Westra, Seth and White, Christopher J. and Kiem, Anthony S. (2016) Introduction to the special issue : historical and projected climatic changes to Australian natural hazards. Climatic Change, 139 (1). pp. 1-19. ISSN 0165-0009 , http://dx.doi.org/10.1007/s10584-016-1826-7

Title: "Introduction to the Special Issue: Historical and Projected Climatic Changes to Australian Natural Hazards"

Authors: Seth Westra, Chris White, Anthony Kiem

1. Introduction

Australia's size and diverse climate zones means that it is vulnerable to a range of natural hazards (Schuster, 2013). Weather-related natural hazards—including tropical and extra-tropical storms, extreme wind and hail, coastal and inland floods, heatwaves and bushfires—collectively account for 93% of Australian insured losses (Schuster, 2013). Furthermore, drought can substantially reduce agricultural productivity, and can place significant stress on municipal and industrial water resources.

Evidence is building in Australia (Insurance Council of Australia, 2013; Schuster, 2013) and globally (Munich Re, 2014) that both the frequency and cost of climate-influenced natural hazards are increasing. Although it is often suggested that the frequency and severity of natural hazards will increase as a result of anthropogenic climate change (IPCC, 2013), other factors, such as increases in reporting rates (Munich Re, 2014) and changes in exposure and vulnerability (Bouwer, 2011; Neumayer and Barthel, 2011), are also likely to play a role in explaining the observed changes.

In recognition of the importance of understanding the specific role of climatic changes on the observed and future changes to Australian natural hazards, a working group on trends and extremes was initiated as part of the Australian Water and Energy Exchanges (OzEWEX) initiative—a regional hydroclimate project run under the auspices of the Global Energy and Water Exchanges (GEWEX) initiative. One of the functions of this working group is to provide a detailed assessment of our current understanding of the role of climate variability and change on Australian natural hazards, identify critical gaps in knowledge and encourage collaborative science.

This Special Issue is a product of this OzEWEX initiative. The Special Issue is divided into seven papers, each covering a major class of climate-influenced natural hazard, specifically: floods, drought, storms, wind and hail, coastal extremes, bushfires, heatwaves and frost. These natural hazards were selected due to their frequency of occurrence in Australia and their clear link to atmospheric and/or oceanic processes. Geophysical hazards such as earthquakes and tsunamis are not covered as climate processes are not the principal causative agent for these hazards.

2. Linking large-scale climate processes to Australian natural hazards

Accounting for the role of anthropogenic climate change on Australian natural hazards requires an understanding of the complex processes that link climate to the hazards. The cascade of processes is illustrated in the Stommel diagram in Figure 1, with changes to global-scale greenhouse gas concentrations propagating through a range of processes and scales to ultimately affect the natural hazard. This section provides a brief overview of the approach taken in this Special Issue to assess how historical and projected changes to Australia's natural hazards are linked to large-scale changes in climate.

At the largest scale, Australia's natural hazards are influenced by long-term shifts in the mean state of atmospheric and oceanic variables, as well as shifts in circulation patterns. In addition to these shifts in mean state, Australia's climate is influenced by several hemispheric-scale patterns of climate variability, which can cause periods of lowered or elevated hazard activity. The most important patterns for Australia are the El Niño-Southern Oscillation phenomenon, the Indian Ocean Dipole and the Southern Annular Mode; historical and future changes to these processes, as well as their connection to each of the seven natural hazards reviewed in this Special Issue, are summarised in Table 1.

At smaller space-timescales of the Stommel diagram, natural hazards are influenced by a number of meteorological processes, in particular convective cells, thunderstorms and (anti-) cyclones. These process are particularly relevant to wind and hail hazard and are reviewed in Walsh et al (this issue) whichdetails likely changes in tropical cyclones, extratropical cyclones and their cold fronts, thunderstorms and east coast lows (coastal low pressure systems along parts of the east Australian coastline). As shown in Figure 1, some of these meteorological processes are also relevant to floods and coastal extremes but Johnson et al (this issue) and McInnes et al (this issue) cross reference Walsh et al where relevant.

