Dear Hans, 22.08.2017

We have made all changes as mentioned in our initial response to reviewers, as well as some minor additional improvements to the manuscript that enhance clarity and readability. All revisions are indicated by track changes. Changes that are not tracked include modifications on existing figures/tables/references listed below.

We also addressed the concerns by the Data Stewardship Team (Short Comment) by updating the supplement table 1 with references and links to the original data repositories entrees. This table is likely subject to further changes as records are in the progress of being added to the public repositories. As soon as those links are available, we will update the table for final publication.

Changes to the manuscript other than track-changed:

Reviewer #1:

- Additional supplementary figure included showing effects for different baseline

Reviewer #2:

- Koch et al. 1983 and Hutchinson et al. 1995 reference were inserted describing the homogeneity analysis of the gridded AWAP dataset

Short Comment:

- Updated table with References and original data repository links

General:

- Figures 1, 4, 7 and 9 were modified according to comments by reviewer #1 and reviewer #2 (indicated within the replies)

Please see the following point-by-point replies to the referees (reply in blue) and the revised manuscript with track changes.

Sincerely,

Mandy Freund,
on behalf of the authors

Reply to the Interactive comment on "Multi-century cool and warm season rainfall reconstructions for Australia's major climatic regions" by Mandy Freund et al., by **Anonymous Referee #1,**

This paper is generally good and well written. I have a few comments, most of which are relatively minor.

Reply: We want to thank Anonymous Referee #1 for his/her careful and constructive review of our paper. We will take into account all his/her valuable advice for the revision of the manuscript. The reviewer's comments are in black. Below are our replies to his/her comments in blue. Comments in italic are suggested changes to the manuscript.

Major Comments

1. The abstract refers to cool and warm season rainfall reconstructions as being sub- annual. Elsewhere in the abstract they are referred to as seasonal and on p11 as bi- seasonal. Sub-annual is confusing. What they really are is half-year reconstructions, with the two parts of the year based on the cold and warm part of the year. Stick with one definition for them. Bi-seasonal seems best, sub-annual doesn't mean anything.

We agree with the reviewer and see that multiple definition could lead to confusion. We will change all references to: bi-seasonal.

2. When using CPS and rescaling using the mean and SD from the calibration period, you are assuming a normal distribution. How good is this for some of the smaller NRM regions? Particularly for the warm season, some regions show large positive spikes indicating that the distributions for some regions will be positively skewed. This makes using CPS more difficult, and it might be that proxies are less good at differentiating wet seasons from one another, but it could be worth a comment.

We agree with the reviewer and add a plot to the supplement showing the individual distributions. Most of the seasonal and regional rainfall distributions tend to follow a normal distribution. All instrumental cool season time series are approximate normally distributed (Chi-square test, 5% significance level). The distribution of instrumental rainfall during the warm season in the Central Slopes, Rangelands and Southern Slopes doesn't follow a normal distribution (Chi-square test, 5% significance level) and shows positive skewness (see Supporting Figure 1 for details).

We add a statement as followed p.5 l.24:

"It should be noted that not all of the records strictly follow a normal distribution."

3. You've used deciles based on the period 1900-2014, so for the proxy series the last 30 years up to 2014 is based on instrumental data. Do your results get altered by basing both on the period from 1900-1984 and not padding with instrumental data? Also you do pad with 30 years, not the 20 you say, as 2014 is 30 years after 1984.

We agree with the reviewer. Deciles strongly depend on the baseline. We added a plot to the supplement showing different baselines (S.Figure 2) and refer to it on page 6 line 22:

"It is important to note that deciles deliver quantitative statements only in conjunction with a baseline period and duration (see details in supplementary figure 2)."

4. What would be useful in Table 1, when text on p9 discusses the cool and warm season rainfall series, is to add a % value for how much the cool or the wet season contributes to the overall 'annual' total. You could base this on a April to March year. This could help in the importance of some of the rainfall declines. Some regions get much more rain in one season compared to the other.

We agree with the reviewer and add the contribution of seasonal rainfall in percentages to the annual average in table 1.

5. Is it worth also concluding that the 400-year reconstruction didn't produce a drought as extreme as the 3 in the instrumental period? As these are different lengths, did you go back and look at droughts of different lengths of numbers of years. The Millennium drought was 13, the WW2 drought 11 and the Federation drought 9.

Yes, this comment is true based on the 3 instrumental droughts we have been looked at. This is again true only in conjunction with a baseline period and duration of these droughts. Looking at other past drought events of different duration and intensity hasn't been done in this study and remains for future work.

Minor Comments

1. In the abstract or in the Introduction you mention the high-variability of Australian rainfall. This could be emphasized a bit more, as Australian averages (when expressed in percentage terms) are highly variable compared to other parts of the world. I recall seeing a plot of N and separately S Australian averages (Giorgi regions) compared to other similar sized regions of the world and Australia needed a different scale from all other regions.

Good point, we added the citation: {Nicholls:1997gh} to p.2 line 2.

2. On p2 lines 19-26 you talk about decrease in rainfall. Might be worth mentioning in impact terms that the costs of droughts are much more than the costs of floods. I'm assuming this is the case?

Not necessarily and depends on multiple factors. It is hard to quantify the costs of natural disasters. For example, the total economic cost of Queensland floods is estimated as $14bn (http://australianbusinessroundtable.com.au/our-papers/social-costs-report) compared to $7bn caused by Black Saturday bushfires. A report by the WMO estimated the cost of the 1981 drought with US$15.15bn (http://www.wmo.int/pages/prog/drr/ transfer/2014.06.12-WMO1123_Atlas_120614.pdf). It is hard to integrate and compare those costs and beyond the scope of this study, we therefore back away from any statement.

3. Add in on p3 that Cook has also produced the OWDA (Old World Drought Atlas) with a paper in 2016 in Science Advances.

Yes, we will add this reference!

4. Line 12, change Europe to Eurasia as there are lots of proxies across the whole boreal forest zone and from eastern Asia.

Yes, we have changed that.

5. Useful if Figure 1 and Table 1 could be linked and the map named the 8 regions. It took me a while to realize that the big bit in the middle was called 'Rangelands'. I t also seems as though this region is just what's left from naming the other regions.

Yes, we add this into the Figure caption 1:

"Full names of the Natural Resource Management (NRM) clusters shown on Australian continent as abbreviations are given in table 1."

6. P4, line 16, these two references are missing (BJ93 and T et al.2015).

We will add those.

7. Another ref missing on p6 line 4. A better ref here would be Cook et al (1994, IJC, 14, 379-402).

We will add this missing reference.

8. On p6, the dates of the various droughts do overlap – maybe they are close regions and overall only affect part of Australia? Worth mentioning this though.

Those droughts are historical reported droughts from different regions. Back in those days, they might have affected the entire continent, but were only reported in the settlement areas along the coast but those historical droughts seem to be have been indeed quite regionally constrained to a certain area. Overlapping periods will be definitely be future work but we will show individual years in an animation/video.

9. P7 introduces STRP and STRI, but Table 1 just refers to STRI and STRL. How do these two relate to STRP?

We will correct that in table 1.

10. On p8 the cool season paragraph refers to 3 regions which extend back to 1200, 1260 and 1366. This is OK, but in the next paragraph the wet season 3 regions extend back to just 2 years?

Good point, we changed in to p.8, line 15-16:

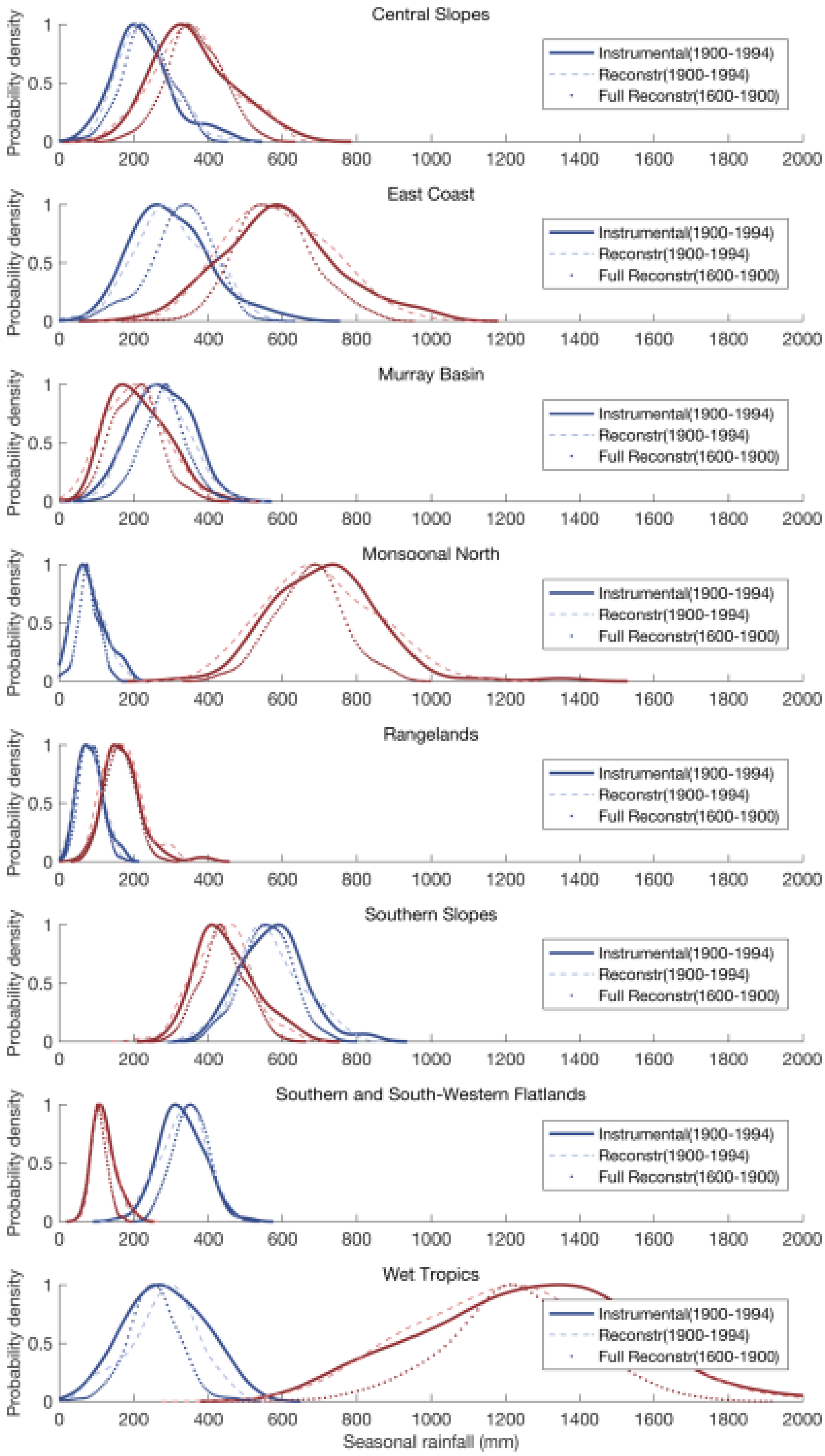
"In the warm season, the Southern and Southwestern Flatlands, Wet Tropics, and Murray Basin warm season reconstructions are skillful (CE > 0) for the longest period, extending back to 1200,1200 and 1234, respectively "

11. Remove the 'as' before ENSO's on line 14 of p12. 12. Move the left bracket on line 7 of p13, so begin with Cook et al. (2016) found. . ..

Will be changed.

13. In Table 1, SE Drought is in twice in the third column. This is why it doesn't get a date the first time? I presume all these dates are the accepted dates?

We will correct that in table 1.



Supporting Figure 2: Normalised probability density distribution of the instrumental records (1900-1994), the reconstructed records during the instrumental period (1900-1994) and through the entire reconstructed period (1600-1900). Cool season records are shown in blue, warm season records are shown in red. Note all cool season records follow approximate a normal distribution according to a Chi-square test (5% significance level) while warm season records of Central Slopes, Rangelands and Southern Slopes are not normally distributed.

Reply to the Interactive comment on "Multi-century cool and warm season rainfall reconstructions for Australia's major climatic regions" by Mandy Freund et al., by **Anonymous Referee #2,**

RC2: With appropriate corrections, this paper will be a useful contribution to the literature related to the character and causes of variation in Australian hydroclimatology. Much of what is done is interesting, and the sub annual approach is great to see, but there needs to be some additional attention to detail, particularly related to the rationale and specifics of the research methodology, and a more critical approach to the results presented would be ideal. The paper has the potential to be very good, but I think it has some way to go to get there. Below, I discuss aspects of the paper sequentially, explicitly highlighting what I consider critical points that I think must be addressed and major points that should be. Trivial points are collected at the end. Abstract The abstract reads well, but minor changes will be required if the authors accept some of the criticisms that follow (e.g. the statement [p1, 15] that the rainfall reconstruction aligns well).

Reply: We want to thank Anonymous Referee #2 for his/her careful and constructive review of our paper. Given comments and suggestions are extremely helpful to clarify our manuscript. We will take into account all his/her advice for the revision of the manuscript. The reviewer's comments are in black. Below are our replies to his/her comments in blue. Comments in italic are suggested changes to the manuscript.

1 Introduction

[p2, 15]. State when instrumental data collection started. More generally, make sure that you are not assuming your readers are Australians when it comes to what may seem to be common knowledge.

Good point, we added this information in line 15.

"Over the 20th century many regions in Australia have experienced prolonged pluvial and drought periods that are documented in the gridded, instrumental records starting in 1900."

[p2, 28–33]. This is a useful paragraph, but it would it be useful to extend it slightly with a comment on the relevance of palaeoclimate reconstructions under future conditions of changed boundary conditions.

We agree and added the following statement to line 33.

"Palaeoclimate data can provide a unique window into long-term rainfall variability and emerging spatial and temporal trends. Such knowledge has practical applications for water resources management, seasonal forecasting, future climate predictions and constraints on boundary conditions."

Major. [p3, 11–17]. It might be useful to rephrase "process-based methodology" to more clearly capture the atmospheric dynamical aspect of what you are doing. Also, you need to explain why this approach will maximise skill and utility. If I recollect correctly, the advocates of the Cook approach of point-based regression would argue that this achieves the same. You need to justify your claim here.

We agree and clarified this aspect to a more dynamical-focused methodology. In contrast to the point-by-point regression approach by Cook, our reconstruction is constrained by dynamical processes rather than a certain distance to the target in order to allow for remote proxy to be possible predictors.

"We utilize a more dynamically-focused methodology driven by dynamical relationships to include remote proxies and maximize the skill and widespread utility of our reconstructions of Australian rainfall"

Major. [p3, 11–17]. I was surprised to see the analysis based on NRM regions. The approach is contrary to what seems the more common and sophisticated approach of examining relationships at finer spatial resolution, so I would like to see some rationalisation for the choice here. A key criticism is that the spatial scale is too coarse for some regions to adequately capture the character of spatial hydroclimatological extremes and risks conflating contrasting regions into an unhelpful whole. My concerns here returned when I encountered Figure 4, where it is clear from the instrumental data that the regionalisation approach has some undesirable consequences. For the millennium drought, the bipolar R region pattern cancels out; for the WW2 drought, widespread drought in the west is lost; for the Federation drought, the centres of drought are dis- placed east. I do appreciate that you are not in a position to revise the analysis, but think you should give a more convincing rationale for the approach taken, and follow up with a paragraph in the discussion to discuss the implications and outline if you think an alternative approach would be useful (or not).

We concentrate on larger regions that are developed by the Department of Environment as the eight natural resource management clusters and maximize its comparability and usability in connection with the reports by Climate Change in Australia to extend the records back in time. We compromise our analysis to a full spatial picture of hydroclimate variability over Australia (which isn't provided by the ANZDA) and concentrate on a smaller temporal scale rather than spatial scale. This coarse resolution compromises between available proxy data and the quality of instrumental data too.

