Natural hazards in Australia: heatwaves

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Abstract

As part of a special issue on natural hazards, this paper reviews the current state of scientific knowledge of Australian heatwaves. Over recent years, progress has been made in understanding both the causes of and changes to heatwaves. Relationships between atmospheric heatwaves and large-scale and synoptic variability have been identified, with increasing trends in heatwave intensity, frequency and duration projected to continue throughout the 21st century. However, more research is required to further our understanding of the dynamical interactions of atmospheric heatwaves, particularly with the land surface. Research into marine heatwaves is still in its infancy, with little known about driving mechanisms, and observed and future changes. In order to address these knowledge gaps, recommendations include: focusing on a comprehensive assessment of atmospheric heatwave dynamics; understanding links with droughts; working towards a unified measurement framework; and investigating observed and future trends in marine heatwaves. Such work requires comprehensive and long-term collaboration activities. However, benefits will extend to the international community, thus addressing global grand challenges surrounding these extreme events.

1. Introduction

Heatwaves are natural hazards that have substantial impacts on human health, the economy and environment, occurring in the atmosphere and the ocean. They are Australia's most deadly natural hazard, causing 55% of all natural disaster related deaths (Coates et al. 2014) and burden the Australian workforce by ~US$6.2 billion every year (Zander et al. 2015). The January 2009 Victorian heatwave killed over 370 people (Alexander and Tebaldi 2012) with an insured loss of US$1.3 billion (Munich Re 2009). Heatwaves are also a key contributor to bushfires (Sharples et al. 2015, in this Special Issue).

Heatwaves also occur in the marine environment; for example, the 2011 Western Australia marine heatwave (Pearce and Feng 2013) had substantial impacts on marine biodiversity (Wernberg et al. 2013). Extreme heat events also impact agriculture and aquaculture industries, respectively harming grain harvest yields (Barlow et al. 2013) and reducing livestock in salmon farming.

Despite their importance, research into atmospheric heatwaves in Australia is generally lagging behind the global effort. Recent studies over Europe have demonstrated how the land interacts with synoptic systems (e.g. Fischer et al. 2012; Quesada et al. 2012) to influencing heatwave variability. Moreover, several studies have indicated that anthropogenic forcing has contributed to specific European events (e.g. Stott et al. 2004), while others indicate increases in the frequency of future heatwaves under greenhouse conditions (Orlowsky and Seneviratne 2012). However, a unified approach in understanding and characterizing atmospheric heatwaves in Australia is currently missing. This is lacking despite improved understanding of relationships between heatwaves and large-scale modes of climate variability (Parker et al. 2014a; Perkins et al. 2015) dominant synoptic patterns (Pezza et al. 2012) and increases in heatwave frequency since the 1950s (Indian Ocean Climate Initiative 2012; Perkins and Alexander 2013). In the case of marine heatwaves, only a handful of studies focus on the dynamics and impacts of specific events (Oliver et al. 2014a; Benthuysen et al. 2014), with a measurement framework only recently proposed (Hobday et al. 2016).

This paper reviews the scientific literature on the measurement, causes, observed trends and future projections of both atmospheric and marine heatwaves across Australia. We conclude with principal findings and provide key recommendations on future research priorities. While atmospheric heatwaves also occur during cooler seasons. the focus here is limited to austral summer heatwaves when the scale of impacts are generally larger.

2. Understanding heatwaves

2.1 Measuring atmospheric heatwaves

Atmospheric heatwaves are often classified as prolonged periods of excessive heat (Perkins and Alexander 2013), although no universal definition exists. They can be measured using different characteristics – such as intensity, frequency, duration, timing and spatial extent – and calculated using daily maximum, minimum, or average temperatures (e.g. Furrer et al. 2010; Fischer and Schär 2010; Russo et al. 2014). In most Australian studies, a relative threshold (or percentile) is used to determine excessive heat, where prolonged periods of heat last for at least three days (Tryhorn et al. 2006; Alexander and Arblaster 2009; Pezza et al. 2012). A relative threshold is useful since what is considered extreme in one location and/or time of year may not be extreme under other circumstances (Perkins and Alexander 2013).