Variability and long-term changes to the climatic and meteorological processes can be measured through a set of atmospheric and oceanic variables (green circles in Figure 1). The connection between these variables and each natural hazard can be complex, with multiple variables acting jointly to influence the hazard (Leonard et al., 2014). Taking 'floods' as an example, extreme rainfall is generally regarded as the proximate cause for most fluvial floods, although the variables that drive evapotranspiration and hence the catchment moisture content prior to the extreme rainfall event may also influence flood magnitude (see Johnson et al., this issue, for a more detailed discussion). Similarly, pressure and wind anomalies can influence storm surges, which can lead to modified flood hazard in coastal and estuarine areas (McInnis et al., this issue).

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 temperatures, but in different ways. Heatwaves are caused by one or several days of extreme temperature (Perkins et al., this issue). Frosts occur on similar timescales to heatwaves but at the other end of the temperature scale, and Crimp et al. (this issue) show somewhat surprisingly that the prevalence of frosts can increase despite an increase in mean atmospheric temperature. The links between temperature and fire are complex, with high (but not necessary extreme) temperatures being a necessary but not sufficient condition for the occurrence of severe wildfires (Scharples et al., this issue). Finally, the relationship between temperature and drought arises through evapotranspiration processes that occur on timescales of months or years (Kiem et al., this issue).

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 in Figure 1 (using the hazard 'floods' for illustration). In many cases the historical records of the natural hazards themselves are sparse, and historical changes to the hazards are often determined from multiple climatic and non-climatic processes. Therefore, models linking the climatic and meteorological variables (green circles, Figure 1) to the hazards (blue circles, Figure 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, Figure 1), which must be taken into account. 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 fire influences 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 takes the following approach to summarising historical and projected changes to Australian natural hazards:

- Information on historical and projected changes in the hazards themselves (blue circles, Figure 1) is covered in the relevant hazard paper. The models linking atmospheric and oceanic variables to that hazard are also covered (red lines, Figure 1) as research into each hazard typically uses a unique set of models. Finally, the influence of other hazards on the topical hazard of each paper (blue lines, Figure 1) is also covered; for example the influence of drought on flooding is covered in the 'floods' paper.
- The atmospheric and oceanic variables (green circles, Figure 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 frequency and magnitude of natural hazards to climatic and non-climatic causes—and developing projections of future change—is progressing rapidly, a variety of knowledge gaps still exist. The authors of each paper have therefore identified research priorities for their hazard that would 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; for example, the need for a more unified framework to identify atmospheric heatwave events (Perkins et al., this issue), and better exploration of the relative importance of alternative runoff-generating mechanisms and the way this relates to future changes in flood risk (Johnson et al., this issue). 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, and the link between coastal and inland processes in the context of flood hazard in estuarine regions (Johnson et al., this issue; McInnes et al., this issue).

Although most papers in this Special Issue highlighted the complexity and high levels of uncertainty related to attributing historical changes in natural hazards and developing projections on 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, palaeontology, geography, engineering and statistics.

Therefore, in addition to summarising the current state-of-the-science with regards to the influence of anthropogenic climate change on Australian natural hazards, it is hoped that 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.

