Climatic Change (2016) 139:37–54
DOI 10.1007/s10584-016-1798-7

Natural hazards in Australia: droughts

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Received: 3 February 2016 / Accepted: 26 August 2016 / Published online: 19 September 2016

Abstract Droughts are a recurrent and natural part of the Australian hydroclimate, with evidence of drought dating back thousands of years. However, our ability to monitor, attribute, forecast and manage drought is exposed as insufficient whenever a drought occurs. This paper summarises what is known about drought hazard, as opposed to the impacts of drought, in Australia and finds that, unlike other hydroclimatic hazards, we currently have very limited ability to tell when a drought will begin or end. Understanding, defining, monitoring, forecasting and managing drought is also complex due to the variety of temporal and spatial scales at which drought occurs and the diverse direct and indirect causes and consequences of drought. We argue that to improve understanding and management of drought, three key

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This article is part of a Special Issue on "The effect of historical and future climate changes on natural hazards in Australia" edited by Seth Westra, Chris White and Anthony Kiem.

Electronic supplementary material The online version of this article (doi:10.1007/s10584-016-1798-7) contains supplementary material, which is available to authorized users.

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research challenges should be targeted: (1) defining and monitoring drought characteristics (i.e. frequency, start, duration, magnitude, and spatial extent) to remove confusion between drought causes, impacts and risks and better distinguish between drought, aridity, and water scarcity due to over-extractions; (2) documenting historical (instrumental and pre-instrumental) variation in drought to better understand baseline drought characteristics, enable more rigorous identification and attribution of drought events or trends, inform/evaluate hydrological and climate modelling activities and give insights into possible future drought scenarios; (3) improving the prediction and projection of drought characteristics with seasonal to multidecadal lead times and including more realistic modelling of the multiple factors that cause (or contribute to) drought so that the impacts of natural variability and anthropogenic climate change are accounted for and the reliability of long-term drought projections increases.

Keywords Drought · Attribution · Climate variability · Climate change, palaeoclimate · Water resources · Hydrology

1 Introduction

The World Economic Forum estimates that drought costs $US6–8 billion a year globally due to losses in agriculture and related businesses alone – this does not include non-agricultural economic costs or harder to define and measure non-economic costs (e.g. impacts on mental health and well-being, changes to community/culture, environmental damage etc.) (Below et al. 2007; Botterill and Cockfield 2013). The socioeconomic impacts of drought are particularly severe in Australia, even though droughts are a natural and recurrent feature, because the large spatial and temporal hydroclimatic variability that exists (e.g. Murphy and Timbal 2008; Risbey et al. 2009; Gallant et al. 2012) was not properly taken into account when agriculture and water storage/supply infrastructure and systems were designed (Williams 2003; McKernan 2005). For example, recent prolonged dry conditions associated with the 1997–2010 Millennium drought (or 'Big Dry') (e.g. Murphy and Timbal 2008; Verdon-Kidd and Kiem 2009; Kiem and Verdon-Kidd 2010; Gallant et al. 2012; van Dijk et al. 2013) triggered water restrictions in major cities and heavily reduced (in some cases to zero) irrigation allocations across the Murray-Darling Basin, the largest agriculture region in Australia, resulting in major socioeconomic and environmental impacts (e.g. Kiem 2013; Kiem and Austin 2013; van Dijk et al. 2013.

Despite their significance, droughts and the physical factors that contribute to droughts are still poorly understood (e.g. van Dijk et al. 2013; Blauhut et al. 2015), making attribution and development of robust mitigation and management strategies challenging. One reason for this is because, unlike natural hazards with more graphic, immediate and measurable impacts (e.g. floods, cyclones, bushfires etc.), droughts develop gradually, are spatially extensive, can persist for years, and often go unnoticed until a wide-spread water, food, energy, economic, health or environmental issue is triggered (e.g. Wilhite et al. 2007). By the time a drought is

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identified, it is usually already well underway, remediation costs are mounting, and the opportunity for proactive mitigation or adaptation is gone. Complicating this are uncertainties or knowledge gaps around defining, monitoring and forecasting drought (including the termination of drought) (e.g. Parry et al. 2016) and for deriving accurate and practically useful quantification of drought likelihoods and consequences.

While most natural hazards are rare, drought has the added complication that all major droughts in Australia since ~1900 have had different spatial and temporal characteristics (Verdon-Kidd and Kiem 2009). This, combined with strong and complex interactions with a continuously changing agriculture, infrastructure and society context means that there have been limited opportunities to learn, adapt and prepare for droughts (van Dijk et al. 2013). Multidecadal climate variability (e.g. Kiem and Franks 2004; Gallant et al. 2012; Ho et al. 2015b; Vance et al. 2015), as well as projected impacts of anthropogenic climate change (e.g. CSIRO and Australian Bureau of Meteorology 2015), also means that drought will remain a key concern for Australia.

This paper, undertaken as part of the Australian Water and Energy Exchanges Initiative (OzEWEX, www.ozewex.org) working group on ‘Trends and Extremes’, reviews the state of understanding of the causes of Australian droughts, how drought has changed over time (instrumental and pre-instrumental), and how drought is projected to change in the future. The paper concludes by highlighting the major uncertainties and science challenges relating to drought in Australia, many of which are also applicable globally, along with some recommendations for how to address these challenges. It should be noted that the focus of this paper is the drought hazard rather than the impacts of or on the drought hazard. How agricultural, environmental, hydrological, and/or socioeconomic impacts combine with the drought hazard to change drought risk (and what can be done to mitigate that risk) is also an important research question but one that is beyond the scope of this paper (see Van Loon et al. (2016a, b) for recent work on links between drought characteristics and drought impacts).