The Australian Bureau of Meteorology has devised the Excess Heat Factor (EHF; Nairn and Fawcett 2013) index that takes account how hot a three-day period is compared to the previous month, as well as the climatological 95th percentile. Furthermore, a multi-characteristic framework has been developed (Perkins and Alexander 2013), employing five metrics of heatwave intensity, frequency and duration (see Fischer and Schär 2010) for three different definitions. This approach allows for a more consistent analysis, whilst providing useful information to a range of impacts communities, and is similar to the "hot-spell" (periods of extreme heat similar to heatwaves) approach of Furrer et al. (2010), where heatwave characteristics are modelled as a function of covariates, for example, time.

2.2 Large-scale mechanisms of atmospheric heatwaves

Recently, there have been Australian and international advances in understanding drivers and mechanisms of atmospheric heatwaves (e.g. Lokith and Broccoli, 2012; Horton et al. 2015; Krueger et al, 2015; Grotjahn et al. 2015). Figure 1 explains how physical mechanisms underpinning atmospheric heatwaves over various timescales may interact in the lead-up to a heatwave. Several studies have examined the relationship between modes of large-scale climate variability and land surface temperatures across Australia (Nicholls et al. 1996; Jones and Trewin 2000; Arblaster and Alexander 2012). While the El Niño-Southern Oscillation (ENSO) is regarded as the primary large-scale driver of inter-annual variations of Australian rainfall (Risbey et al. 2009), its role on temperature extremes is more varied (e.g. Arblaster and Alexander 2012; Min et al. 2013). Significantly more heatwave days, and longer and more intense events are observed over northern and eastern Australia during El Niño compared to La Niña (Perkins et al. 2015), yet different relationships occur in the southeast (Trewin 2009; Parker et al. 2014a, Boschat et al. 2015). White et al. (2013a) found that the Indian Ocean Dipole has a positive relationship over southern Australia for austral winter and spring.

Southeastern Australia heatwaves are associated with the Madden Julian Oscillation (MJO) phases 3-6 during austral summer (Parker et al. 2014a), yet during spring, MJO phases 2-3 are more influential (Marshall et al. 2013). Over most of Australia, the likelihood of extreme temperature increases during negative phases of the Southern Annular Mode (Marshall et al. 2013), but relationships with summertime heatwaves are less clear (Perkins et al. 2015). Large-scale teleconnections to sea surface temperature (SST) and atmospheric conditions are also suggested (e.g. Pezza et al. 2012).

2.3 Atmospheric heatwave meteorology and land surface influences

The most important weather system for Australian heatwaves is the persistent anticyclone, positioned adjacent to the affected area (Marshall et al. 2013) and largely associated with planetary-scale Rossby waves (Pezza et al. 2012; Parker et al. 2014b). Anticyclonic high-pressure systems bring warm air from the interior of the continent to the heatwave affected area, sustaining conditions for a number of days (Steffen et al. 2014). For southeastern Australia, anticyclone systems are generally centred over the Tasman Sea in line with the subtropical ridge (Hudson et al. 2011; Marshall et al. 2013). Parker et al. (2014b) found an association with propagating and overturning Rossby waves, dynamically influencing the development of southeast heatwaves. Across the southwest, anticyclone systems are typically centred over the Great

Australian Bight (Pezza et al. 2012). Other influential features include intra-seasonal drivers of variability (Marshall et al. 2013; White et al. 2013a), rainfall deficits (Nicholls 2004), the Australian monsoon and tropical cyclones (Parker et al. 2013). Mechanisms of extreme-heat build-up include advection from lower latitudes, large-scale subsidence transporting higher potential temperature air from upper levels, or development and replacement of the diurnal mixed layer (McBride et al. 2009).

