Exploring the stationarity of Australian temperature, precipitation and pan evaporation records over the last century

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Abstract

Australia has experienced regional climate trends over recent decades with consequences for agriculture and water management. We investigate the statistical significance of these trends at annual and seasonal scales using the concept of stationarity. Using long-term high quality regional-scale observations of temperature, precipitation and pan evaporation (a measure of atmospheric evaporative demand), we find that despite highly significant increases in temperature that are non-stationary, few regions of Australia have experienced annual or seasonal changes in precipitation or pan evaporation that are outside the range of observed variability over the last century. Despite a common assumption of increasing water demand under a warming climate, atmospheric evaporative demand (as measured by pan evaporation) largely remains unchanged. This is because evaporative demand depends strongly on factors other than temperature. Similarly, seasonal and annual precipitation over the last century is found to be stationary in most (but not all) regions. These findings suggest that the Australian precipitation has largely remained within the bounds of observed variability to date and emphasises the need to better account for variability in water resource management.

1. Introduction

At the spatial scales of interest to agriculture, ecology and hydrology (~1–100 km) observations demonstrate large year-to-year variations in seasonal and annual precipitation. The magnitude of the season-to-season and year-to-year variations are generally large compared to the projected changes under climate change in the long-term mean annual precipitation (Collins et al 2013). In many regions, precipitation trends take many decades to emerge from the background climatic variability (Morin 2011). It is therefore challenging to detect long-term change in annual and seasonal precipitation at spatial scales critical to agriculture, ecology and water resources.

Australia presents an extreme challenge for detection of long-term climate trends. As the driest permanently inhabited continent, agricultural activities, ecological responses, water resource management and the broader society are all routinely affected by climate variability. Indeed, Australia has one of the most variable climates in the world (McMahon et al 1992, Nicholls et al 1997), which leaves the country vulnerable to both short- and long-term changes in water availability and makes the detection of robust long-term trends in water availability particularly important and challenging. Accordingly, there are many previous studies on Australian climatic variability and trends. Most notably, southwestern Australia has experienced a 15%–20% decline in precipitation since the 1970s, coincident with large decreases in water reservoir inflows (Petrone et al 2010). Similarly, autumn and winter precipitation, which supports economically important agricultural
activities and is important for streamflow generation (Cai and Cowan 2013), has declined throughout southeast Australia since the 1950s (Dey et al 2019b). In contrast, northwestern Australia has experienced significant rainfall increases since the 1950s during the austral summer, when the region receives most of its annual rainfall (Feng et al 2012, Dey et al 2019a).

However, climatic variability is not just about precipitation, with atmospheric evaporative demand also playing an important role in setting the regional water availability. Australia is fortunate to have a national network of class A evaporation pans professionally maintained by the Australian Bureau of Meteorology. While not as extensive as the high quality precipitation database, the current network of 60 sites provides a basic reference since 1975 for assessing changes in atmospheric evaporative demand (Jovanovic et al 2008). Contrary to a common expectation of increasing atmospheric evaporative demand under global warming (Nicholls 2004, Dai et al 2018), pan evaporation in Australia largely declined or remained unchanged until the mid-2000s (Roderick and Farquhar 2004, Rayner 2007, Jovanovic et al 2008), a finding also confirmed globally (Roderick et al 2009, McVicar et al 2012). Underlying physical principles show that atmospheric evaporative demand as measured by pan evaporation is sensitive to radiation, humidity, wind and air temperature (Rotstayn et al 2006). Initial attribution studies revealed that the decline in atmospheric evaporative demand over Australia was mostly due to national declines in wind speed and declines in solar radiation (potentially linked with increasing cloud cover) throughout many parts of northern Australia (Rayner 2007, Roderick et al 2007, McVicar et al 2008, 2012). Some stations, especially those in southern Australia have experienced increased pan evaporation since the mid-2000s, attributed to higher temperatures, but about half of the available stations continued to show declining trends (Stephens et al 2018).

