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Natural hazards in Australia: heatwaves

S.E. Perkins-Kirkpatrick[1], C.J. White [2,3] L.V. Alexander[1], D. Argüeso[1], G. Boschat[4], T. Cowan[5,6], J.P. Evans[1], M. Ekström[7], E.C.J. Oliver[8,9], A. Phatak[10], A. Purich[1,5]*

1. Climate Change Research Centre & ARC Centre of Excellence for Climate System Science, UNSW, Australia
2. School of Engineering and ICT, University of Tasmania, Australia
3. Antarctic Climate and Ecosystems Cooperative Research Centre, University of Tasmania, Australia
4. ARC Centre of Excellence for Climate System Science, Melbourne University, Australia
5. CSIRO Oceans and Atmosphere Flagship, Aspendale, Australia
6. School of Geosciences, The University of Edinburgh
7. CSIRO Land and Water Flagship, Canberra, Australia
8. Institute for Marine and Antarctic Studies, University of Tasmania, Australia
9. ARC Centre of Excellence for Climate System Science, University of Tasmania, Australia
10. Department of Mathematics and Statistics, Curtin University, Australia

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**Corresponding Author:*

Sarah E. Perkins-Kirkpatrick

Climate Change research Centre

Level 4, Mathews Building

The University of New South Wales

Sydney, Australia, 2052

Email: Sarah.Kirkpatrick@unsw.edu.au

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 observed 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 knowledge gaps, recommendations of this paper 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 across many sectors. However, benefits will extend to the international community, thus addressing global grand challenges surrounding these remarkable extreme events.

1. Introduction

Heatwaves occur in the atmosphere and ocean and are natural hazards that have substantial impacts on human health, the economy and the environment. 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 about US$6.2 billion every year (Zander et al. 2015). The 2009 Victorian heatwave preceding the devastating Black Saturday bushfires killed over 370 people (Alexander and Tebaldi 2012) with insured loses of US$1.3 billion (Munich Re 2009). Heatwaves are also a key influence of bushfires, however the causal link between extreme temperatures and bushfires are the subject of a separate companion paper in this special issue (Sharples et al. 2015, this issue).

Heatwaves impact the natural environment; temperatures above 42 °C in 2002 killed over 3500 flying foxes in New South Wales (NSW) (Welbergen et al. 2008) and the 2011 Western Australia marine heatwave (Pearce and Feng 2013) had substantial impacts on marine biodiversity patterns (Wernberg et al. 2013). Extreme heat events can also impact the agriculture and aquaculture industries, respectively harming grain harvest yields such as wheat (Barlow et al. 2013) and reducing livestock in salmon farming industries.

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), thus an important influence on 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 enhanced greenhouse conditions (Orlowsky and Seneviratne 2012). However, there lacks a unified approach in understanding and characterizing atmospheric heatwaves in Australia, despite an improved understanding of the relationship between heatwaves and large-scale modes of climate variability (Parker et al. 2014a; Perkins et al. 2015), their dominating 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, less is understood. Only a handful of studies have focussed 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. 2015).

This paper reviews the scientific literature on the measurement, causes and observed trends and future projected changes of both atmospheric and marine heatwaves across Australia, forming part of a special issue on changes in Australian natural hazards. While it is recognized that atmospheric heatwaves also occur during cooler seasons, the focus of this paper is limited to austral summer heatwaves when the scale of impacts are generally larger. This paper concludes with principal findings and provides key recommendations on future research priorities.

2. Understanding heatwaves

2.1 Measuring atmospheric heatwaves

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

In recent years, the Australian Bureau of Meteorology has adopted its own index, the Excess Heat Factor (EHF; Nairn and Fawcett 2013), taking into account how hot a three-day period is compared to the prior month, as well as the climatological 95th percentile. Furthermore, a multi-definition, 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 broad range of impacts communities. The approach of Perkins and Alexander (2013) is similar to the "hot-spell" approach of Furrer et al. (2010). In both frameworks all heatwave characteristics are modelled as a function of covariates, such as time.