2 Defining drought

Drought is possible in virtually all regions of the world, regardless of precipitation or temperature regimes, but what is considered a drought varies markedly. The simplest definition of drought is: a deficit of water compared with normal conditions (e.g. Tallaksen and Van Lanen 2004; Sheffield and Wood 2011). But what is normal? How long does the deficit have to persist or how severe does it need to be to be considered a drought? What is meant by water: rainfall, snow, ice, streamflow, water in a storage reservoir, groundwater, soil moisture, or all of these? The answer to these questions depends very much on the local situation in terms of climate and water use, which varies significantly in space and time and is why the simplest definition of drought is so vague.

Such questions also reinforce the concept that droughts are arguably one of the most complex of all natural hazards to analyse and understand (Wilhite et al. 2007). Droughts have a wide-range of cascading impacts (Fig. 1) that may be caused or exacerbated by different drought aspects or other external factors (i.e. such as those discussed in Section 3). Recent research (e.g. Peterson et al. 2013; Masih et al. 2014; Garner et al. 2015; Van Loon 2015) has increased understanding of the drought phenomenon and – based on the acknowledgement that drought is more than a lack of rainfall – led to many different drought definitions and categories. Five commonly used drought categories or types are:

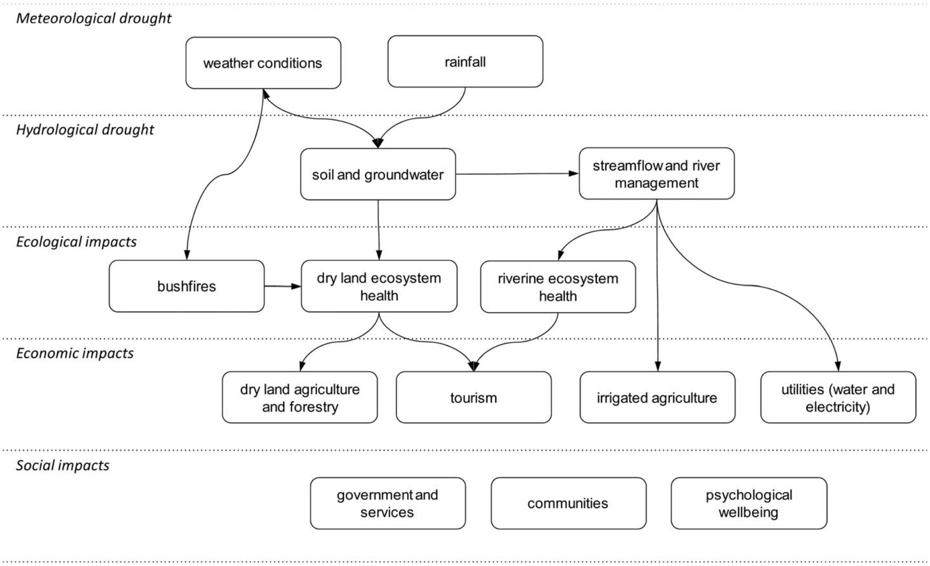

Fig. 1 From van Dijk et al. (2013). Millennium drought propagation through the hydrological cycle and associated ecological, economic, and social impacts. Only key impacts and links that are understood are shown

- *Meteorological drought*: extent and severity of drought in terms of deficits in precipitation from average conditions, possibly combined with increased potential evapotranspiration.
- *Soil moisture (or agricultural) drought*: deficit of soil moisture (mostly in the root zone), emphasising availability of soil moisture to support vegetation growth (usually crop or pasture growth, meaning the terms soil moisture drought and agricultural drought are often used interchangeably).
- *Ecological drought*: prolonged and widespread deficit in soil moisture, or biologically available water, that imposes multiple stresses in terrestrial and aquatic ecosystems.
- *Hydrological or water resources drought*: departure in surface or sub-surface water supplies from average conditions.
- *Socioeconomic drought*: the impacts of one or more of the other types of drought on humans, communities and/or the economy, defined based on social expectations, perceptions and other measures (e.g. employment levels, income and debt levels, mental and physical health).

Although these drought categories are widely accepted and used, some caveats and confusions exist. First, for the reasons detailed by Van Loon (2015), droughts should not be confused with other indicators of water deficit, including, chronic natural or man-made low flows, aridity, water scarcity or desertification. Second, droughts are unique in their timing: usually only becoming apparent months or years after they have started developing (compared with minutes to days for other natural hazards) and once a drought is occurring it will typically take unusually wet conditions to return to normal circumstances. As a consequence, drought characteristics such as onset and duration are less clearly defined compared to other natural hazards which only persist while extraordinary meteorological conditions continue (i.e. rarely for more than a week). Finally, unlike other natural hazards, drought definitions and categorisations introduce confusion between causes, impacts and risks (e.g. one does not refer to ‘agricultural floods’ or ‘socioeconomic cyclones’) and even between different categories of drought (e.g. socioeconomic drought does not refer to a type of drought but to the combined impacts of other types of drought). This creates problems when attempting to attribute drought to various potential causes and also for drought monitoring, forecasting and management.