Against this backdrop of changes in both the supply (precipitation) and the demand (atmospheric evaporative demand as measured by pan evaporation), most previous investigations have focussed on detecting long-term (linear) trends and their statistical significance. An alternate and more general approach is to ask whether the climate variables of interest have remained stationary. The concept of stationarity is widely known in the climate sciences (von Storch and Zwiers 1999), it is rarely used in climate change studies. A stationary process is one where the underlying distribution does not change over time (for a more formal definition see Brockwell and Davis 1987).

In a recent global study, Sun et al (2018) found that 14% of the world’s land surface has experienced non-stationary changes in annual precipitation during 1940–2009, including some parts of central and northeastern Australia. This result implies that any long-term trends have not yet emerged above the background variability over the remaining 86% of the land surface.

Here we apply the concept of stationarity for the first time to better understand trends and variability in observed annual and seasonal climate in Australia over the last century in the context of water management. These time scales are relevant for water resource management and for quantifying meteorological, agricultural and hydrologic drought. An assumption of stationarity underpins many hydrological applications and water resource planning (Milly et al 2008), we explore whether this assumption is appropriate under a changing climate. We focus on precipitation and pan evaporation (as the only directly observed estimate of atmospheric evaporative demand) and also investigate whether the near-surface air temperature record has remained stationary over the last century. Our aim is to identify regions where the principal elements of the climate are non-stationary.

2. Materials and methods

2.1. Datasets

Area-averaged monthly observations of temperature, precipitation and pan evaporation were obtained from the Bureau of Meteorology (BoM; http://bom.gov.au/climate/change/) for six climatological regions (figure 1). We focus on these variables as they are freely available at annual and seasonal scales over the same regions allowing a direct comparison and describe key parts of the climate relevant for water resources. The temperature observations span 1910–2018, precipitation observations 1900–2018 and pan evaporation observations 1975–2018. The different time periods reflect the different availability of sufficient observational coverage for each variable. The variables were analysed for seasonal averages for austral winter (JJA), spring (SON), summer (DJF) and autumn (MAM), as well as annual averages (defined as March–February to match the seasonal periods).

The BoM regional temperature data have been derived from the Australian Climate Observations Reference Network-Surface Air Temperature (ACORN-SAT) homogenised gridded dataset at 0.05° spatial resolution (http://bom.gov.au/climate/data/acorn-sat/). The precipitation data are from a BoM gridded product at 0.05° spatial resolution developed for the Australian Water Availability Project (AWAP; Jones et al 2009). Pan evaporation spatial averages were constructed from a high quality network of 61 pan evaporation stations (Jovanovic et al 2008; see http://bom.gov.au/climate/change/about/evap_timeseries.shtml for spatial distribution of stations).

We used the six climatological regions as they reflect broad climatological features of Australia but we also present an analysis for seven administrative regions (states and territories) in the Supplementary Information (figure S7, table S1 is available online at
In addition to using the climatological and administrative regions provided by BoM, we quantified per-pixel precipitation and temperature changes using the monthly gridded AWAP dataset to provide further spatial context.

2.2. Statistical methods

We use the so-called weak stationarity (or sometimes called covariance stationarity) framework to assess the long-term stationarity of the Australian climate. According to the definition of weak stationarity, a time series can be considered stationary when the mean is constant and the autocorrelation remains independent of the time lag (Kendall et al 1983, von Storch and Zwiers 1999, Sun et al 2018). For changes in the mean, we calculated linear trends using ordinary least squares and also examined the decadal-scale mean for each variable (details below). For the pixel-wise precipitation analysis, we use the same approach and also provide trend estimates using the non-parametric Mann–Kendall test including Sen’s slope (Sen 1968, Kendall 1975) for comparison (figure S1). The autocorrelation, also called serial correlation, measures the statistical similarity of a time series with itself at a given time lag and is an important part of the formal definition of the stationarity of a time series. To estimate autocorrelation, we use the sample autocorrelation estimator for the coefficient (\(r\)) at lag \(k\):