2.2 Large-scale mechanisms of atmospheric heatwaves

Over recent years, there has been international advance in understanding the drivers and mechanisms of atmospheric heatwaves (e.g. Lokith and Broccoli, 2012; Horton et al., 2015; Krueger et al, 2015; Grotjahn et al., 2015), and Australia is no exception. Figure 1 provides a schematic explaining how physical mechanisms over various timescales that underpin atmospheric heatwaves may interact in the lead-up to an event.

Several studies have examined the relationship between modes of large-scale climate variability and land surface temperatures across Australia (e.g. Nicholls et al. 1996; Jones and Trewin 2000; Arblaster and Alexander 2012; Min et al. 2013). While El Niño-Southern Oscillation (ENSO) is regarded as the primary large-scale driver of interannual variations of Australian rainfall (Risbey et al. 2009), the role of ENSO on the frequency and pattern of temperature extremes is varied (e.g. Arblaster and Alexander 2012; Min et al. 2013). Significantly more heatwave days, longer and more intense events are observed over northern and eastern Australia during El Niño phases compared to La Niña phases (Perkins et al. 2015), yet different relationships occur in the far southeast (Trewin 2009; Parker et al. 2014a, Boschat et al. 2015). White et al. (2013a) find that the Indian Ocean Dipole (IOD) has a positive relationship over southern Australia on weekly–averaged maximum temperatures for austral winter and spring – the seasons when the IOD is active.

Heatwaves in southeastern Australia are associated with phases 3-6 of the Madden Julian Oscillation (MJO) during the 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 temperatures increase during negative phases of the Southern Annular Mode (SAM; 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 have also been 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 area affected (Pezza et al. 2012; 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, anticyclonic 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 heatwaves over the southeast. Across the southwest, anticyclonic high-pressure systems are typically centred over the Great Australian Bight (Pezza et al. 2012). Other features include intra-seasonal drivers of variability (Marshall et al. 2013; White et al. 2013a), rainfall deficits (Nicholls 2004), and the Australian monsoon and tropical cyclones (Parker et al. 2013). Mechanisms of extreme-heat build-up can 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 the land-surface provides important feedbacks that can exacerbate or dampen heatwave intensity (Seneviratne et al. 2006). These include the albedo, surface roughness and soil moisture (e.g. Miralles et al. 2012; 2014). The first study of its kind for Australia, 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 for Australian 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 has been found to compound temperature increases due to global warming (Argüeso et al. 2014; 2015).

2.4 Measuring marine heatwaves

Marine heatwaves are also measured using many metrics. Numerous studies simply quote 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 of at least 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 (e.g., 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). However, the study of marine heatwaves is in its infancy, with a recent study seeking to generate a standardized definition (Hobday et al. 2015). This is based on consecutive exceedances of the calendar day 90th percentile of temperature for at least five consecutive days. 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 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, 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 temperatures have warmed twice as fast as the combined average. Several studies have assessed various aspects of Australian extreme temperature trends (e.g. Tryhorn and Risbey 2006; Alexander and Arblaster 2009; Pezza et al. 2012; Perkins and Alexander 2013; Perkins et al. 2012; Donat et al. 2013). Heatwave characteristics and the metrics used to define them (see Section 2.1) can vary markedly between studies, which limits consistent comparisons.

Heatwave intensity, frequency and duration have increased across many Australian regions since the middle of the 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 the average intensity over all days, 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 extreme heat similar to heatwaves) increased over 1958-2010, but with a slight decrease in duration (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 tended to decrease. While emerging studies are explaining the dynamic/thermodynamic components of changes in Northern Hemisphere extreme temperatures (e.g. Horton et al., 2015), similar studies with an Australian focus do not currently exist.