We added a statement about discrepancies between the patterns reflected by the regions and gridded observations in the data section line 9.

"The Climate Change in Australia report (CSIRO and Bureau of Meteorology, 2015) applied a regionalisation scheme to define eight Natural Resource Management (NRM) regions with similar climatic and biophysical features. These regions reflect broad pattern of large-scale rainfall variability but may not capture finer scale patterns".

In the discussion (p.17 line 6) we added possible future work to emphasize the need of finer resolution to resolve important features as followed:

"Our multi-century, seasonally and spatially resolved reconstructions provide new opportunities to study the dynamics of meteorological droughts across the Australian continent. Future work should consider further sub-division to resolve finer scale hydroclimate patterns important for regional assessments. This could include a sub-division of large regions such as the Rangelands and regions of complex rainfall regimes like Tasmania as suggested by the NRM sub-clusters (CSIRO and Bureau of Meteorology, 2015)."

[p3, 23]. The NRM regions cannot be clearly distinguished on Figure 1. Figure 4 is much better.

We agree, will clarify Figure 1 and refer the reader to Figure 4.

2.1 Instrumental data

[p4, 8–10]. Some expansion of the description of the AWAP data would be good. For example, it would be useful to state what homogeneity analysis has been undertaken (by BoM).

We agree and added this statement to p.4 line 8:

"The monthly AWAP dataset based on precipitation anomalies generated from a varying number of station observations using the Barnes successive-correction (KOCH et al., 1983) *and a three-dimensional smoothing spline interpolation* (HUTCHINSON, 1995)*."*

Major. [p4, 11–18; Table 1]. Insufficient information is provided on the climate drivers. For example, the metrics for the intensity and position of the subtropical ridge [over Australia] are not common knowledge, ditto blocking, and there are multiple indices for the SOI. All of this can be simply solved by adding an appropriate descriptor to Table 1. SAM appears to be missing from the table. The IPO is mentioned later but not used in the analysis and there is no equivalent west-pole Southern Oscillation index (you have one for SST, I presume that is what NWP is). Perhaps a little more rationalisation would be appropriate.

We thank the reviewer and agree that important information is missing in Table 1. SAM was missing and has been added to Table 1. Details about the computation of the individual climate indices is added at two points. First, we added a reference within the instrumental data section in p. 4 line 11:

"We also use several climate indices to link climate drivers with Australian rainfall (Table 1(a)) that have previously been used to characterize the relationship between rainfall and large-scale drivers (Risbey et al., 2009). *Details on the computation of the individual climate indices follow strictly the metrics described in the references given in Table 1 and references within."*

Secondly, we corrected our table description to refer to the original publications within Table 1 and add the following descriptor to the table:

"Summary of climate drivers, regions and droughts used in this study. (a) Climate indices and reference for computational information, (b) Natural Resource Management (NRM) regions of Australia and (c) Instrumental and historical droughts."

Furthermore, the role of the position and strength of subtropical ridge has been highlighted in (Fiddes and Timbal, 2016; Timbal and Drosdowsky, 2012; Timbal et al., 2006). We cite those publications in line 31-32 and would refer the reader to those publications for further details. The role of blocking has been highlighted by (Pook and Gibson, 1999; Risbey et al., 2009)undertaking similar analysis during the instrumental period only. The SOI index partially incorporates information about west-pole conditions of the atmosphere by the accounting for pressure differences over Darwin. We didn't include the IPO in our analysis as we are focusing on year-to-year variability only. Given our approach of the moving correlation window of 30 years, decadal- variability such as expressed by the IPO has been not considered.

2.2 Palaeoclimate data

Critical. [Section 2.2]. Overall, Section 2 seems too superficial. The reader needs a better understanding of this fundamental data in order to interpret the subsequent results. See following for specific details.

Major. [p4, 20; Figure 1]. A cross-reference to details in the supplement is needed here. Also, the mapping is not up to the task of showing the spatial distribution (need zoomed in insets for high density areas) – e.g. I can only see one of the five speleothem proxy locations. It would also be useful to colour-code the symbols to show the spatial degradation back in time. Also, is it possible to distinguish those proxies actually used? Table S1 indicates numerous proxies that were not used for any region (all zeros).

We agree, and add an inset to Figure 1 showing the spatial distribution and degradation back in time following a color-code and add a cross-reference to the supplement.

Critical. [Missing details – proxy data pre-processing]. It is common practice to pre- process proxy data in ways that unavoidably affect the frequency response of any climate reconstruction. It appears (and you should state) that you do not re-process the data to ensure consistency, but it is essential that you comment on what has been done by the original workers (or subsequently). Without this information, your readers may incorrectly assume that Australian hydroclimatology is characterised by essentially no centennial-scale variability, when in fact the case is that it has been removed. Although a critical omission, the solution is very simple – you just need to state what frequency information is credible in the reconstruction. A related paragraph in the discussion would also be appropriate.

We agree with the reviewer and add this to the data section p.4 line 28:

"No further data treatment has been applied other than suggested by the original publication which involves the removal of non-climatic biological trends in tree-ring records using the signal-free method preserving much of the medium-frequency variability (timescales of decades to a century). *(see S. Table for references and details)"*

Critical. [Missing details – proxy dating fidelity]. Similar to the above, you are assuming that the dating of the proxies is accurate. That is fine, but a comment to the effect that dating is not revisited here may be appropriate. However, Table S1 indicates that you have used a number of non-annual proxies, yet I see no comment on how these are meaningfully included in an annual-resolution reconstruction. The rationale, the explicit methodology (interpolation?), and the implications should be mentioned.

Good point, sub-annually resolved records were binned into seasonal averages. We added to the data section p4. Line 31:

"Samples within the seasonal window (six consecutive months) are equality averaged onto a regular time grid of 2 samples a year, whereas the dating of annually resolved records follows the original author. "

3.1 Reconstruction

[p5, 3–15]. Good to see this focus on stationarity. Looking at only linear relationships and ignoring lag relationships is simplified but acceptable. But can something more be said about the interquartile range approach? i.e. where exactly does this come from and has it been tested for this purpose? I presume this analysis relates to the binary scores in Table S1 (the table caption does not provide the relevant information).

The interquartile range approach has been used as a straightforward indicator of stationarity. To the knowledge of the authors this approach hasn't been used anywhere else in this context. Several studies have shown that the relationships of Australian rainfall and climate drivers such as ENSO have periods of varying strength of the teleconnection (e.g. (King et al., 2014; Lewis and LeGrande, 2015)). The interquartile range ensures the teleconnection to be stable in at least 50% during the overlapping period but accounts for fluctuations. If the correlation sign varies too much (swings between positive correlation to anticorrelation and vice versa) and those changes occur frequent, it won't be considered as a stationary signal as indicated by the binary scores in Table S1. We clarified and added this relevant information to the table caption.

[p5, 9, and relevant to multiple other places]. Statistical significance is mentioned here for the first time. Why 0.1 (seems a fairly weak test) and how are significance levels adjusted for autocorrelation?

In this study, the significance level has been chosen fairly weak ($p<0.1$) for two reasons. First, we are using moving windows and focus on the consistency across successive periods. The number of samples is limited and based on 30-year moving windows. Due to the moving approach, correlations rely on partial overlapping periods, therefore we didn't correct for autocorrelation but focused on the interquartile range. The sign test assesses the temporal stability of the link between climate driver and NRM precipitation, and climate driver and proxy records only and is therefore relatively independent of the chosen significance level. Secondly, the sign test and correlation approach has been applied in order to act as a first stage "screening" approach. It limits the pool of available proxy records to be a possible predictor for a particular NRM region. The pre-selection procedure is comparable to a distances screening and probabilities commonly applied by the point-by-point approach (Cook et al., 1999). The final reconstruction and its significance level relies on a bigger sample size (common period 1900-1984) and might be considered more robust.

Critical. [p5, 17–24]. This section describes the reconstruction methodology. The credibility of the work rests on this, so the reader needs to thoroughly understand the details of what has been done. There is not sufficient detail for me to be sure I completely follow what has been done. While it is appropriate to lean on other references for comprehensive treatment (but relevant cited important references are missing from the references) the onus is on the authors to present sufficient details here. The Tierney et al level of detail is a useful model in this context.

[p5, 24]. How spliced?

Yes, same as Tierney, sliced together on the most replicated nest. We added p5 line 24:

"Nests are spliced together based on the most replicated nest to form a continuous reconstruction."

[p5, 27–28]. 52, 33 years. At face value 1934–1984 & 1900–1933 gives 51, 34. Missing something?

Yes, we will correct that to p5 27-28:

"During the common period, 60% of the data are used for calibration (equal to 51 contiguous years) and the remaining 40% (34 years) are used for verification."

[p5, 30]. ". . .not entirely independent. . ." could be interpreted as mostly independent, which is incorrect.

Agreed and removed from to p5 line 30:

"These different, but not independent, calibration and verification periods are used to build an ensemble of seven reconstructions for the warm and cool seasons. "

3.2 Analysis

[p6, 7–9]. Rationale for this analysis? I don't know what normalized trends means in this context.

Agreed, sentence has been completed as:

"All trends are normalized by the maximum occurrence and presented in histograms."

[p6, 14–16]. Detail redundant here (provided in Table 1).

We agree, and refer the reader to Table 1c.

[p6, 18]. Deciles need a time interval (e.g. 36 months).

Agreed, we added a statement on p.6 line 22:

"The individual duration of deciles depends therefore on the time interval covered by each individual drought, as given in Table 1c."

[p6, 19–21]. Can this be rephrased for clarity? 4.1 Regional climate driver influences

Rephrased as:

"4.1 Influence of climate drivers on regional rainfall"

[p7, 13]. ENSO "stands out" only in the warm season. The cool season map is mostly red, but this is misleading when the more nuanced bar graph results are considered. See later comments on Figure 2.

The map shows the highest correlation only and ENSO stands out for both seasons, although weaker in the cool season.

[p7, 14]. 44% < "most", so presumably you mean something else.

We changed the sentence to:

"Indeed, ENSO explains the greatest proportion of low-latitude rainfall variance during the peak-intensity season (warm season) of up to 44% in the Wet Tropics."

[p7, 24]. SSWF has the only warm season yellow (IOD) bar.

Yes, that is expected. The Indian Ocean Dipole is important in the June-Oct period in the southwest and southeast. That is consistent with (Risbey et al., 2009) showing that the IOD has its most prominent impact on Australian rainfall during the wet period and located to the south.

4.2.1 Reconstruction skill

[p8, 3, 5]. Figure 3 panel labels are given in the text, but are not shown on the figure.

The figure caption includes the information/labeling abbreviation.

Major. [p8, 5–8]. Some clarification of this earliest year comment is required. First, al- though it doesn't say so in the text, the Figure 3 caption indicates that statistics relate to calibration rather than verification statistics. Wouldn't the latter be better? Second, why is half the maximum calibration variance explained an appropriate metric here, rather than a fixed R2 threshold? Third, given that you can only assess skill based on com- paring with observations, I assume that the early dates relate to how reduced data sets (corresponding to nests) perform against the instrumental data. If this is incorrect then some additional explanation is required. Whether correct or not, have you taken into account degraded proxy performance with time outside of the calibration/verification period? Loss of sample depth, and thus signal, is characteristic of the tree ring data, so there is more to reduced performance than simply the number of proxies. Probably nothing much you can do about this, except to note that the early dates will be inflated (too early), but to an unknown degree.

The reviewer is partially correct; the statistics do not relate only to the calibration statistics but also to the verification statistics. We clarified this in Figure 3 caption by adding respectively to p27 line 9:

"the year in which R2v and R2c reduce to half of their maximum value, respectively."

We decided to indicate the degradation of reconstruction performance by a single year for the explained variance only. It should be noted that the given years/numbers, which are based on R2v and R2c, do not serve as a threshold. Those years serve only as indicators how fast/slow the stitched reconstructions of any given region and season half their maximum skill (of course depending on different nests with fewer proxies).

However, the RE and CE years indicate indeed the starting years that has been used as some kind of threshold for the skillful portion of the reconstruction as stated in p.6 line 4-5.

We clarify this by adding a statement to p. 8, line 9:

"The CE years indicate the skillful portion of the reconstruction (CE>0) for further analysis.*"*

4.2.2 Reconstruction time-series

[p8, 22]. Probably best to delete ". . .and past centuries (Fig. 5)", because all comments in this paragraph relate to Figure 4.

Okay

[p8, 29]. Define "low-frequency". I am struck by the lack of it.

We agree and specified the term in p.8 line 29 as followed:

"Decadal-scale frequency variability (decadal) is evident in all warm and cool season reconstructions."

[p8, 26–27]. Perhaps I am missing something here, but doesn't your rescaling methodology force this? If so, then this is not a relevant comment.

The CPS reconstruction method scales on the mean and standard deviation which alters amplitudes but not necessarily the upper percentiles (extreme years) correctly.

Major. [p9, 15–27]. This is an interesting approach, but I am unconvinced by the interpretation. Because 30 years is a fairly short window, I suspect that analysis of serially-correlated random numbers may give similar results to what you see here. If so, then the patterns identified cannot realistically be interpreted in the manner done, although the conclusion would be the same. I am not convinced that it amounts to ". . .an additional verification measure".

We totally agree that it is not an additional verification measure and rephrased the sentence to:

"This indicates a degree of independence between the seasonal reconstructions."

4.3.1 Contextualising recent rainfall trends

[p10, 7–22]. Apart from the apples vs. oranges caveat (see discussion of Figure 6), this seems OK, but it does beg the question why 30/50 year trends are a key metric, rather than, say, 30/50 year means and variance. See previous comment about providing the rationale for this aspect of the methodology.

We agree with the reviewer that these trends are not a key metric. As far we are concerned 30/50 year running means would indicate the similar results. We refer to trends because our study aims to contextualize often cited recent trends in the literature based on short instrumental records. We do not claim an extensive attribution of recent trends but we use our reconstruction to get an extended estimation of the range of natural variability.

4.3.2 Contextualising the spatial extent and intensity of past droughts

[p10, 31–32]. Surely two droughts are not enough to make such a relatively bold statement, especially since the reconstruction gets the significance of the two droughts around the wrong way (gridded AWAP shows WW2 drought is more significant, but reconstruction indicates the Federation drought).

We agree with the reviewer and added to the sentence:

"our reconstruction depicts the intensity of the two drought events during the instrumental period quite well."

Major. [p11, 11–19]. Figure 7 is nice, but here are confusing elements to the results that require explanation. Recon (1900-214) shows central region (R) below average for both the WW2 and Federation droughts. Recon (1600-2014) has WW2 average and Federation very much below average. While I appreciate that deciles are a moving target, drilling down into the results is needed to make sense of what is going on. At face value, Recon (1600-2014) lacks credibility, because it relegates arguably the most significant drought of the instrumental record, based on the instrumental data, to relative insignificance!

We agree with the reviewer and corrected the figure labels. Deciles, its subdivision for plotting reason into 7 categories and a coarse spatial resolution removes some detail. We correct the figure caption of the reconstruction from Recon (1900-2014) to Recon (1900-1990) to make clear that we didn't reconstruct the Millennium drought but sets it into a long-term context.

4.3.4 Extreme years in a long-term context

[p12, 27–28]. This is pushing the envelope, but I am not convinced that you have actually shown that the reconstruction is actually up to this rather demanding task. I would need to see that the instrumental extreme years are captured in roughly the appropriate order.

We agree and tested those claims before. The extreme years during the overlapping period are captured roughly in the same order. Figure 4 indicates some of them.