\[
    r_k = \frac{\sum_{i=1}^{n-k} (Y_i - \bar{Y})(Y_{i+k} - \bar{Y})}{\sum_{i=1}^{n} (Y_i - \bar{Y})^2},
\]

where \(Y\) is a time series, \(i\) denotes the timestep and \(n\) is the number of time steps (\(n = 109\) for temperature, \(n = 119\) for precipitation, and \(n = 44\) for pan evaporation). For a stationary, uncorrelated time series, the 95% confidence limits for the sample autocorrelation estimator (\(CI_{r_k}\)) are given by Brockwell and Davis (1987):

\[
    CI_{r_k} = \pm 1.96/\sqrt{n}.
\]

Autocorrelation at lag zero is one by definition. When the sample autocorrelation is within our specified confidence limits at all non-zero lags, the time series is considered statistically indistinguishable from white noise (Brockwell and Davis 1987). This requires an examination of the sample autocorrelation at all lags. In general, the addition of a ‘low-frequency’ signal, such as a long-term trend, to a stationary time series results in an increase to the sample autocorrelation estimates from that time series. For such long-term trends, we found that we could identify non-stationary behaviour by examining whether the lag-1 autocorrelation was within our confidence limits (Sun et al 2018). (For completeness, we also present maps of the autocorrelation at lags 2–5 for the pixel-wise precipitation analysis in figure S2.) Therefore, when a time series has both a statistically significant linear trend and a lag-1 autocorrelation that is outside our confidence interval, we consider that time series as being non-stationary.

Additionally, we explore changes in decadal means to identify significant longer-term shifts in the variables and the timing of those shifts. Following Sun et al (2018), we calculated 95% confidence intervals for 10 year means to determine when changes in the means over successive decades can be considered statistically significant.
3.1. Temperature

We used our data to calculate the effective sample size $n_c$ as a function of sample size $n$ using:

$$n_c = n \left( \frac{1 - r_1}{1 + n} \right)$$

where $r_1$ is the lag-1 autocorrelation (Zwiers and von Storch 1995).

3. Results and discussion

3.1. Temperature

We first explore trends in observed mean near-surface air temperature to quantify the warming experienced in Australia since 1910. The time series of mean temperature averaged across Australia indicates a statistically significant continent-wide warming trend of around 0.1 °C per decade that has been pronounced especially since the 1960s (figure 2(a)). The autocorrelation is significant for lags up to 28 years, and this represents a clear example of a long-term trend and a non-stationary time series (figure 2(b)). Regionally, all temperature increases are statistically significant ($p < 0.001$; table 1) and have a statistically significant lag-1 autocorrelation implying non-stationarity, with the exception of winter and spring in the southwest and winter in the southeast (figure 2(c)). These results demonstrate that virtually all regions of Australia have experienced warming well beyond the bounds of observed variability during all seasons. Past studies have established that this warming is consistent with anthropogenic global warming (Stott 2003, Karoly and Braganza 2005a, 2005b, Knutson et al 2013) and has occurred at a similar rate to the global mean near-surface air temperature (Hartmann et al 2013). We will next explore what implications the long-term warming has had on water supply and demand via changes in precipitation and pan evaporation.

3.2. Precipitation

The time series of Australia-wide annual precipitation indicates a statistically significant ($p = 0.005$) increase in continent-wide precipitation of $\sim$0.7 mm yr$^{-1}$ over the last century (figure 2(d)). However, the autocorrelation function (figure 2(e)) shows that the autocorrelation is not statistically significant at any lag. Following our criteria, the continent-wide precipitation time series is stationary. Whilst Australia-wide precipitation is not a very useful indicator of trends due to the high spatial variability of precipitation over the continent, these results highlight the fundamentally different nature of the precipitation time series (figure 2(e)) compared to that for the air temperature (figure 2(b)). Overall, 9.5% of Australia’s land area has experienced non-stationary annual precipitation increases (less during individual seasons), but practically no areas show non-stationary declines (table 2). This is compared to 73% of the land area showing non-stationary annual temperature increases. Climate change and associated warming can influence precipitation directly by increasing precipitable water in the atmosphere (following the Clausius–Clapeyron relationship) or indirectly through changing circulation patterns. This leads to highly regionally-specific changes in precipitation which depend on the nature of the climate forcing in a given region and not simply on the change in temperature.