References

Ashok K, Behera SK, Suryachandra AR, Weng H, Yamagata T (2007) El Nino Modoki and its possible teleconnection. Journal of Geophysical Research 112.
Ashok K, Guan Z, Yamagata T (2003) Influence of the Indian Ocean Dipole on Australian winter rainfall. Geophysical Research Letters 30.
Ashok K, Tam C-Y, Lee W-J (2009) ENSO Modoki impact on the Southern Hemisphere storm track activity during extended austral winter. Geophysical Research Letters 36.
Bouwer LM (2011) Have disaster losses increased due to anthropogenic climate change? . Bulletin of the American Meteorological Society 92:39-46.
Cai W, Cowan T (2008) Dynamics of late autumn rainfall reduction over southeastern Austraila. Geophysical Research Letters 35.
Cai W, Cowan T (2009) La Nina Modoki impacts on Australia autumn rainfall variability. Geophysical Research Letters 36.
Chiew FHS, McMahon TA (2002) Global ENSO-streamflow teleconnection, straemflow forecasting and interannual variability. Hydrological Sciences Journal 47:505-522.
Chiew FHS, Piechota TC, Dracup JA, McMahon TA (1998) El Nino / Southern Oscillation and Australian rainfall, straemflow and drought: Links and potential for forecasting. Journal of Hydrology 204:138-149.
Christensen JH, Krishna Kumar K, Aldrian E, An S-I, Cavalcanti IFA, de Castro M, Dong W, Goswami P, Hall A, Kanyanga JK, Kitoh A, Kossin J, Lau N-C, Renwick J, Stephenson DB, Xie S-P, Zhou T (2013) Climate Phenomena and their Relevance for Future Regional Climate Change. in Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (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, United Kingdom and New York, NY, USA.
Colberg F, McInnes KL (2012) The impact of future changes in weather patterns on extreme sea levels over southern Australia. Journal of Geophysical Research - Oceans 117.
Gallant A, Kiem AS, Verdon-Kidd DC, Stone RC, Karoly DJ (2012) Understanding hydroclimate processes in the Murray-Darling Basin for natural resource management. Hydrology and Earth System Sciences 16:2049-2068.
Gillett NP, Kell TD, Jones PD (2006) Regional climate impacts of the Southern Annular Mode. Geophysical Research Letters 33.
Harley MD, Turner IL, Short AD, Ranasinghe R (2010) Interannual variability and controls of the Sydney wave climate. International Journal of Climatology 30:1322-1335.
Harris S, Nicholls N, Tapper N (2014) Forecasting fire activity in Victoria, Australia, using antecedent climate variables and ENSO indices. International Journal of Wildland Fire 23:173-184.
Hartmann DL, Klein Tank AMG, Rusticucci M, *al. e* (2013) Observations: Atmosphere and Surface. Working Group 1 Contribution to the IPCC Fifth Assessment Report - Climate Change: The Physical Science Basis.
Hendon HH, Thompson DWJ, Wheeler MC (2007) Australian rainfall and surface temperature variations associated with the Southern Hemisphere Annular Mode. Journal of Climate 20:2452-2467.
Ho M, Kiem AS, Verdon-Kidd DC (2012) The Southern Annular Mode: a comparison of indices. Hydrological Earth Systems Science 16:967-982.
Insurance Council of Australia (2013) Insurance Council of Australia Submission: Recent trends in and preparedeness for extreme weather events.
IPCC (2013) Summary for Policy Makers. in Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds.) Climate Change 2013: The Physical Science Basis. Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
Kiem AS, Franks SW (2004) Multi-decadal variability of drought flood risk, eastern Australia. Hydrological Processes 18:2039-2050.