International studies have shown that the land surface provides important feedbacks (including the albedo, surface roughness and soil moisture; e.g. Miralles et al. 2012, 2014) that can exacerbate or dampen heatwave intensity (Seneviratne et al. 2006). Kala et al. (2015) demonstrated the impact of soil moisture on the meteorology of the 2009 Black Saturday heatwave, highlighting the significant contribution desiccated soil can have on extreme heat events. Such studies are important, as a better understanding of the strength of these feedback mechanisms may allow for improved land cover management, potentially reducing heatwave severity (Davin et al. 2014). This may be particularly important in urban environments where the urban heat island effect can compound extreme temperature (Argüeso et al. 2014; 2015).

2.4 Measuring marine heatwaves

Marine heatwaves are often measured by the magnitude of ocean temperature anomalies above the monthly seasonal climatology (e.g. Pearce and Feng 2013). Temperature anomalies for specific events have been reported on weekly, daily and finer time scales, using satellite measurements and data loggers (e.g. Olita et al. 2006; Mills et al. 2013). Other studies use more sophisticated metrics including a period (~ three to five days) where ocean temperatures were at least 3-5 °C above average (Sorte et al. 2010), thermal stress anomalies (Selig et al. 2010) or degree-heating weeks (Gleeson and Strong 1995). Extreme ocean temperatures have been examined using the frequency of days above the 95th percentile (Lima and Wethey 2012) and extreme value theory (Oliver et al. 2014a,b). A standardized definition has been recently constructed, based on consecutive exceedances of the calendar day 90th percentile of temperature for at least five consecutive days (Hobday et al.,. 2016). From this definition, a set of metrics are computed that measure marine heatwave intensity, duration, cumulative intensity and rate of onset/decline.

2.5 Large-scale mechanisms of marine heatwaves

Large-scale mechanisms of marine heatwaves are less well understood. ENSO is known to play a role in driving temperature events such as the unprecedented 2011 "Ningaloo Niño" (Pearce and Feng 2013), whereby La Niña conditions drove a stronger than average Leeuwin Current southward along the coast of Western Australia (Kataoka et al. 2013). Off the southeast coast, mesoscale eddies from instabilities in the East Australian Current drive marine heatwaves along the continental shelf (Oliver et al. 2014a). In regions such as coastal South Australia (e.g. Kämpf et al. 2004) and New South Wales (NSW) (e.g. Roughan and Middleton 2004), local winds drive temperature variations due to upwelling and downwelling processes. Globally, high atmospheric temperatures and low winds commonly drive marine heatwaves and this relationship can be expected to hold around Australia (e.g. Olita et al. 2007; Pearce and Feng 2013).

3. Observed changes

3.1 Observed changes and attribution of atmospheric heatwaves

The continentally averaged Australian mean temperature has increased by 0.9 °C since 1950, which is slightly higher than the combined ocean-land global average of 0.85 °C (Bureau of Meteorology 2012), though it is worth noting that globally averaged land-only temperatures have warmed twice as fast as the combined average. There have been various assessments of Australian extreme temperature trends (e.g. Tryhorn and Risbey 2006; Alexander and Arblaster 2009; Pezza et al. 2012; Donat et al. 2013), however heatwave characteristics – and the metrics used to define them – can vary markedly, limiting consistent comparisons.

Heatwave characteristics have increased across many Australian regions since the mid 20th century (Alexander and Arblaster 2009; Donat et al, 2013; Perkins and Alexander, 2013). Over 1971-2008, the hottest day in a heatwave increased faster than average heatwave intensity, with a measurable increase in the duration and frequency of heatwaves (Perkins and Alexander 2013). Similar patterns are found when extending the analysis to 1950-2013 (Steffen et al. 2014; see Figure 2). Throughout southwest Western Australia the frequency and intensity of hot spells (periods of relative extreme heat that can occur throughout the year) increased over 1958-2010, but their duration decreased slightly (Indian Ocean Climate Initiative 2012). Over the same period, inland areas of northwest Western Australia experienced increases in intensity, frequency, and duration, but along coastal areas, intensity decreased. While emerging studies are explaining the dynamic/thermodynamic components of changes in Northern Hemisphere extreme temperatures (e.g. Horton et al. 2015), similar studies have not been undertaken.

