

LETTER • OPEN ACCESS

Potential for tree rings to reveal spatial patterns of past drought variability across western Australia

To cite this article: Alison J O'Donnell *et al* 2018 *Environ. Res. Lett.* **13** 024020

View the [article online](#) for updates and enhancements.

Environmental Research Letters



LETTER

Potential for tree rings to reveal spatial patterns of past drought variability across western Australia

OPEN ACCESS

RECEIVED

22 September 2017

REVISED

6 December 2017

ACCEPTED FOR PUBLICATION

15 December 2017

PUBLISHED

7 February 2018

Original content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



Alison J O'Donnell^{1,4} , Edward R Cook², Jonathan G Palmer³, Chris S M Turney³ and Pauline F Grierson¹

¹ Ecosystems Research Group, School of Biological Sciences, The University of Western Australia, Perth, Western Australia, Australia

² Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York, United States of America

³ Palaeontology, Geobiology and Earth Archives Research Centre and ARC Centre of Excellence for Australian Biodiversity and Heritage, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, New South Wales, Australia

⁴ Author to whom any correspondence should be addressed.

E-mail: alison.odonnell@uwa.edu.au

Keywords: Palmer Drought Severity Index (PDSI), drought atlas, dendrochronology, hydroclimate variability, dendroclimatology

Supplementary material for this article is available [online](#)

Abstract

Proxy records have provided major insights into the variability of past climates over long timescales. However, for much of the Southern Hemisphere, the ability to identify spatial patterns of past climatic variability is constrained by the sparse distribution of proxy records. This is particularly true for mainland Australia, where relatively few proxy records are located. Here, we (1) assess the potential to use existing proxy records in the Australasian region—starting with the only two multi-century tree-ring proxies from mainland Australia—to reveal spatial patterns of past hydroclimatic variability across the western third of the continent, and (2) identify strategic locations to target for the development of new proxy records. We show that the two existing tree-ring records allow robust reconstructions of past hydroclimatic variability over spatially broad areas (i.e. $> 3^\circ \times 3^\circ$) in inland north- and south-western Australia. Our results reveal synchronous periods of drought and wet conditions between the inland northern and southern regions of western Australia as well as a generally anti-phase relationship with hydroclimate in eastern Australia over the last two centuries. The inclusion of 174 tree-ring proxy records from Tasmania, New Zealand and Indonesia and a coral record from Queensland did not improve the reconstruction potential over western Australia. However, our findings suggest that the addition of relatively few new proxy records from key locations in western Australia that currently have low reconstruction skill will enable the development of a comprehensive drought atlas for the region, and provide a critical link to the drought atlases of monsoonal Asia and eastern Australia and New Zealand.

Introduction

Recent prolonged droughts, long-term rainfall declines and extreme pluvial events have highlighted Australia's vulnerability to hydroclimatic extremes and the urgent need to understand the mechanisms and timescales of hydroclimatic variability (e.g. Indian Ocean Climate Initiative 2002, van den Honert and McAneney 2011, Van Dijk *et al* 2013). However, it is becoming increasingly apparent that instrumental climate records for the Australian continent do not capture the full range of hydroclimatic variability required to understand the significance and drivers of recent extreme events. Proxy records of climate (i.e. preserved physical,

biological or chemical evidence of climatic conditions) can be calibrated against instrumental records and used to infer past climatic conditions. However, while proxy records from a diversity of natural archives have been used to significantly extend climate records (by centuries to millennia) and have provided significant insights into the drivers of past hydroclimatic variability in Australia (e.g. from corals (Lough 2007, 2011), speleothems (e.g. Denniston *et al* 2013, 2015, Haig *et al* 2014), sediments (Bowler *et al* 2003, Magee *et al* 2004, Proske *et al* 2014, Rouillard *et al* 2016), ice cores (Tozer *et al* 2015, Turney *et al* 2015, Vance *et al* 2013, 2015) and tree rings (e.g. Allen *et al* 2015, Cook *et al* 2000, Cullen and Grierson 2009, O'Donnell *et al* 2015, 2016),

the sparse spatial coverage of high-resolution proxy records across the Southern Hemisphere continues to limit our understanding of past climatic variability (PAGES 2k Consortium 2017).

In contrast, the comparatively dense spatial coverage of proxy records across the Northern Hemisphere has enabled the development of regional 'drought atlases', which have revealed past spatial and temporal patterns of hydroclimate across North America (NADA and Living Blended drought atlas, LBDA, Cook *et al* 2004, 2007, 2010b), Mexico (MXDA, Stahle *et al* 2016), Monsoonal Asia (MADA, Cook *et al* 2010a) and Europe ('Old World' drought atlas, OWDA, Cook *et al* 2015). Importantly, these drought atlases have been used to place drought periods of the modern era in the context of hydroclimatic variability of the last millennium or more. For example, the NADA and LBDA showed there were drought periods prior to the 19th century in North America that were of a greater duration and magnitude (i.e. 'megadroughts') than any drought period during the 20th Century (Cook *et al* 2010b). Similarly, the OWDA shows that a drying trend since the 1970s in the Mediterranean region is not unusual in the context of the last millennium (Cook *et al* 2015), with the exception of the Levant region of the Middle East, where a recent 15 year drought period was the driest in the last 900 years (Cook *et al* 2016a). These drought atlases have also provided insights into the role of broad-scale circulation features on continental and hemispheric scales. For example, 'megadrought' periods identified in both North America and Europe in the mid-15th Century indicate the possibility that Atlantic atmospheric circulation dynamics (i.e. the North Atlantic Oscillation) may have played a role in synchronising drought across these continents (Cook *et al* 2015, Oglesby *et al* 2012).

The sparse spatial coverage of proxy climate records limits the potential to develop similar drought atlases in Australia. However, hydroclimate in Australia is relatively coherent across large spatial scales, extending over hundreds to thousands of kilometres (D'Arrigo *et al* 2008, Risbey *et al* 2009) owing to low topographic complexity across the continent and strong and spatially broad influences of large-scale ocean-atmosphere modes of variability, such as the Indian Ocean Dipole (IOD), Southern Annular Mode (SAM) and the El Niño Southern Oscillation (ENSO) (see Risbey *et al* 2009 for a discussion of the drivers of rainfall variability in Australia). This high degree of coherency of hydroclimate in Australia may allow the development of robust reconstructions of past temporal and spatial variability of hydroclimate (i.e. drought atlases) across Australia from comparatively fewer climate proxies than other regions of the world. For example, D'Arrigo *et al* (2008) showed the potential to reconstruct hydroclimate (as the Palmer Drought Severity Index, PDSI) across northern and eastern Australia using only three proxies: a tree-ring chronology from northern central Australia (Baker *et al* 2008), a