Kiem AS, Franks SW, Kuczera G (2003) Multi-decadal variability of flood risk. Geophysical Research Letters 30.
Kiem AS, Verdon-Kidd DC (2010) Towards understanding hydroclimatic chagne in Victoria, Australia - preliminary insights into the "Big Dry". Hydrological Earth Systems Science 14.
Kiem AS, Verdon-Kidd DC (2013) The importance of understanding drivers of hydroclimatic variability for robust flood risk planning in the coastal zone. Australian Journal of Water Resources 17:126-134.
Leonard M, Westra S, Phatak A, Lambert M, van den Hurk B, McInnes K, Risbey J, Schuster S, Jakob C, Stafford-Smith M (2014) A compound event framework for understanding extreme impacts. WIREs Climate Change 5:113-128.
Meneghini B, Simmonds I, Smith IN (2007) Association between Australian rainfall and the Southern Annular Mode. International Journal of Climatology 27:109-121.
Meyers GA, McIntosh PC, Pigot L, Pook MJ (2007) The years of El Nino, La Nina, and interactions with the tropical Indian Ocean. Journal of Climate 20:2872-2880.
Micevski T, Franks SW, Kuczera G (2006) Multidecadal variability in coastal eastern Australian flood data. Journal of Hydrology 327:219-225.
Munich Re (2014) Topics Geo - Natural Catastrophes 2014: Analyses, assessments, positions. Munich Reinsurance Company Rep.,, p. 67.
Murphy BF, Timbal B (2008) A review of recent climate variability and climate change in southeastern Australia. International Journal of Climatology 28:859-879.
Neumayer E, Barthel F (2011) Normalising economic loss from natural disasters: A global analysis. Global Environmental Change 21:13-24.
Nicholls N (1989) Sea surface temperatures and Australian winter rainfall. Journal of Climate 2:965-973.
Nicholls N (2009) Local and remote causes of the southern Australian autumn-winter rainfall decline, 1958-2007. Climate Dynamics.
O'Grady JG, McInnes KL, Colberg F, Hemer MA, Babanin AV (2015) Longshore wind, waves and currents: climate and climate projections at Ninety Mile Beach, southeastern Australia. International Journal of Climatology.
Power S, Casey T, Folland C, Colman A, Mehta V (1999) Inter-decadal modulation of the impact of ENSO on Australia. Climate Dynamics 15:319-324.
Pui A, Lall A, Sharma A (2011) How does the Interdecadal Pacific Oscillation affect design floods in Australia? . Water Resources Research 47.
Ranasinghe R, McLoughlin R, Short A, Symonds G (2004) The Southern Oscillation Index, wave climate, and beach rotation. Marine Geology 204:273-287.
Risbey J, Pook M, McIntosh P, Wheeler M, Hendon H (2009) On the remote drivers of rainfall variability in Australia. Monthly Weather Review 137:3233-3253.
Saji NH, Goswami BN, Vinayachandran PN, Yamagata T (1999) A dipole mode in the tropical Indian Ocean. Nature 401:360-363.
Schuster S (ed.): (2013) Natural hazards and insurance, John Wiley and Sons, Cambridge, UK.
Taschetto AS, England MH (2009) El Nino Modoki impacts on Australian rainfall. Journal of Climate 22:3167-3174.
Taschetto AS, Ummenhofer CC, Sen Gupta A, England MH (2009) Effect of anomalous warming in the central Pacific on the Australian monsoon. Geophysical Research Letters 36.
Ummenhofer CC, England MH, McIntosh PC, Meyers GA, Pook MJ, Risbey JS, Sen Gupta A, Taschetto AS (2009) What causes southeast Australia's worst droughts? . Geophysical Research Letters 36.
van Dijk AIJM, Beck HE, Crosbie RS, de Jeu RAM, Liu YY, Podger GM, Timbal B, Viney NR (2013) The millenium drought in southeast Australia (2001-2009): National and human causes and implications for water resources, ecosystems, economy and society. Water Resources Research 49:1-18.
Verdon DC, Franks SW (2005) Indian Ocean sea surface temperature variability and winter rainfall: eastern Australia. Water Resources Research 41.

Verdon DC, Kiem AS, Franks SW (2004a) Multi-decadal variability of forest fire risk - eastern Australia. International Journal of Wildland Fire 13:165-171.
Verdon DC, Wyatt AM, Kiem AS, Franks SW (2004b) Multidecadal variability of rainfall and streamflow: Eastern Australia. Water Resources Research 40.
Ward PJ, Jongman B, Kummu M, Dettinger MD, Weiland FCS, Winsemius HC (2014) Strong influence of El Nino Southern Oscillation on flood risk around the world. Proceedings of the National Academy of Sciences 111:15659-15664.
White NJ, Haigh ID, Church JA, Keon T, Watson CS, Pritchard T, Watson PJ, Burgette RJ, Eliot M, McInnes KL, You B, Zhang X, Tregoning P (2014) Australian Sea Levels - Trends, Regional Variability and Influencing Factors. Earth-Science Reviews 136:155-174.
Williams AAJ, Karoly DJ (1999) Extreme fire weather in Australia and the impact of the El Nino Southern Oscillation. Australian Meteorological Magazine 48:15-22.

Figures and Tables

Table 1: Observed and projected changes in hemispheric-scale patterns of climate variability, and their link to Australian natural hazards. INSTRUCTIONS FOR LEAD AUTHORS: Can you please fill in the relevant section for your paper? If the process does not relate to your natural hazard or if there is insufficient evidence to make a statement, please just say this.