[p13, 2–16]. Some of this material may be better in the discussion.

We agree and move those lines into the discussion.

[p13, 18–28]. Results in this section have to be taken at face value because the tabled presentation is not well suited to "seeing" the claimed patterns.

We agree with the reviewer and will show each individual year by a map with a supplementary video.

4.6 Comparing our reconstruction with previously published

[p13, 33–34]. Please be explicit about the degree of overlap (%).

We agree and added the degree of overlap to the text:

"(~60%)"

[p14, 4]. Is linear correlation against the PDSI appropriate? I don't recall if the PDSI scales linearly and it is also a water balance approach, so has significant memory. My point here is that you might be short changing yourselves by an overly simplistic inter-comparison.

We agree that the correlation analysis might be very simplistic and further analysis is required. We add a statement to p.14 line 5:

"Figure 9 shows the linear correlations not accounting for memory effects between the austral summer season (DJF) PDSI reconstruction (ANZDA) with our cool and warm season rainfall reconstructions"

[p14, 8–10]. I don't understand where you are going with this the last sentence. It reads like a criticism of the PDSI, but I suspect that is not your intention. The temperature dependence targets evaporation, making PDSI arguably a superior drought index. And the spatially unresolved parts presumably relates to the point-based approach, which is also arguably superior (you certainly have not convinced me otherwise).

Yes, it is not our intention to criticise the PDSI. We have to keep in mind that we are comparing apple and oranges as our reconstruction is calibrated to rainfall not PDSI. It is not expected to align perfectly and highlights aspects of both, the PDSI and rainfall reconstruction. We add this statement to underline those differences to p14 line 2-3.

"In addition, the ANZDA drought reconstruction differs substantially in its temporal (DJF) and spatial resolution (gridded), since it is a point-by-point gridded reconstruction, mostly verified for Eastern Australia and targets the PDSI, which accounts not only rainfall but also temperature-depending effects during summer (DJF) and memory effects accounting for soil moisture. The PDSI is therefore more likely to reflect agricultural droughts than meteorological droughts observed in rainfall. "

Major. [p14, 10]. The poor warm season agreement with the PDSI analysis, except for one region, is quite alarming, especially the near-zero relationships in regions containing the cities where most Australians live. Given that this affects the perceived credibility of Australian drought reconstruction, it might be appropriate to follow up on this here, or in the discussion.

We partially agree but don't see a strong disagreement with the PDSI reconstruction as we are comparing two different targets, spatial and temporal resolutions. We should highlight again, that the PDSI reconstruction covers mostly Eastern Australia and is highly spatially resolved. Regions containing the cities where most Australians live e.g. Sydney, Melbourne, Canberra, Adelaide are not well represented by the ANZDA reconstruction either. Areas such as the Murray-Darling Basin, which collects and drains off much of its precipitation into catchments for major cities, shows agreement.

[p14, 14–17]. The cool season SE results are encouraging (water resources implications), but not so the dry season. Coupled with the poor agreement with the drought atlas, and the unconvincing relationship with the coastal records, I'm left doubting the credibility of the reconstruction.

The drought atlas is based on PDSI and even during the instrumental period, the PDSI differs strongly from rainfall among others due to its temperature component and memory effect. We added a few more comments on the differences including the different seasonality (see above) to remind the reader.

5 Discussion and conclusion

[p15, 6]. "Eastern Australian" is too broad a phrase – agreement is much more spatially restricted. Personally, I think "high-level" is overselling things. Given that you are reconstructing the same thing (drought) from significantly similar data sets, I was expecting to see most variance in common, and you are well shy of that.

We disagree with that and suspect confusion about the cool and warm season. We reconstruct rainfall, not drought, which might come closest to a description as meteorological drought. Correlation analysis shows highly significant connections between ANZDA and the rainfall reconstruction during the warm season close to the East Coast and Central Slopes of at least $r = 0.6$. This becomes clear from figure 9. To avoid further confusion, we increase the font size of the season names in figure 9.

[p15, 7–8]. I suggest you limit the "compared well" comment to the cool season.

We disagree with that. See comment above.

[p15, 11]. Interesting comment about highlighting the quality, because to me they high- lighted the limitations.

A comparison with early documentary records is only possible for Southeastern Australia where we have early records. That is indeed limiting for other regions but provides opportunities for comparison with Southeastern Australia.

[p15, 14]. This is a reasonable statement. But not picked up is some notable evolution in patterns for some regions. For example, MN & R in Figure 6 appear to have increased variability in the late 20th c. Is this real, or a splicing artefact?

That is true and an interesting point for future work. This increase of variability is actually also visible in the instrumental data. Further work is need to investigate this increase in variance. For example, the Rangeland cover the largest region, mostly deserts but not many instrumental observations. Further research could investigate if those changes reflect actual increase in variability or are an artifact of inhomogeneities in the underlying AWAP dataset.

[p15, 14–]. I remain unconvinced by this regression slope analysis approach. It can tell you about the rate of change and its significance, but is that really the important metric in terms of the process explanations you then mention? It also misses important cumulative impacts. For example, the SS and SSWF results show a cumulative decline to a mean substantially lower and with the most extreme droughts all relatively recent. MN and R show the reverse. A different type of analysis would be required to assess the significance of these changes.

We agree with the reviewer and don't claim any assessment of significance or process explanation. We set the most recent trends into a longer term context, which is often not possible with short instrumental records. This approach provides useful information about how usual or unusual those decadal-scale changes are but doesn't refer to processes causing those changes.

Major. [p16, 2–3]. Comparison of instrumental vs. reconstructed trends can only reasonably be made with relevant caveats associated with the pre-processing of the palaeo data. Pre-processing has likely reduced supressed multi-decadal trends, so your histograms in Figure 6 will be pulled in at the tails, which clearly will affect your assessment of how the instrumental data trends (which have not been similarly treated) compare. Note though that recognising this actually reinforces your conclusion about recent trends being within the range of natural variability.

We don't agree with the reviewer on this point. All proxy data has been used as provided by the original author and described in cited publications. We did not pre-process or filter the data other than as done by the original publication by removing non-climatic trends (e.g. biologic growth trend in tree-rings).

Major. [p16, 9–10]. The discussion in this paragraph follows on and emphatically restates earlier comments about the quality of the reconstruction of historical droughts that I think can reasonably be challenged (see [p11, 11–19], above). First, surely you only have two droughts. The millennium drought is outside your proxy data period, so it is essentially spliced instrumental data, is it not? If so, then agreement of spatially- averaged instrumental data with the original gridded data is meaningless, although it does point to issues with spatial units that are too large (a paragraph discussing this spatial scaling issue would be appropriate). For the other two droughts, you can only really claim good agreement for the Federation drought. As previously stated, I think the WW2 drought reconstruction is severely awry, and suggests to me that the methodology may only be suitable for capturing some types of drought (perhaps some additional forcings are not captured by the proxy network). The credibility of the reconstruction is challenged by the poor representation of what the instrumental data shows to be the most extreme drought in the instrumental period (Figure 7, left column).

We agree with the reviewer and add a statement highlighting the spatial scaling issues to the discussion p.16 line 10:

"The major droughts during the instrumental period are well represented in terms of their spatial extent, intensity and duration considering the reduced spatial representation of regional averages."

We can only compare the WW2 and Federations drought during the instrumental period, which is limiting but both droughts are reasonably well captured by comparing the gridded AWAP (first col), and NRM AWAP (second col) and reconstruction (third col). Again especially South Eastern Australia, Central Slopes and East Coast but also the Rangelands agree well. Great differences show up when looking at the WW2 in a long-term context (fourth col) but again Southern, Central and Eastern Slopes show still conditions well below average.

[p16, 27–33]. This is an interesting point. Can you relate it back to the drivers?

Good point and referred as further work in the discussion as followed:

"Independent palaeoclimate reconstructions could help to infer the rainfall amounts back to the climatic drivers causing these diverse drought characteristics and could provide important insights into the climate modes."

Major. [p17, 3–4]. I don't disagree with this, but it does presuppose that teleconnection patterns will remain stable in a future warming world. The flip side of this is that the reconstructions extend back into a globally cooler period. If teleconnection were different then (and there is evidence to suggest they were for some of your proxies), what then are the implications for your reconstruction (because the transfer function will be wrong. Moreover, drought is not just rainfall. Australian researchers have shown that droughts have intensified in response to increasing T (and thus evaporation), have they not? So a rainfall-only analysis is only part of the story. Surely worth some serious commentary.

We totally agree that droughts are not only a consequence of suppressed rainfall but also temperatures and subsequently evaporation. We added a comment into the discussion part by

"It should be pointed out that our seasonal reconstruction represents rainfall only. Droughts are a result of complex interactions of various atmospheric variables and interactions of different time-scales. Important factors contributing to droughts are temperature, soil moisture and evaporation, which are not accounted for in this reconstruction."

Table 1. SAM is missing. Additional details of indices would be useful (e.g. I assume NCT and MWP are SST based). A sentence or two describing each index would be useful. Surprising you have not included a west pole pressure index.

Yes, we will add SAM and its reference. For details on the individual indices we refer the reader to the original publications. The information about pressure conditions over the west pole is included in the calculation of the SOI due to pressure differences between Darwin and Tahiti and therefore not further being looked at in this study.

Table 2. The caption could usefully be reworded for clarity. Is the information for "Instru" the reconstructed data for the instrumental period, the same but with instrumental data spliced on the end, or the instrumental data? This seems a rather ineffectual way of presenting the information – visualisation would highlight temporal patterns, temporal clustering, and inter-regional patterns in a way that tabled numbers do not.

We agree, and will reword the caption.

Figure 1. See previous comment about inability to resolve the proxies and the regions on this map.

Also, given that many proxies were eliminated, would it not be more useful to limit the map to those proxies that actually end up being used. Moreover, it would be interesting to see this broken down by region in the supplement. Without a laborious process of extracting the relevant information from Table S1 and remapping, this useful information about contributing proxies is unavailable to the reader.

We agree, and will add a supplementary figure showing all contributing proxies on a map

Figure 2. It appears that the SOI is generally superior or comparable to the other three ENSO indices. That point could be made in the text and this figure simplified. There is a wealth of information in the bar charts, but the maps are unsophisticated in the treatment of this, and I think counterproductive in oversimplifying matters. I don't recall comment in the text related to the logic of pooling SAM and BLK. It would be useful to include the region codes along with their long names on the bar charts (also on the maps). Consider adding a horizontal line separating the two parts of the figure. Because you don't have axis labels, you need to explicitly state in the caption that the bar graphs show correlations. See previous comment about uncertainty about whether autocorrelation has been allowed for in the significance levels cited (see [5, 9] above).

We agree that the SOI is generally superior. Great point! Maybe its direct computation from atmospheric pressure shows stronger connection with atmospheric processes causing rainfall anomalies in Australia. We will add a horizontal line separating the two parts of the figure, add the code names for the regions and add a statement about the correlations. The pooling was applied only for visualization purpose to draw distinctions amongst tropical (ENSO and IOD), subtropical (STRL and STRI) and extratropical drivers (SAM and BLK). We will add this information to the caption.

Figure 3. It would be useful to have the years corresponding to the plotted statistics shown.

We refer to some of the corresponding years already on page 8, line 10-20.

Figure 4. There are several instances where the reconstruction is outside the ensemble range. Having gone to the trouble of calculating the ensembles (a good thing), why isn't a mean/median (or other measure of central tendency) used for the reconstruction? Doing so would "fix" some of the points of difference with the instrumental data (e.g. in MB, MN, WT). It would introduce other issues, but the net benefit may be positive, and a transfer function based on the full data rage may be more robust. Just a thought.

Thanks for this comment and finding this error! We mislabeled the instrumental data with the reconstructed data in figure 4 and will change that plot. The reconstruction falls within the ensemble range, so sorry for this. We haven't looked at the ensemble mean/median caused we would have to deal with other issues such as an inadequate representation of amplitudes due to the averaging process.

Figure 7. I presume that the millennium drought is "missing" for Recon (1900–2014), because you only have instrumental data. If that is true, I don't get why it appears in Recon (1600–2014) – its not reconstructed, its spliced instrumental data isn't it? Need to specify the time periods for decile calculation (12/24/36 months?).

Deciles are computed according to the duration of the drought we are looking at. The duration of droughts is indicated by their start and end years in table 1c.

Figure 8. Please expand the caption to better explain exactly what is being shown here. How is the starting point for each drought determined?

We agree and added to the caption:

“Decile Plots for a) significant drought periods (according to table 1c) …”

Minor points

We will account for all minor points.

[p2, 8]. Delete “a” at the end of the line.

[p2, 10]. This style of referencing with a list of references at the end of a paragraph is unfortunate. They presumably don’t all relate to the last point, and if they do then there are missing references in the body of the paragraph.

[p3, 27]. Do you mean “Compile”?

[p10, 32]. New paragraph (millennium drought)?

[p11, 11]. [somewhat] similar?

[p11, 33]. provide[s] insight.

[p12, 3]. Suggest you change “many” to “several”? 4–5/8 and only cool season.

[p12, 14]. Seems to [be] a result.

[p12, 24]. Breaking up paragraph into smaller ones would help readability.

[p12, 26]. Expand “Black Thursday” for benefit of non-Australian readers.

[p14, 5]. Reconstruction[s]?

[Table 2, 4]. referred [to] as.

[Figure 8, 3]. Delete “a” (3rd last word).

[Figure 9]. Fenby et al should be Fenby and Gergis.

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Reply to the Interactive comment on “Multi-century cool and warm season rainfall reconstructions for Australia’s major climatic regions” by Mandy Freund et al., by **D.s Kaufman,**

Essential additions for this paper:

(1) Add a "Data Availability" section to include a URL/Data Citation to a landing page that lists the datasets used in this paper (Table S1) and the URL/Data Citation for the primary output of this study.

We agree and will add the data availability information to the landing page. Does Climate of the past have an opportunity to provide a URL/Data Citation for the primary output internally?

(2) Add Data Citations or URLs (in addition to publication citations) for each of the 185 records used in for the rainfall reconstructions in this study. For those records not already in a persistent public repository, submit the essential metadata along with the proxy data and add the corresponding Data Citation (or URL) in Table S1.

We agree and will add all data citations and metadata to an additional Table in the supplement. The 185 chronologies used in our analyses are the products of several different research groups and are in various states of pre- and post-publication Most of the records have already been lodged in publicly available repositories (typically the ITRDB). In a supplementary file, we provide the essential metadata for the remaining chronologies. These include: chronology name, site/location, length, type, and collector/contact person.

(3) Submit the primary outcome of this study, the regional rainfall reconstructions for cool and warm seasons (Fig 5), to a public repository and include the Data Citation in "Data Availability".

We will do that

(4) Archive the instrumental time-series targets for the reconstructions (Fig 4) along with the reconstructions.