Classically, studies analysing the role of human influence on observed extreme temperature events are based on monthly/seasonal anomalies for large spatial domains (e.g. Stott et al. 2004). In Australia, the intensity of the 2012/2013 summer was five times more likely to occur in a climate under the influence of anthropogenic greenhouse gases, compared to a climate without these influences (Lewis and Karoly 2013). Moreover, Australia’s hottest spring on record (2013) would not have occurred without anthropogenic influence (Lewis and Karoly 2014; Knutson et al. 2014). Although attribution studies are specific to the event and domain analysed, there is evidence that a relationship exists between larger-scale, longer-term extreme temperature anomalies, and those over smaller spatial and temporal scales (Angelil et al. 2014). Hence, the studies of Lewis and Karoly are indicative that a human signal exists in observed heatwaves over smaller domains and shorter temporal scales. Indeed, the intensity and frequency of heatwaves during the 2012/2013 Australian summer increased in occurrence by respectively two- and three-fold respectively due to anthropogenic influence (Perkins et al. 2014a). While the aforementioned studies employed the same methodology (fraction of attributable risk, see Allen 2003), other methods also exist for determining anthropogenic influence (Allen and Tett 1999; Kokic et al. 2014). Such analyses have looked at long-term trends in daily extreme temperatures at global and continental scales (e.g. Kim et al. 2015), but have not yet been applied to Australian heatwaves.

3.3 Recent unprecedented heatwave events across Australia

Australia has experienced extreme heatwaves during the last decade. In late January and early February 2009, a severe heatwave occurred over Victoria that was followed by the most devastating bushfires in Australian history (the “Black Saturday” fires). Several records were set for high day- and night-time temperatures as well as for the duration of the event (National Climate Centre 2009). The heatwave occurred in association with a slow moving surface anticyclone and propagating Rossby waves.

The land surface had also been particularly dry in the preceding weeks, which combined with the presence of a tropical low off northwest Western Australia and an active monsoon trough, provided ideal conditions for the advection of hot air towards southern Australia (Parker et al. 2013). Recent research also suggests that unprecedented Antarctic warming and a polar anticyclone over the Southern Ocean was at least partly responsible for the 2009 Victorian heatwave (Fiddes et al. 2015).

In January 2013, a record-breaking persistent heat event affected the majority of the continent, which was unprecedented spatially and temporally in observational records (Bureau of Meteorology 2013). Extremely hot air masses developed across north Australia that were driven southwards ahead of a series of cold fronts, creating a persistent hot air mass that sat over the continent (Bureau of Meteorology 2013). The event was associated with a delayed monsoon onset and slow moving weather systems over the continent, following a drier than average end to 2012. The heatwave affected set a new national daily maximum temperature record of 40.33 °C on 7th January 2013, consisting of seven consecutive days with maximum temperature above 39 °C (Bureau of Meteorology 2013).

4. Future changes

4.1. Projections of heatwave events

4.1.1. Heatwave projections from Global Climate Models

Heatwaves are expected to continue in a world under anthropogenic influence, with recent studies suggesting an increase in their frequency and duration (Orlowsky and Seneviratne 2012; Coumou and Robinson 2013; Fischer et al. 2014). Large efforts have been devoted to understanding the impact of anthropogenic climate change on heatwaves in North America and Europe (e.g. Lau and Nath 2012, 2014; Andrade et al. 2014), but this is less so for Australian heatwaves. Relevant work for Australia are summarised below.

Tryhorn and Risbey (2006) and Alexander and Arblaster (2009), employing a single climate model, and the Coupled Model Intercomparison Project (CMIP) phase 3 climate models respectively, found a projected increase in heatwave duration and warm nights in the 21st century under greenhouse forcing. Recently, revised regional climate change projections for Australia provide a regional assessment of plausible future projections of extreme temperatures (CSIRO 2015). Projections based on 24 CMIP phase 5 (CMIP5) climate models for the Representative Concentration Pathways (RCP) 4.5 (medium-low) and 8.5 (high) emission scenarios (Taylor et al. 2012) show that changes in extremes are similar to changes in annual means, consistent with observations (Alexander et al. 2007). Projected changes in the frequency of warm spells (including heatwaves) by 2100 show a significant increase among the CMIP5 ensemble for both RCP4.5 and RCP8.5 (CSIRO 2015).