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 associated with above average rainfall – especially eastern Australia from June to February – and increased flood risk (Chiew and McMahon, 2002; Chiew et al., 1998; Kiem et al., 2003; Verdon et al., 2004b; Ward et al., 2014).	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.
	Droughts: El Niño associated with below average rainfall – especially eastern Australia from June to February – and increased drought risk (Gallant et al., 2012; Kiem and Verdon-Kidd, 2010; Murphy and Timbal, 2008; Risbey et al., 2009; van Dijk et al., 2013).		
	Storms: To complete.		
	Sea level and coastal extremes: Mean sea level enhanced over northern Australia during La Niña. Wave climate on east coast modulated by ENSO and affects beach erosion (above average beach erosion during El Niño/La Niña) (above average beach erosion during El Nino/La Nina; e.g. Harley et al., 2010; Ranasinghe et al., 2004; White et al., 2014).		
	Bushfires: El Niño associated with hotter, drier conditions and increased bushfire risk (Harris et al., 2014; Verdon et al., 2004a; Williams and Karoly, 1999).		
	Heatwaves: To complete.		
	Frost: To complete.		
ENSO Modoki and/or central equatorial Pacific ENSO	**Floods:** Possible enhancement of traditional ENSO impacts (Ashok et al., 2007; Ashok et al., 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).	***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 mode projections.
	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 (i.e. a seasonal not typically influenced by traditional ENSO events).		
	Storms: To complete.		

	Sea level and coastal extremes: Insufficient evidence currently available. **Bushfires:** To complete. **Heatwaves:** To complete. **Frost:** To complete.		
Pacific Decadal Variability (PDV) mechanisms such as the Interdecadal Pacific Oscillation (IPO) and/or Pacific Decadal Oscillation (PDO)	**Floods:** IPO/PDO negative epochs 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). This leads to increased flood risk due to both more precipitation and also increased antecedent moisture conditions. **Droughts:** IPO/PDO positive epochs 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 La Niña events combined with a reduction in the recharging effect of the La Niña events that do occur. **Storms:** To complete. **Sea level and coastal extremes:** Insufficient evidence currently available. **Bushfires:** To complete. **Heatwaves:** To complete. **Frost:** To complete.	***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***.
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 northward the fronts which bring rain to Western Australia due to a deceleration of Indian Ocean climatological mean anticyclone and northwardshift of the subpolar westerlies Negative IOD increases spring rainfall in south east 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:** To complete.	**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 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	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. The IOD will ***very likely*** remain active, with interannual variability unchanged in projections of Indian Ocean SSTs.

	Sea level and coastal extremes: Insufficient evidence currently available. **Bushfires:** To complete. **Heatwaves:** To complete. **Frost:** To complete.	marine cloudiness, and decreasing precipitation, in the east equatorial Indian Ocean. Atmospheric reanalysis products have difficulty representing these changes.	
Southern Annular Mode (SAM)	**Floods:** Ishak et al (2013) show that flood trends can be partially explained by variability in SAM based on a set of streamflow stations concentrated largely in south-eastern Australia. **Droughts:** SAM has links to Australian rainfall and temperature, and therefore drought, that vary 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 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:** To complete. **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). **Bushfires:** To complete. **Heatwaves:** To complete. **Frost:** To complete.	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 SAM has become more positive since the 1950s.	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. 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 2: Index of the atmospheric and oceanic variables that are described in each paper. INSTRUCTIONS FOR LEAD AUTHORS: Can you please describe which atmospheric and/or oceanic variables are reviewed in your paper? We have attempted to fill in as much as possible based on the papers that have been completed thus far.

		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				Summer temperature extremes	
	Ocean temperature				Thermosteric sea level rise		Marine temperature extremes	
	Precipitation	Extreme rainfall	Dry Seasons		Coincident events in estuarine regions only			
	Wind		As it influences evapotranspiration	Tropical cyclones and thunderstorms	Wind and swell waves (wave setup); storm surges (wind setup) meteo-tsunamis			
	Humidity		As it influences evapotranspiration	High relative humidity at low levels influences thunderstorms				
	Hail			Hail-producing storms				
	Lightning			Link to thunderstorms only				
	Pressure		High pressure systems only	East coast lows	Storm surge (inverse barometer effect); meteo-tsunamis			

