural hazards. The Special Issue is divided into seven papers, each covering a major class of climate-influenced natural hazard: floods,

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✉ Seth Westra
seth.westra@adelaide.edu.au

[1] School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide, Australia

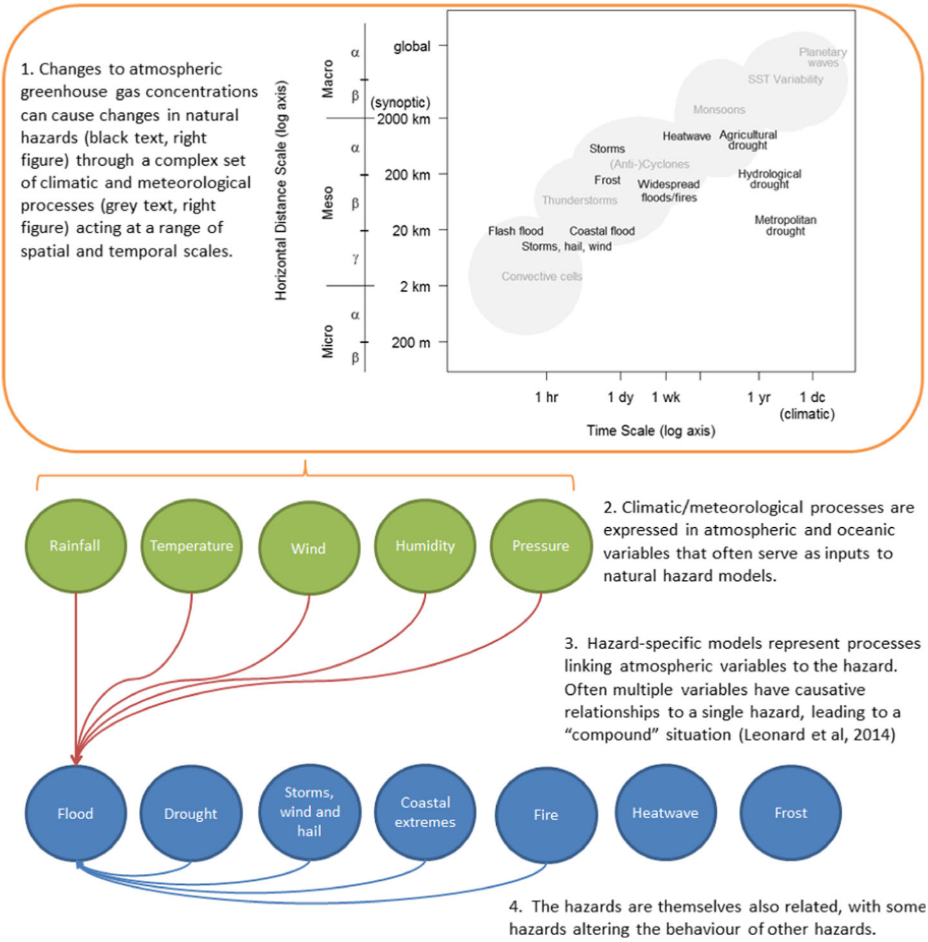
[2] School of Engineering and ICT, University of Tasmania, Tasmania, Australia

[3] Centre for Water, Climate and Land Use, Faculty of Science and IT, University of Newcastle, Newcastle, Australia

drought, storms (including wind and hail), coastal extremes, bushfires, heatwaves and frost. The work was initiated by the Working Group on Trends and Extremes from the Australian Water and Energy Exchanges (OzEWEX) initiative, which is a regional hydroclimate project run under the auspices of the Global Energy and Water Exchanges (GEWEX) initiative.

2 Linking large-scale climate processes to Australian natural hazards

The structure of the Special Issue is illustrated in Fig. 1, in which anthropogenic climate change and associated large-scale climate patterns are related to each natural hazard through a complex cascade of processes and scales. Although the emphasis is on the natural hazards (bottom row of Fig. 1), the significant interrelationships between the hazards themselves, as well as between each hazard and larger-scale climate, has necessitated reviewing each hazard



1. Changes to atmospheric greenhouse gas concentrations can cause changes in natural hazards (black text, right figure) through a complex set of climatic and meteorological processes (grey text, right figure) acting at a range of spatial and temporal scales.