.The CMIP5 models project heatwaves to become more frequent, hotter, and longer across Australia by the end of the 21st century (Cowan et al. 2014). Patterns of change are similar under RCP4.5 (Figures 3a,b) and RCP8.5 (Figures 3c,d), but scale with anthropogenic influence. Projections for northern Australia show the largest increase in heatwave days, due to the narrow temperature distribution in the tropics (e.g. Diffenbaugh and Scherer 2011). Increases in intensity and frequency across the southern regions are substantial (Figures 3a,b,c,d). Under a moving-threshold heatwave definition, which removes the effect of an increase in mean temperature, future changes in frequency are minimal, indicating a similar rate of increase to mean temperature (Cowan et al. 2014). However, the intensity across central-southern Australia still increases, implying that heatwaves are getting hotter at a faster rate than mean temperature in this region.

4.1.2. Regional and downscaled climate projections

Projected changes in temperature extremes have been quantified using dynamical downscaling techniques across Australia (Perkins et al. 2014b), resolution Tasmania (White et al. 2013b), and for NSW and the Australian Capital Territory (Evans et al. 2014) . White et al. (2013b) show a significant average increase in warm spell duration including by 2100, relative to the current baseline for a high-emissions scenario across Tasmania.

While regional climate ensemble projections agree with large-scale trends from their host models, such studies add spatial detail in extreme temperature frequency and intensity projections (Perkins et al., 2014b). For example, Figures 3e and 3f illustrate this using 50 km regional simulations for heatwave intensity and frequency respectively (Evans et al. 2014).

4.2. Projected changes in atmospheric circulation

Currently, understanding the dynamic/thermodynamic components behind future projections of Australian heatwaves is limited. Purich et al. (2014) found that under climate change, a poleward shift and intensification of the most severe heatwave-inducing anticyclones can be expected, consistent with projected subtropical ridge and SAM changes (e.g. Timbal et al. 2010; Kent et al. 2013). However, the significant rise in the number of heatwave events across southern and central Australia is currently predominantly attributed to thermodynamic changes (Purich et al. 2014).

There are suggestions that SSTs influence synoptic conditions associated with heatwaves globally (Della-Marta et al. 2007; Trenberth and Fasullo 2012), although whether local SST anomalies are caused by, or are responsible for, Australian heatwaves remains uncertain (e.g. Pezza et al. 2012; Boschat et al. 2015). Moreover, evidence provided by observations is limited, and the CMIP5 models fail to capture observed SST patterns prior to southern Australian heatwaves (Purich et al. 2014). Further research is required on this topic, as well as how future changes in the large-scale modes will impact Australian heatwaves (see Parker et al. 2014a), given that models project significant increases in extreme El Niño and La Niña events (Cai et al. 2014, 2015) and a continuation of positive SAM trends in the RCP8.5 scenario (Zheng et al. 2013).

4.3 Projections of marine heatwaves

As marine heatwaves is an emerging field, there are few studies exploring future changes. Southeastern and southwestern Australia are identified as hotspots of ocean warming (Foster et al. 2014), with the Tasman Sea in particular experiencing surface warming three-to-four times the global rate (Holbrook and Bindoff 1997; Ridgway 2007). The CMIP5 models project a net warming (relative to 1986-2005) of SST in the Australia region of 0.6565 °C65 ^{O}C by 2050 under RCP2.6, rising to 0.99 °C9 ^{O}C and 1.22 °C2 ^{O}C under RCP4.5 and RCP8.5, respectively (Lenton et al. 2015). The strongest signals are seen off the coasts of Tasmania and southwestern Australia, consistent with observed historical trends, and off the northwest shelf. This background warming is a significant driver of marine heatwaves, as the probability of large heat anomalies becomes much greater. In addition, changes in drivers such as ENSO can significantly impact marine heatwave occurrences off Western Australia

(Feng et al. 2015). Changes in wind stress curl over the high-latitude South Pacific (e.g. through variations in the SAM) can impact eddy-driven marine heatwaves off southeastern Australia (Oliver et al. 2014a; Oliver and Holbrook 2014). However, there remains a large gap in understanding what future projections of marine heatwaves might entail.