tree-ring and coral-based reconstruction of PDSI from Java, Indonesia (D'Arrigo *et al* 2006) and a coral-based reconstruction of rainfall from north-eastern Australia (Lough 2007). More recently, these same tree-ring and coral chronologies along with 174 tree-ring chronologies from western and northern Australia, Tasmania and New Zealand were utilised to develop a drought atlas for eastern Australia and New Zealand (the ANZDA; Palmer *et al* 2015). The development of a robust reconstruction of drought across eastern Australia from these remote chronologies was possible because of strong teleconnections between Indonesia, eastern Australia and New Zealand, driven by ocean-atmosphere circulation features over the Pacific Ocean (e.g. ENSO and the Interdecadal Pacific Oscillation, IPO) (Palmer *et al* 2015). Similarly, an apparent teleconnection in the Indian Ocean mid-latitudes that links the climate of eastern Antarctica with that of eastern Australia (Tozer *et al* 2015, Vance *et al* 2013, 2015, and potentially southwest Australia, van Ommen and Morgan 2010) has enabled reconstructions of both the IPO and eastern Australian rainfall using sea salt records from ice cores at Law Dome, Antarctica (Tozer *et al* 2015, Vance *et al* 2013).

While broad-scale teleconnections have allowed high-resolution reconstructions of northern and eastern Australian hydroclimate from remote proxies in the Australasian region, the same is not necessarily true for western Australia. Across northern and eastern Australia, ocean-atmosphere circulation in the Pacific is the dominant influence on hydroclimate; however, the influence of Pacific Ocean climate is generally much weaker and more variable in western Australia (Risbey *et al* 2009). Hydroclimate across western Australia is more strongly influenced by ocean-atmosphere circulation features over the Indian and Southern Oceans, such as the IOD, Ningaloo Niño (NN) and SAM (Doi *et al* 2015, Fierro and Leslie 2013, Hendon *et al* 2007, 2014, Kataoka *et al* 2013, Marshall *et al* 2015, Raut *et al* 2014, Risbey *et al* 2009). Consequently, different climate influences may lead to disparate spatio-temporal patterns of drought between western Australia and northern and eastern Australia, which may limit what can be interpreted across western Australia from existing remote proxies. This gap in our understanding of long-term hydroclimatic variability across western Australia is of considerable concern given that recent changes in precipitation patterns have been observed across the region. For example, since the 1960s, temperate southwest western Australia has been severely impacted by a drastic (~20%) multi-decadal decline in rainfall during the dominant rainfall season (autumn-winter; Cai and Cowan 2006, Indian Ocean Climate Initiative 2002). At the same time, the semi-arid and tropical north of western Australia has experienced an increase in summer-autumn rainfall (Lavender and Abbs 2013, O'Donnell *et al* 2015, Shi *et al* 2008). The significance of these recent changes in the context of long-term climatic variability remains unclear.

Our aim here is to determine the extent to which the only two high-resolution tree-ring chronologies developed in western Australia (for the inland north (O'Donnell *et al* 2015) and south (Cullen and Grierson 2009)) can explain variability in hydroclimate (as PDSI) across western Australia. We also test if including 175 more remote tree-ring and coral records from the Australasian region in addition to the two western Australian records can improve the reconstruction skill for PDSI across western Australia. We seek to identify areas of low reconstruction skill that can be specifically targeted for the development of new proxies needed to extend understanding of long-term hydroclimatic variability across western Australia.

Data

Palmer Drought Severity Index

We use the Palmer Drought Severity Index (PDSI) for our reconstructions to maintain consistency with previous studies. The PDSI has been the preferred metric for reconstructing past variations in hydroclimate in the drought atlas studies of North America (Cook *et al* 2007), Mexico (Stahle *et al* 2016), Europe (Cook *et al* 2015), Asia (Cook *et al* 2010a) and eastern Australia and New Zealand (Palmer *et al* 2015). The PDSI is a widely used measure of meteorological drought or more specifically, soil moisture availability, which is based on a water balance model calculated using instrumental records of precipitation and temperature and a general soil water holding capacity parameter (Palmer 1965, van der Schrier *et al* 2013). The PDSI incorporates previous months conditions resulting in strong temporal autocorrelation over several months (Wells *et al* 2004).

We used the global 0.5° grid of the self-calibrating PDSI (sc-PDSI; van der Schrier *et al* 2013) available by application from the British Atmospheric Data Centre (<http://badc.nerc.ac.uk>). We extracted sc-PDSI data for each of the 923 0.5° grid points in the western Australian region (12–36°S and 110–130°E). We excluded sc-PDSI data prior to 1910 from further analyses because there are very few instrumental precipitation and temperature records across western Australia prior to 1910 (figure S1(a) available at stacks.iop.org/ERL/13/024020/mmedia), making the earliest (1901–1909) sc-PDSI data for this region relatively unreliable. For much of western Australia, mean PDSI over the 1910–2012 period is below zero. Prior to analysis, we calculated anomalies of the observed PDSI (i.e. re-centred PDSI to a mean of zero) to highlight wet and dry periods in relation to the baseline conditions for each grid point.

Chronologies

We utilised two chronologies developed from ring widths of *Callitris columellaris* trees in the inland north (O'Donnell *et al* 2015) and south (Cullen and

Grierson 2009) of western Australia (figure 1). We also utilised another 175 tree-ring and coral chronologies from the Australasian region that were used to develop the ANZDA (see Palmer *et al* 2015 and Cook *et al* 2016b for details.)

Both western Australian chronologies are located in semi-arid climate zones, where water availability is the main factor limiting tree growth. The climate of the south chronology is characterised as semi-arid Mediterranean, where the majority of the ca. 250 mm average annual rainfall falls in the austral autumn and winter (March to September) (see Cullen and Grierson 2009). Over the last half century at least, autumn-winter rainfall in this region has been most strongly influenced by atmospheric blocking activity, particularly in the Great Australian Bight region (O'Donnell *et al* 2011, Risbey *et al* 2009). Atmospheric blocking refers to the formation of high-pressure systems over the Southern Ocean, which block the west–east movement of low-pressure systems in the mid-latitudes, driving cut-off lows towards the equator. When these blocking high-pressure systems form in the Great Australian Bight region (~120°E) they favour rainfall over the south coast of western Australia (Risbey *et al* 2009). The south site is also occasionally subject to episodic extreme rainfall events in the summer and early autumn months (December–March) associated with tropical cyclones tracking from the northwest coast of the continent (O'Donnell *et al* 2011). The climate of the north chronology is considered sub-tropical semi-arid with an average annual rainfall of ca. 300 mm, which falls predominantly in the austral summer and autumn months (December–May). More than half of all rainfall at the north site is attributed to intense episodic events in summer-autumn associated with long-lived closed lows (i.e. monsoonal depressions and tropical cyclones; Lavender and Abbs 2013). Over at least the last half century, summer-autumn rainfall in this region has been most strongly influenced by the Southern Annular Mode (O'Donnell *et al* 2015, Risbey *et al* 2009), which, during its positive phase in summer-autumn, drives a poleward shift in the subtropical dry zone resulting in higher rainfall in the subtropics of the Southern Hemisphere (Hendon *et al* 2014).