2. Climatic/meteorological processes are expressed in atmospheric and oceanic variables that often serve as inputs to natural hazard models.

3. Hazard-specific models represent processes linking atmospheric variables to the hazard. Often multiple variables have causative relationships to a single hazard, leading to a "compound" situation (Leonard et al, 2014)

4. The hazards are themselves also related, with some hazards altering the behaviour of other hazards.

Fig. 1 Illustration of the complex processes that link large-scale climate variability to a natural hazard. The *arrows* illustrate the processes for floods (see Johnson et al. 2016, for further information) as part of a larger, interconnected system. This section briefly summarises the approach taken in this Special Issue to account for these interrelationships.

Starting at the global scale, Australia's natural hazards are influenced by changes in the global energy balance, as well as by shifts in global circulation patterns. These changes are documented in the Intergovernmental Panel on Climate Change (IPCC) reports (e.g. IPCC 2013) and are not covered further in the Special Issue. Australia's climate is also influenced by several hemispheric-scale patterns of climate variability, which can cause periods of lowered or heightened potential hazard activity. The most important patterns for Australia are the El Niño-Southern Oscillation phenomenon, the Indian Ocean Dipole and the Southern Annular Mode (e.g. Risbey et al. 2009b). An updated summary of historical and future changes to these patterns, as well as their connection to each of the seven natural hazards reviewed in this Special Issue, is provided in Table 1, and is referred to in a number of the specific hazard papers.

At smaller spatial and temporal scales, natural hazards are influenced by a variety of meteorological processes. A number of these processes have been summarised in Walsh et al. (2016), and include tropical cyclones, extratropical cyclones and their cold fronts, thunderstorms and east coast lows (coastal low pressure systems along parts of the east Australian coastline). These weather systems are often hazards themselves (e.g. leading to extreme wind and hail), and some are also causes of other hazards including floods (reviewed in Johnson et al. 2016) and coastal extremes (reviewed in McInnes et al. 2016).

In attempting to understand and attribute historical and future changes to natural hazards, significant emphasis is often placed on understanding changes to various atmospheric and oceanic variables, including temperature, rainfall, wind, humidity and atmospheric pressure (green circles in Fig. 1). There are multiple reasons for focusing on these variables as indicators of large-scale change, including the availability of long instrumental records, the ability of climate models to simulate the variables and the relatively limited influence of other human activities (e.g. land use change and the regulation of river systems) that can confound attempts to directly attribute changes to the natural hazards themselves. However, the connection between these variables and each natural hazard can be complex, with multiple variables usually acting jointly to influence the hazard (Leonard et al. 2014). For example, extreme rainfall is generally regarded as the proximate cause for most fluvial floods; however, annual average rainfall and the variables that drive evapotranspiration can collectively influence the catchment moisture content prior to the extreme rainfall event, and thus can also have a significant influence on flood magnitude (see Johnson et al. 2016, for a more detailed discussion).

In many cases, the mechanisms by which the atmospheric and oceanic variables and processes influence hazards are common to multiple hazards, albeit with subtle (but often important) distinctions. For example, heatwaves, frosts, bushfires and droughts are all influenced by atmospheric temperature, but in different ways. Heatwaves are one or several days of extremely high temperature (Perkins-Kirkpatrick et al. 2016), whereas frosts occur on time-scales that are similar to heatwaves but at the other end of the temperature scale. Interestingly, Crimp et al. (2016) show somewhat surprisingly that the prevalence of frosts can increase despite an increase in mean atmospheric temperature. In the case of bushfires, high (but not necessary extreme) temperatures are a necessary but not sufficient condition for the occurrence of severe bushfires (Sharples et al. 2016). Finally, the relationship between temperature and drought arises through evapotranspiration processes that occur on timescales of months or years (Kiem et al. 2016).