Classically, studies analysing the role of human influence on observed extreme temperature events are based on monthly or seasonal anomalies for large spatial domains (e.g. Stott et al., 2004; Lewis and Karoly 2013, 2014). In the Australian context, 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, it is virtually impossible that Australia's hottest spring on record (2013) would have occurred without anthropogenic influence (Lewis and Karoly 2014; Knutson et al. 2014). While it must be made clear that 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). This means that the studies of Lewis and Karoly (2013, 2014) 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 respectively increased in occurrence by two- and three-fold 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 (e.g. Allen and Tett, 1999; Kokic et al. 2014). Such analyses have been conducted on long-term trends in daily extreme temperatures at global and continental scales (e.g. Kim et al. 2015), however, these methods not yet been specifically applied to Australian heatwave trends.

3.3 Recent unprecedented heatwave events across Australia

Australia has experienced some unprecedented and extreme heatwaves during the last decade. Between January 27th to February 8th 2009 an extremely severe heatwave occurred over Victoria and was followed by the most devastating bushfires (the "Black Saturday" fires) in Australian history (Parker et al. 2013). The land had been particularly dry in the weeks preceding the event, and the extreme conditions rapidly spread throughout southeastern Australia. Many records were set for high day and night-time temperatures as well as for the duration of extreme heat (National Climate Centre 2009). The heatwave occurred in association with a slow moving surface anticyclone and propagating Rossby waves at upper levels. Combined with the presence of a tropical low off northwest Western Australia and an active monsoon trough, ideal conditions were provided 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).

The January 2013 heatwave produced a record breaking persistent extreme heat event that was unprecedented spatially and temporally (Bureau of Meteorology 2013). The main part of the heatwave, affecting the majority of the continent, lasted from the 4th to 18th January, however parts of central and Western Australia experienced heatwave conditions during late December 2012 (Bureau of Meteorology 2013). The event set a new nationally-averaged daily maximum temperature record of 40.33 °C (7th January, 2013), and consisted of seven consecutive days with maximum temperature above 39 °C (Bureau of Meteorology 2013). This heatwave was associated with a delayed monsoon onset, and slow moving weather systems over the continent, following from a drier than average end to 2012. 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 for over two weeks (Bureau of Meteorology 2013).

4. Future changes

4.1. Projections of heatwave events

4.1.1. Heatwave projections from Global Climate Models

Heatwave trends are expected to continue in a world under anthropogenic influence, with recent studies suggesting an increase in the frequency and duration of heatwaves over this century (Orlowsky and Seneviratne 2012; Coumou and Robinson 2013; Fischer et al., 2014). Much effort has 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), yet a similar effort has been lacking for Australia. The relevant studies are explored in this section.

Tryhorn and Risbey (2006) and Alexander and Arblaster (2009), employing a single climate model and the Coupled Model Intercomparison Project phase 3 climate models respectively, found a projected increase in heatwave duration and warm nights in the 21st century under greenhouse forcing. The 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 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 the annual means, consistent with observations (Alexander et al., 2007). Projected changes in the frequency of warm spells (including heatwaves) by 2100 show a dramatic and significant increase among the CMIP5 ensemble for both RCP4.5 and RCP8.5 (CSIRO 2015).

Also using CMIP5 models, Cowan et al (2014) show heatwaves becoming more frequent, hotter, and longer across Australia by the end of the 21st century, consistent with revised regional projections (CSIRO 2015). 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 also are substantial (Figures 3a,b,c,d). Under a moving-threshold heatwave definition, 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 at 60km resolution (Perkins et al. 2014b). Higher resolutions of up to 10km have been applied to Tasmania through the Climate Futures for Tasmania project (White et al. 2013b) and for, NSW and the Australian

Capital Territory (ACT) as part of the Regional Climate Modelling (NARCliM) project (Evans et al. 2014). Specifically, White et al. (2013b) show a significant average increase in warm spell duration (which also includes heatwaves) by 2100, relative to current baseline for a high-emissions (A2) 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. Figures 3e and 3f illustrate this using 50 km NARCLiM simulations for heatwave intensity and frequency, respectively (Evans et al. 2014). Australia-wide, changes in heatwave intensity are zonally distributed, with the largest changes located in tropical areas (Figures 3a,c,e).