We updated the south (Cullen and Grierson 2009) chronology to 2013 with new samples collected in April 2014. Both chronologies were detrended in a signal-free framework (Melvin and Briffa 2008) and indices calculated as ratios from an age-dependent spline (Melvin *et al* 2007). Both chronologies are strongly and positively correlated with precipitation ($r > 0.7$) during their respective dominant rainfall seasons, i.e. in the summer-autumn season (December–May) for the north chronology (O'Donnell *et al* 2015) and in the autumn-winter season (March–September) for the south chronology (Cullen and Grierson 2009). The south chronology is 359 years long (1655–2013) but the north chronology only covers the 1802–2012 period. Consequently, we only use the 211-year period

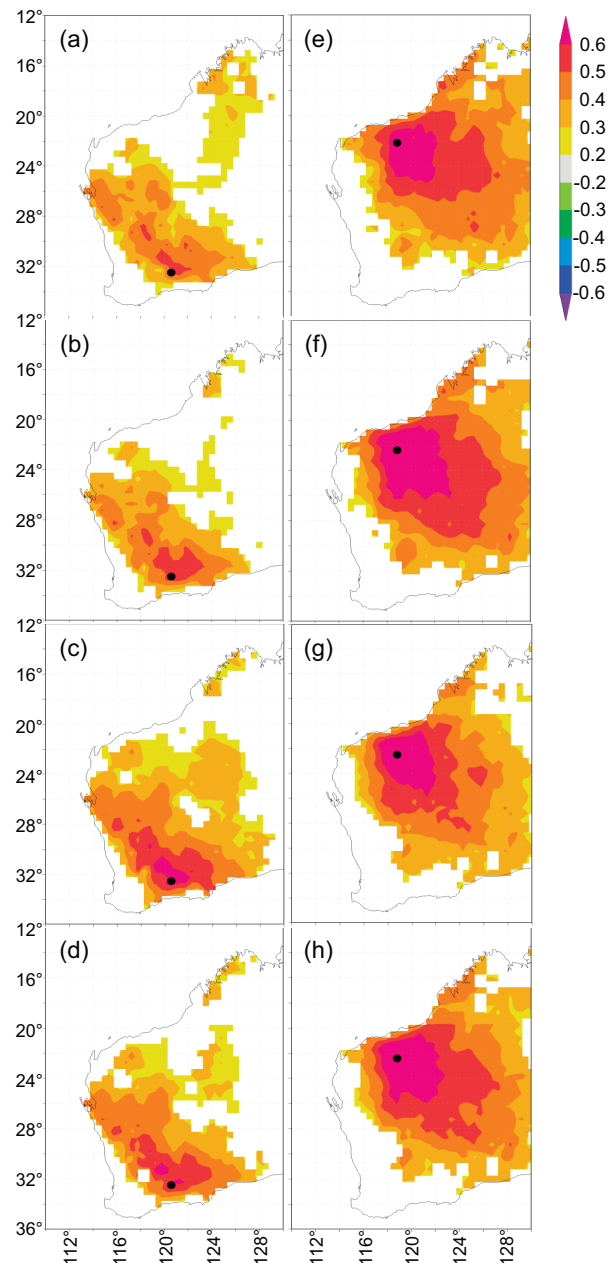


Figure 1. Significant ($\alpha = 0.05$) correlations between gridded PDSI and the south (a)–(d) and the north (e)–(h) western Australian tree-ring chronologies (1910–2010 C.E.), for (a) and (e) austral summer (December–February); (b) and (f) austral summer–autumn (December–May); (c) and (g) austral autumn–winter (March–August); and (d) and (h) austral summer–winter (December–August). PDSI data are the Climatic Research Unit’s scPDSI version 3.25; available from Climate Explorer: <http://climexp.knmi.nl/>. Correlation maps were produced using Climate Explorer. The locations of the chronologies are indicated by black dots.

(1802–2012) common to both chronologies in further analyses.

Methods

Spatial reconstruction of PDSI

PDSI has strong month-to-month autocorrelation ($r_1 = 0.897$) prescribed in its calculation (Palmer 1965, Wells *et al* 2004). Consequently, despite the dominant rainfall season of inland north-western Australia (austral summer–autumn) leading that of inland south-western Australia (austral autumn–winter) by

several months, both of the western Australian tree-ring chronologies were significantly correlated with PDSI throughout the austral summer–autumn–winter months across broad regions of western Australia (figure 1). The season with the strongest correlation ($r > 0.6$) that was common to both chronologies was autumn–winter (March–August) of the current year of tree growth (figures 1(c) and (g)). Consequently, we chose the austral autumn–winter (March–August) period as the season of PDSI to reconstruct in western Australia. All previous drought atlas studies, including the eastern Australian and New Zealand drought atlas (ANZDA; Palmer *et al* 2015) used a three-month

summer period (December–February in the Southern Hemisphere and June–August in the Northern Hemisphere) as the season to reconstruct. We did not use the same season here because the three-month summer (December–February) season does not fully capture the main season of rainfall (autumn–winter; March–August) and therefore meaningful drought for inland south-western Australia (figure 1(a)). Given the inherent autocorrelation in the calculation of monthly PDSI, each of the PDSI reconstructions represents the hydroclimatic conditions of much broader seasons than their prescribed season of calculation. Consequently, despite differences in the seasons used for reconstruction, the western Australian and eastern Australian reconstructions (Palmer *et al* 2015) reflect hydroclimatic conditions across broad and overlapping seasons.

We used the point-by-point regression method (PPR, Cook *et al* 1999, 2007, 2010a) to reconstruct gridded PDSI across western Australia using the two western Australian tree-ring chronologies as predictors, first separately and then together. The ‘search radius’ parameter of PPR is usually used to include only those chronologies proximal to each grid point and therefore likely to be mechanistically linked to climate at each grid point (Cook *et al* 2010a). However, given the low topographic variability in western Australia, broad spatial coherence of climate, and distance between the two western Australian chronologies (>1000 km), we relaxed this option (search radius of 2000 km) to allow our two chronologies to reconstruct PDSI at all grid points across the region. A similarly expanded search radius was used to reconstruct the ANZDA in eastern Australia (Palmer *et al* 2015).