We next explore regional precipitation changes, with figure 2(f) showing the lag-1 autocorrelation for each region and season during the 1900–2018 period as well as the statistical significance of linear trends. Table 1 further summarises the precipitation trends and their significance levels. None of the 30 regional time series show both statistically significant lag-1 autocorrelation and linear trend, suggesting that annual and seasonal precipitation can be considered stationary in all climatological regions (figure 2(f)). The only region/season combination to show a statistically significant lag-1 autocorrelation is winter precipitation over eastern Australia and the Murray–Darling basin (MDB) with both regions having spatial overlap (figure 1). For those regions, the lag-1 autocorrelation is negative implying a very slight tendency for wet winters to follow dry winters (and vice versa) rather than the presence of a long-term trend. This tendency is evident in the pixel-wise analysis across parts of coastal Queensland and northern New South Wales (figure 3).

Several other regions have experienced statistically significant linear trends but the lag-1 autocorrelation remains within the confidence limits. For example, in the northern region which is dominated by monsoonal summer precipitation, the annual precipitation has increased by 1.05 mm yr$^{-1}$ since 1901, almost entirely due to increased summer precipitation (0.78 mm yr$^{-1}$) (figure S3(a); table 1). The lag-1 autocorrelation for the entire northern region is not statistically significant (figure 2(f)) but a pixel-wise analysis shows that many parts of northern Australia have statistically significant lag-1 autocorrelation, particularly in the northwest in the summer, autumn and annually (figure 3), suggesting non-stationary changes. The cause of the precipitation increase remains unclear but increased monsoonal flow due to anthropogenic aerosols has been suggested as a possible mechanism, particularly in the northwest (Rotstyn et al 2007). In southwestern Australia, a winter-autumn precipitation decline has been widely reported (Hennessy et al 1999, Gallant et al 2007) but the 119 year precipitation time series remains stationary (figure 2(f)). The annual precipitation in that region has decreased by $\sim$0.15 mm yr$^{-1}$ and is almost entirely due to declines in both autumn ($\sim$0.31 mm yr$^{-1}$) but especially
Figure 2. Annual and seasonal temperature ($T$), precipitation ($P$) and pan evaporation ($E_{pan}$) trends and autocorrelation. Panels (a), (d) and (g) show the time series of each variable averaged for Australia, with the linear trend in blue and decadal means as black bars. The middle dashed line shows the time series mean and the outer dashed lines the 95% confidence intervals calculated from equation (3). Panels (b), (e) and (h) show the autocorrelation of each variable averaged for Australia, with 95% confidence limits (equation 2) marked by the dashed lines. Panels (c), (f) and (i) summarise the lag-1 autocorrelation for each region and season, with 95% confidence intervals shown by the dashed lines. Statistically significant linear trends ($p < 0.05$) are shown with $+/-$ symbols to denote increasing/decreasing linear trends. The regions are eastern (EAUS), southern (SAUS), northern (NAUS), southeastern (SEAUS), southwestern (SWAUS) and the Murray–Darling Basin (MDB).
winter (−0.81 mm yr\(^{-1}\)) (Table 1). Decadal winter precipitation amounts in that region have been below the long-term mean since the 1970s and significantly different from the long-term mean during the last two decades (Figure S3(c)). Moreover, the last decade (2009–2018) is the driest decade for winter precipitation in the instrumental record, 112 mm (33%) below the long-term mean. The region receives most of its precipitation during the cool season, with a substantial amount of precipitation received from frontal systems. The precipitation decline has been attributed to a declining frequency in frontal systems due to circulation changes driven by greenhouse gas emissions, as well as a possible influence from land use change increasing moisture divergence over the region (Dey et al. 2019b and references therein). The cool season precipitation declines have had a strong impact on streamflow, with a 16%–65% reduction in inflows to Perth’s major water supply reservoirs since the 1970s (Petrone et al. 2010).