4.2. Projected changes in atmospheric circulation

Currently, there is minimal research in understanding the dynamic/thermodynamic components behind future projections of Australian heatwaves. 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 previous studies of 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 in central Australia is currently predominantly attributed to thermodynamic changes (Purich et al. 2014).

There have been 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 responsible for, Australian heatwaves is uncertain (eg Pezza et al., 2012; Boschat et al., 2015). Moreover, current evidence provided by observations is limited and CMIP5 models fail to capture the observed SST patterns prior to southern Australian heatwaves (Purich et al. 2014), possibly due to the general deficiency in CMIP5 models' representation of SST variability (Wang et al. 2015). Thus, 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 during this century (Zheng et al. 2013).

4.3 Projections of marine heatwaves

Marine heatwaves is an emerging field, and as such, there are only a handful of studies exploring future changes. Projected changes around Australia are driven by the overall uplift in the ambient ocean temperatures as well as changes in the large-scale modes of climate variability. Southeastern and southwestern Australia are identified as hotspots of ocean warming (Foster et al. 2014), with the Tasman Sea in particular experiencing surface warming that is three-to-four times the global rate (Holbrook and Bindoff 1997; Ridgway 2007). Lenton et al. (2015) show that CMIP5 models project a net warming (relative to a 1986-2005 baseline) of SST in the Australia region of $0.65^{O}C$ by 2050 under an RCP2.6 scenario, rising to $0.9^{O}C$ and $1.2^{O}C$ under RCP4.5 and RCP8.5 scenarios respectively. The strongest signals are seen off the coasts of Tasmania and southwestern Australia, consistent the observed historical trends, as well as off the northwest shelf. This overall uplift 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 the west coast of Australia (Feng et al. 2015) and changes in wind stress curl over high-latitude regions of the 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 the literature in 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 has summarized 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 measure heatwaves, it is clear that they have increased in their intensity, frequency and duration as anthropogenic influences on the climate increases. Future shorter-term research efforts 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 appropriate methods already applied internationally.

Considerable advancements have 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; Boschat et al. 2015; Parker et al. 2014b). However, there is no comprehensive, Australia-wide study documenting the physical dynamics behind heatwaves. An increased scientific focus in untangling the causes and changes in Australian heatwaves should therefore be prioritized. This should include land surface feedbacks and antecedent soil moisture, dynamic/thermodynamic components of observed and future changes in heatwaves, and increases in the land-sea temperature gradient. The latter has not yet been studied in relation to Australian heatwaves, yet may be very important, especially over coastal regions. Moreover, researching physical connections with drought (Kiem et al. 2015, this issue) would be of substantial benefit to stakeholders of both hazards. Therefore, such work is imperative towards a greater understanding of atmospheric heatwaves, as well as advancing Australia's international contribution towards this important field.

There is also a significant amount of research effort to be undertaken on marine heatwaves. Given local events in recent years (Pearce and Feng 2013) and the proposal of a measurement framework (Hobday et al. 2015), the Australian community is in a great position to lead this research field. However, a considerable amount of work is required to understand future projections of marine heatwaves, as well as interactions between driving mechanisms. Such work should be prioritized in order to place our understanding of marine heatwaves in line with atmospheric events.

Lastly, there is a need to work towards a more unified framework for identifying atmospheric events. At least in this case, the global impact of Australian research on marine heatwaves is more advanced than atmospheric events. The identification of events underpins subsequent research on dynamics, changes or impacts, thus a more unified framework allows for a consistent approach across relevant studies and fields of research. This would require a large amount of collaboration across all relevant 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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Figures