We used methods consistent with Cook *et al* (2010a, 2015) and Palmer *et al* (2015) and ran a series of 16 models with or without autoregressive modelling in which the tree-ring series found within the search radius of each grid point were weighted by a power (0, 0.1, 0.25, 0.5, 0.67, 1.0, 1.5, or 2.0) of their correlation with PDSI at the grid point over the calibration period. The ensemble members were then averaged together to form a 16 member ensemble mean reconstruction. To test the robustness of the model, we undertook split-period calibration/verification analysis (Cook and Kairiukstis 1990, Fritts 1976). We used the 1955–2012 period for calibration and the 1910–1954 period for verification. We chose the 1955–2012 period for calibration to ensure that our models were calibrated on the highest-quality climate data period; the number and spatial coverage of climate stations in western Australia, particularly in inland areas of western Australia, were much greater in the latter (1955–2012) than in the early (1910–1954) period (figure S1(b)). We used two rigorous tests of fit, the reduction of error (RE) and the coefficient of efficiency (CE) to verify the model for each grid point.

In parallel with the above, we also investigated the potential to improve the spatial coverage and strength

of our model by including 175 other tree-ring and coral proxy records from the Australasian region. We included existing tree-ring chronologies from northern and eastern Australia (Northern Territory and Tasmania), Indonesia and New Zealand as well as a coral chronology from north-eastern Australia (i.e. all chronologies used to produce the ANZDA; see Palmer *et al* 2015) as predictors of western Australian PDSI. We used the same methods as described above, but altered the calibration (1940–1975) and verification (1910–1939) periods to allow for several of the New Zealand chronologies that do not extend beyond 1975 to be included in the model. As above, the latter period (1940–1975) was used for calibration, as this was the period with greater spatial coverage of instrumental climate stations across western Australia (figure S1(b)). We also relaxed the search radius criterion further (to 7000 km) to allow all chronologies to potentially be included in the model.

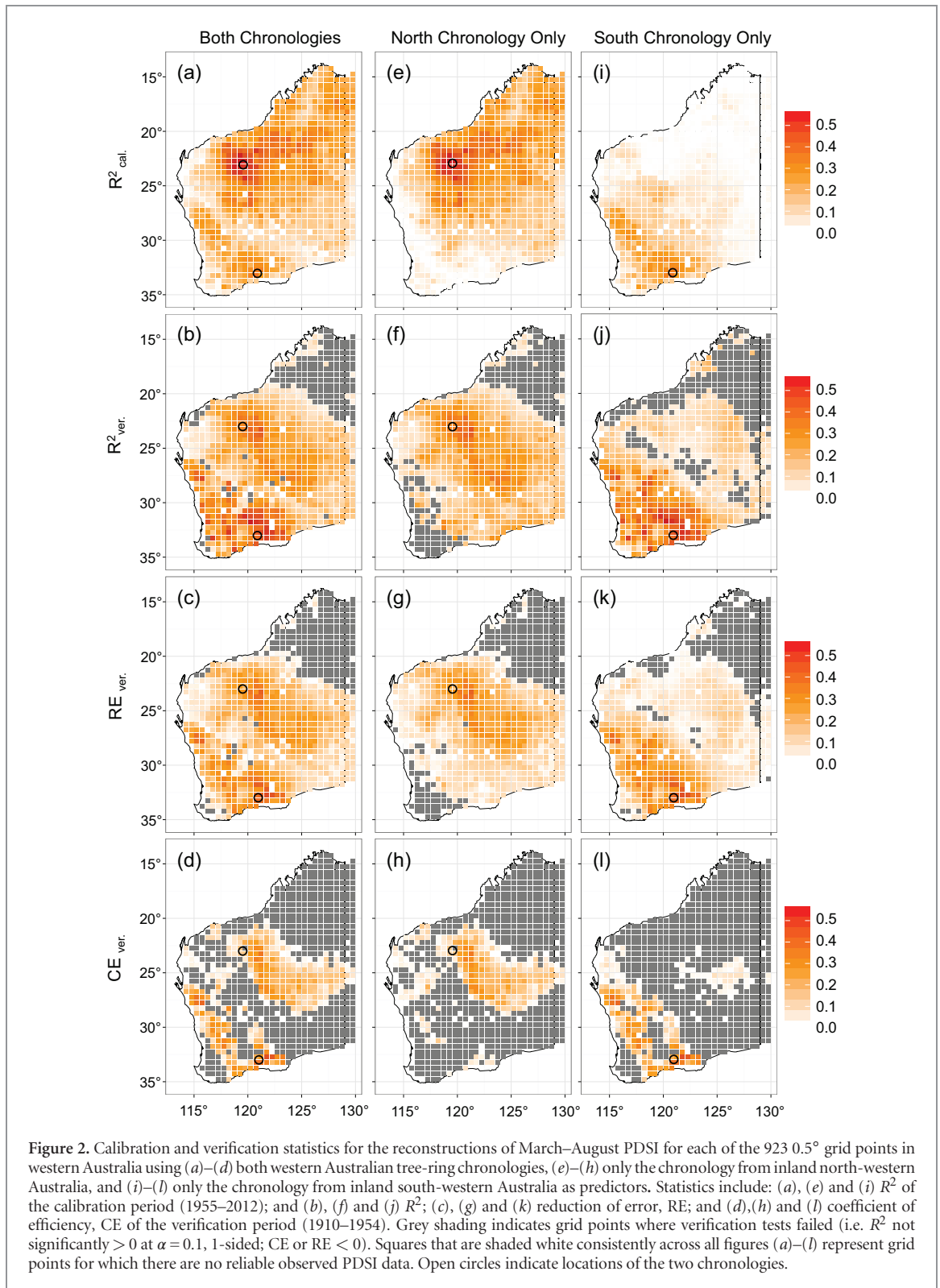
Temporal reconstructions of PDSI

We spatially averaged the ensemble reconstructed March–August PDSI anomalies to generate time series of past hydroclimatic variability for areas of western Australia where the PPR model passed all calibration and verification tests. In particular, we selected two areas of arbitrary size where the variance explained (calibration and verification R^2) by the two chronologies in the PPR models was relatively high (i.e. > 0.3) and tests of fit were passed (CE and RE > 0). Consequently, we chose two areas: 21.5–24.5°S, 119–122°E in the north and 30.5–34°S, 120–122.5°E in the south of western Australia. We rescaled the variance of reconstructed PDSI anomalies to match the variance of the observed PDSI over the calibration period to allow comparisons to be made between extreme events in the observed period and those in the past. We used a 20 year loess smoothing curve to highlight decadal-scale variation in the reconstructed and observed PDSI anomalies.

Results and discussion

Potential to reconstruct spatial patterns of drought from tree rings

Each of the models using only one chronology as a predictor passed all calibration (R^2_{cal}) and verification tests (R^2_{ver} , RE_{ver}, CE_{ver}) across broad regions (i.e. > 3° × 3°) near each of their locations in the inland north and inland south of western Australia (figures 2 (e)–(l)). Using both chronologies as predictors, the final model can robustly reconstruct March–August PDSI (i.e. pass all calibration and verification tests) over much of inland western Australia, but the strongest explanatory power (R^2_{cal} and R^2_{ver} > 0.3) remains in the two broad regions centred on the locations of the two chronologies (figures 2 (a)–(d)). We further examine reconstructed PDSI in these areas in the following section.