3 Factors that cause (or contribute to) droughts

It is difficult to compare one drought to another since each drought is different, droughts are caused by a variety of both ocean-atmospheric and hydrological factors and it is rare, especially during the relatively short period covered by Australia’s instrumental hydroclimate records, that these factors are in similar states across multiple drought periods (e.g. Verdon-Kidd and Kiem 2009; van Dijk et al. 2013). Therefore, the challenge is how to attribute observed trends or variability in drought characteristics when drought is caused and terminated by some combination of oceanic, atmospheric and hydrological (including land-surface interactions) factors operating at global, hemispherical/continental and local scales.

At the largest scale, Australian drought is influenced by global climate (e.g. anthropogenic climate change) and hemispheric-scale patterns of variability such as the El Niño/Southern Oscillation (ENSO), Interdecadal Pacific Oscillation (IPO), Indian Ocean Dipole (IOD), and Southern Annular Mode (SAM). These large-scale processes have been associated with many characteristics of historical droughts in Australia (i.e. frequency, seasonality, duration, magnitude, location and spatial extent) (e.g. Murphy and Timbal 2008; Risbey et al. 2009; Verdon-Kidd and Kiem 2009; Kiem and Verdon-Kidd 2010; Gallant et al. 2012; van Dijk et al. 2013) and are also linked to the storms (Walsh et al. 2016) and heavy rainfall events (Johnson et al. 2016) that can end a drought. The impacts of these large-scale processes are further reviewed in Westra et al. (2016).

The large-scale processes mentioned above are linked to Australian drought through more direct (or proximate) causes of drought such as precipitation deficits (Section 3.1), processes that drive evaporative demand (Section 3.2) and the combined influence of precipitation and evaporation on soil moisture and groundwater (Section 3.3). Land-surface feedbacks that can exacerbate droughts (Section S1.1) and factors influencing the propagation of drought impacts through water systems (Section S1.2, van Dijk et al. 2013; Van Loon 2015) are also reviewed and discussed in the Supplementary Material.

3.1 Precipitation deficits (or absence of extreme rainfall events)

Generally, droughts are caused by a ‘prolonged’ deficiency in precipitation relative to ‘normal’ conditions. This can manifest as a decrease in the amount of precipitation per event, a decrease in the number of precipitation events, or a shift in when or where precipitation occurs (e.g. Verdon-Kidd and Kiem 2009; Rajah et al. 2014; Van Loon 2015). The period the precipitation deficit is required to persist to produce a drought also varies within Australia (e.g. below average rainfall over several months is enough to cause agricultural or hydrological drought in southwest and southeast Australia but the failure of major summer rains for several consecutive years is required to affect water resources in the semi-arid northwest (Sheffield et al. 2009; Rouillard et al. 2015)).

Known causative mechanisms of precipitation deficits in Australia include: warming of the eastern and central tropical Pacific Ocean (El Niño and/or positive IPO conditions) (e.g. Kiem and Franks 2004; Gallant et al. 2012); cool sea-surface temperatures in the Indian Ocean to the northwest of Australia (Verdon and Franks 2005; Ummenhofer et al. 2009a, b); the presence of blocking high pressure systems south of Australia (Risbey et al. 2009); north-south movement of the Antarctic belt of prevailing westerly winds, with positive SAM (westerlies further south than usual) in winter/spring causing drier conditions in southern Australia (e.g. Gallant et al. 2012) and negative SAM (westerlies further north than usual) in summer/autumn linked to drier conditions in central-west and northwest Australia (e.g. Fierro and Leslie 2013; O'Donnell et al. 2015); monsoon failure (D'Arrigo et al. 2008; Cook et al. 2010); and lack of storms (e.g. tropical cyclones or east coast lows (e.g. Walsh et al. 2016)).

3.2 Actual and potential evapotranspiration and driving variables

The important role of actual and potential evapotranspiration in contributing to droughts emphasises that drought is not just a lack of precipitation (Nicholls 2004). However, the role of evapotranspiration, and the processes that drive it, in influencing drought is sometimes ignored. For example, meteorological drought is often assessed by the widely used rainfall-based Standardised Precipitation Index (SPI), although more complex indices such as the Standardised Precipitation-Evapotranspiration Index (SPEI, Vicente-Serrano et al. 2010a, 2010b) have recently been developed. There is also debate in the literature about whether and how evapotranspiration should be considered in estimating drought (e.g. Karoly et al. 2003; Nicholls 2004; Roderick and Farquhar 2004; Cai and Cowan 2008; Cai et al. 2009; Gallant and Karoly 2009; Lockart et al. 2009). The major reason for contention is the order of causation: do higher temperatures cause drought via increased potential evapotranspiration or are they a response to drought, given there is less water available and hence less actual evapotranspiration, less evaporative cooling and less shading by cloud cover?

The argument for the role of temperature in causing increased evaporative demand stems from observed increases in Australian average, minimum and maximum temperatures of ~0.9 °C since 1910 (Murphy and Timbal 2008; CSIRO and Bureau of Meteorology 2015). It has been suggested that the severity of the recent Millennium drought (~1997–2010) is partly caused by these increased temperatures (Cai et al. 2009; Ummenhofer et al. 2009a), with Cai and Cowan (2008) suggesting that a 1 °C rise in annual average temperature leads to a 15 % reduction in annual streamflow. Several studies (e.g. Karoly et al. 2003; Nicholls 2004; CSIRO and Bureau of Meteorology 2015) also conclude that higher temperatures lead to increased frequency and severity of droughts.