5. Conclusions and remaining questions

As part of this Special Issue on Australian natural hazards, this paper summarizes scientific advances in the measurement and understanding of Australian atmospheric and marine heatwaves, and the state of our knowledge on future changes. While there is no single way to define heatwaves, it is clear that their intensity, frequency and duration has increased as anthropogenic influences on the climate has increased. Immediate research could focus on developing more impact-relevant projections on finer spatial scales. Moreover, investigating the human influence on observed trends in Australian heatwaves could be undertaken using internationally applied methods.

Considerable advance has been made in understanding the physical mechanisms driving Australian heatwaves, particularly relationships between ENSO and other modes of variability (Parker et al. 2014a; Perkins et al. 2015) and synoptic-scale dynamics (Pezza et al. 2012; Parker et al. 2014b; Boschat et al. 2015). However, there is no comprehensive, Australia-wide study documenting the dynamics behind heatwaves. Consequently untangling causes and changes in Australian heatwaves should be prioritized, including land surface feedbacks and antecedent soil moisture, dynamic/thermodynamic components of heatwaves, and increases in the land-sea temperature gradient. The latter has not yet been studied in relation to Australian heatwaves, yet may be important, especially over coastal regions. Understanding the physical connections between heatwaves and drought (Kiem et al. 2015 in this Special Issue) would also be beneficial to stakeholders of both hazards. Such work is imperative towards a greater understanding of atmospheric heatwaves, as well as advancing Australia's international contribution towards this important field.

Much work remains to better understand marine heatwaves. Given local events in recent years (Pearce and Feng 2013) and the proposal of a measurement framework (Hobday et al. 2016), the Australian community is in a leading position. However, considerable work is required to to generate future projections of marine heatwaves and understand interactions between driving mechanisms. Such work should be prioritized to bring our understanding of marine heatwaves in line with atmospheric events.

Lastly, there is a need for a more unified framework for identifying atmospheric events, following recent Australian efforts applied to marine events. The identification of events underpins subsequent research on dynamics, changes and impacts, thus a more unified framework allows for consistency across relevant studies and fields of research. This would require large collaboration across different research and industry sectors, and would need to be conducted at the global scale. This is an area that is likely to be active for many years to come, yet is imperative in addressing both regional and global grand challenges of heatwaves.