Models are commonly used to describe our understanding of the relationship between the atmospheric and oceanic variables and the natural hazard, and these are depicted as red arrows

Table 1 Observed and projected changes in hemispheric-scale patterns of climate variability, and their link to Australian natural hazards

Large-scale ocean/atmospheric process	Nature of influence on Australian natural hazards	Observed changes in the ocean/atmospheric process (since 1900), as reported by the IPCC Fifth Assessment Report (e.g. Christensen et al. 2013; Hartmann et al. 2013).	Projected changes in the ocean/atmospheric process (up to 2100) with respect to late 20th century, as reported by the IPCC Fifth Assessment Report (e.g. Christensen et al. 2013; Hartmann et al. 2013)
El Niño/Southern Oscillation (ENSO)	**Floods:** La Niña is associated with above average rainfall and increased flood risk, especially eastern Australia from June to February (Chiew and McMahon 2002; Chiew et al. 1998; Kiem et al. 2003; Verdon et al. 2004b; Ward et al. 2014). **Droughts:** El Niño is associated with below average rainfall and increased drought risk, especially eastern Australia from June to February (Gallant et al. 2012; Kiem and Verdon-Kidd 2010; Murphy and Timbal 2008; Risbey et al. 2009b; van Dijk et al. 2013). **Storms:** El Niño is associated with reduced tropical cyclone incidence along most of coastline, and La Niña is associated with increased incidence (Chand et al. 2013) (Kuleshov et al. 2008). No relationship has been found with tropical cyclones north of the Northern Territory. Severe thunderstorm relationships are limited by availability of reliable storm data but in the Brisbane area thunderstorms are more likely in neutral years than in El Niño years (Yeo 2005). There is little evidence of relationships between ENSO and thunderstorms in other regions but there is the potential for a wider extent of severe thunderstorm development	There is *insufficient evidence* for specific statements on the existence, magnitude or direction of observed trends or changes in ENSO. The IPCC's Fifth Assessment Report (AR5) added that large variability on interannual to decadal time scales and differences between data sets *precludes conclusions on long-term changes in ENSO*.	Climate model projections of changes in ENSO variability and the frequency of El Niño or La Niña episodes as a consequence of increased greenhouse gas concentrations are *not consistent*, and so there is *low confidence* in projections of changes in the ENSO phenomenon. There is *high confidence* that ENSO will remain the dominant mode of interannual variability in the tropical Pacific.

Table 1 (continued)

Large-scale ocean/atmospheric process	Nature of influence on Australian natural hazards	Observed changes in the ocean/atmospheric process (since 1900), as reported by the IPCC Fifth Assessment Report (e.g. Christensen et al. 2013; Hartmann et al. 2013).	Projected changes in the ocean/atmospheric process (up to 2100) with respect to late 20th century, as reported by the IPCC Fifth Assessment Report (e.g. Christensen et al. 2013; Hartmann et al. 2013)
	during La Niña (Allen and Karoly 2014). There is little relationship with east coast low incidence (Dowdy et al. 2013), whereas an increase in winter mid-latitude cyclone incidence is seen over and south of south-east Australia during La Niña conditions (Pezza et al. 2008). **Sea level and coastal extremes:** Mean sea level is higher over northern Australia during La Niña. Wave climate on the east coast is modulated by ENSO and affects beach erosion (above average beach erosion during El Niño/La Niña; e.g. Harley et al. 2010; Ranasinghe et al. 2004; White et al. 2014). **Bushfires:** El Niño is associated with hotter, drier conditions and increased bushfire risk (Harris et al. 2014; Verdon et al. 2004a; Williams and Karoly 1999). **Heatwaves:** El Niño is associated with increased frequency, intensity and duration of heatwaves in northeast Australia (Arblaster and Alexander 2012; Min et al. 2013; Perkins et al. 2015), yet different relationships in the far southeast (Boschat et al. 2015; Parker et al. 2014). **Frost:** El Niño is associated with an increased incidence of frost events due to drier soil		

Table 1 (continued)