However, others (e.g. Roderick and Farquhar 2004; Murphy and Timbal 2008; Lockart et al. 2009) argue that because actual evapotranspiration is constrained by the amount of liquid water available (which is low during droughts) then increased temperature is a consequence of drought rather than a cause because more radiative energy is partitioned into sensible heat (i.e. increased temperature) rather than latent heat. This is supported by Sheffield et al. (2012), who find that despite observed increases in temperature globally there has been little change in global drought frequency over the past 60 years, and Teuling et al. (2013), who mention in their discussion that for dry regions lower than average actual evapotranspiration "during drought will be common, leading to reduced evaporative cooling and strong coupling to temperature dynamics".

Another source of contention occurs because actual evapotranspiration is difficult to measure directly. Therefore models are used to estimate potential evapotranspiration and the choice of model strongly affects conclusions on the relationship between drought and evapotranspiration (Roderick and Farquhar 2004; Donohue et al. 2010; Sheffield et al. 2012). The choice of model includes the relationship between actual and potential evapotranspiration and the variables and equations that are used to quantify that, with Donohue et al. (2010) demonstrating that – in addition to temperature – net radiation, vapour pressure, and wind speed are also important influences on potential evapotranspiration. This relates to the pan evaporation paradox (Roderick and Farquhar 2002), which describes the mismatch between the widespread assumption that increased temperatures result in increased potential evapotranspiration (see previous two paragraphs) and the finding that despite temperature increases, pan evaporation (a proxy for potential evapotranspiration) has actually been decreasing over the last 50 years. Decreasing trends in Australian pan evaporation have been attributed to decreasing wind speed or ‘stilling’ (e.g. McVicar et al. 2012) and solar radiation changes (Roderick and Farquhar 2004; Roderick et al. 2007; Kirono et al. 2008; Lockart et al. 2009; Johnson and Sharma 2010).

These issues indicate that our understanding of macro-scale relationships between large-scale circulation, evapotranspiration, temperature, wind, solar radiation and drought is in its infancy. Furthermore, widely used temperature-based methods of measuring and modelling evapotranspiration (e.g. Thornthwaite 1948), and drought indicators which depend on those formulations (e.g. the Palmer Drought Severity Index (PDSI)) likely oversimplify the complex changes that might take place and are the source of much uncertainty when it comes to climate model based projections of future drought characteristics. This points to the need for “improvements in the observation and modelling of evapotranspiration and all its forcings at a large scale” (Trenberth et al. 2014).

3.3 Soil moisture deficits and groundwater

Soil moisture deficits are a type of drought (Section 2) but they are also related to below average moisture conditions within a catchment and therefore contribute to or enhance hydrological or water resources drought (Van Loon 2015), as well as heatwaves (Perkins-Kirkpatrick et al. 2016) and bushfires (Sharples et al. 2016). The opposite is true for ‘antecedent catchment wetness’ (i.e. soil moisture surplus) which reduces the chance of hydrological or water resources drought but increases the likelihood and magnitude of flooding (Rouillard et al. 2015; Johnson et al. 2016).

Depletion of soil moisture can be caused by lack of rainfall, evaporation from the soil, evapotranspiration through vegetation, drainage to groundwater, or runoff to streams (Hobbins et al. 2008; McGrath et al. 2012). During dry periods, rainfall and runoff are low, or even nil in large parts of the continent, and the ability to meet evaporative demand from open (but contracting) water bodies is reduced. This can lead to increased actual evapotranspiration (i.e. an extra loss of water) from soil. In extreme drought, a lack of available soil moisture and wilting of plants (and associated stomatal closure, reduction in leaf transpiration rate and/or reduction in leaf area of vegetation) can constrain actual evapotranspiration, limiting moisture in the atmosphere and locally generated precipitation, potentially further exacerbating drought conditions.

Large soil moisture deficits that are common during droughts are also associated with decreased or ceased recharge to groundwater systems, increased capillary rise and groundwater uptake by plants, falling groundwater levels and decreased groundwater discharge to surface streams and open water bodies (e.g. Crosbie et al. 2011; Mitchell et al. 2012). The fact that there is often a lag of months to years between rainfall deficits (or surplus) and the progressive depletion (or restoration) of surface, soil and groundwater stores (e.g. Figure 2) explains why several months of above-average rainfall are required to end protracted droughts, like the Millennium drought. Depending on the magnitude of rainfall and characteristics of the surface-groundwater system, there may be a delay of weeks to decades between the return of 'normal' precipitation, the return of soil moisture surplus at different depths, and re-establishment of the connectivity between groundwater and water bodies at the surface (e.g. Evans 2007). Changes