All of the models showed low reconstruction skill in areas of western Australia that are more remote from the locations of the chronologies (figures 2 (a)–(d)). The final (two-predictor) PPR model passed all verification tests ($CE_{ver.}$ and $RE_{ver.}$) for grid points along the mid-west coast and central inland areas of western Australia, but the variance explained in these areas was relatively low ($R^2_{ver.} < 0.2$; figure 2(b)). Hence, while the two existing chronologies contain useful

information about the variability of past hydroclimate in these regions, for our purposes we consider that the variance explained is not sufficient to reliably reconstruct PDSI in these areas. Consequently, we excluded areas with $R^2_{ver.} < 0.2$ from further interpretation of reconstructed PDSI. The final model failed to skilfully reproduce variability of drought (failed $CE_{ver.}$, $RE_{ver.}$ and/or $R^2_{ver.}$) in the southwest, southeast and the north of western Australia (figures 2(b)–(d)). Differences in

the dominant drivers (see Risbey *et al* 2009) and hence variability of hydroclimate among these areas mean that hydroclimatic variability of these areas cannot be reliably reconstructed using only the two existing tree-ring chronologies.

Nevertheless, the final model shows strong potential to reliably reconstruct past drought variability across remarkably large areas of western Australia (figures 2(a)–(d)). Our results suggest that the development of only a few new chronologies from strategic locations (i.e. particularly the north, the coastal southwest and southeast as well as central inland areas of western Australia) would dramatically improve reconstructions of both spatial and temporal hydroclimatic variability across the western Australian region.

Remarkably, the inclusion of 175 other proxy records from the Australasian region (see Palmer *et al* 2015) did not improve the reconstruction verification skill for western Australia compared to using only the two western Australian proxies (figure S2). We suggest that the influence of the Pacific Ocean on hydroclimate throughout much of western Australia is relatively modest compared to the eastern and northern continental regions (Risbey *et al* 2009), which limits what can be interpreted of western Australian hydroclimate from these 175 Australasian chronologies. This finding again reinforces the need to develop several new proxy records from within western Australia to be able to capture spatial variation in hydroclimate across the region.

Past hydroclimatic variability in inland western Australia

Our analysis has revealed that the western Australian chronologies can provide significant insight into climatic variability for two broad regions in the inland south and north of western Australia as well as the relationship between the two regions over time. The final reconstruction models (using both chronologies as predictors) explained almost 50% of the variance in observed PDSI in inland north ($R^2 = 0.49$) and south-western ($R^2 = 0.48$) Australia. The resulting reconstructions reveal inter-annual to multi-decadal-scale variability of PDSI in inland north and south-western Australia as well as years and multi-year periods of synchronous drought and wetter than average conditions in both regions (black lines in figures 3(a) and (b)). Synchronicity of drought and wet periods among the two regions is not attributed to both models sharing the same predictors as the reconstructions remain essentially unchanged when based only on the local chronology as the single predictor (red lines in figures 3(a) and (b)).

Our reconstructions show a prolonged period of drought in the 1950s in both the inland north and south of western Australia, which matches instrumental climate records well, and also reveals prolonged droughts occurred across much of inland western Australia in the 1830s and 1880s (figures 3(a) and (b)). There

are few readily available historical reports of climatic conditions in the 19th Century for western Australia. However, a drought that affected crops in the agricultural regions east of Perth in the southwest of western Australia was reported in the late 1830s (Foley 1957). Similarly, there are reports of prolonged drought in the late 1870s and early 1880s that restricted tilling activities around Perth (Foley 1957). These independent historical reports corroborate the occurrence of drought conditions in southwest Australia during the periods when our reconstructions reveal drought was influencing the inland north and south of western Australia. Our reconstructions thus provide new evidence that these documented prolonged drought periods in southwest western Australia in the 19th Century were likely much more widespread across the western Australian region than hitherto believed.

Synchronous periods of above average rainfall are also evident in both the inland north and south of western Australia over the last two centuries, though these were generally of a shorter duration (several years) than drought periods ($>$ decade; figures 3(a) and (b)). Two multi-year wet periods occurred in the early 1870s (wet years in 1872 and 1873) and in the late 1910s (wet years in 1915 and 1917; figures 3(a) and (b)). Synchronous wet years seen in both reconstructions were likely caused by widespread rainfall derived from tropical cyclones or other closed lows tracking from the northwest Australian coast inland towards the southeast coast of western Australia. Much of inland western Australia receives 30%–60% of its average annual rainfall from (ex-)tropical cyclones or other closed lows (Lavender and Abbs 2013). Unfortunately cyclone track records do not extend prior to the 1970s to confirm whether synchronous wet years in the 1870s and 1910s are related to single intense rain events (such as from a tropical cyclone) or coincident rain events derived from multiple sources. Further investigation of the oxygen isotope ratios ($\delta^{18}\text{O}$) of tree rings could help to disentangle potential sources of rainfall, where anomalously low (depleted) $\delta^{18}\text{O}$ isotope values typically indicate that rainfall (and soil water) was likely derived from tropical cyclones (Miller *et al* 2006, Mora *et al* 2006, 2007). Historical documents, where available, can also confirm the occurrence of tropical cyclones and other rain-bearing systems. Historical reports indicate that a ‘disastrous’ severe tropical cyclone influenced the Pilbara region of northwest Australia in April 1872 (‘Disastrous Cyclone at Roebourne’, *The Herald*, Fremantle, 18 May 1872) and while there are no available historical reports of rainfall in the south of western Australia during this time, storms of ‘unprecedented severity’ (also described as ‘tornadoes’ and ‘hurricanes’) were reported along the southwest coast in the months prior (February and March 1872; ‘The Gale on Sunday’, *The Inquirer and Commercial News*, Perth, 13 March 1872; ‘Hurricane at Geraldton’, *The Inquirer and Commercial News*, Perth, 21 February 1872) suggesting that there were multiple extreme rain events