Large-scale ocean/atmospheric process	Nature of influence on Australian natural hazards	Observed changes in the ocean/atmospheric process (since 1900), as reported by the IPCC Fifth Assessment Report (e.g. Christensen et al. 2013; Hartmann et al. 2013).	Projected changes in the ocean/atmospheric process (up to 2100) with respect to late 20th century, as reported by the IPCC Fifth Assessment Report (e.g. Christensen et al. 2013; Hartmann et al. 2013)
	conditions and greater atmospheric stability enhancing nocturnal radiative heat loss (Crimp et al. 2015; Murphy and Timbal 2008; Pezza et al. 2008; Stone et al. 1996).		
ENSO Modoki and/or central equatorial Pacific ENSO	**Floods:** Possible enhancement of traditional ENSO impacts (Ashok et al. 2007a, 2009; Cai and Cowan 2009) but also high uncertainty and conflicting conclusions in the literature (Cai and Cowan 2009; Taschetto and England 2009; Taschetto et al. 2009). **Droughts:** As with floods, possible enhancement of traditional ENSO impacts, but Taschetto and England (2009) also identify a potential link between El Niño Modoki events and reduced rainfall over many parts of Australia during autumn (a season not typically influenced by traditional ENSO events). **Storms:** Suppression of formation of tropical cyclones off the Queensland coast during El Niño Modoki (Chand et al. 2013); less suppression off the coast of western Australia; and no relationship north of the Northern Territory. Insufficient evidence for severe thunderstorms and east coast lows. ENSO Modoki suppresses mid-latitude cyclone activity over southwest Western Australia (Ashok et al. 2009).	*Medium confidence* in past trends toward more frequent central equatorial Pacific ENSO events.	*Low confidence* in projections of changes in ENSO Modoki or central equatorial Pacific ENSO events due to insufficient agreement of climate model projections.

Table 1 (continued)

Large-scale ocean/atmospheric process	Nature of influence on Australian natural hazards	Observed changes in the ocean/atmospheric process (since 1900), as reported by the IPCC Fifth Assessment Report (e.g. Christensen et al. 2013; Hartmann et al. 2013).	Projected changes in the ocean/atmospheric process (up to 2100) with respect to late 20th century, as reported by the IPCC Fifth Assessment Report (e.g. Christensen et al. 2013; Hartmann et al. 2013)
	Sea level and coastal extremes: Insufficient evidence currently available. **Bushfires:** No literature available, though inferences can be made through the literature relating to drought. **Heatwaves:** No literature available. **Frost:** No literature available.		
Pacific decadal variability mechanisms such as the Interdecadal Pacific Oscillation (IPO) and/or Pacific Decadal Oscillation (PDO)	**Floods:** IPO/PDO-negative periods are associated with increased frequency of La Niña events that also typically have more rain associated with them than La Niña events that occur when the IPO/PDO is positive (Kiem et al. 2003; Kiem and Verdon-Kidd 2013; Micevski et al. 2006; Power et al. 1999; Pui et al. 2011). The IPO is associated with increased flood risk due to both more precipitation and also increased antecedent moisture conditions, although the extent to which the influence of the IPO on extreme rainfall is distinct from the influence of ENSO on extreme rainfall is still under debate (Power et al. 2006; Westra et al. 2015). **Droughts:** IPO/PDO-positive periods are associated with decreased frequency of La Niña events (Kiem and Franks 2004; Kiem et al. 2003) resulting in increased drought risk due to both the decreased frequency of	*No significant trends* in either the IPO or PDO are evident since 1900. IPCC AR4 noted climate impacts associated with the 1976–1977 IPO/PDO phase transition (from negative to positive) but recent studies suggest a shift out of IPO/PDO positive may have occurred at the end of the 1990s or early 2000s.	PDO/IPO does not exhibit major changes in spatial or temporal characteristics under greenhouse gas warming in most climate models, although some models indicate a weak shift toward more occurrences of the negative phase of the PDO/IPO by the end of the 21st century. However, given that the models strongly underestimate the PDO/IPO connection with tropical Indo-Pacific SST variations, the credibility of IPO/PDO projections remains uncertain and *confidence is low in projections of future changes in PDO/IPO*.