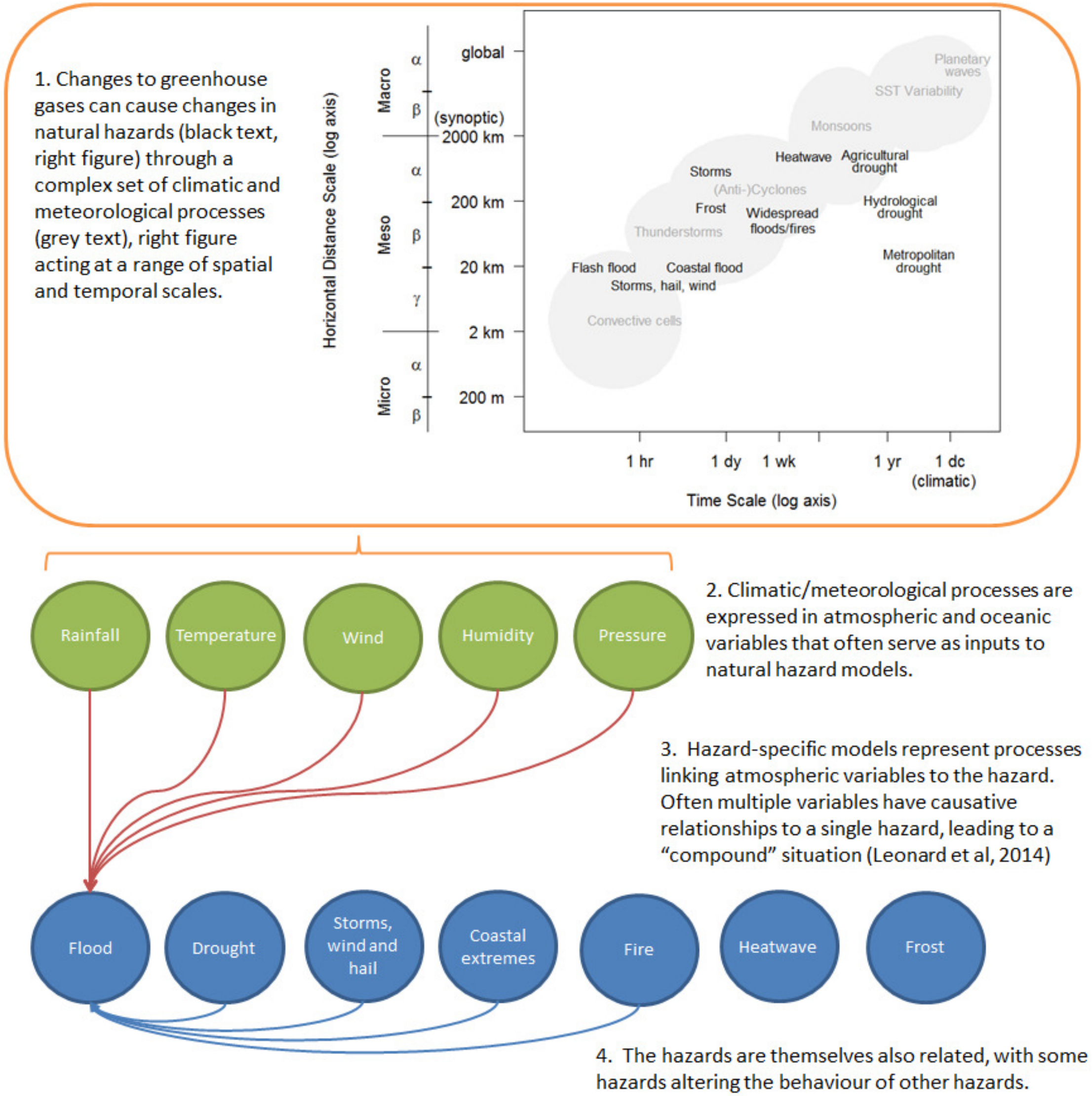

Figure 1: Illustration of the complex processes that link large-scale climate variability to a natural hazard. The arrows illustrate the processes for floods (see Johnson et al., this issue, for further information).