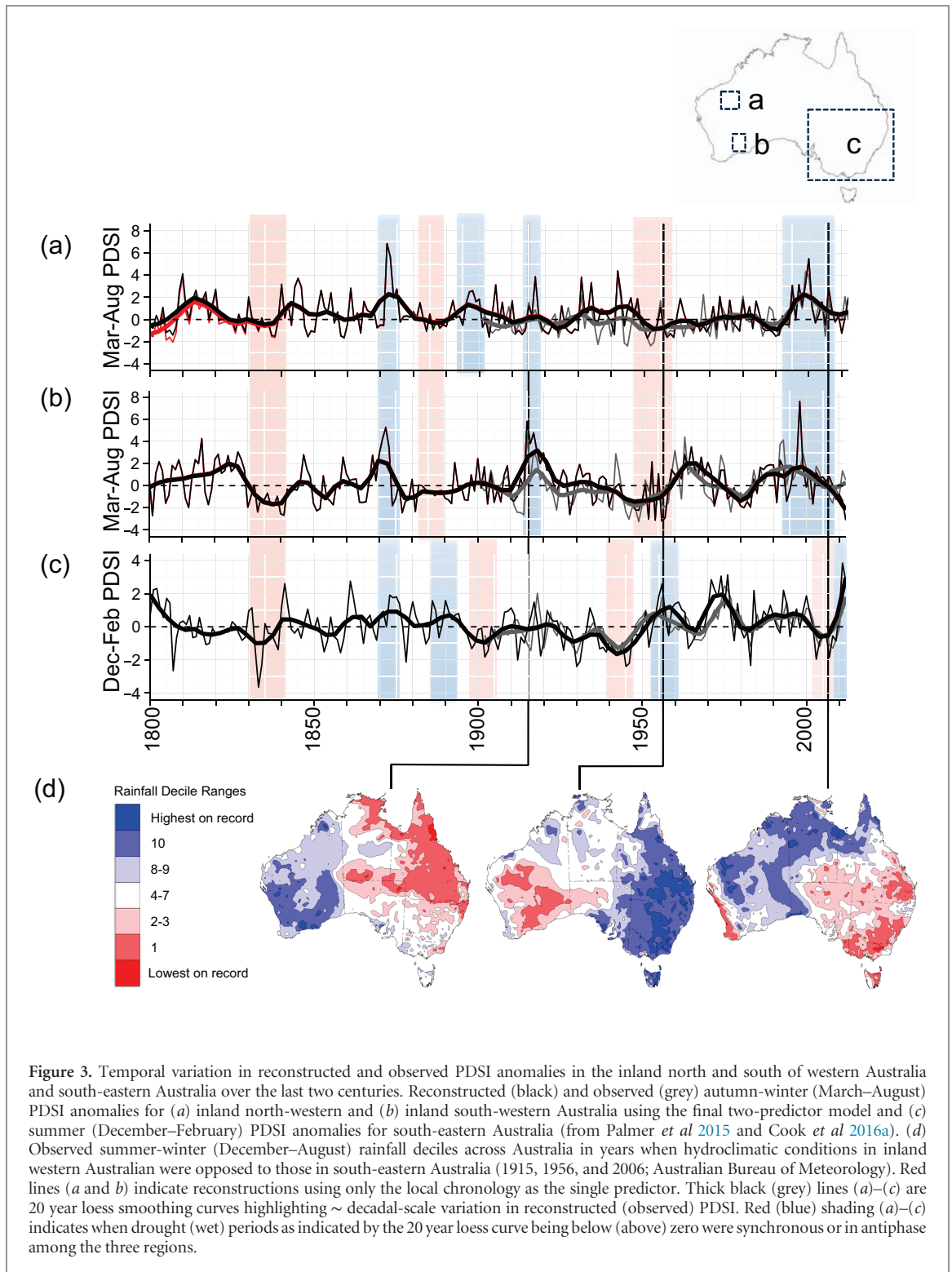


Figure 3. Temporal variation in reconstructed and observed PDSI anomalies in the inland north and south of western Australia and south-eastern Australia over the last two centuries. Reconstructed (black) and observed (grey) autumn-winter (March–August) PDSI anomalies for (a) inland north-western and (b) inland south-western Australia using the final two-predictor model and (c) summer (December–February) PDSI anomalies for south-eastern Australia (from Palmer *et al* 2015 and Cook *et al* 2016a). (d) Observed summer-winter (December–August) rainfall deciles across Australia in years when hydroclimatic conditions in inland western Australian were opposed to those in south-eastern Australia (1915, 1956, and 2006; Australian Bureau of Meteorology). Red lines (a and b) indicate reconstructions using only the local chronology as the single predictor. Thick black (grey) lines (a)–(c) are 20 year loess smoothing curves highlighting ~ decadal-scale variation in reconstructed (observed) PDSI. Red (blue) shading (a)–(c) indicates when drought (wet) periods as indicated by the 20 year loess curve being below (above) zero were synchronous or in antiphase among the three regions.

(possibly multiple tropical cyclones) across western Australia during this season.

An unusual prolonged (multi-decadal) wet period is evident in both reconstructions in the most recent decades (beginning in the 1980s in the inland south and in the 1990s in the inland north; figures 3(a) and (b)). This period is distinctive in both regions as the longest wet period (as indicated by PDSI) in the last two centuries. This ‘wetting’ trend across semi-arid inland western Australia (Fierro and Leslie 2013,

O’Donnell *et al* 2015) and an opposing trend in the temperate southwest of western Australia (i.e. west of 118°E, south of 32°S; Cai and Cowan 2006, Raut *et al* 2014) have been attributed to changes in the behaviour of broad-scale climate drivers, particularly the Southern Annular Mode, over the same period.

Interestingly, many of the prolonged drought and wet periods evident over the last two centuries in our reconstructions appear to have been in antiphase with those of eastern Australia (figures 3(a)–(c)), which

is also evident in instrumental rainfall records for the most recent century (figure 3(d)). For example, two of the three major drought periods in inland western Australia (i.e. 1880s and 1950s) coincided with relatively wet periods in south-eastern Australia (figures 3(a)–(d); Cook *et al* 2016b, Palmer *et al* 2015). In fact, the 1950s drought in western Australia coincided with the highest decadal-scale stream flow of the Murray River (in south-eastern Australia) in the last 200 years (Gallant and Gergis 2011). The prolonged wet period in the last two decades in inland western Australia also contrasts with much of eastern Australia, which was influenced by a severe drought during this time (i.e. the ‘Millennium drought’, ca. 1997–2010; figures 3(a)–(d)). Furthermore, while eastern Australia was experiencing some of the most severe drought conditions in the last two centuries during the ‘Federation’ (1896–1902) and ‘World War II’ (1937–1945) droughts, hydroclimatic conditions in inland western Australia appear to have been comparatively mild (figures 3(a)–(c); Verdon-Kidd and Kiem 2009).

Despite the high incidence of antiphase hydroclimatic conditions, we find at least one period of extreme drought during the 1830s was synchronous between inland (north and south) western and eastern Australia in the last two centuries (Cook *et al* 2016b, Gallant and Gergis 2011, Ho *et al* 2015, Palmer *et al* 2015, figures 3(a)–(c)). This finding suggests it is possible that drought conditions were widespread across the continent during this period; however, a more precise understanding of the spatial signature of this drought period (and other past drought and wet periods) is contingent upon the development of an Australia-wide drought atlas.