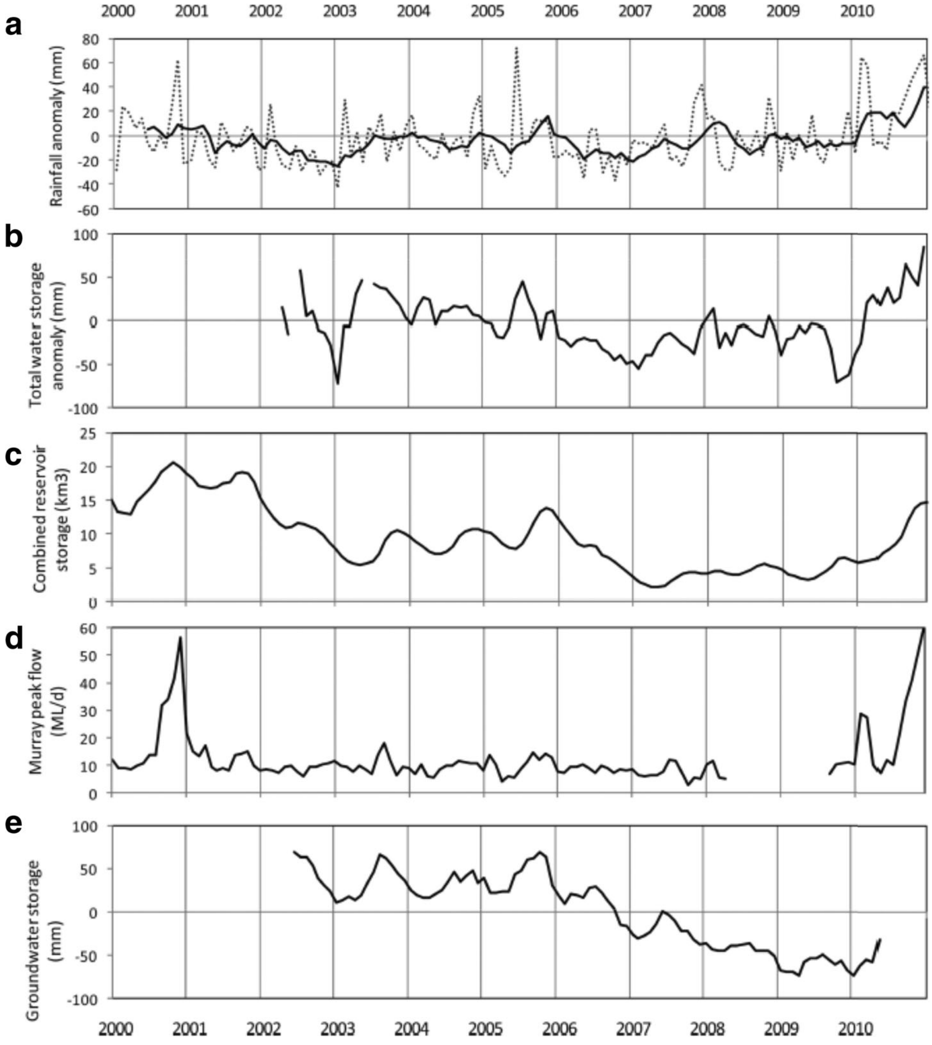

Fig. 2 From van Dijk et al. (2013). Millennium drought propagation through the hydrological cycle in the Murray-Darling Basin (MDB), Australia: **a** monthly rainfall anomalies (dotted) and 6 month running average (solid) ; **b** GRACE satellite-observed average monthly terrestrial water storage; **c** combined storage in public reservoirs; **d** daily peak flow for each month (Murray River at Wentworth); **e** estimated MDB groundwater storage

in the timing/distribution of rainfall are also critical in southern Australia because soil moisture stores are ‘normally’ replenished and streamflow is high when actual evapotranspiration is low (during winter and early spring). Less rainfall becomes streamflow or alleviates soil moisture deficits if rainfall occurs later in spring (or in summer) when actual evapotranspiration rates are higher – the number of rain days, days between rainfall events, and amount of rainfall per rainfall event are also critical in determining how much water becomes streamflow or alleviates soil moisture deficits (e.g. Verdon-Kidd and Kiem 2009; Kiem and Verdon-Kidd 2010; Mitchell et al. 2012).

3.4 Land-surface feedbacks and propagation of drought impacts through water systems

Vegetation and land-surface feedbacks are also important factors that can cause or exacerbate drought (see Section S1.1) as is the propagation of drought impacts through water systems (Section S1.2; van Dijk et al. 2013; Van Loon 2015).

4 Australia’s drought history

4.1 Instrumental period (~1900-present)

Three protracted droughts have occurred during the instrumental history of Australia (‘Federation drought’ (~1895–1902), ‘World War II drought’ (~1937–1945) and the ‘Millennium drought’ (~1997–2010)) along with several other shorter duration droughts. Each protracted drought differed in severity, spatial signature, and seasonality, and was likely driven by different climate processes (e.g. Murphy and Timbal 2008; Risbey et al. 2009; Verdon-Kidd and Kiem 2009; Kiem and Verdon-Kidd 2010; Gallant et al. 2012; van Dijk et al. 2013). For example, the Millennium drought only spread to parts of northwest Australia during 2002–2009 (McGrath et al. 2012), and parts of northwest Australia even experienced unusually wet conditions from 1995 to 2012 (O’Donnell et al. 2015; Rouillard et al. 2015). Similarly, drought in coastal southeast Australia is not as strongly linked to ENSO and IPO as it is in northeast Australia or non-coastal southeast Australia (Kiem and Verdon-Kidd 2010; Gergis and Ashcroft 2013; Vance et al. 2013, 2015). Asadi Zarch et al. (2015) examined the changes in drought characteristics in Australia over 1960–2009, and highlighted the important role of incorporating potential evapotranspiration into drought modelling efforts.