We will do that

Multi-century cool and warm season rainfall reconstructions for Australia's major climatic regions

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Abstract. Australian seasonal rainfall is strongly influenced by large-scale ocean-atmosphere climate influences. In this study, we exploit the links between these large-scale precipitation influences, regional rainfall variations, and palaeoclimate proxies in the region to reconstruct Australian regional rainfall between four and eight centuries into the past. We use an extensive network of palaeoclimate records from the Southern Hemisphere to reconstruct cool (Apr-Sep) and warm (Oct-Mar) season rainfall in eight natural resource management (NRM) regions spanning the Australian continent. Our bi-seasonal rainfall reconstruction aligns well with independent early documentary sources and existing reconstructions. Critically, this reconstruction allows us, for the first time, to place recent observations at a bi-seasonal temporal resolution into a pre-instrumental context, across the entire continent of Australia. We find that recent 30-year and 50-year trends towards wetter conditions in tropical northern Australia are highly unusual in the multi-century context of our reconstruction. Recent cool season drying trends in parts of southern Australia are also very unusual, although not unprecedented, across the multi-century context. We also use our reconstruction to investigate the spatial and temporal extent of historical drought events. Our reconstruction reveals that the spatial extent and duration of the Millennium drought (1997-2009) appears either very much below average or unprecedented in southern Australia over at least the last 400 years. Our reconstruction identifies a number of severe droughts over the past several centuries that vary widely in their spatial footprint, highlighting the high degree of diversity in historical droughts across the Australian continent. We document distinct characteristics of major droughts in terms of their spatial extent, duration, intensity, and seasonality. Compared to the three largest droughts in the instrumental period (Federation drought [1895-1903], World War II drought [1939-1945], and the Millennium drought [1997-2005]), we find that the historically documented Settlement drought [1790-1793], Sturt drought [1809-1830] and the Goyder Line drought [1861-1866] actually had more regionalised patterns and reduced spatial extents. This seasonal rainfall reconstruction provides a new opportunity to understand Australian rainfall variability, by contextualising severe droughts and recent trends in Australia.

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1 Introduction

Australia's climate varies between extreme states of severe dry conditions and devastating wet episodes affecting large areas of the continent (Nicholls et al., 1997). Shaped by high variability and persistence, floods, heat waves and droughts, Australia is highly vulnerable to changes in the climate system. One reason for the diversity in climate states is the influence of, and interactions among, large-scale ocean-atmosphere modes of variability. These include the El Niño Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the southern annular mode (SAM), and atmospheric characteristics such as the strength and location of the Subtropical Ridge (STR) and the presence of atmospheric blocking (BLK). Critically, these tropical and extra-tropical modes of variability operate at and across different temporal scales and their individual and interacting influences have strong—and diverse—seasonal and regional effects on Australia's climate (Cai et al., 2014; Drosdowsky, 1993; Larsen and Nicholls, 2009; Maher and Sherwood, 2014; McBride and Nicholls, 1983; Oliveira and Ambrizzi, 2016; Ummenhofer et al., 2011a; Wang and Hendon, 2007; Watterson, 2009; 2011).

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Over the 20th century many regions in Australia have experienced prolonged pluvial and drought periods that are documented in the gridded, instrumental records starting in 1900. The Federation drought (1895-1903) was one of the first multi-year periods of below average rainfall since European instrumental data collection began in Australia. There were also pronounced rainfall deficits during the World War II drought (1939-1945) and the Millennium drought (1997-2005), with devastating effects on regional agriculture and the broader economy(van Dijk et al., 2013).

In addition to these discrete drought events, there have also been a number of trends observed in Australian rainfall in recent decades. While there has been a general decrease in rainfall, particularly across southern Australia, these changes appear to have strong seasonal and regional components. For example, rainfall has declined in autumn across southern Australia (Larsen and Nicholls, 2009; McBride and Nicholls, 1983; Murphy and Timbal, 2008; Timbal et al., 2006), in the south-west during winter (Allan and Haylock, 1993; Cai and Cowan, 2008; Hope et al., 2009) and in southeast Queensland during summer (Smith, 2004; Speer et al., 2009). At the same time, regions in the north have received increasing rainfall (Feng et al., 2013; Taschetto and England, 2009; Wardle, 2004). The Millennium drought, observed most severely in south-western and south-eastern Australia, was predominately due to deficits in cool season rainfall (Verdon-Kidd and Kiem, 2009a).

Given the presence of decadal (or longer) variability in the known climate drivers, short observational records are unlikely to provide a reliable estimate of the full extent of natural variability in Australia's climate system. In building a picture of the future likelihood of observed late 20th Century trends continuing and the underlying likelihood of prolonged drought, it is essential that we understand the longer-term climatic context and its sources of variability. Palaeoclimate data can provide a unique window into long-term rainfall variability and emerging spatial and temporal trends. Such knowledge has practical applications for water resources management, seasonal forecasting, future climate predictions and potential to evaluate simulated past climate variations.

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There have been a number of palaeoclimate reconstructions of hydrological variables in Australia (Allen et al., 2015; Cullen and Grierson, 2008; Gallant and Gergis, 2011; Gergis et al., 2011; Heinrich et al., 2009; Lough et al., 2015). Palmer et al.

(2015) recently introduced the Australia and New Zealand Drought Atlas (ANZDA), using the approach developed for Asia (Monsoon Asia Drought Atlas (MADA) (Cook et al., 2010)), Europe (Old World Drought Atlas (OWDA) (Cook et al., 2015b)) and North America by Cook et al. (2010). The ANZDA reconstructs the past 500 years of Palmer Drought Severity Index (PDSI) for a 0.5 x 0.5 degree grid over eastern Australia and New Zealand using a network of 176 tree ring records and one coral record. Each of these reconstructions has advanced our knowledge of hydroclimatic variability at the bi-seasonal or annual scale for specific regions of Australia. To date, however, none have performed bi-seasonal reconstructions for the entire Australian continent.

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The network of palaeoclimate proxies in Australia prior to the instrumental period is much sparser than for other regions such as Eurasia and North America. However, the strong links between large-scale remote climate drivers and Australian climate means that remote proxies can contain a useful climate signal. Several recent studies have used remote teleconnections and climate drivers to obtain skilful reconstructions (Palmer et al., 2015; Tozer et al., 2016; Vance et al., 2015). In this study, we introduce a new method to reconstruct regional rainfall by systematically relating instrumental rainfall and proxy information to remote climate influences. We utilise a more dynamically-focused methodology driven by dynamical relationships to include remote proxies and maximise the skill and widespread utility of our reconstructions of Australian rainfall.

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Rainfall variations over the Australian continent show a large degree of spatial coherence at seasonal and longer time-steps, due to the relatively simple terrain geometries and orography. The Climate Change in Australia report (CSIRO and Bureau of Meteorology, 2015) applied a regionalisation scheme to define eight Natural Resource Management (NRM) regions with similar climatic and biophysical features. The NRM clusters and their abbreviations are listed in Table 1 and shown on the map in Figure 1. In this study, we use a diverse network of local and remote palaeoclimate proxies to perform a reconstruction of cool and warm season rainfall in these eight NRM regions of Australia.

The aims of this study are to:

1. Consolidate relevant hydroclimate-sensitive palaeoclimate records;
2. Assess the sensitivity of the palaeoclimate records to the influences of large-scale climate influences and test the stationarity of these relationships;
3. Exploit the sensitivity of palaeoclimate proxies to large-scale climate influences and develop skilful palaeoclimate reconstructions of seasonal rainfall in eight NRM regions for several centuries into the past; and
4. Compare the occurrence of wet and dry periods in the past to those in the instrumental period to provide a longer-term context for recent observed events and trends.

Our study is organised as follows: Sections 2 and 3 describe the data and our methods, respectively. Section 4.1 presents a summary of the regional rainfall signature of modes of variability in the instrumental period. Section 4.2 presents the results of the reconstruction. In Section 4.3, we present an investigation of the trends, droughts and extreme years in a multi-centennial context, as well as a comparison to existing reconstructions. We finish by discussing these results and their broader implications in Section 5.

2. Data

2.2 Instrumental data

Our analysis is based on the Australian Bureau of Meteorology's gridded monthly precipitation dataset from the Australian Water Availability Project (AWAP) (Jones et al., 2009). The monthly AWAP dataset is based on precipitation anomalies generated from varying number of station observations using the Barnes successive-correction (KOCH et al., 1983) and a three-dimensional smoothing spline interpolation (HUTCHINSON, 1995). Seasonal and regional averages are computed from the gridded observational dataset at its highest spatial resolution of 0.05°×0.05° for the period 1900-2015. The eight Natural Resource Management (NRM) regions reflect broad pattern of large-scale rainfall variability but may not capture finer scale patterns.

We also use several climate indices to link climate drivers with Australian rainfall (Table 1(a)), that have previously been used to characterize the relationship between rainfall and large-scale drivers (Risbey et al., 2009). Computation of the individual climate indices strictly follow the descriptions in references given in Table 1. The indices describe tropical influences (El Niño Southern Oscillation (ENSO) and Indian Ocean dipole (IOD/DMI) (Saji et al., 1999)) as well as extra-tropical drivers (Southern Annular Mode (SAM), the intensity and position of the Subtropical Ridge strength (STRI and STRP (Drosdowsky, 1993)) and atmospheric blocking (BLK) (Pook and Gibson, 1999)). ENSO is described by multiple indices, each of which relates to a different aspect of the coupled ocean-atmosphere mode. Here we use indices that are related to sea surface temperatures anomalies in the Eastern Pacific (NCT) and the Western Pacific (NWP) (Ren and Jin, 2011), the Southern Oscillation index (SOI) that measures the atmospheric component of ENSO, and the effects of Central-Pacific type events denoted by the ENSO Modoki index (EMI) (Ashok et al., 2007).

2.2 Palaeoclimate data

A palaeoclimate network of 185 individual records is compiled for the Southern Hemisphere (Fig. 1a). The multi-proxy network includes local and remote sites from a broad area that are related either directly or tele-connected to Australian climate (Fig. 1a). The majority of the records used are derived from the underlying network of the recently developed Australia and New Zealand summer drought atlas (ANZDA) (Palmer et al., 2015) and the Ocean2k project that is part of the PAGES (Past Global Changes) program (Neukom and Gergis, 2012; Tierney et al., 2015). The entire network includes 131 tree-ring records from the Australasian Pacific area, 36 coral-derived records from the tropical Pacific and Indian Oceans, and five speleothem-derived records. In addition, 13 records derived from Antarctic ice-cores are included, as they are related to relevant large-scale high-latitude drivers such as SAM (Tozer et al., 2016; Vance et al., 2015). All records in the network extend back to at least 1880 CE and the majority cover the past 250 years. No further data treatment has been applied other than the removal of non-climatic biological trends in tree-ring records using the signal-free method that preserves much of the medium-frequency variability (timescales of decades to a century). (see Table S1 for references and details). Approximately half the records extend back before 1600 CE. Twenty records extend back to 1200 CE or earlier (Fig. 1b). Within this network, 160 proxy records are annually resolved records and 25 are sub-annually resolved (derived from corals) (Fig. 1c). Sub-annually resolved records are binned into seasonal averages according to a warm (Oct–Mar) and cool season (Apr–Sep). Samples within the seasonal window (six consecutive months) are averaged onto a regular time grid of two samples a year, whereas the dating of annually resolved records follows the original author.

3 Methodology

3.1 Reconstruction

The ocean-atmosphere processes that influence Australia's hydroclimate have distinct, but variable, seasonal and geographical characteristics (Risbey et al., 2009). In this study, we first consider the relationships between the selected climate indices and warm (Oct–Mar) and cool (Apr–Sep) season rainfall in each NRM region. The influence of each driver is determined by linear correlation for the concurrent season only. We exclude lag relationships between each driver and rainfall, which are generally weaker (Risbey et al., 2009). Relationships between precipitation and ocean-atmosphere processes can vary in strength over time (Gallant et al., 2013). We therefore use moving correlation windows (window length = 30 year) to assess statistically significant ($p < 0.1$) correlations for temporal stability. A relationship is considered stable if the interquartile range of windowed correlations remains of the same sign for the entire period of overlap between the two data sets. This approach ensures, on one hand, that the climate drivers have an approximately time-stable relationship with rainfall, but also allows some degree of variation in the strength of the teleconnection. The same procedure to test stability was applied to the relationships between each proxy record (as listed in Table S1) and each climate index (as listed in Table 1 (a)). Only proxies with a significant and time-stable relationship with an index were used as predictors for NRM regions with a time-stable relationship between that same index and precipitation (Table S2).

We use a nested, composite-plus-scale (CPS) approach (Bradley and Jones, 1993; Tierney et al., 2015) to reconstruct regionally averaged rainfall for each NRM region. Our CPS approach combines principal components of proxy records into regional composites based on a weighted averaging procedure. The weight, w, is determined by 1) the coefficient of determination between each record and its target during the common period (1900-1984) and 2) the significance of this relationship, $w=r^2(1-p)$, where p denotes the p-values of the correlation, similar to Tierney et al. (2015). The resulting composite is re-scaled to the mean and standard deviation during the calibration period. It should be noted that not all of the records strictly follow a normal distribution (Supp. Fig. 7). Using a nested approach entails the calculation of multiple reconstructions, each reconstruction, or nest, extending further back in time but including fewer proxies as the proxies successively drop out (Fig. 1 b). Nests are spliced together to form a continuous reconstruction. Nests are spliced together, based on the most replicated nest (most number of records available at a given time), to form a continuous reconstruction. This process maximises the length of the final reconstruction and ensures all proxies meeting the selection criteria are used at each point in time. The common period of palaeoclimate records and instrumental data (1900-1984) is used for calibration and verification. During the common period, 60% of the data are used for calibration (equal to 51 contiguous years) and the remaining 40% (34 years) are used for verification. We assess the sensitivity of our reconstruction to different calibration and verification periods by shifting our calibration window of 51 years across the common period in steps of 5 years. These different, but not independent, calibration and verification periods are used to build an ensemble of seven reconstructions for the warm and cool seasons.

Each final regional rainfall reconstruction is evaluated against a set of skill metrics. The coefficient of determination (R^2c), is a measure of variance explained by the reconstruction in the calibration period, and R^2v is the variance explained in the verification period. Further skill statistics include the reduction of error (RE) and the coefficient of efficiency (CE), which both indicate statistical skill by positive values (Cook et al., 1994). Further analysis is conducted on the skillful portion of the reconstruction (CE>0). We report our best reconstruction as that which maximises the time-integrated RE.

3.2 Analysis

Linear trends in the warm and cool season from instrumental and reconstructed precipitation are compared by fitting a linear trend line to the time series in 30- and 50-year moving windows. All trends are normalized by the maximum occurrence across each region and presented in histograms. All trend calculations are based on overlapping moving windows with a 1-yr time step.

We investigate multi-year instrumental and historical periods of extremely low rainfall. During the instrumental period, three major droughts are assessed. These are the Millennium (1997-2009), World War II (1935-1945) and Federation droughts (1895-1903). Since European settlement, seven historical droughts are often reported in historical and documentary records. These include the Settlement drought (1790-1793), the Murray Darling Basin drought (1797-1805), the Great Drought (1809-1814), Sturt's drought (1809-1830), South East Australia drought (1836-1845), the Black Thursday drought (1849-1866) and the Goyder Line drought (1861-1866) (Helman, 2009). Details provided in Table 1c.

We evaluate historical periods of drought by calculating seasonal and annual rainfall deciles based on the entire length of available data. For instrumental data, deciles are relative to the 1900-2014 long-term climatology, while reconstructed rainfall deciles include all positively verified years. The extended reconstruction includes all verified reconstructed years up

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to 1984, extended for the most recent 30 years of instrumental data up to 2014. The individual duration of deciles therefore depends on the time interval covered by each individual drought, as given in Table 1c. It is important to note that deciles deliver quantitative statements only in conjunction with a baseline period and duration, which may differ (example of different baseline periods Supp Fig.8). Resulting deciles are then categorised into: highest on record, very much above average (10), above average (8-9), average (4-7), below average (2-3), very much below average (1) and lowest on record.

Drought durations are a challenge to compare using a decile-based approach alone. We therefore apply the concept of "drought-depth-duration" (DDD), following (Fiddes and Timbal, 2017; Timbal and Fawcett, 2013) to compare droughts of different duration. We present the percentage reduction below the long-term average of dry episodes ranging from 1 to 10 years. Our seasonal rainfall reconstruction uses the long-term average of the entire reconstruction as the baseline and presents the drought depth duration as the percentage reduction below this long-term average.