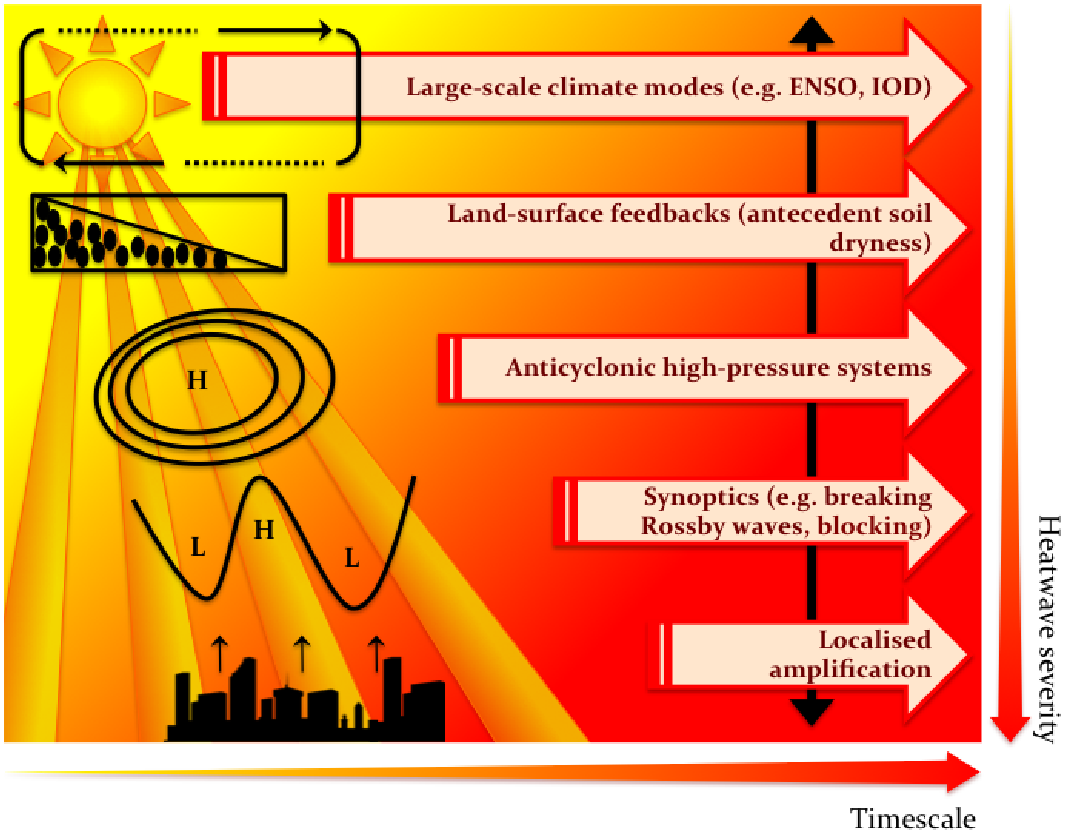

Figure 1: Heatwave schematic illustrating the various physical processes contributing to heatwaves, the interactions and feedbacks existing between them, and the timescales on which they operate. Not all processes need to be present for a heatwave to occur however (e.g. Fischer et al. 2007; Miralles et al. 2014).