This raises the questions: (i) since European settlement (1788), or the start of the instrumental record (~1900), has Australia experienced the worst drought possible (i.e. when influential climate phenomena are locked into their dry phase)?; (ii) to what extent is drought severity associated with (potentially predictable) anomalies in hemispheric-scale patterns of variability compared to (less predictable) stochastic weather variability (i.e. if/when influential climate phenomena are locked into their dry phase is this a coincidence or are there physical reasons for this that can be modelled/predicted)?; (iii) what is the potential for (and can we quantify likelihoods of) droughts occurring in the future that are more severe than the worst droughts in Australia’s instrumental record?; (iv) how much of the true range of Australia’s drought characteristics (especially spatial and interannual to multidecadal variability) has been captured by the instrumental record? (v) what have been the dominant processes behind, and impacts of, severe and protracted droughts in Australia and have they been changing in recent decades? Answering these questions requires an understanding of the pre-instrumental history (Section 4.2) combined with utilisation of climate informed stochastic frameworks (e.g. Verdon and Franks 2006, 2007; McMahon et al. 2008; Henley et al. 2011; Ho et al. 2015b) to more robustly quantify (and manage) what is possible with respect to drought in Australia (Section 6, Challenge 2d).

4.2 Pre-instrumental period (prior to ~1900)

Annually resolved pre-instrumental hydroclimate data for Australia consist predominantly of tree ring, speleothem, coral and Antarctic ice core proxies (e.g. Vance et al. 2013, 2015; Bradley 2015; Ho et al. 2015a, 2015b; Tozer et al. 2016) while sediments from lakes and wetlands provide sub-decadal to multi-millennial reconstructions (e.g. McGowan et al. 2012; Gouramanis et al. 2012; Burrows et al. 2014). The development of new datasets is also the focus of ongoing research (e.g. Neukom and Gergis 2012; Barr et al. 2014; Palmer et al. 2015; Tyler et al. 2015).

Based on existing palaeoclimate information relevant to Australia (see Section S2 in the Supplementary Material for an overview and Fig. 3 for an example) it appears that, similar to other drought sensitive regions, a temporal continuum exists within Australian hydrological variability (e.g. Ault et al. 2013) and that palaeoclimate data can assist in better understanding droughts. Certainly, there appears to be a strong connection between the low frequency variability in ENSO and eastern Australian moisture balance (e.g. Marx et al. 2009; Barr et al. 2014; Burrows et al. 2014). Furthermore, multiple lines of independent evidence across the continent also suggest that the instrumental period does not capture the full range of drought conditions that have occurred (or are possible) in Australia (e.g. McGowan et al. 2012; Vance et al. 2013, 2015; Barr et al. 2014; Bradley 2015; Ho et al. 2015a, 2015b; Rouillard et al. 2016; Tozer et al. 2016; Cook, Palmer, Cook, Turney, Allen, Fenwick, O'Donnell, Lough, Grierson, Ho and Baker, The paleoclimate context and future trajectory of extreme summer hydroclimate events in eastern Australia, Journal of Geophysical Research - Atmospheres, In Review).

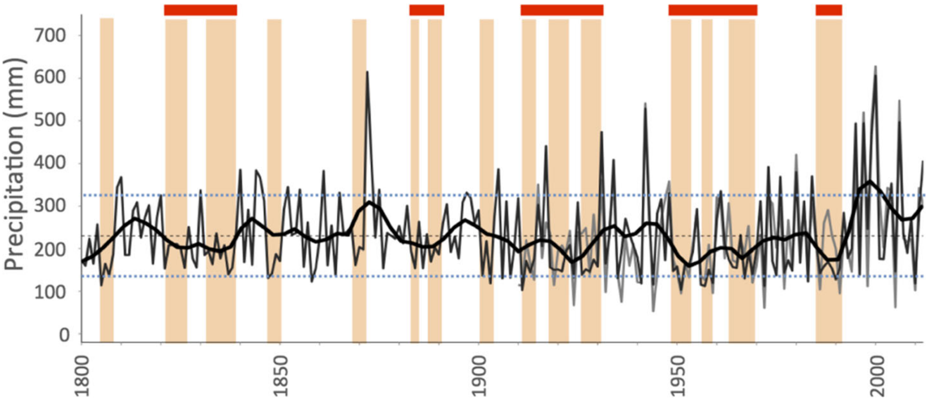

Fig. 3 Adapted from O’Donnell et al. (2015). Rainfall during the dominant rainfall season (December to March) in the Pilbara region (northwest Australia) reconstructed from tree rings. Solid black line =20-year loess curve; Dashed line = long-term average rainfall (1802–2012); Dotted blue line = +/− 1SD; Orange shading = multi-year drought; red shading = extended drought periods (20-year loess curve below long-term average)

5 Future changes to droughts and factors that cause (or contribute to) droughts

There is increasing evidence that the Hadley cells are likely to expand as a result of anthropogenic climate change and this will cause changes to continental drought and aridity. Globally, the largest drought increases over the twenty-first century are projected for America, southern Europe and Southern Africa (Zhao and Dai 2015). While not as pronounced as the aforementioned regions, decreases in rainfall and runoff, and associated increases in the frequency and duration of meteorological drought, are projected for some parts of Australia (Zhao and Dai 2015). For example, the southwest of Western Australia is projected to experience up to 80 % more meteorological drought months by 2070 (CSIRO and Australian Bureau of Meteorology 2015) when compared to a 1986–2005 baseline, and the South Eastern Australia Climate Initiative (SEACI, www.seaci.org/) projects a decrease in rainfall of 0–9 % (2–22 % for runoff) in southeast Australia per 1 °C increase in annual global average temperature (CSIRO 2012). Anthropogenic climate change is also projected to impact large-scale ocean-atmospheric processes in ways that suggest increases to at least meteorological and agricultural drought for some parts of Australia (refer to Table 1 in Westra et al. (2016) for further details).