Conclusions

Our results clearly demonstrate the considerable potential for developing a drought atlas for western Australia, complementing the recent development of a drought atlas for eastern Australia and New Zealand (Palmer *et al* 2015). This analysis emphasises the urgent need for the development of proxy records across western Australia to better understand the trends of different climate modes and changing teleconnections across the continent on multi-decadal to centennial timescales. The development of an Australia-wide drought atlas would greatly improve our understanding of the spatial and temporal variability of drought and wet periods across the continent and provide a context to interpret the spatial scale and magnitude of recent hydroclimatic events.

Acknowledgments

This research was supported by the Australian Research Council under projects LP120100310, DP130104156, and DP170101033) and The University of Western

Australia (Research Collaboration Award awarded to A O’Donnell). Lamont-Doherty Earth Observatory contribution number 8174.

ORCID iDs

Alison J O’Donnell  <https://orcid.org/0000-0001-7597-7965>

References

- Allen K J, Nichols S C, Evans R, Cook E R, Allie S, Carson G, Ling F and Baker P J 2015 Preliminary December–January inflow and streamflow reconstructions from tree rings for western Tasmania, southeastern Australia *Water Resour. Res.* **51** 5487–503
- Baker P J, Palmer J G and D’Arrigo R D 2008 The dendrochronology of *Callitris intratropica* in northern Australia: annual ring structure, chronology development and climate correlations *Aust. J. Bot.* **56** 311–20
- Bowler J M, Johnston H, Olley J M, Prescott J R, Roberts R G, Shawcross W and Spooner N A 2003 New ages for human occupation and climatic change at Lake Mungo, Australia *Nature* **421** 837–40
- Cai W and Cowan T 2006 SAM and regional rainfall in IPCC AR4 models: Can anthropogenic forcing account for southwest western Australian winter rainfall reduction? *Geophys. Res. Lett.* **33** L24708
- Cook B I, Anchukaitis K J, Touchan R, Meko D M and Cook E R 2016a Spatiotemporal drought variability in the mediterranean over the last 900 years *J. Geophys. Res. Atmos.* **121** 2060–74
- Cook B I *et al* 2016b The paleoclimate context and future trajectory of extreme summer hydroclimate in eastern Australia *J. Geophys. Res. Atmos.* **121** 820–12 838
- Cook E R, Anchukaitis K J, Buckley B M, D’Arrigo R D, Jacoby G C and Wright W E 2010a Asian monsoon failure and megadrought during the last millennium *Science* **328** 486–9
- Cook E R, Buckley B M, D’Arrigo R D and Peterson M J 2000 Warm-season temperatures since 1600 BC reconstructed from Tasmanian tree rings and their relationship to large-scale sea surface temperature anomalies *Clim. Dyn.* **16** 79–91
- Cook E R and Kairiukstis L A 1990 *Methods of Dendrochronology—Applications in the Environmental Sciences* (Dordrecht: Kluwer Academic Publishers)
- Cook E R, Meko D M, Stahle D W and Cleaveland M K 1999 Drought reconstructions for the continental United States *J. Clim.* **12** 1145
- Cook E R, Seager R, Cane M A and Stahle D W 2007 North American drought: Reconstructions, causes, and consequences *Earth-Science Rev.* **81** 93–134
- Cook E R, Seager R, Heim R R, Vose R S, Herweijer C and Woodhouse C 2010b Megadroughts in north America: placing IPCC projections of hydroclimatic change in a long-term palaeoclimate context *J. Quat. Sci.* **25** 48–61
- Cook E R *et al* 2015 Old World megadroughts and pluvials during the common Era *Sci. Adv.* **1** 1–10
- Cook E R, Woodhouse C, Eakin C M, Meko D M and Stahle D W 2004 Long-term aridity changes in the western United States *Science* **306** 1015–8
- Cullen L E and Grierson P F 2009 Multi-decadal scale variability in autumn–winter rainfall in south-western Australia since 1655 AD as reconstructed from tree rings of *Callitris columellaris* (Cupressaceae) *Clim. Dyn.* **33** 433–44
- D’Arrigo R, Baker P, Palmer J, Anchukaitis K and Cook G 2008 Experimental reconstruction of monsoon drought variability for Australasia using tree rings and corals *Geophys. Res. Lett.* **35** L12709
- D’Arrigo R, Wilson R, Palmer J, Krusic P, Curtis A, Sakulich J, Bijaksana S, Zulaikah S and Ngkoimani L O 2006 Monsoon drought over java, Indonesia, during the past two centuries *Geophys. Res. Lett.* **33** 4–7