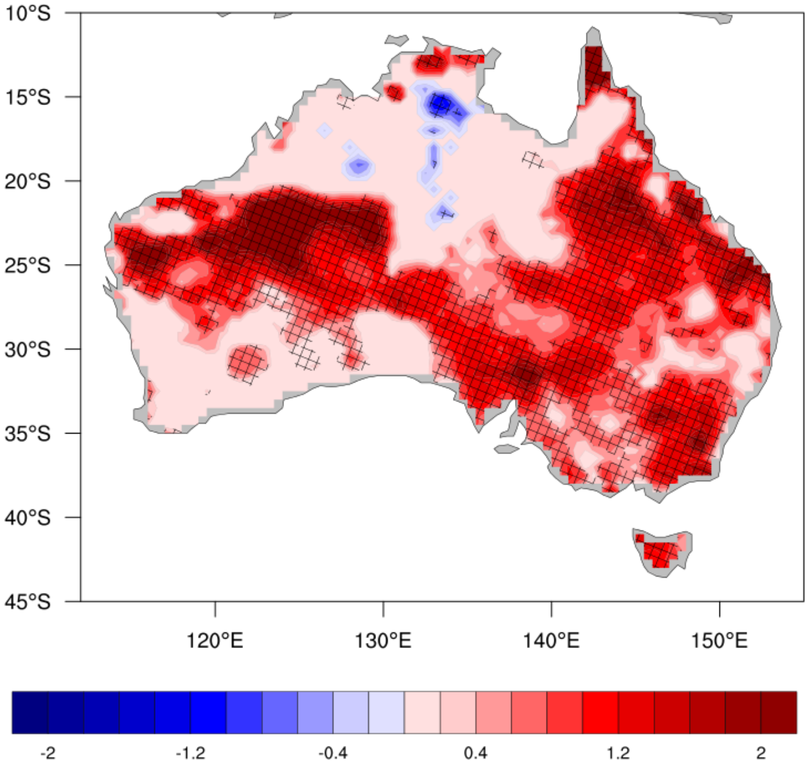

Figure 2: Observed trends in Australian heatwave days over 1950-2013. A heatwave day must belong to a period of three or more consecutive days that have positive excess heat values (see Nairn and Fawcett 2013) Hatching indicates statistical significance at the 5% level. Updated from Perkins and Alexander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

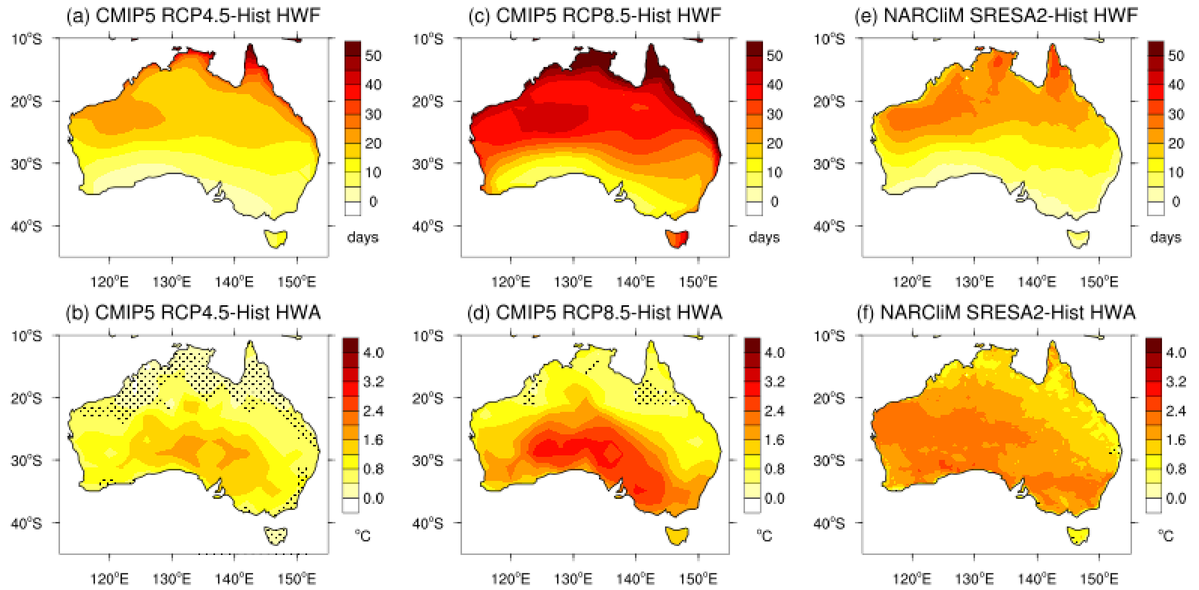

Figure 3: Austral summer heatwave increases compared to the historical climatology. (top) Ensemble average heatwave frequency (HWF; days per summer), and (bottom) heatwave amplitude (HWA; °C). (**a**,**b**) CMIP5 RCP4.5, (**c**,**d**) CMIP5 RCP8.5, and (**e**,**f**) 50km downscaled NARCliM for SRES A2.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