In addition to indirect effects of anthropogenic climate change discussed above, future changes to droughts will also be influenced more directly by anthropogenic activity such as land use change and increased water abstraction (e.g. through their impacts on (eco)system resilience). For agricultural and hydrological drought these direct anthropogenic effects might be much more important than the indirect effects associated with the projected impacts of anthropogenic climate change (e.g. Bagley et al. 2014; Wanders and Wada 2015; Van Loon et al. 2016a, b).

Further, assessment of future changes to droughts depends on how drought is defined and quantified (Trenberth et al. 2014; Wanders and Wada 2015; Wanders et al. 2015), how much we know about the factors that cause or contribute to drought (Section 3), and how realistically climate models simulate those processes. As summarised in Westra et al. (2016) and Walsh et al. (2016), many of the processes associated with rainfall variability in Australia, and other factors that cause or contribute to droughts (Section 3), remain poorly represented in climate models (Kiem and Verdon-Kidd 2011; Kirono et al. 2011; Orlowsky and Seneviratne 2013) and this results in high uncertainty associated with magnitude, direction, spatial extent and seasonality of projected changes. The cause-effect relationships between drought and the variety of factors that contribute to it are complicated and not yet properly understood (especially at the local/catchment scale), let alone satisfactorily monitored, modelled or predicted (Orlowsky and Seneviratne 2013). This makes drought attribution challenging, means assessment of future changes to drought is uncertain and unreliable, results in minimal practically useful insights into drought, and presents significant challenges and limitations for natural resource managers and decision makers trying to plan for the future.

6 Knowledge gaps, research challenges, and recommendations

The nature of historical (Section 4) and future (Section 5) changes to Australian drought and its drivers is poorly understood. Insights depend on drought classification, including different definitions of drought onset/termination/spatial extent, and approaches to separate drought from man-made water scarcity or shifts towards permanent or semi-permanent (i.e. persisting for decades or more) aridity or desertification. Historical records (including instrumental and pre-instrumental) are generally incomplete, and process understanding is often hampered by the large number of variables involved and the range of space and time scales that are relevant. Finally, the link between drought, long-term climate trends (e.g. caused by anthropogenic climate change) and other modes of variability remains unclear.

To address these issues, we identify three key research challenges that should be prioritised over the next decade. While the three key research challenges focus on the drought hazard, it is acknowledged that other factors (including increases in population and associated demand for water and food) will also result in significant changes to drought risk (which is a function of the likelihood, consequence and exposure to the hazard) regardless of hydroclimatological influences. How agricultural, environmental, hydrological, and/or socioeconomic impacts combine with the drought hazard to change drought risk (and what can be done to mitigate that risk) is also an important research challenge but one that is beyond the scope of this paper (see Van Loon et al. (2016a, 2016b) for recent work on links between drought characteristics and drought impacts). Nevertheless, we argue that an understanding of current and future drought risk will be substantially improved through a coordinated effort to better understand the characteristics and causes of different types of drought hazards as outlined in the following three key research challenges:

Challenge 1: improve definition and real-time monitoring of the start, duration, magnitude, and spatial extent of drought This will help reduce confusion between drought causes, impacts and risks and better distinguish between drought (a temporary phenomenon), aridity, and water scarcity due to over-extractions. This should include monitoring and modelling of the “drought cascade” (Fig. 1 and Fig. 2) to, for example, help determine when a meteorological drought becomes a hydrological drought. Specific recommendations to address this challenge include:

a. Develop an agreed set of drought definitions/categories that clearly differentiates drought from long-term changes in aridity and water scarcity, and that captures attributes of drought such as start, duration, magnitude and spatial extent. Such definitions should account for the heterogeneity of Australia’s climate zones, the wide variety of end-users and applications of drought monitoring information, and the diversity of droughts that have occurred in the past. There is no ‘one-size-fits-all’ drought definition or indicator but this diversity of droughts should be acknowledged and there should be a common understanding/framework of what a drought is that takes into account the “drought cascade” and the differences between drought, aridity and man-made water scarcity;
b. Integrate traditional (e.g. gauge-based and model-derived) datasets with emerging datasets (e.g. remotely sensed soil moisture, palaeoclimate information) to provide more comprehensive information and real-time assessments of the state of each category of drought (see also AghaKouchak et al. 2015; Van Loon 2015; Van Loon et al. 2016a, b).