Ranking the seasonal rainfall totals in ascending order identifies extreme dry and wet years. The 10 highest and lowest years in the best reconstruction are reported in Table 2. As above, to provide a long-term context, the 10 driest and wettest years during the extended period (both the instrumental and the reconstruction periods) are identified.

In addition to pure statistical verification, we compare our results to other studies that have used historical documentary records and paleoclimate archives to describe or reconstruct past hydroclimatic variability. Data from other studies with bi-seasonal resolution are averaged into the same warm and cool seasons used as the basis for reconstructions in this study. Annually resolved data are compared to both seasons. Single location records are compared to each of our regions. For the ANZDA (Palmer et al. 2015), area averages of the NRM clusters are extracted for comparison with the NRM regions.

4 Results

4.1 Influence of climate drivers on regional rainfall

The influence of climate drivers on rainfall variability across the NRM regions is significant and widespread. The influence of ENSO stands out across the tropical north and subtropical regions for both warm and cool seasons (Fig. 2a & b). Indeed, ENSO explains the greatest proportion of low-latitude rainfall variance (up to 44%) during the peak-intensity season (warm season) in the Wet Tropics. The dominant effect of ENSO decreases along a north-south gradient, with multiple-drivers becoming more important in the south. In southwest and southeast Australia (Flatlands, Southern Slopes, Murray Basin) the influence of mid-latitude pressure systems encapsulated by SAM and atmospheric blocking (BLK) increases. This north-south gradient is stronger during the cool season. In southern Australia (Southern Slopes and the Murray Basin) where cool season rainfall dominates, the strength and positive influence of the Subtropical Ridge (STRP) is important. In southeastern Australia, the correlation between rainfall and the STRP is as strong as r=0.78, highlighting the importance of the subtropical

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4.2 The Reconstruction

4.2.1 Reconstruction Skill

Our reconstruction captures 30-60% of seasonal rainfall variability across the regions. Skill statistics of the reconstruction (Fig.3) show that the variance explained during the calibration period (1934-1984) is around 37% (R^2c [0.2-0.5]) for the cool season and 34% (R^2c [0.2-0.6]) for the warm season (Fig. 3a&b). During the independent verification period (1900-1933), a slightly larger magnitude of variance is explained by the reconstruction, with about 46% (R^2v [0.2-0.6]) for the cool season and 48% (R^2v [0.3-0.6]) for the warm season. These high and stable proportions of variance captured by the reconstructions are found for both seasons. The RE and CE statistics are positive for all regions, indicating reconstruction skill for both seasons across Australia (Fig. 3a&b). Given that our reconstruction is based on a nested approach, with a varying set of proxies over time, we indicate on Figure 3 the timeframe during which the individual reconstructions show reliable skill for each region and season. The years shown on each region for the R^2 panels (Figures 3a, b, e, and f) indicate the earliest year in which the reconstruction exceeds half of its maximum skill; years shown on the RE and CE panels (Figures 3c, d, g, and h) indicate the earliest year in which the RE and CE statistics remain positive, allowing for brief periods of negative skill, of duration less than 5 years. The year shown on the CE plots indicates the earliest year for which the reconstruction is considered skilful (ie, CE>0).

During the cool season, the Central Slopes, Wet Tropics, and South and Southwestern Flatlands indicate the longest skilful (CE>0) reconstructions, extending back to 1200, 1260 and 1366, respectively. The rainfall reconstruction in the Rangelands is only skilful back to 1811 and represents the shortest skilful reconstruction during the cool season. Most of south and southeastern Australia in the cool season can be reconstructed back to at least 1749 (Southern Slopes).

In the warm season, the Southern and Southwestern Flatlands, Wet Tropics, and Murray Basin warm season reconstructions are skilful (CE > 0) for the longest period, extending back to 1200, 1200 and 1234, respectively. The warm season rainfall reconstruction in the Monsoonal North has the shortest skilful reconstruction, back to 1707. Warm season reconstructions for south and southeastern Australia indicate slightly longer periods of skill than the cool season reconstructions.

4.2.2 Reconstruction time-series

Seasonal time-series of our reconstructed rainfall across Australia show high rainfall variability over the instrumental period (Fig. 4). Interannual and decadal-scale rainfall variability is well-characterised by the reconstructions. For example, the pluvial periods in the mid 1950s and late 1970s during the warm season in the eastern regions (top three panels) are remarkably well reconstructed. Although different calibration and verification periods indicate some differences at interannual scales (grey shading), encouragingly, decadal variability is well-represented by the ensemble. In particular, seasons which dominate the total rainfall are well captured in terms of their amplitude, for example, the warm season in the Wet Tropics and cool season in the Murray Basin.

Decadal variability is evident in all warm and cool season reconstructions (Fig. 5 & Supp. Figs. 8, 9). At decadal time scales, both the warm and cool seasons show synchronous decades of enhanced/reduced rainfall across different regions. For example, the very dry warm seasons (Supp. Fig. 9) observed in the 1960s (Central Slopes, Murray Basin, Rangelands, Southern Slopes, Southern and Southwestern Flatlands, Wet Tropics) are also seen in the 1760s across similar regions (Central Slopes, Murray Basin, Monsoonal North, Southern Slopes, Southern and Southwestern Flatlands, Wet Tropics). During the 1740-50s extreme wet conditions prevailed in southern and south-eastern Australia. Rainfall during those 20 years was mostly above average for much of Eastern Australia (Central Slopes, East Coast, Murray Basin). In the 1970s similar regions saw a decade of higher than normal warm season rainfall (Central Slopes, East Coast, Rangelands, Wet Tropics). There seems to be no general pattern of prolonged decadal drought or pluvial conditions associated with specific regions in our reconstructions.

The magnitude of the warm season pluvials during the 1970s and 1740-50s are not anomalously high based on the cool season reconstructions (Supp. Fig 8). Only East Coast and Rangelands show similarly high rainfall amounts, while other regions show average or sightly drier conditions (Central Slopes). Most of the cool season decadal trends show very distinct regional patterns. Wetter than normal conditions in the 1870s are only evident in the Central Slopes and East Coast. Even geographically proximate regions such as the Murray Darling Basin region and the Southern Slopes show dissimilarities in terms of decadal-scale variability. Overall, warm season rainfall seems to show slightly more concurrent decades across the regions than during the cool season.

To assess the degree to which the reconstructions are seasonally distinct, shaded areas in Figure 5 highlight periods when the warm and cool season reconstructions are significantly correlated (30-year moving window, abs(correlation)>0.5). There are a small number of periods during which the cool and warm season rainfall are in phase (positively correlated, shown in red) or out-of-phase (negatively correlated, shown in blue). However, for the most part, there is little dependence between the seasonal reconstructions. Although some regions show periods in which warm and cool season reconstructed rainfall are in-

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4.3 Australian rainfall and drought in a multicentury context

4.3.1 Contextualising recent rainfall trends

Since the start of instrumental records in Australia, several major droughts and extended pluvial periods have been observed. Some influences can be regarded as temporary changes in the mean-state due to, for example, natural decadal climate variability from the Interdecadal Pacific Oscillation (IPO, (Henley et al., 2015; 2017)). Other changes appear to be more strongly related to long-term changes in atmospheric circulation. These changes are spatially and temporally diverse, and strong interannual variability makes it hard to distinguish between low-frequency variability from externally forced long-term changes. Here we use our rainfall reconstructions to place recent observed trends in a long-term centennial context.

The histograms in Fig. 6 summarise all 30-year and 50-year linear trends in the regional reconstructions and instrumental data over the period 1600-2014. The distributions of trends distinguish between pre-1970 variability (grey), trends since 1970 or 1950 (depending on the fitted trend length of 30/50 years; shown in light blue/red for cool/warm season) and the trend from the most recent 30 or 50 years. The regional reconstructions show recent tendencies towards drier cool seasons in the south (Murray Basin, Southern Slopes, Southern and Southwestern Flatlands) and wetter warm seasons in the north (Monsoonal North, Rangelands, Wet Tropics). The distribution of historical trends derived from the reconstructions are of a generally Gaussian distribution. Some trends starting after 1950/1970, including the most recent trend, are shifted towards the upper and lower quartile range of the pre-1950/1970 trends. Trends starting after 1950/1970, including the most recent trend (ending in 2014) appear unusual, but not unprecedented. In recent years, during the warm season, tropical regions in particular show a strong increase in rainfall. This is strongest in the Monsoonal North, followed by the Rangelands and Wet Tropics (Supp. Fig. 4). Some subtropical regions show a warm season decrease in rainfall, strongest in the Southern Slopes, but again not unprecedented. All regions, except the Monsoonal North, show a decline in rainfall in the cool season during the most recent 30-yr and 50-yr periods. This decline is most pronounced in the Southern Slopes, Southern and South-Western Flatlands and the Murray Darling Basin. Cool season rainfall, which contributes the majority of subtropical rainfall, has clear negative shifts in southern Australia, compared to earlier trends. In particular, cool season rainfall in the Murray Basin saw declines over the last 30 and 50-years of the order of 90mm.

4.3.2 Contextualising the spatial extent and intensity of past droughts

Extended periods of low rainfall have different characteristics in their temporal and spatial structure. The assessment of drought risk depends critically on the range of estimated natural variability. Here we assess the severity of major drought episodes using deciles across both instrumental (1900-2014) and multi-century reconstruction (1600-2014) periods. Our regional rainfall reconstruction comparisons here extend the timespan of the instrumental record by a factor of four, which enables us to view droughts such as the Millennium Drought in a very long-term multi-century context. Deciles based on different datasets, baselines and durations are shown in Fig. 7. Comparing the spatial pattern of the reconstructed droughts to the gridded and NRM region instrumental (AWAP) spatial patterns, our reconstruction depicts the intensity of the two drought events during the instrumental period quite well. The gridded and regional representation of the Millennium drought is indicated as the lowest on record for parts of the Southern Slopes and the Murray Basin and very much below average for the East Coast and the South and Southwestern Australia, in agreement with other studies (Cai et al., 2014; Gergis et al., 2011; Verdon-Kidd and Kiem, 2009b). In the context of the full reconstruction period (1600-2014), the Millennium drought remains the worst drought since 1749 in the Southern Slopes (observable too in Fig. 5f) and very much below average for East Coast, Murray Basin and Southern and Southwestern Flatlands. In line with probability estimates for south-eastern Australia by Gergis et al. 2011 and (Cook et al., 2015a), the 12-year period of the Millennium drought is unprecedented for the Southern Slope region. The rainfall reconstruction of the Murray Basin reveals that periods in the late 1700s and early 1800s and at the time of the Federation drought are of similar or larger reductions in rainfall over a 12-year period (Fig. 5c). The Federation drought period is also apparent in the Southern and Southwestern Flatlands reconstruction, along with other periods of rainfall reductions the late 1600s (see Fig. 5g).

The World War II drought and the Federation drought appear to be of somewhat similar character during the instrumental period in terms of their area and intensity (Fig. 7 gridded and NRM regional plots). Considering the last 400 years, the World War II drought is a period of average rainfall for all regions except the Murray Basin, Central Slopes and East Coast. In contrast, the Federation drought (1895-1903) is much higher in intensity and spatial coverage. In Fig. 7 we compare the Federation drought during its instrumental period and full (including pre-instrumental) period. During the observational period (the latter part), the Federation drought shows only slightly below average conditions. In the multi-century context, the Federation drought shows a wider extent. Along the east coast (Central Slopes, East Coast), central parts (Rangelands, Murray Basin, Southern Slopes) and north Australia (Monsoonal North, Wet Tropics) the Federation drought has been of very much below average and lowest on record for Monsoonal North and Murray Basin.

Historical droughts during the pre-instrumental period (Table 1c, Fig. 7 and Fig S.6), as documented mainly in South Eastern Australia due to the concentration of European settlement there, are captured by the reconstruction. The Goyder line drought, Sturt's drought and the Great Drought appear to have affected only certain distinct regions. The Settlement drought shows regions clearly below average, especially coastal regions and the Murray Basin, similarly to (Palmer et al., 2015) and (Gergis et al., 2010). The representation in terms of affected regions aligns very well with historical reports (e.g. historical reports by Sturt or the definition of the Goyder line). Most of the historical droughts have been below average in certain regions but none of these droughts appear to exceed the spatial extent and intensity of the three major instrumental-period droughts.

4.3.3 Contextualising the duration and seasonality of past droughts

We apply the concept of drought-depth-duration (DDD) to our reconstructions to further assess the duration and intensity of the different droughts (see Sec. 3.2 for details). The DDD plots provide a method to compare the temporal structure of drought periods. Additionally, our bi-seasonal reconstruction resolution provides an opportunity to investigate the seasonal nature of protracted droughts and therefore provides insight into their climatic influences and potential causes.

Using the DDD analysis we can categorise droughts into long and short-term droughts and distinguish the primary season of the droughts. The Millennium drought is among the worst droughts in terms of its duration across several of the NRM regions in southern and eastern Australia (Fig. 8, dark blue lines). In particular, during the cool season, the reduction in rainfall extends over very long periods for central and eastern regions (Central Slopes, East Coast and Murray Basin). By comparing short periods (2<yrs) to longer periods (>6yrs) the Millennium drought is revealed as a persistent drought, with its worse impacts being felt over the longer timeframe. The Murray Darling Basin drought is predominately caused by cool seasonal rainfall deficiencies over long-periods, plus a slight accumulated rainfall deficit during the warm season in the Southern Slopes. The World War II drought had similar cool season rainfall reductions, however the warm season rainfall was also affected. These are similar to the findings of (Verdon-Kidd and Kiem, 2009b). The Murray Basin, the East Coast and the Wet Tropics, all had strong reductions in both cool and warm season rainfall of similar magnitude, about 70% below the long-term mean. In some regions, the Federation Drought was a strong warm season feature (Central Slopes) while in the tropical regions (Wet Tropics& Monsoonal North), rainfall reached remarkably low values. The intensity of the Federation Drought during the first few years seems to be a result of re-occurring El Niño episodes at that time and highlights ENSO's different spatial effects on Australian rainfall (Ummenhofer et al., 2009). Droughts such as the Murray Basin drought can be clearly identified as an extended warm season drought, not only in the Murray Basin but also along the East Coast and the Rangelands. Periods of severe long-term rainfall reductions highlight the spatial complexity of rainfall variability. There was abnormally low rainfall during the southeastern Australia drought over an extended period of up to 10 years (Monsoonal North, Murray Basin, Southern and Southwestern Flatlands). This reduction was clearly a warm season feature that was most severe along the East Coast and the Central Slopes. Sturt's Drought is another example of a spatially distinct localised warm

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season drought in South-Eastern Australia that was also expressed as a long cool season drought in the Rangelands. One of the strongest short-term drought episodes was the Black Thursday drought in which warm season rainfall was 60% below the long-term average and cool season rainfall was 30% below the long-term mean. These deficits are likely to have contributed to the severe bushfires in 1851.

4.3.4 Extreme years in a long-term context

Severe short-term reductions of rainfall leading to events like the Black Thursday bushfires make clear the devastating effects that single extreme seasons can have. Our seasonally resolved reconstruction provides for the first time the opportunity to assess not only extreme years, but to assess individual extreme seasons.

Existing annually resolved reconstructions are likely to exhibit a specific seasonal bias, which may dilute the impacts of bi-seasonal effects across the year. Seasonal windows of drought indices often exhibit an integrated signal from multiple months to possibly years (Keyantash and Dracup, 2002). The rainfall reconstructions presented in this study enable us to identify temporally finer-scale extreme seasons of above/below rainfall. We identified the driest and wettest seasons for our regions by selecting the 10 strongest events using the instrumental (1900-2014) and reconstruction (1600-2014) periods.