Table 1 (continued)

Large-scale ocean/atmospheric process	Nature of influence on Australian natural hazards	Observed changes in the ocean/atmospheric process (since 1900), as reported by the IPCC Fifth Assessment Report (e.g. Christensen et al. 2013; Hartmann et al. 2013).	Projected changes in the ocean/atmospheric process (up to 2100) with respect to late 20th century, as reported by the IPCC Fifth Assessment Report (e.g. Christensen et al. 2013; Hartmann et al. 2013)
	La Niña events combined with a reduction in the recharging effect of the La Niña events that do occur. **Storms:** Short length of reliable tropical cyclone and severe thunderstorm records makes assessment of relationships difficult. There is also insufficient information on relationship with east coast lows. Mid latitude cyclones south of Australia are generally less intense during negative PDO, and more intense but less numerous during the positive phase (Pezza et al. 2007). **Sea level and coastal extremes:** Insufficient evidence currently available. **Bushfires:** Enhanced fire danger during El Niño episodes can be exacerbated by negative IPO periods (Verdon et al. 2004a, b). **Heatwaves:** No literature available. **Frost:** No literature available.		
Indian Ocean Dipole (IOD) and/or sea surface temperature (SST) in different parts of the Indian Ocean	**Floods:** England et al. (2006) find that the IOD shifts the fronts which bring rain to Western Australia northward due to a deceleration of Indian Ocean climatological mean anticyclones, and also cause a northward shift of the subpolar westerlies. Negative IOD increases spring rainfall in south east	Basin-wide average Indian Ocean SST has risen steadily for much of the 20th century. However, the SST increase over the North Indian Ocean since about 1930 is noticeably weaker than for the rest of the basin. In the equatorial Indian Ocean, coral isotope records off Indonesia indicate a reduced SST	It is *likely* that the tropical Indian Ocean will feature reduced warming and decreased rainfall in the east and increased warming and rainfall in the west, a pattern especially pronounced during August to November and broadly consistent with observed changes over the 20th century.

Table 1 (continued)

Large-scale ocean/atmospheric process	Nature of influence on Australian natural hazards	Observed changes in the ocean/atmospheric process (since 1900), as reported by the IPCC Fifth Assessment Report (e.g. Christensen et al. 2013; Hartmann et al. 2013).	Projected changes in the ocean/atmospheric process (up to 2100) with respect to late 20th century, as reported by the IPCC Fifth Assessment Report (e.g. Christensen et al. 2013; Hartmann et al. 2013)
	Australia. Gallant et al. (2012) find significantly more (less) heavy rainfall events during years with warmer (cooler) eastern Indian Ocean SSTs. **Droughts:** During IOD positive phases (i.e. negative (cool) east and positive (warm) west Indian Ocean SST anomalies), lower than average winter/spring rainfall over southeast Australia is likely, and vice versa for the opposite phase of the IOD (Ashok et al. 2003; Meyers et al. 2007; Saji et al. 1999; Ummenhofer et al. 2009). However, several studies show a similar modulation of rainfall with eastern Indian Ocean SSTs only (Cai and Cowan 2008; Nicholls 1989, 2009; Verdon and Franks 2005), suggesting that the influence of the Indian Ocean SST gradient (the west–east dipole) on southeast Australian drought is not as important as the state of eastern Indian Ocean SSTs alone (Gallant et al. 2012). **Storms:** The IOD has some influence on tropical cyclone numbers, with the relationship most pronounced during La Niña events off the coast of Queensland (Liu and Chan 2012), but with a limited number of IOD events so far. There is insufficient evidence for severe thunderstorms, and little	warming and/or increased salinity during the 20th century. From ship-borne surface measurements, an easterly wind change especially during July to October has been observed over the past six decades, a result consistent with a reduction of marine cloudiness, and decreasing precipitation, in the east equatorial Indian Ocean. Atmospheric reanalysis products have difficulty representing these changes.	The IOD will *very likely* remain active, with interannual variability unchanged in projections of Indian Ocean SSTs.