Challenge 2: document and explain historical (instrumental and pre-instrumental) variation in drought behaviour across the different drought classifications This will help provide more robust estimates of baseline drought characteristics (i.e. frequency, magnitude, timing, duration, location and spatial extent), enable more rigorous identification and attribution of drought events or trends, inform/evaluate hydrological and climate modelling and give insights into possible future drought scenarios. This requires compilation of longer-term and more spatially complete drought histories via the merging of palaeoclimate information with instrumental, satellite, and reanalysis data to: (i) better understand instrumental and pre-instrumental drought behaviour; and (ii) put droughts observed in the instrumental record into context with respect to what has occurred in the pre-instrumental past. Some examples of such work, concentrating on drought in Australia, are emerging (e.g. Allen et al. 2015; Ho et al. 2015a, 2015b; Palmer et al. 2015; Vance et al. 2015; Tozer et al. 2016; Cook et al. in review) and reveal huge potential. To fulfil this potential we need to:

a. Continue to collect and produce palaeo-records, and develop methods that better utilise the existing palaeoclimate information (e.g. Ho et al. 2014; Vance et al. 2015) to reconstruct drought histories over a period spanning at least the last 2000 years. This is crucial to obtain better spatial and temporal coverage of drought history (especially megadroughts);
b. Increase collaboration between palaeoclimatologists, hydrologists, climate modellers and water resource managers and better integrate methods, datasets and models such that longer-term drought histories (and futures) can be compiled (including information on atmosphere, soil moisture, land-surface/vegetation and groundwater conditions such that all categories of drought can be considered);
c. Develop improved methods to identify the causes of drought. This includes disentangling the role of large-scale ocean-atmospheric processes, climate variability, anthropogenic climate change and direct anthropogenic influences (e.g. land use change, water abstraction etc.) and their relationships with the different categories, and spatial and seasonal characteristics, of drought;
d. Translate information on historical drought into practically useful information for decision makers and water resource managers responsible for ensuring water security. Despite previous research on drought mechanisms and hydroclimatic variability demonstrating the invalidity of the stationary climate assumption (see Section 3 and 4), simple stochastic models that do not account for climate variability or change (i.e. they assume hydroclimatic stationarity) and are based on short, and often incomplete, instrumental records are still popular for developing long-term drought management and planning strategies in Australia (e.g. Thyer et al. 2006). While there have been some developments in stochastic modelling that incorporate instrumental and pre-instrumental variability to better articulate the probability of severe droughts (e.g. Verdon and Franks 2006, 2007; McMahon et al. 2008; Henley et al. 2011; Ho et al. 2015b) the uptake in practice has been limited, mostly due to the knowledge gaps outlined above (e.g. lack of spatial and temporal coverage of palaeoclimate information, focus mainly on meteorological drought, lack of insight into actual processes (or combination of processes) causing drought etc.). Techniques to assess drought severity-frequency-area-duration also exist (e.g. Sheffield

et al. 2009; Rahmat 2014) but, as with stochastic modelling approaches, these are currently limited to meteorological drought and only use instrumental observations that do not adequately capture the spatial and temporal variability of drought in Australia.

Challenge 3: improve predictions/projections of drought start, duration, magnitude and spatial extent (as opposed to the current focus on just rain or streamflow) with seasonal to multidecadal lead times While it is true that short-term (months to seasons) drought predictions are very different to long-term (decades) drought projections, both in the approaches used to provide them and the purposes for which they are used, some commonalities exist. Predictions/projections both require understanding and realistically modelling the influence of multiple large-scale climate drivers on the persistent advection of weather systems into the drought region, as well as the local land-atmosphere feedbacks that alter the resulting precipitation, evaporation and atmospheric circulation (meteorological drought). Predictions/projections also require a better understanding of soil properties at small and large-scales to capture the soil moisture dynamics (agricultural drought) and the hydrologic connectivity within the system (hydrological drought). Improved drought predictions/projections will be enabled by addressing the other research challenges, as improved definitions, monitoring, and understanding of historical droughts will be necessary to develop and validate the drought prediction/projection methods. The drought predictions (and longer-term projections) also need to meet stakeholder requirements in terms of lead-time, skill/reliability, and seasonality/timing. For the longer-term drought projections in particular it is especially important that the climate models producing those projections more realistically simulate the processes and impacts of natural climate variability and how anthropogenic climate change will contribute to or alter that.

7 Conclusion

Drought is a ‘creeping disaster’ (e.g. Van Loon 2015) as it is only noticed months or years after it has started and may persist for many months or years. We currently have very limited ability to tell when a drought will end, whereas we know other hazards typically do not persist for more than a week. Understanding, defining, monitoring, forecasting and managing drought is also complex due to the variety of temporal and spatial scales at which drought occurs and the diverse direct and indirect causes and consequences of drought. Indeed, a major challenge identified is the need for rigorous approaches to distinguish between correlation and causation with respect to drought, such as the question of whether increased temperatures or abnormally dry antecedent conditions are a cause or a sign of drought? This work, undertaken as part of the OzEWEX working group on ‘Trends and Extremes’, summarises what is known and unknown about drought hazard in Australia so as to establish future research directions for the Australian science and engineering communities. The knowledge gaps, challenges and recommendations identified are relevant beyond the Australian context and it is hoped that this paper contributes to a further understanding of drought in general and guides future research towards minimising the negative impacts of droughts when they inevitably occur.

Acknowledgments This paper was a result of collaboration through the working group 'Trends and Extremes' as part of the Australian Water and Energy Exchanges Initiative (OzEWEX, www.ozewex.org). J. Evans was supported through Australian Research Council (ARC) Future Fellowship FT110100576. A. van Dijk was supported through ARC Discovery Project DP40103679. S. Westra and F. Johnson were supported through ARC Discovery Project DP150100411. J. Tyler was supported through ARC Discovery Project DP140104093. C. Barr was supported by ARC Discovery Project DP150103875. B. Sivakumar was supported through ARC Future Fellowship FT110100328.

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