Extreme years identified during the instrumental period reveal regional dependencies and differentiated seasonal aspects of dry and wet years (Table 2). In the pre-instrumental period similar patterns of spatially widespread extreme conditions in multiple regions occur (e.g., extreme dry 1481, 1607, 1760, & 1817 (cool season), extreme wet 1759, 1826, 1871 & 1879 (cool season)). Conditions affecting multiple regions with similar magnitudes were rarer for wet than dry extremes. Warm season rainfall during the first half of the 18th century (1720, 1731, 1732, 1740, 1752) was wettest across multiple regions, while dry conditions of similar magnitude occurred most frequently during the latter half of the 18th century (1761, 1760, 1814) affecting the East Coast, Southern Slopes and the South-Western Flatlands.

The intensity of widespread extreme conditions such as 2010/2011 (wet) or 1982/1983 (dry) is much reduced during the pre-instrumental period. Based on our reconstructions pre-instrumental seasons with an amplitude comparable to the 2010 pluvial include 1759 (East Coast) or 1826 (Central Slopes) and were only extreme across a few regions. Seasonally explicit extremes highlight the value of the finer temporal resolution resolved by these reconstructions. In 1833, East Coast reconstructed rainfall shows extreme dry conditions during the cool season followed by extremely wet conditions in the following warm season.

4.6 Comparing our reconstruction with previously published

Here we compare our results with published studies based on palaeo-records and early documentary compilations. We begin by comparing our results to the first spatially resolved reconstruction of Australian and New Zealand summer drought variability, the ANZDA (Palmer et al., 2015). As there is significant overlap in proxy records used in this study (~60%) and in Palmer et al (2015), the two studies are not independent in their source data. Nevertheless, ANZDA is based on tree-ring

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Moved down [1]: The record breaking wet years 2010/2011 accompanied by the strong La Niña episode were extreme during the warm season across all regions. During that time the Murray Darling Basin had the largest rainfall anomalies since 1900 (CSIRO, 2012). In the much longer context of our rainfall reconstruction, 2010/2011 was one of the wettest warm seasons in the past several centuries, not only in Murray Basin but also in Monsoonal North, Rangelands, Southern Slopes, East Coast. Cook et al. (2016) found similar results based on the ANZDA reconstruction of spatial variability in the PDSI. The 1979-1983 period of dry conditions in eastern Australia and the 1983 warm season and 1984 cool season wet anomalies in the East Coast, Wet Tropics and Monsoonal North are also captured in the reconstructions. The consecutive 1927 (cool), 1928 (warm) and 1928 (cool) seasons experienced extremely dry conditions in the Central Slopes region. Interestingly, extreme cool and warm season wet conditions affected multiple regions, while extreme dry conditions appear to have occurred more often in single regions. This relationship persists into the pre-instrumental period. The known asymmetry of the different ENSO phases impacting Australian rainfall could explain those differences (Cai et al., 2012). While El Niño-induced rainfall reductions are not related to the event amplitude, the La Niña phase of ENSO produces more extreme pluvial events. This is consistent with observations that La Niña is more strongly teleconnected to rainfall, and hence extreme rainfall events (Cai et al., 2010; King et al., 2013) than El Niño events are to rainfall deficit.

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records and a single coral record (that is not seasonally resolved), whereas our reconstruction includes seasonally resolved corals, as well as speolethem and ice-core records. In addition, the ANZDA differs substantially in its temporal (DJF) and spatial resolution, since it is a point-by-point gridded reconstruction, mostly verified for Eastern Australia. The ANZDA also targets the PDSI, which is based not only on rainfall, but also temperature, and includes memory effects that account for soil moisture. The PDSI is therefore more likely to reflect agricultural droughts than meteorological droughts observed in rainfall. Figure 9 shows the correlations not accounting for memory effects between the warm season (DJF) PDSI reconstruction (ANZDA) with our cool and warm season rainfall reconstructions. Non-significant correlations during the cool season and highly significant warm season correlations, of up to 0.67 for the East Coast region, highlight agreement between our seasonal reconstruction and the summer season hydroclimatic features detected by the PDSI reconstruction. It also reiterates the highly seasonal nature of ANZDA and its bias (intentional) towards only warm season drought compared with our reconstructions. The strong temperature dependence of PDSI may explain some of the differences inland and why large parts of central Australia and all of Western Australia were not resolved by the ANZDA reconstruction.

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The study by Ashcroft et al. (2014) details early documentary records of fine temporal resolution across southeastern Australia that are entirely independent of the data used in this study. The temporal coverage of the documentary records, however, is often less than 30 years. Nevertheless, there are strong positive correlations between the documentary-based record and the rainfall reconstruction for both the warm and cool seasons over the period 1832-1859 (Fig. 9). There are positive correlations between these records and our rainfall reconstructions across large areas in southeastern Australia, especially the Murray Basin (cool season). Figure 9 also shows a comparison of our reconstructions with rainfall variability as recorded in 18th- 19th century (1788 – 1860) records from the populated coastal centres (Ashcroft et al., 2014; Fenby and Gergis, 2012). Years classified by Fenby and Gergis (2012) as dry or wet conditions are partially reflected in our Central Slopes reconstruction. The years 1790-93, 1810-13, and 1836-37 are consistently classified as dry years, whereas 1788, 1806 and 1830 coincide with years classified as wet. Consecutive years of dry conditions from 1820-28 appear to coincide, but single years such as 1801 and 1802 appear to be not in agreement with our reconstruction. This may be the result of more localised rainfall variability than is resolved by our regional Central Slopes reconstruction. Discrepancies between our reconstruction and documentary sources might also arise from the use of annual means, which might dilute a seasonal signal. Comparing annual means of our seasonal reconstructions (not shown) extreme years such as 1860 (East Coast) stand out and mostly agree with the wet and dry classified years found by Gergis and Ashcroft (2012) for South East Australia.

5 Discussion and Conclusions

In this study we used an extensive palaeo-climate proxy network derived from tree-rings, corals, ice cores, and speleothem records to reconstruct precipitation in the eight NRM regions across Australia. This is the first Australia-wide reconstruction of seasonal rainfall extending ~400 years into the past. The relationships between climate process indices were evaluated for the strength and stability of their relationship with precipitation in each NRM region for both the warm and cool seasons. We simultaneously assessed the strength and stability of relationships between individual proxy records and these same processes. This process-based approach enabled the reconstruction of precipitation based on teleconnections with major processes known to be related to Australian rainfall (Hendon et al., 2007; Risbey et al., 2009). The screening of predictors based on the strength and stability of their relationship with the climate indices constrains the inclusion of predictors during the instrumental period but relies still on a continuing stationarity assumption on multidecadal timescales. All reconstructions successfully verified over the 1749-1984 period, and many back to the early 16th century. A comparison with the ANZDA reconstruction showed a high-level of agreement with Eastern Australian drought conditions during the warm season. Independent high-resolution early documentary records by Ashcroft et al. 2014 compared well with the cool and warm season reconstructions. It should be pointed out that our seasonal reconstructions represent rainfall only. Droughts are a result of complex interactions of various atmospheric variables and interactions at different time scales. Important factors contributing to droughts are temperature, soil moisture and evaporation, which are not accounted for in this reconstruction. We also assessed extreme years of high and low rainfall with published documentary sources. A majority of years previously identified as having anomalously high or low rainfall events agree well with our seasonal reconstructions. Most of those comparisons are confined to southeastern Australia due to regional biases in documentary records. Nevertheless, these additional verification approaches highlight the quality of our seasonal reconstruction and its ability to represent past rainfall variability.

On decadal to multi-decadal time scales, substantial low-frequency variability is present across the regions and seasons. An investigation of recent trends revealed evidence for unusual tendencies towards wetter conditions in the north in the warm season and drier conditions in the south in the cool season. Northern regions (Monsoonal North, Wet Tropics) have experienced an increase over the last 30-50 years in rainfall, predominantly during the warm (wet) season (Nicholls, 2006; Taschetto and England, 2009) when the majority of rainfall occurs. The significance of this increase is difficult to determine due to high intrinsic variability in the tropical North. The extended baseline of our reconstruction helps to place these changes into a long-term context. In particular, after the 1970s the increase of warm season rainfall in the Monsoonal North (and the Rangelands) is highly unusual relative to past centuries. Possible mechanisms could be strengthening of the monsoon modulated by the ENSO conditions in the western Pacific (Fig. 2), intensification and shifts in deep convection related to the monsoon trough (Taschetto and England, 2009), and anthropogenic forcing enhancing rainfall and cloud formation (Cai et al., 2014). Possible enhancement of atmospheric pressure systems over the Indian Ocean in conjunction with a strengthening of SAM (Feng et al., 2013) is a further possibility. From the correlation analysis of possible drivers (Fig. 2) neither the IOD nor SAM are significantly correlated with rainfall in the northern regions, so this latter possibility seems unlikely.

The tendency towards drier conditions in southern Australia is less clear. Our analysis showed that the most recent decline in rainfall in the Southern Slopes is within the range of variability given by the reconstruction. The cool season decline in the south is often associated with the intensification of the subtropical ridge (Timbal and Drosdowsky, 2012; Timbal et al., 2006), changes in large-scale atmospheric circulation such as the Indian Ocean (Ummenhofer et al., 2011b), and the observed upward trend in SAM (Cai and Cowan, 2006). All of these processes are significantly linked to interannual rainfall variability in the south (Fig. 2), but are not particularly unusual in terms natural variability resolved by the reconstruction. Strong decadal to multidecadal variability can be observed across all of the regions that account for declines similar to the most recently observed trends. At least in terms of 30- to 50-year trend periods, the declining trends are within the range of intrinsic reconstructed variability. The declining trend of rainfall during the cool season is particularly strong in the Murray Basin. The most recent trends starting after 1950s and 1970s are not unprecedented, but are below the 25th percentile, pointing towards a drying tendency. Further work could specifically focus on the long-term declining trend for the cool season in South and Southwestern Australia (Fig. 6) observed since around 1910.

In order to assess the severity of droughts in a long-term context, reconstructions need to be consistent with the representation of droughts in the instrumental record. All three major droughts during the instrumental periods are well represented in terms of their spatial extent, intensity and duration considering the reduced spatial representation of regional averages (Fig. 7) (cf. (Verdon-Kidd and Kiem, 2009b). The three protracted droughts remain severe when considered in the ~400-year context provided by our reconstructions, especially in south and southeastern Australia. Although all three droughts have very distinct spatial footprints, the spatial extent and concurrent drought conditions across broad areas are quite unique compared to historical droughts. The Millennium drought stands out as an unprecedented drought in the Southern Slope region (Fig. 7). The World War II drought seems not to be as exceptional when considering the full reconstruction period back to 1600; only central and eastern regions were very much below average. The Federation drought, which was mostly prior to the observational period, is confirmed as one of the worst periods of suppressed rainfall in the Murray Basin and the Monsoonal North region. Compared to droughts during the longer period, these three major droughts affected large parts of Australia, whereas pre-instrumental drought episodes such as the Great Drought appeared to be much more regionally constrained.

The record breaking wet years 2010-2011 accompanied by the strong La Niña episode were extreme during the warm season across all regions. During that time the Murray Darling Basin had the largest rainfall anomalies since 1900 (CSIRO, 2012). In the much longer context of our rainfall reconstruction, 2010-2011 was one of the wettest warm seasons in the past several centuries, not only in Murray Basin but also in Monsoonal North, Rangelands, Southern Slopes, East Coast. Cook et al. (2016) found similar results based on the ANZDA reconstruction of spatial variability in the PDSI. The 1979-1983 period of dry conditions in eastern Australia and the 1983 warm season and 1984 cool season wet anomalies in the East Coast, Wet Tropics and Monsoonal North are also captured in the reconstructions. The consecutive 1927 (cool), 1928 (warm) and 1928

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(cool) seasons experienced extremely dry conditions in the Central Slopes region. Interestingly, extreme cool and warm season wet conditions affected multiple regions, while extreme dry conditions appear to have occurred more often in single regions. This relationship persists into the pre-instrumental period. The known asymmetry of the different ENSO phases impacting Australian rainfall could explain those differences (Cai et al., 2012). While El Niño-induced rainfall reductions are not related to the event amplitude, the La Niña phase of ENSO produces more extreme pluvial events. This is consistent with observations that La Niña is more strongly teleconnected to rainfall, and hence extreme rainfall events (Cai et al., 2010; King et al., 2013) than El Niño events are to rainfall deficit.

The spatial extent of various droughts and pluvial episodes may help to identify the specific drivers behind the individual events. For 20th Century droughts, the interaction of climate modes and anthropogenic warming may have played a significant role in the drought episodes (Cai et al., 2014). However, the longer historical perspective provided by our rainfall reconstructions could help to attribute those factors in further studies by considering individual climate modes and their interactions.

New insights about drought characteristics are derived from the comparison of instrumental and historical droughts of different duration. Independent palaeoclimate reconstructions could help to relate the rainfall variability back to the climatic drivers causing these diverse drought characteristics in terms their spatial and temporal characteristics and could provide important insights into the climate modes. Different contributing processes are difficult to examine with only a few events during the instrumental period. Droughts confined to a specific season can be distinct and classified by intensity, extent and duration. Again, the three major drought events during the instrumental period stand out in terms of their intensity and number of regions affected. The Millennium drought as a cool season feature and the Federation drought as a warm season feature clearly highlight the merits of a seasonally resolved reconstructions (Fig. 8). Another example is the Southeastern Australia drought, which had persistent dry conditions during the warm season for up to 10 years.

Natural variability and, in particular, the low-frequency contributions from decadal modes such as the IPO could contribute to those dry conditions in various ways. Additional realisations of multi-year droughts can help to understand physical mechanisms that lead to dry conditions, untangle dynamical interactions of various climatic modes, and lead to a better understanding of future drought risks. Inverse approaches and additional palaeoclimate reconstructions could help to deduce the climatic drivers causing these diverse drought characteristics and could provide important insights into the climate modes, their interactions, and influences on Australian droughts and pluvials. Our multi-century, bi-seasonal and spatially resolved reconstructions provide new opportunities to study the dynamics of meteorological droughts across the Australian continent. For example, do similar settings such as a positive IOD, a positive ENSO, and a positive IPO lead to similar impacts on Australian droughts? It is imperative that we answer questions like this due to Australia's significant

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vulnerability to prolonged drought episodes. Future work should consider further sub-division to resolve finer scale hydroclimatic patterns important for regional assessments. This could include a sub-division of large regions such as the Rangelands and regions of complex rainfall regimes like Tasmania as suggested by the NRM sub-clusters (CSIRO and Bureau of Meteorology, 2015).