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Figure captions

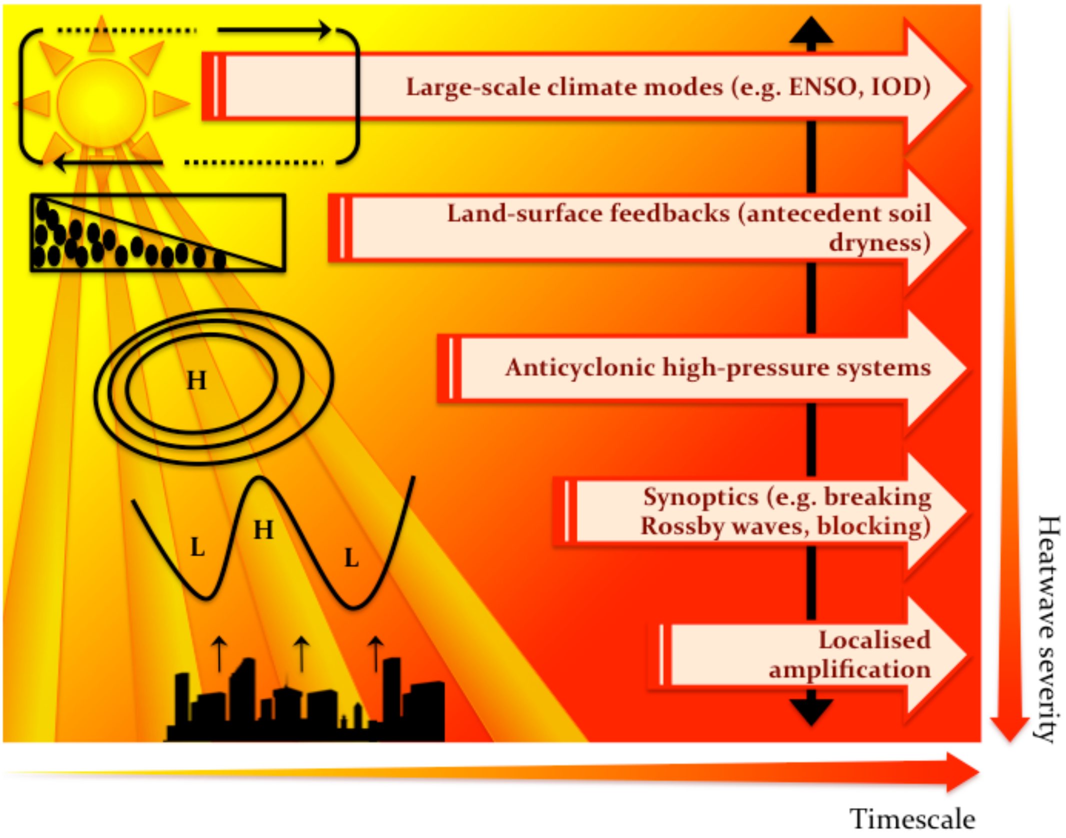
Figure 1: Heatwave schematic illustrating the various physical processes contributing to heatwaves, the interactions and feedbacks existing between them, and timescales on which they operate. Note that not all processes need to be present for a heatwave to occur (Fischer et al. 2007; Miralles et al. 2014). Coloured shading indicates the severity of a heatwave (red being more severe), the arrow thickness on the x-axis indicates the temporal length of key mechanisms, and the arrow on the y-axis indicates how the mechanisms on their various timescales may amplify heatwave severity. For example, A particular phase of climate modes may increase the likelihood of heatwaves, which then become more severe once other, shorter time-scale mechanisms (e.g. dry soil and high-pressure systems) also occur.

Figure 2: Observed trends in Australian heatwave days over 1950-2013. A heatwave day must belong to a period of three or more consecutive days that have positive excess heat values (Nairn and Fawcett 2013). Hatching indicates statistical significance at the 5% level. Updated from Perkins and Alexander (2013).

Figure 3: Austral summer heatwave increases compared to historical climatology. (top) Ensemble average heatwave frequency (HWF; days per summer), and (bottom) heatwave amplitude (HWA; °C). (**a**,**b**) CMIP5 RCP4.5, (**c,d**) CMIP5 RCP8.5, and (**e,f**) 50km downscaled NARCliM SRES A2. CMIP5 increases are calculated over 2081-2100 compared to 1950-2005 climatology. NARCliM increases are calculated over 2060-2079 compared to 1990-2009 climatology. Heatwaves are based on the definition described in Pezza et al. (2012), where a heatwave occurs when at least thee consecutive days are above the monthly 90th percentile for maximum temperaturef.

Stippling indicates where future and historical climatologies are *not* significantly different at the 95% confidence level. (**a-d**) adapted from Fig. 3 in Cowan et al. (2014) and based on 15 CMIP5 models.