In eastern Australia, changes in cool season precipitation have received a lot of attention due to its importance for agricultural activities, including winter cropping, and streamflow generation (Nicholls 2010, Cai and Cowan 2013, Dey et al. 2019a). Several studies have reported a decline in southeastern autumn and (early) winter precipitation since the 1950s, particularly 1990s onwards (Cai and Cowan 2013, Dey et al. 2019b). We also find a long term decadal-scale decline in southeastern autumn precipitation from the 1970s to around 2010 (figure S3(e)) but records in the most recent decade show a return to the long-term mean (figure S3(e)), emphasising the high degree of precipitation variability on several (seasonal, annual and longer) time scales. More generally, we find no statistically significant long-term linear trends or lag-1 autocorrelation in autumn and winter precipitation over southeastern, eastern or MDB regions during the 119 year instrumental record (figure 2(f); Table 1). The tentative conclusion is that precipitation in those regions has remained stationary. However, the decadal-scale variability, measured using the standard deviation, has been especially low in the last twenty years (figure S3(f)) and is a consequence of a reduced number of high rainfall years since the 1990s (figures S3(e), (f)) over southeastern Australia. The pixel-wise analysis shows that some local regions in Victoria and Tasmania have experienced statistically significant declines in autumn-winter rainfall, especially along the southern coast of Victoria (Figure 3). However, the

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### Table 1: Temperature (°C yr\(^{-1}\)), precipitation and pan evaporation (mm yr\(^{-1}\)) trends for each region and season.

| Variable | Region   | Annual   | Winter   | Spring   | Summer   | Autumn   |
|----------|----------|----------|----------|----------|----------|----------|
| Temperature | Eastern | 0.013*** | 0.013*** | 0.014*** | 0.013*** | 0.014*** |
|           | Southern | 0.013*** | 0.011*** | 0.013*** | 0.016*** | 0.013*** |
|           | Northern | 0.013*** | 0.012*** | 0.016*** | 0.010*** | 0.013*** |
|           | Southeastern | 0.011*** | 0.009*** | 0.010*** | 0.015*** | 0.012*** |
|           | Southwestern | 0.013*** | 0.009*** | 0.011*** | 0.017*** | 0.015*** |
|           | MDB      | 0.013*** | 0.012*** | 0.011*** | 0.014*** | 0.014*** |
| Precipitation | Eastern | 0.36     | −0.06    | 0.10     | 0.34     | −0.01    |
|            | Southern | 0.27     | −0.09    | 0.10     | 0.28***  | −0.03    |
|            | Northern | 1.05**   | −0.05    | 0.14*    | 0.78***  | 0.18     |
|            | Southeastern | −0.04    | −0.08    | 0.04     | 0.15     | −0.14    |
|            | Southwestern | −1.15*** | −0.81*** | −0.16    | 0.13     | −0.31*** |
|            | MDB      | 0.28     | −0.07    | 0.13     | 0.28**   | −0.07    |
| Pan evaporation | Eastern | 4.03*    | −0.00    | 0.38     | 2.60**   | 1.06*    |
|                | Southern | 1.08     | 0.20     | 0.78     | −0.26    | 0.35     |
|                | Northern | −0.54    | −0.53*   | −0.96    | 0.91     | 0.04     |
|                | Southeastern | −0.07    | −0.18    | 0.35     | −0.32    | 0.07     |
|                | Southwestern | 5.02***  | 0.28*    | 2.05***  | 2.02***  | 0.67*    |
|                | MDB      | 0.49     | −0.27    | 0.24     | 0.44     | 0.08     |