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Table 1. Summary of climate drivers, regions and droughts used in this study. (a) Climate indices and references for computational information, (b) Natural Resource Management (NRM) regions of Australia mean, minimal and maximal seasonal contributions to annual rainfall totals (in %) and (c) Instrumental and historical droughts

(a) Climate Indices			**(b) NRM Regions**			**(c) Droughts**	
Climate Index	**Name**	**Ref**	**Region Abbrev.**	**Region name**	**Annual rainfall Cool (C)/Warm(W) Avg (Min/Max)**	**Drought name**	**Period**
SOI	Southern Oscillation Index	BOM	MN	Monsoonal North	C: 10% (1-25%) W: 90% (75-95%)	Millennium Drought	1997-2009
NCT	Niño Cold Tongue Index	(Ren and Jin, 2011)	WT	Wet Tropics	C: 18% (7-39%) W: 82% (61-93%)	World War II Drought	1935-1945
NWP	Niño Warm Pool Index	(Ren and Jin, 2011)	EC	East Coast	C: 33% (14-62%) W: 67% (38-86%)	Federation Drought	1895-1903
EMI	El Niño Modoki Index	(Ashok et al., 2007)	CS	Central Slopes	C: 37% (14-66%) W: 63% (34-86%)	SE Drought	1836-1845
BLK	Blocking Index	(Pook and Gibson, 1999)	MB	Murray Basin	C: 56% (35-77%) W: 44% (23-65%)	Goyder Line Drought	1861-1866
STRI	Subtropical Ridge Intensity	(Drosdowsky, 1993)	SSWF	Southern and Southwestern Flatlands	C: 72% (43-87%) W: 28%(13-57%)	MD Basin Drought	1797-1805
STRP	Subtropical ridge Position	(Drosdowsky, 1993)	SS	Southern Slopes	C: 56% (44-66%) W: 44%(34-56%)	Great Drought	1809-1814
DMI	Indian Ocean Dipole	(Saji et al., 1999)	R	Rangelands	C: 32% (9-55%) W: 68%(45-91%)	Sturt Drought	1809-1830
SAM	Southern Annual Mode	(Marshall, 2003)				Black Thursday	1849-1866
						Settlement Drought	1790-179

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Table 2. Extreme years. Summary of the ten driest and wettest seasons for each NRM region for different baselines. Different baselines refer to the instrumental period (Instru: 1900-2014) and the extended reconstruction period (Pre-Instru: 1200-2014). Years highlighted in bold are among the ten-highest/lowest values for the entire reconstruction and instrumental period and therefore referred as extreme. Note the reconstruction period starts for verified periods only and differs for regions and seasons.

Region	Extreme	Period	Warm Season	Cool Season
CS	Driest	Instru	**1902**, **1919**, **1930**, **1951**, **1941**, 1901, 1905, 1900, 1918, 1942	**1994**, 1982, 2002, 1941, 1959, 1932, 1972, 1940, 1929, 1902
		Pre-Instru	**1433**, **1868**, **1791**, **1391**, **1431**, 1833, 1542, 1695, 1386, 1692	**1896**, **1305**, **1607**, **1535**, **1623**, **1521**, **1569**, **1530**, **1380**, 1502
	Wettest	Instru	**2011**, **1970**, **1962**, **1971**, **1950**, **1983**, **1910**, **2010**, **1974**, 1973	**1998**, **1983**, **1920**, **1988**, **1990**, 1950, 1921, 1915, 1938, 1952
		Pre-Instru	**1644**, 1618, 1662, 1748, 1716, 1370, 1613, 1739, 1628, 1733	**1557**, **1878**, **1796**, **1513**, **1745**, 1212, 1206, 1764, 1405, 1432
EC	Driest	Instru	**1919**, 1942, 1905, 1945, 1936, 1901, 1937, 1902, 2006, 1992	**1946**, **1918**, **2004**, **1994**, 1951, 1960, 1968, 1965, 1982, 1991
		Pre-Instru	**1386**, **1383**, **1413**, **1807**, **1428**, **1542**, **1391**, **1499**, **1474**, 1385	**1800**, **1716**, **1681**, **1679**, **1871**, **1860**, 1760, 1714, 1680, 1758
	Wettest	Instru	**2010**, **1970**, **1974**, **1971**, **1975**, **1973**, 1960, 1962, 1910, 1955	**1983**, **1988**, **1989**, **1998**, **1931**, 1912, 1913, 1924, 1920, 1949
		Pre-Instru	**1752**, **1740**, **1732**, **1875**, 1627, 1731, 1602, 1753, 1743, 1742	**1728**, **1820**, **1726**, **1769**, **1879**, 1770, 1786, 1742, 1787, 1833
MB	Driest	Instru	**1902**, **1900**, 1905, 1901, 1931, 1918, 1925, 1932, 1963, 1951	**1982**, **1976**, **1994**, **1966**, **2006**, **1980**, 2002, 1925, 1936, 1914
		Pre-Instru	**1540**, **1691**, **1251**, **1695**, **1542**, **1485**, **1543**, **1394**, **1900**, 1899	**1778**, **1779**, **1811**, **1838**, 1480, 1817, 1885, 1481, 1607, 1780
	Wettest	Instru	**2010**, **1992**, **2011**, **1950**, 1973, 1971, 1955, 1983, 1970, 1956	**1915**, **1916**, 1955, 1973, 1956, 1970, 1974, 1968, 1975, 1917
		Pre-Instru	**1694**, **1668**, **1588**, **1751**, **1340**, **1750**, 1298, 1795, 1693, 1732	**1572**, **1516**, **1706**, **1495**, **1649**, **1532**, **1523**, **1575**, 1537, 1721
MN	Driest	Instru	**1951**, **1902**, **1905**, **1991**, 1935, 1919, 1989, 1965, 1918, 1953	**1926**, **1931**, **1930**, **1935**, **1932**, **1933**, 1994, 2002, 1964, 1934
		Pre-Instru	**1896**, **1761**, **1837**, **1838**, **1899**, **1814**, 1746, 1760, 1762, 1758	**1745**, **1818**, **1684**, **1783**, 1878, 1667, 1658, 1760, 1808, 1900
	Wettest	Instru	**2010**, **2000**, **1973**, **1999**, **2008**, **1950**, **1976**, **1998**, **1975**, **2003**	**2010**, **2006**, **1955**, **1910**, **1959**, **2000**, **1950**, **1956**, **1983**, 1974
		Pre-Instru	1893, 1720, 1887, 1886, 1731, 1879, 1870, 1802, 1722, 1805	**1694**, 1882, 1881, 1887, 1826, 1879, 1669, 1739, 1801, 1690
R	Driest	Instru	**1965**, 1964, 1905, 2004, 1951, 1963, 1912, 1925, 1902, 1953	**1925**, **1940**, **1976**, **1902**, **1994**, **2002**, 1946, 1926, 1941, 1944
		Pre-Instru	**1745**, **1746**, **1607**, **1872**, **1611**, **1696**, **1683**, **1698**, **1760**, 1868	**1891**, **1832**, **1855**, **1812**, 1838, 1817, 1849, 1888, 1868, 1862
	Wettest	Instru	**2010**, **1999**, **2000**, **2011**, **1979**, **1980**, **1973**, **1978**, **1976**, **1975**	**1998**, **2010**, **1974**, **1970**, **1978**, **1968**, **1973**, 1992, 1933, 1904
		Pre-Instru	1664, 1673, 1886, 1855, 1720, 1690, 1735, 1672, 1663, 1633	**1879**, **1825**, **1826**, 1819, 1829, 1870, 1881, 1880, 1861, 1894
SS	Driest	Instru	**1919**, **1963**, **2006**, 1997, 1913, 2002, 2012, 1982, 1977, 1967	**1940**, **1902**, **1982**, **1999**, **1966**, 2008, 1937, 1977, 1967, 1987
		Pre-Instru	**1439**, **1381**, **1437**, **1799**, **1438**, **1744**, **1868**, 1818, 1413, 1433	**1855**, **1865**, **1888**, **1887**, **1817**, 1840, 1799, 1869, 1833, 1784
	Wettest	Instru	**2010**, **1910**, **1955**, **1974**, **1950**, 1930, 1992, 1948, 1956, 1988	**1961**, **1960**, **1974**, **1958**, **1975**, **1962**, **1973**, 1942, 1956, 1953
		Pre-Instru	**1890**, **1731**, **1398**, **1372**, **1894**, 1649, 1892, 1740, 1730, 1887	**1789**, **1872**, **1848**, 1774, 1871, 1759, 1810, 1750, 1859, 1843
SSWF	Driest	Instru	1951, 1975, 1905, 1965, 1930, 1990, 1963, 2004, 1949, 1900	**1957**, **2006**, **1914**, **1976**, **1940**, 1994, 1982, 2010, 2002, 1911
		Pre-Instru	**1814**, **1445**, **1610**, **1559**, **1536**, **1449**, **1223**, **1255**, **1247**, **1297**	**1514**, **1376**, **1481**, **1492**, **1488**, 1550, 1494, 1459, 1555, 1509
	Wettest	Instru	**1999**, **1914**, **1916**, **1933**, **1938**, **2005**, **2011**, 1959, 1992, 1942	1931, 1915, 1917, 1909, 1907, 1927, 1908, 1910, 1942, 1920
		Pre-Instru	**1417**, **1565**, **1588**, 1340, 1427, 1586, 1245, 1649, 1218, 1239	**1871**, **1603**, **1370**, **1470**, **1367**, **1605**, **1612**, **1759**, **1368**, **1808**
WT	Driest	Instru	**1982**, **1905**, 1941, 1925, 1965, 1902, 1904, 1968, 1991, 1946	1967, 1953, 1965, 1966, 1968, 1915, 2008, 1923, 1991, 1997
		Pre-Instru	**1314**, **1671**, **1251**, **1504**, **1313**, **1317**, **1761**, **1335**, 1305, 1433	**1607**, **1251**, **1495**, **1391**, **1540**, **1584**, **1608**, **1536**, **1284**, **1223**
	Wettest	Instru	**2010**, **1975**, **1973**, **1974**, **1998**, 2000, 1976, 1971, 1910, 1917	**2006**, **1989**, **1990**, 1976, 1983, 1981, 1956, 1945, 1971, 1972
		Pre-Instru	**1469**, **1752**, **1886**, **1467**, **1678**, 1242, 1425, 1241, 1874, 1471	**1245**, **1231**, **1212**, **1210**, **1881**, **1661**, **1340**, 1413, 1228, 1209

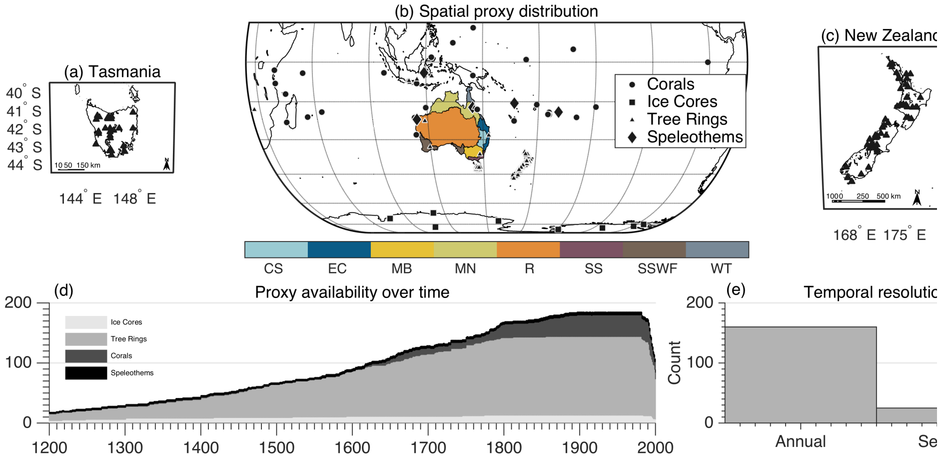

Figure 1. Overview of Southern Hemisphere multi-proxy network. a) Spatial distribution of tree-ring sites in Tasmania b) Spatial distribution of 202 individual proxy records by archive type; National Resource Management (NRM) clusters shown on Australian continent corresponding to abbreviations given in Table 1 a. c) Spatial distribution of tree-ring sites in New Zealand d) Record availability as a function of archive and time period covered, e) Temporal resolution of the palaeoclimate records

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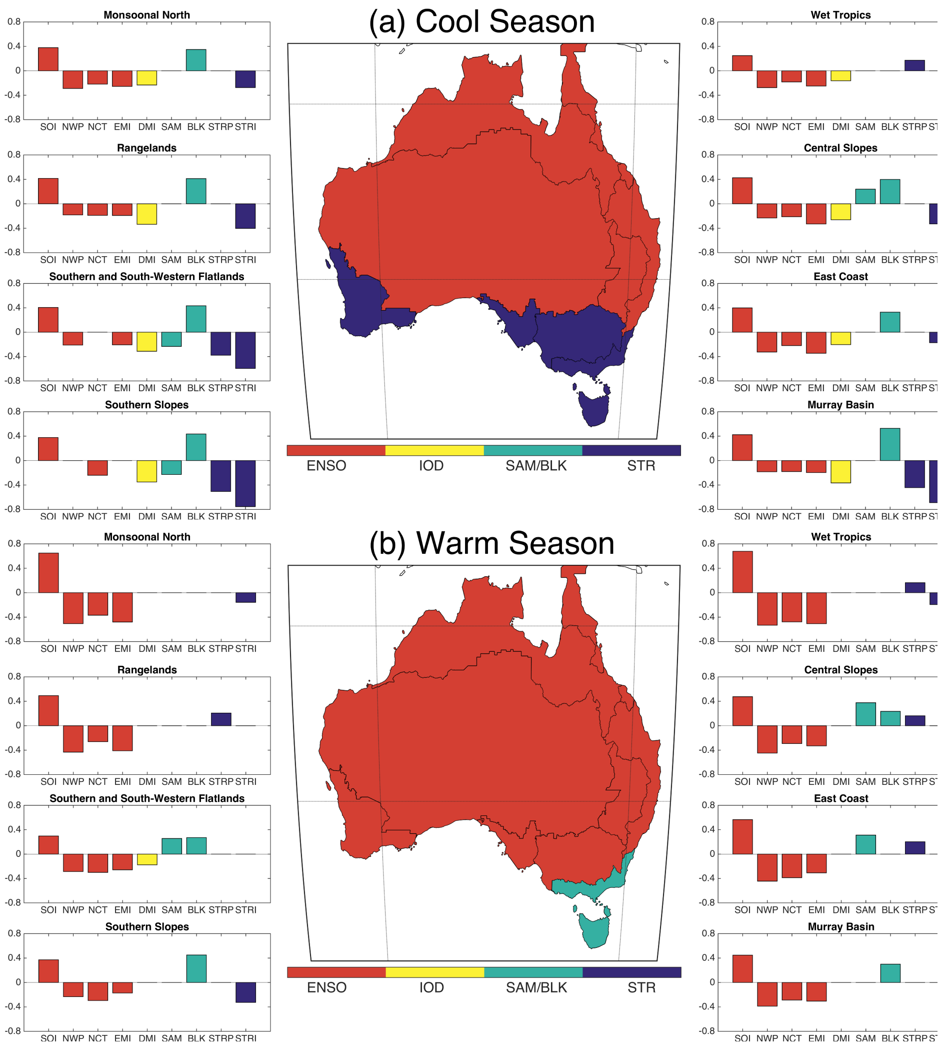

(a) Cool Season
(b) Warm Season
Monsoonal North
Rangelands
Southern and South-Western Flatlands
Southern Slopes
Wet Tropics
Central Slopes
East Coast
Murray Basin
ENSO
IOD
SAM/BLK
STR
SOI NWP NCT EMI DMI SAM BLK STRP STRI

Figure 2. NRM regions and their dominant climate influences on cool and warm season rainfall. Centre maps show the climate driver with the highest correlation to seasonal precipitation according to the NRM regions. The drivers are summarised into four major categories: ENSO, IOD, SAM/BLK and STR (See Table 1a)). Individual correlations between regional rainfall and each climate driver index are given in surrounding bar plots. Only significant correlations exceeding the 10% significance level are shown.