Figures



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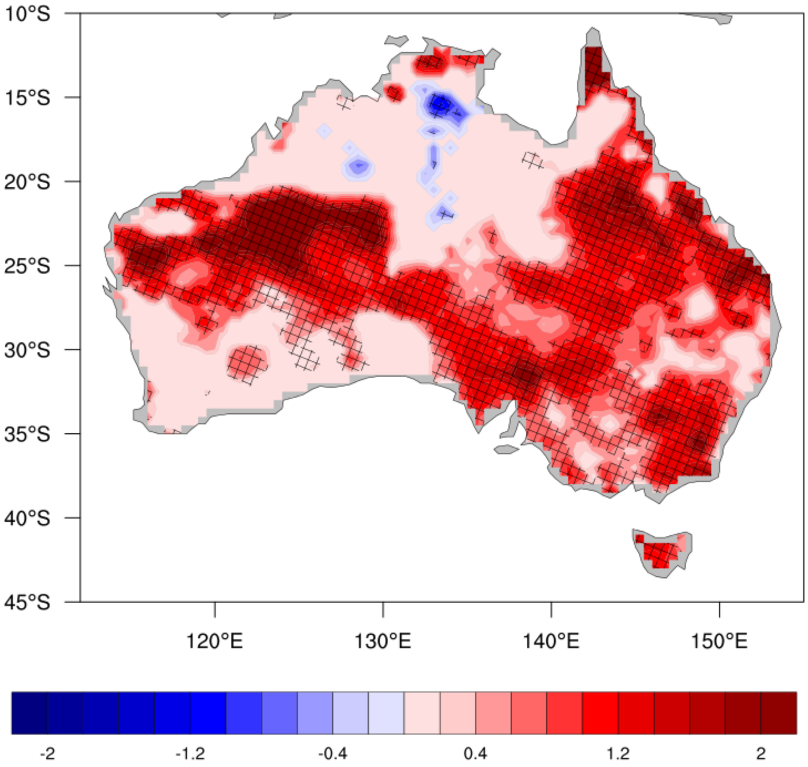

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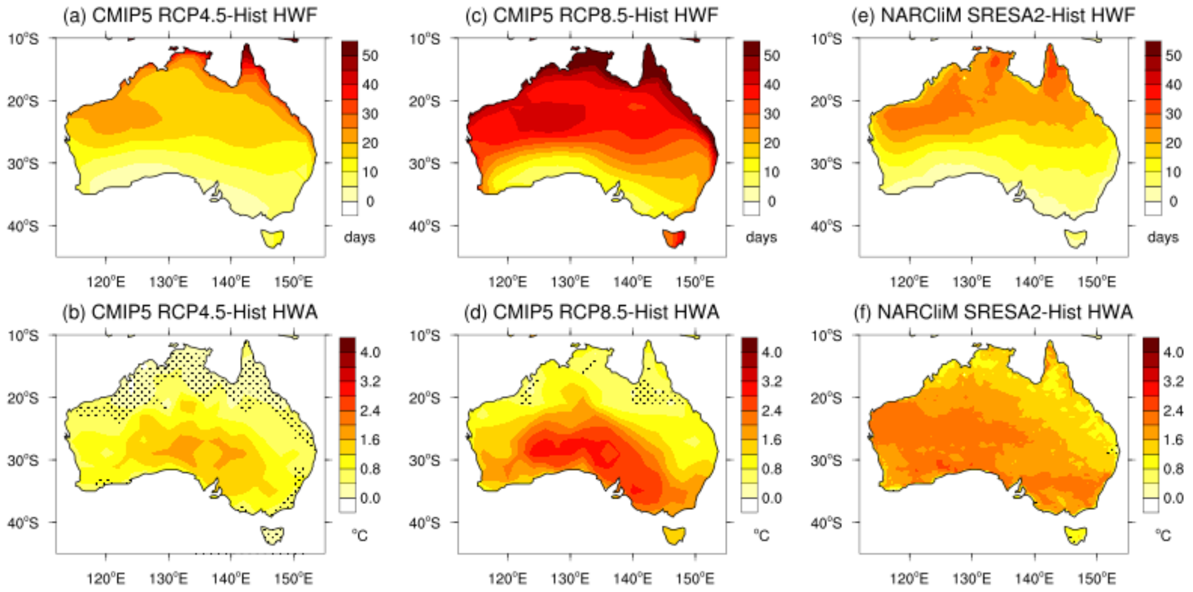

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