Table 1 (continued)

Large-scale ocean/atmospheric process	Nature of influence on Australian natural hazards	Observed changes in the ocean/atmospheric process (since 1900), as reported by the IPCC Fifth Assessment Report (e.g. Christensen et al. 2013; Hartmann et al. 2013).	Projected changes in the ocean/atmospheric process (up to 2100) with respect to late 20th century, as reported by the IPCC Fifth Assessment Report (e.g. Christensen et al. 2013; Hartmann et al. 2013)
	influence on east coast lows (Dowdy et al. 2013). Decreases have been observed in winter mid-latitude cyclone activity during positive IOD phases (Ashok et al. 2007b). **Sea level and coastal extremes:** Insufficient evidence currently available. **Bushfires:** High inter-annual variability of extreme fire weather is driven in part by the combined influence of ENSO and IOD (Jolly et al. 2015). **Heatwaves:** Positive relationship with maximum temperatures during winter and spring (Min et al. 2013; White et al. 2013). **Frost:** No literature available.		
Southern Annular Mode (SAM)	**Floods:** Ishak et al. (2013) show that flood trends are associated with variability in SAM based on a set of streamflow stations concentrated largely in south-eastern Australia, although the extent to which this is a causative relationship is not known. **Droughts:** SAM has links to Australian rainfall and temperature, and therefore drought, that varies regionally and seasonally (Gillett et al. 2006; Hendon et al. 2007; Ho et al. 2012; Meneghini et al. 2007). During SAM positive phases, a poleward contraction of the mid-latitude storm track results in a	In the past few decades the SAM has exhibited a positive trend in austral summer and autumn, a change attributed to the effects of ozone depletion and, to a lesser extent, the increase in greenhouse gases. Therefore, it is *likely* that circulation features have moved poleward since the 1970s, involving a widening of the tropical belt, a poleward shift of storm tracks and jet streams, and a contraction of the northern polar vortex. Evidence is more robust for the northern hemisphere but it is still *likely* that	The austral summer/autumn positive trend in SAM is likely to weaken considerably as ozone depletion recovers through to the mid-21st century. There is *medium confidence* from recent studies that projected changes in SAM are sensitive to boundary processes, which are not yet well represented in many climate models currently used for projections, for example, stratosphere-troposphere interaction, ozone chemistry, solar forcing and atmospheric response to Arctic sea ice loss.

Table 1 (continued)

Large-scale ocean/atmospheric process	Nature of influence on Australian natural hazards	Observed changes in the ocean/atmospheric process (since 1900), as reported by the IPCC Fifth Assessment Report (e.g. Christensen et al. 2013; Hartmann et al. 2013).	Projected changes in the ocean/atmospheric process (up to 2100) with respect to late 20th century, as reported by the IPCC Fifth Assessment Report (e.g. Christensen et al. 2013; Hartmann et al. 2013)
	southward displacement of rain-bearing cold fronts and cyclones during winter which typically leads to dry conditions for the southern third of Australia. However, during spring and summer, a positive SAM induces changes to local circulation patterns that draw moist easterly winds inland and increases the likelihood of rainfall across much of eastern Australia, including west of the Great Dividing Range and across much of the Murray-Darling Basin. **Storms:** A possible relationship between tropical cyclones and SAM has been found off the east coast, but no physical mechanism yet established (Diamond and Renwick 2015). There is increased risk of cold-season severe thunderstorms during negative SAM (Kounkou et al. 2009), but no apparent relationship with east coast lows. There are fewer mid-latitude cyclones during the positive phase of the SAM (Pezza et al. 2008). **Sea level and coastal extremes:** Positive SAM lowers extreme sea levels along southern Australia (e.g. Colberg and McInnes 2012) and increases westward wave energy and littoral currents over eastern Victoria during summer (O'Grady et al. 2015).	the SAM has become more positive since the 1950s.	SAM is also influenced by teleconnections to the tropics, primarily associated with ENSO. Changes to the tropical circulation, and to such teleconnections, as the climate warms could further affect SAM variability but *understanding and confidence into this is low* due in part to large uncertainty associated with projections of ENSO and IPO/PDO.