(*) denotes \( p \leq 0.1 \), (**) \( p \leq 0.05 \) and (***) \( p \leq 0.001 \).
Figure 3. Seasonal and annual precipitation trends and lag-1 autocorrelation calculated per pixel from the gridded AWAP dataset. Stippling indicates (left panels) statistically significant trends and (right panels) lag-1 autocorrelation at the 95% confidence level. Pixels with >10% of the time series missing were masked out (shown in white). For all other pixels, missing values were gap-filled using the long-term monthly means prior to calculating the statistics. The trends were calculated using ordinary least squares regression, trends calculated with the Mann–Kendall test are shown in figure S1 for comparison. Autocorrelation for lags 2–5 is shown in figure S2.
lack of significant lag-1 autocorrelations in those regions suggests the precipitation has remained stationary and the declines might be a consequence of the severely dry conditions during the Millennium drought (~2001–2009; van Dijk et al 2013) that occur towards the end of the record.

The only statistically significant changes in the eastern parts of the continent are increases in summer precipitation (table 1), which has increased in the MDB and the southern half of Australia, and less strongly in northeastern Australia (figures 2(f) and 3). At the annual scale, this has led to a near-zero change in the southeast and a positive, but non-significant linear trend in the MDB, and southern and eastern Australia. At a gross level, these results indicate a shift of the seasonal precipitation regime from cool to warm seasons across many parts of Australia (figure 3). We also note that regions with increasing precipitation generally show higher decadal variability (e.g. northern Australia), whereas regions with declining precipitation show lower decadal variability (e.g. southwestern Australia) (see examples in figure S3).

The implication is that periods of enhanced decadal-scale variability in precipitation are associated with high rainfall events that provide a mechanism for terminating droughts and replenishing water resources during exceptionally wet periods.

### 3.3. Pan evaporation

Finally, we explore changes in pan evaporation to understand how atmospheric evaporative demand has changed since 1975. Many previous studies have suggested climate change will lead to increasing evaporative demand due to higher temperatures, exacerbating droughts and water scarcity (e.g. Nicholls 2004, 2006, Sherwood and Fu 2014). The Australia-wide pan evaporation time series shows no statistically significant change during the entire 44 year period (figure 2(g)). Similarly, the autocorrelation function for the continental time series is non-significant at all lags (figure 2(h)). The pan evaporation records thus suggest no coherent change in continental scale atmospheric water demand, despite significant concurrent increases in air temperature (see figure 2(a) for the entire air temperature record and figure S4 for the air temperature record over the 44 year pan evaporation period).

Regionally, four time series in southwestern Australia (annual, spring and summer) and in eastern Australia (summer) show a statistically significant linear trend and lag-1 autocorrelation (figures 2(i) and S5). Elsewhere, no changes are detected where both linear trends and lag-1 autocorrelation are statistically significant. However, several regions show a significant positive lag-1 autocorrelation in the absence of statistically significant linear trends, e.g. southeastern (annual, winter) and northern Australia (annual) (figure 2(i)). An inspection of these time series suggests that this result is likely due to abrupt, but opposing changes in the time series during the study period rather than a long-term trend. For example, the annual time series for northern Australia shows a decline during the first half of the time period that is reversed post-2000, leading to a statistically significant lag-1 autocorrelation but very little long-term change (figure S6(e)). Similarly, annual pan evaporation in southeastern Australia shows a time series punctuated by large decadal-scale variability but very little overall linear trend (table 1, figure S6(c)). In eastern Australia, the annual and autumn pan evaporation show statistically significant lag-1 autocorrelation but the linear trends are not yet statistically significant at the 95% level (table 1; figures S6(a), (b)).