- Denniston R F *et al* 2015 Extreme rainfall activity in the Australian tropics reflects changes in the El Niño/Southern Oscillation over the last two millennia *Proc. Natl Acad. Sci. USA* **112** 4576–81
- Denniston R F *et al* 2013 A stalagmite record of Holocene Indonesian–Australian summer monsoon variability from the Australian tropics *Quat. Sci. Rev.* **78** 155–68
- Doi T, Behera S K and Yamagata T 2015 An interdecadal regime shift in rainfall predictability related to the Ningaloo Niño in the late 1990s *J. Geophys. Res. Ocean.* **120** 1388–96
- Fierro A O and Leslie L M 2013 Links between central west Western Australian rainfall variability and large-scale climate drivers *J. Clim.* **26** 2222–46
- Foley J C 1957 Droughts in Australia: review of records from earliest years of settlement to 1955 *Bureau of Meteorology* (Melbourne: Commonwealth of Australia)
- Fritts H C 1976 *Tree Rings and Climate* (London: Academic)
- Gallant A J E and Gergis J 2011 An experimental streamflow reconstruction for the River Murray, Australia, 1783–1988 *Water Resour. Res.* **47** W00G04
- Haig J, Nott J and Reichert G-J 2014 Australian tropical cyclone activity lower than at any time over the past 550–1500 years *Nature* **505** 667–71
- Hendon H H, Lim E-P and Nguyen H 2014 Seasonal variations of subtropical precipitation associated with the Southern Annular Mode *J. Clim.* **27** 3446–60
- Hendon H H, Thompson D W J and Wheeler M C 2007 Australian rainfall and surface temperature variations associated with the Southern Hemisphere annular mode *J. Clim.* **20** 2452–67
- Ho M, Kiem A S and Verdon-Kidd D C 2015 A paleoclimate rainfall reconstruction in the Murray-Darling basin (MDB), Australia: 2. Assessing hydroclimatic risk using paleoclimate records of wet and dry epochs *Water Resour. Res.* **51** 8380–96
- Indian Ocean Climate Initiative 2002 *Climate Variability and Change in South West Western Australia* (East Perth, Western Australia: Department of Environment, Water and Catchment Protection)
- Kataoka T, Tozuka T, Yamagata T and Behera S 2013 On the Ningaloo Niño/Niña *Clim. Dyn.* **43** 1463–82
- Lavender S L and Abbs D J 2013 Trends in Australian rainfall: contribution of tropical cyclones and closed lows *Clim. Dyn.* **40** 317–26
- Lough J M 2011 Great Barrier Reef coral luminescence reveals rainfall variability over northeastern Australia since the 17th century *Paleoceanography* **26** PA2201
- Lough J M 2007 Tropical river flow and rainfall reconstructions from coral luminescence: Great Barrier Reef, Australia *Paleoceanography* **22** PA2218
- Magee J W, Miller G H, Spooner N A and Questiaux D 2004 Continuous 150 k.y. monsoon record from Lake Eyre, Australia: Insolation-forcing implications and unexpected Holocene failure *Geology* **32** 885–8
- Marshall A G, Hendon H H, Feng M and Schiller A 2015 Initiation and amplification of the Ningaloo Niño *Clim. Dyn.* **45** 2367–85
- Melvin T M and Briffa K R 2008 A ‘signal-free’ approach to dendroclimatic standardisation *Dendrochronologia* **26** 71–86
- Melvin T M, Briffa K R, Nicolussi K and Grabner M 2007 Time-varying-response smoothing *Dendrochronologia* **25** 65–9
- Miller D L, Mora C I, Grissino-Mayer H D, Mock C J, Uhle M E and Sharp Z 2006 Tree-ring isotope records of tropical cyclone activity *Proc. Natl Acad. Sci.* **103** 14294–7
- Mora C I, Miller D L and Grissino-Mayer H D 2006 Tempest in a tree ring: paleotempestology and the record of past hurricanes *Sediment. Rec.* **4** 4–8
- Mora C I, Miller D L and Grissino-Mayer H D 2007 Oxygen isotope proxies in tree-ring cellulose: tropical cyclones, drought, and climate oscillations *Stable Isotopes as Indicators of Ecological Change* ed R T W Siegwold and T E Dawson (Amsterdam: Academic) pp 63–75
- O’Donnell A J, Allen K J, Evans R M, Cook E R, Trouet V and Baker P J 2016 Wood density provides new opportunities for reconstructing past temperature variability from southeastern Australian trees *Glob. Planet. Change* **141** 1–11
- O’Donnell A J, Boer M M, McCaw W L and Grierson P F 2011 Climatic anomalies drive wildfire occurrence and extent in semi-arid shrublands and woodlands of southwest Australia *Ecosphere* **2** art127
- O’Donnell A J, Cook E R, Palmer J G, Turney C S M, Page G F M and Grierson P F 2015 Tree rings show recent high summer-autumn precipitation in northwest Australia is unprecedented within the last two centuries *PLoS ONE* **10** e0128533
- Oglesby R, Feng S, Hu Q and Rowe C 2012 The role of the Atlantic Multidecadal Oscillation on medieval drought in north America: synthesizing results from proxy data and climate models *Glob. Planet. Change* **84** 56–65
- PAGES 2k Consortium 2017 A global multiproxy database for temperature reconstructions of the common Era *Sci. Data* **4** 170088
- Palmer J G, Cook E R, Turney C S M, Allen K J, Fenwick P, Cook B I, O’Donnell A, Lough J, Grierson P and Baker P 2015 Drought variability in the eastern Australia and New Zealand summer drought atlas (ANZDA, CE 1500–2012) modulated by the Interdecadal Pacific Oscillation *Environ. Res. Lett.* **10** 124002
- Palmer W C 1965 *Meteorological Drought. Research Paper No. 45* (Washington, DC: US Department of Commerce, Weather Bureau)
- Proske U, Heslop D and Haberle S 2014 A Holocene record of coastal landscape dynamics in the eastern Kimberley region *Aust. J. Quat. Sci.* **29** 163–74
- Raut B A, Jakob C and Reeder M J 2014 Rainfall changes over southwestern Australia and their relationship to the southern annular mode and ENSO *J. Clim.* **27** 5801–14
- Risbey J S, Pook M J and McIntosh P C 2009 On the remote drivers of rainfall variability in Australia *Mon. Weather Rev.* **137** 3233–53
- Rouillard A, Skrzypek G, Turney C, Dogramaci S, Hua Q, Zawadzki A, Reeves J, Greenwood P, O’Donnell A J and Grierson P F 2016 Evidence for extreme floods in arid subtropical northwest Australia during the Little Ice Age chronozone (CE 1400–1850) *Quat. Sci. Rev.* **144** 107–22
- Shi G, Cai W, Cowan T, Ribbe J, Rotstayn L and Dix M 2008 Variability and trend of north west Australia rainfall: observations and coupled climate modeling *J. Clim.* **21** 2938–59
- Stahle D W *et al* 2016 The Mexican drought atlas: tree-ring reconstructions of the soil moisture balance during the late pre-Hispanic, colonial, and modern eras *Quat. Sci. Rev.* **149** 34–60
- Tozer C R, Vance T R, Roberts J, Kiem A S, Curran M A J and Moy A D 2015 An ice core derived 1013 year catchment scale annual rainfall reconstruction in subtropical eastern Australia *Hydrol. Earth Syst. Sci. Discuss.* **12** 12483–514

- Turney C S M, Fogwill C J, Klekociuk A R, Van Ommen T D, Curran M A J, Moy A D and Palmer J G 2015 Tropical and mid-latitude forcing of continental Antarctic temperatures *Cryosphere* **9** 2405–15
- van den Honert R and McAneney J 2011 The 2011 Brisbane floods: causes, impacts and implications *Water* **3** 1149–73
- van der Schrier G, Barichivich J, Briffa K R and Jones P D 2013 A scPDSI-based global data set of dry and wet spells for 1901–2009 *J. Geophys. Res. Atmos.* **118** 4025–48
- Van Dijk A I J M, Beck H E, Crosbie R S, De Jeu R A M, Liu Y Y, Podger G M, Timbal B and Viney N R 2013 The Millennium Drought in southeast Australia 2001–2009: Natural and human causes and implications for water resources, ecosystems, economy, and society *Water Resour. Res.* **49** 1040–57
- van Ommen T D and Morgan V 2010 Snowfall increase in coastal East Antarctica linked with southwest western Australian drought *Nat. Geosci.* **3** 267–72
- Vance T R, Roberts J L, Plummer C T, Kiem A S and Van Ommen T D 2015 Interdecadal Pacific variability and eastern Australian megadroughts over the last millennium *Geophys. Res. Lett.* **42** 129–37
- Vance T R, Van Ommen T D, Curran M A J, Plummer C T and Moy A D 2013 A millennial proxy record of ENSO and eastern Australian rainfall from the law dome ice core, east Antarctica *J. Clim.* **26** 710–25
- Verdon-Kidd D C and Kiem A S 2009 Nature and causes of protracted droughts in southeast Australia: Comparison between the Federation, WWII, and Big Dry droughts *Geophys. Res. Lett.* **36** 1–6
- Wells N, Goddard S and Hayes M J 2004 A self-calibrating Palmer Drought Severity Index *J. Clim.* **17** 2335–51