Table 1 (continued)

Large-scale ocean/atmospheric process	Nature of influence on Australian natural hazards	Observed changes in the ocean/atmospheric process (since 1900), as reported by the IPCC Fifth Assessment Report (e.g. Christensen et al. 2013; Hartmann et al. 2013).	Projected changes in the ocean/atmospheric process (up to 2100) with respect to late 20th century, as reported by the IPCC Fifth Assessment Report (e.g. Christensen et al. 2013; Hartmann et al. 2013)
	Bushfires: Shifts in SAM combined with shifts in larger scale drivers contribute to rainfall decreases across southern Australia, which directly and indirectly affect the moisture content of bushfire fuels (Hendon et al. 2014; O'Donnell et al. 2015) **Heatwaves:** Likelihood of extreme temperatures increases during negative phases (Marshall et al. 2013; Min et al. 2013); relationships with summertime heatwaves are less clear (Perkins et al. 2015). **Frost:** During SAM positive phases, a poleward contraction of the mid-latitude storm track resulting in drier more stable atmospheric conditions interspersed by anomalous cold air advection from the poles during anomalously strong ridging high pressure activity (Cai and Cowan 2006; Frederiksen and Frederiksen 2007; Hope et al. 2006; Risbey et al. 2009a).		

in Fig. 1 (using the hazard 'floods' for illustration). The need for models arises because in many cases historical records of the natural hazards themselves are sparse, so that historical changes to the hazards need to be inferred from our understanding of changes to key causative processes. Therefore, models linking the climatic and meteorological variables (green circles, Fig. 1) to the hazards (blue circles, Fig. 1) often represent the primary line of evidence for how the hazards are affected by climate change. It is therefore critical to scrutinise the assumptions in the models, including decisions related to the processes that are included and the way they are represented, as this can have a significant influence on assessments of historical and future changes to the hazard.

There are also important interrelations between each of the natural hazards themselves (blue arrows, Fig. 1). For example, the prevalence of droughts can influence whether a catchment is wet or dry prior to a heavy rainfall event (linking drought and flood), whereas fires can influence the vegetation and soil properties of the catchment, and thus affect the conversion of rainfall to runoff (linking fire, drought and flood). In estuarine catchments, coastal processes including mean sea level and storm tides can combine with the fluvial flood to increase the overall flood hazard (linking sea level extremes with flood). These complex linkages between atmospheric/oceanic variables and the hazards highlight the need to take a consistent and unified approach to reviewing the evidence of change across all of the Australian natural hazards.

Given the complexity of the hazards and their causative mechanisms, this Special Issue therefore takes the following approach to reviewing historical and projected changes to Australian natural hazards:

- Information on historical and projected changes in the hazards themselves (blue circles, Fig. 1) is covered in the relevant hazard paper. The models linking atmospheric and oceanic variables to that hazard are also covered in those papers (red lines, Fig. 1) as research into each hazard is typically informed by a hazard-specific set of models. Finally, the influence of other hazards on the topical hazard of each paper (blue lines, Fig. 1) is also covered; for example the presence of a drought can influence the catchment moisture stores, which is one of the factors that influence the flood hazard.
- The atmospheric and oceanic variables (green circles, Fig. 1) are each covered in the most relevant natural hazard paper. A guide to where individual atmospheric and oceanic variables are covered is provided in Table 2.
- The influence of large-scale patterns of climate variability that can influence Australian natural hazards are summarised in Table 1, with more detailed information provided in various Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report chapters, most notably the chapters by Christensen et al. (2013) and Hartmann et al. (2013).