Earlier studies also found no evidence for a consistent increase in atmospheric water demand with warming (Roderick and Farquhar 2004, Jovanovic et al 2008, Stephens et al 2018), and our results both confirm and extend those studies by examining, for the first time, the autocorrelation of pan evaporation observations. Jovanovic et al (2008) showed that inter-annual variability in pan evaporation correlates significantly with air temperature but that correlation cannot generally explain long-term trends. Other studies have shown that evaporative demand is more strongly driven by solar radiation (Matsoukas et al 2011, Maes et al 2019) and wind speed (Rayner 2007, Roderick et al 2007, McVicar et al 2008) than temperature, and these factors do not necessarily change in response to climate change (Roderick et al 2014). Our results support this conclusion by showing a lack of statistical relationship between the increasing temperatures and pan evaporation. Future work should explore the causes of recent pan evaporation trends in the context of stationarity of the underlying drivers (radiation, humidity, wind) in more detail.

### 4. Conclusions

We used the formal statistical concept of stationarity to explore long-term seasonal and annual changes in Australian climate over the last century, an approach that is not commonly applied. Australia has experienced widespread increases in seasonal and annual mean air temperature since 1910 that exceeded the range of natural variability >30 years ago. We show that the seasonal and annual air temperature time series are clearly not stationary. It had been thought that this warming would lead to increasing atmospheric water demand, exacerbating water deficits via increased evaporation (e.g. Sherwood and Fu 2014, Dai et al 2018). However, we show that atmospheric water demand as measured by pan evaporation has largely remained stationary and within bounds of observed variability over most of Australia since 1975. The fundamental physical reason is that evaporative demand depends on more variables (e.g. radiation,
humidity, wind) than just the temperature (Roderick et al. 2007, Donohue et al. 2010). Similarly, with a few notable exceptions (see discussion below), seasonal and annual precipitation over most regions has either remained stationary or is increasing. These results point to the much higher inter-annual and decadal scale variability in the seasonal and annual precipitation and pan evaporation compared to temperature and caution against directly relating temperature changes to water cycle changes at regional scales.

Nevertheless, several regions have experienced recent changes in water availability. Most notable have been the cool season rainfall declines in parts of the southwest where the last two decades have been the driest on record. Despite not being statistically significant in the context of long-term variability, these changes have had marked consequences for water supply and regional ecosystems, including large streamflow declines (Petrone et al. 2010, Zhang et al. 2016). As precipitation in the region approaches non-stationarity, this cautions against using historical climate records alone to characterise variability in water resource assessments. The results also point to a change in rainfall seasonality across the country, with a tendency towards both higher summer and lower cool season precipitation (figure 3). This is likely to have consequences for runoff generation and soil moisture recharge due to higher water fluxes to the atmosphere during summer, although the future net changes in water availability will depend on complex interactions between climatic conditions, vegetation dynamics and human influences (Ukkola et al. 2016a, 2016b, Zhang et al. 2016). Future work exploring the stationarity of runoff and its drivers would be valuable for better understanding changes in water availability.

Future projections of precipitation remain highly uncertain for most regions of Australia, with the exception of the southwest where precipitation declines are projected to continue (Collins et al. 2013, Dey et al. 2019b). Projections of evaporative demand generally indicate increased demand, but the trends are sensitive to the method used to determine evaporative demand (Roderick et al. 2015, Milly and Dunne 2016, Yang et al. 2019) and cannot be directly compared to empirical pan evaporation estimates. It thus largely remains unclear how the observed trends will evolve in the future, making long-term water resource planning challenging. Nevertheless, even without impacts associated with climate change, there is a need to better take variability into account in water resource management and when assessing significance of change, particularly in the highly variable climates that characterise Australia. Maintenance of the existing observational network will be critical for characterising those changes. In a more general sense, it is very unlikely that the relatively short century-scale instrumental records used here capture the full range of natural variability typical for Australia (Vance et al. 2015, Tozer et al. 2016), further emphasising the need to assess the climate in a longer term context.

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Data availability

The regional data that support the findings of this study are openly available at http://bom.gov.au/climate/change/. The gridded AWAP precipitation data are available from the corresponding author upon reasonable request.

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