3 Knowledge gaps and future research needs

This Special Issue documents our current understanding on historical and possible future climatic changes to the frequency and severity of Australian natural hazards. Although the science of detecting and attributing changes in the historical natural hazards—and developing projections of future changes—is progressing rapidly, a variety of knowledge gaps still exist. The authors of each paper have therefore identified research priorities for the hazard that would

Table 2 Index of the atmospheric and oceanic variables that are described in each paper

		Hazard paper						
		Flood	Drought	Storm, wind and hail	Sea level and coastal extremes	Fire	Heatwaves	Frost
Atmospheric or oceanic variable	Land temperature		As it influences evapotranspiration (and vice versa)			As it relates to fire danger rating and fuel moisture content	Summer temperature extremes	Mean and extreme minimum temperatures (i.e. 10th, 50th and 90th percentiles). Focus is on August to November
	Ocean temperature			As related to major climate drivers	Thermosteric sea level rise		Marine temperature extremes	As related to major climate drivers
	Precipitation	Extreme rainfall	Dry Seasons	Tropical cyclones	Coincident events in estuarine regions only	Antecedent rainfall influences fire danger rating via the Drought Factor. Also affects the moisture state of live and dead fuels		
	Wind		As it influences evapotranspiration	Tropical cyclones, thunderstorms, east coast lows, mid-latitude cyclones	Wind and swell waves (wave setup); storm surges (wind setup) meteo-tsunamis	As it relates to fire danger rating and consequences for rate of spread and fire growth. Wind change is particularly important.		
	Humidity		As it influences evapotranspiration	High relative humidity at low levels influences thunderstorms		As it relates to fire danger rating and impact on fuel moisture content		
	Hail			Hail-producing storms				
	Lightning			Link to thunderstorms only		Relates to ignition probability and can result after pyrocumulonimbus development		
	Pressure		High pressure systems only	East coast lows	Storm surge (inverse barometer effect); meteo-tsunamis	Certain synoptic types relate to episodes of extreme fire weather		High pressure systems and their position and intensity

lead to a significant improvement in our collective understanding of the role of climate change in Australian natural hazards over a timeframe of about a decade.

Numerous suggestions for research priorities were common to many of the papers, including the need to revitalise our observational network to specifically monitor changes to the prevalence of Australia's natural hazards. Similarly, increasing the resolution of our large-scale climate models (as well as including improved physics schemes to simulate certain processes such as tropical cyclones) continues to be a major priority, as it enables the inclusion of a greater number of scales within a single modelling framework. For many of the hazards, the role of paleo-climate data, which can assist in placing changes to natural hazards within a longer historical context, was also identified as a potential avenue for augmenting the often limited instrumental records.

There were also more specific suggestions that were unique to each hazard. Examples include the need for a unified framework to identify atmospheric heatwave events (Perkins-Kirkpatrick et al. 2016), and the need to better understand the role of alternative runoff-generating mechanisms and their relationship to future changes in flood risk (Johnson et al. 2016). In many cases the authors also called for better integration of research across different natural hazards; for example, the connections between drought and the land-atmosphere feedbacks that produce heatwaves (Kiem et al. 2016; Perkins-Kirkpatrick et al. 2016), and the link between coastal and inland processes in the context of flood hazard in estuarine regions (Johnson et al. 2016; McInnes et al. 2016).

Although most papers in this Special Issue highlighted the complexity and high levels of uncertainty of attributing historical changes in natural hazards and developing projections of future changes, there are grounds for optimism that the state of the science is improving. Land- and space-based remote sensing technology continues to yield data that enable investigations of change at increasing resolutions across the Australian continent; the increase in computing power and storage is leading to increasingly advanced models that can bridge a greater range of scales; and the increased information from the paleoclimate community is leading to improved understanding of how natural hazards have changed over long timescales. Furthermore, research into changes in natural hazards requires a focus on fostering interdisciplinary collaborations, and initiatives such as GEWEX and OzEWEX continue to serve the function of enhancing dialogue and collaborations between experts in diverse disciplines including meteorology, hydrology, oceanography, ecology, paleoclimatology, geography, engineering and statistics.

It is therefore hoped that, in addition to summarising the current state-of-the-science, this Special Issue will also provoke discussion and debate about future research priorities and directions. Only by taking a coordinated and strategic approach—one that accounts for the wide range of scales and processes that influence each hazard—will we be able to overcome the substantial scientific obstacles involved in understanding the nature and causes of historical and future changes to Australia's natural hazards.

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