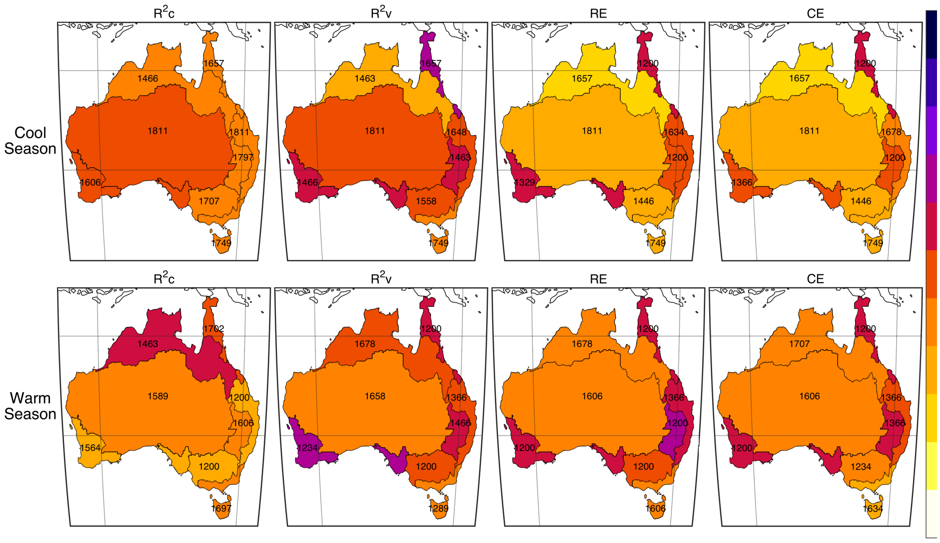


Figure 3. Maps of calibration and verification statistics for the NRM regions. Columns from left to right are: Variance explained in the calibration period (R^2c), Variance explained in the verification period (R^2v), Reduction of Error (RE) and Coefficient of Efficiency (CE) statistics for both the cool season (top row) and the warm season (bottom row). Statistics shown apply to the most replicated nest of the reconstruction. Numbers shown in each region indicate, for explained variance, the year in which R^2c and R^2v reduce to half of their maximum value, respectively; and for RE and CE, the year in which RE and CE remain positive, allowing for brief periods of negative skill of duration less than 5 years.

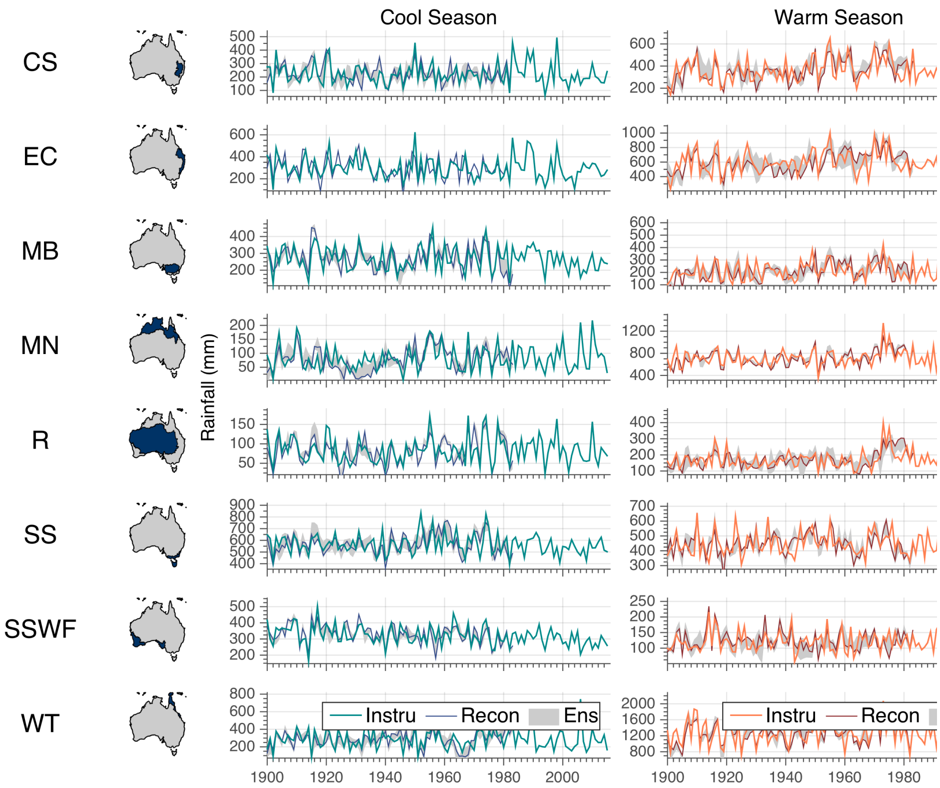
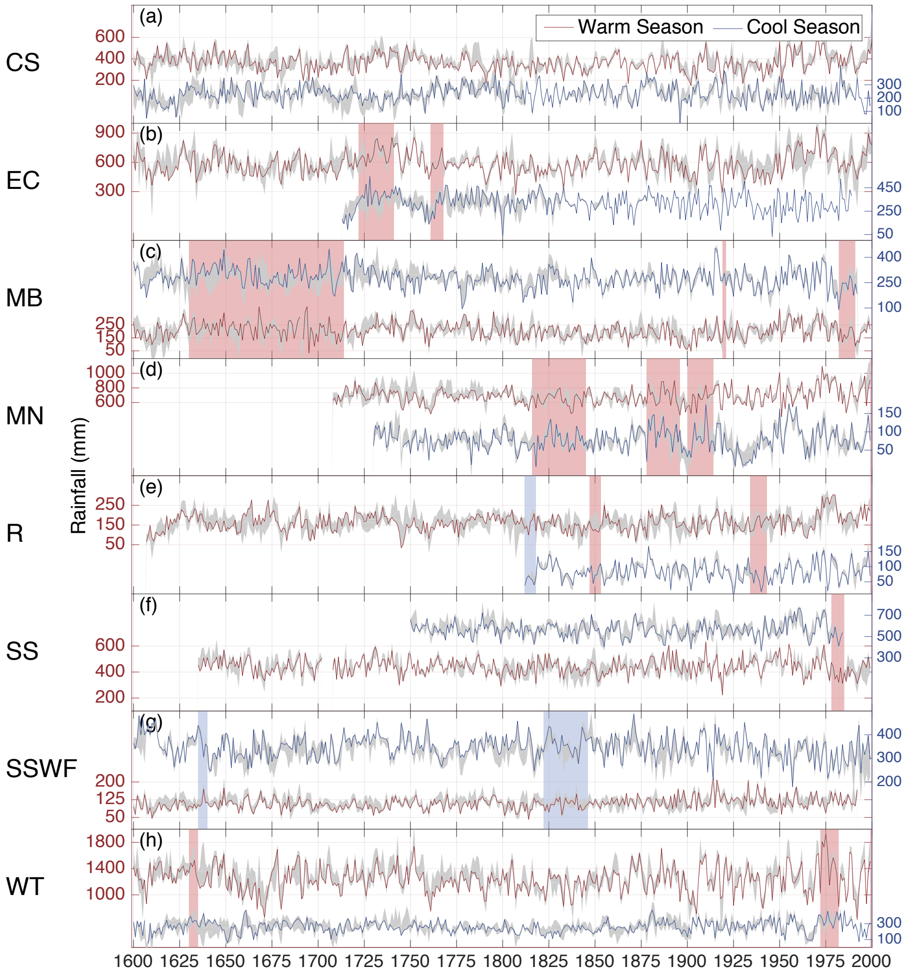


Figure 4. Australian regional rainfall reconstructions during the instrumental period (1900-2015). Reconstructed cool (left) and warm (right) season rainfall is compared with the instrumental. Shaded in grey are uncertainty estimates based on the ensemble spread.



Warm Season
Cool Season
CS
EC
MB
MN
SS
SSWF
WT
R
Rainfall (mm)
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
1600 1625 1650 1675 1700 1725 1750 1775 1800 1825 1850 1875 1900 1925 1950 1975 2000

Figure 5. Australian regional rainfall reconstructions in cool and warm seasons. Regional reconstructions for warm (red line) and cool season rainfall (blue line) from 1600- 1984, extended with instrumental data from 1985-2015. Note, multiple axes (warm season rainfall according to left axis, cool season refers to right axis). Shaded in grey are uncertainty estimates based on the ensemble spread. Red and blue shaded periods indicate in phase and out-phase relationships between the seasons based on windowed correlations (30-yrs)> 0.5.

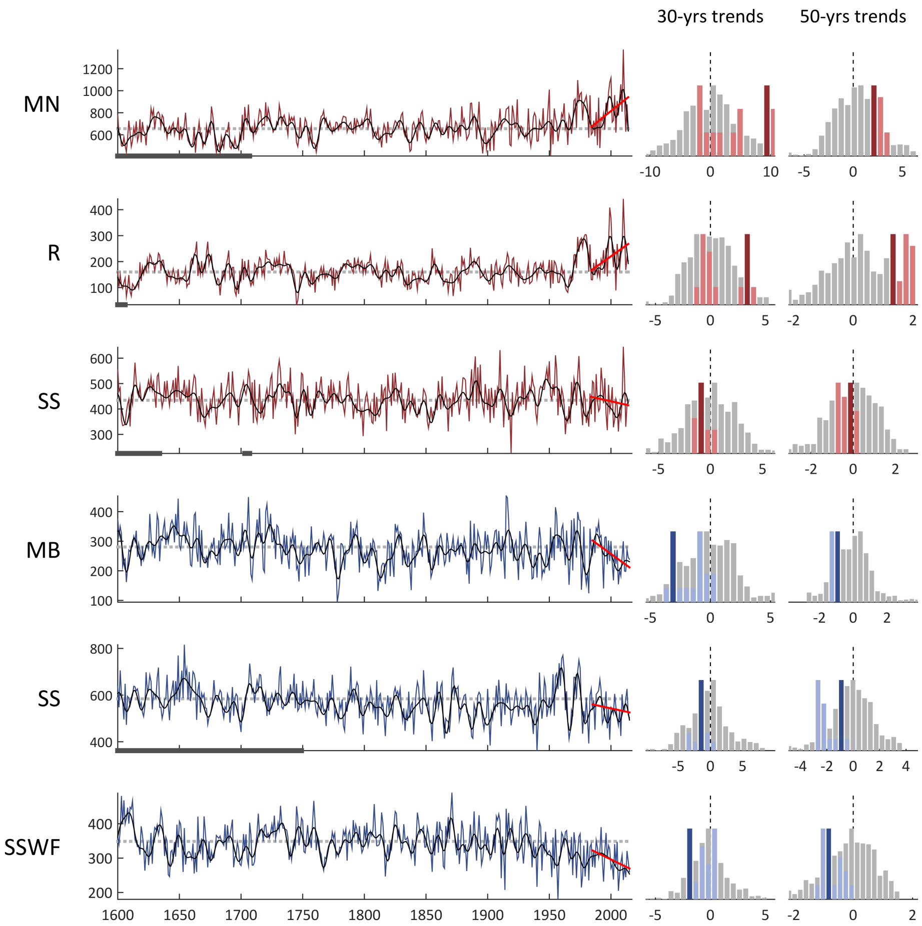


Figure 6. Contextualising recent observed trends in regional Australian rainfall. Left panels show regional rainfall reconstructions since 1600 for the warm (red) and cool season (blue) with the 10-yr low pass Chebyshev filtered series shown as a black line. Grey bars along the x-axis denote non-verified

periods for each reconstruction. Right panels show histograms of 30-yr and 50-yr regional rainfall trends (mm/yr). Grey shaded bars indicate the full range of the trends prior to 1970 (for 30-year periods) and 1950 for 50-year periods. Light red / blue colouring highlights the trends since 1970 (for 30-year periods) or 1950 for 50-year periods. The dark coloured bars indicate the trend in the most recent period. Bar heights are normalised by the maximum occurrence for each region.

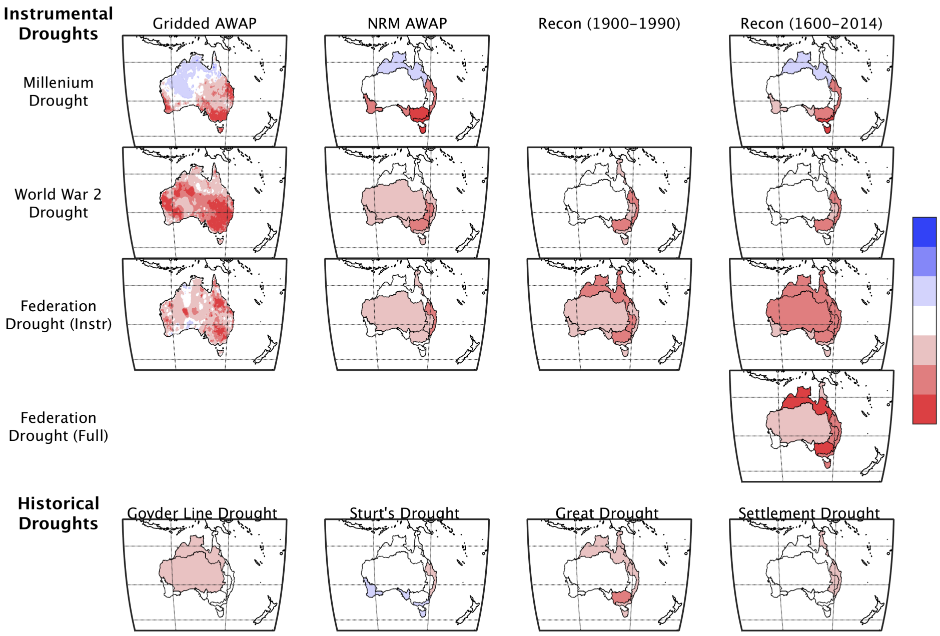


Figure 7. Annual deciles for major droughts. Plots for a) Significant drought periods (according to Table 1c) during the instrumental period. Rankings of drought intensity are shown for three major instrumental period droughts, Column 1: AWAP gridded rainfall (1900-2014), column 2: NRM clusters

(1900-2014), column 3: Regional reconstructions during instrumental period (1900-1990), column 4: Regional reconstructions during a four-century period (1600-2014). b) Rankings of major drought periods during the reconstruction period (1600-2014).

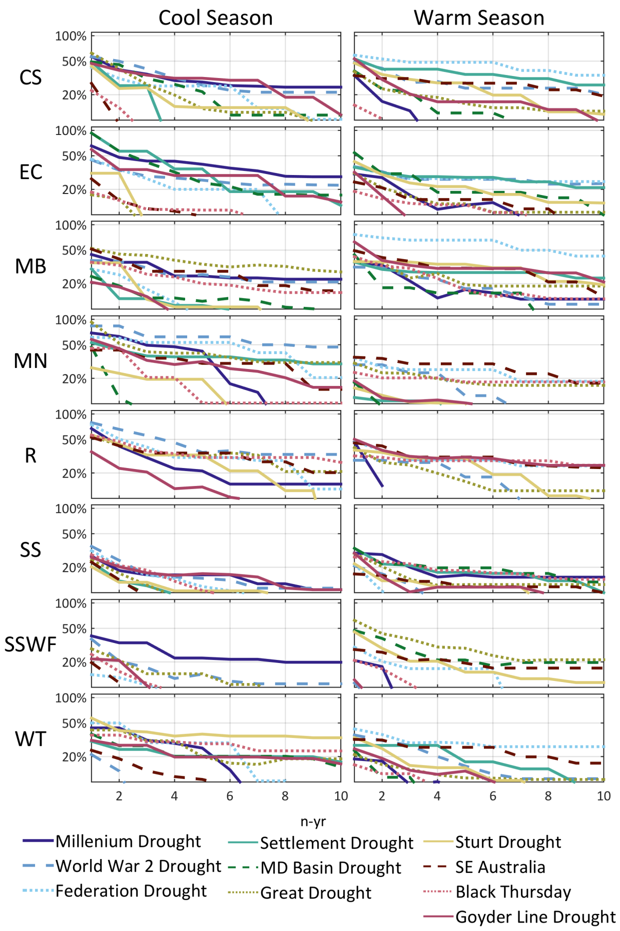


Figure 8. Rainfall drought depth duration percentages across the regions. The percentage reduction below the long-term average of the driest years of variable duration (1-10 years) within the selected drought periods, for the cool season (left) and warm season (right).

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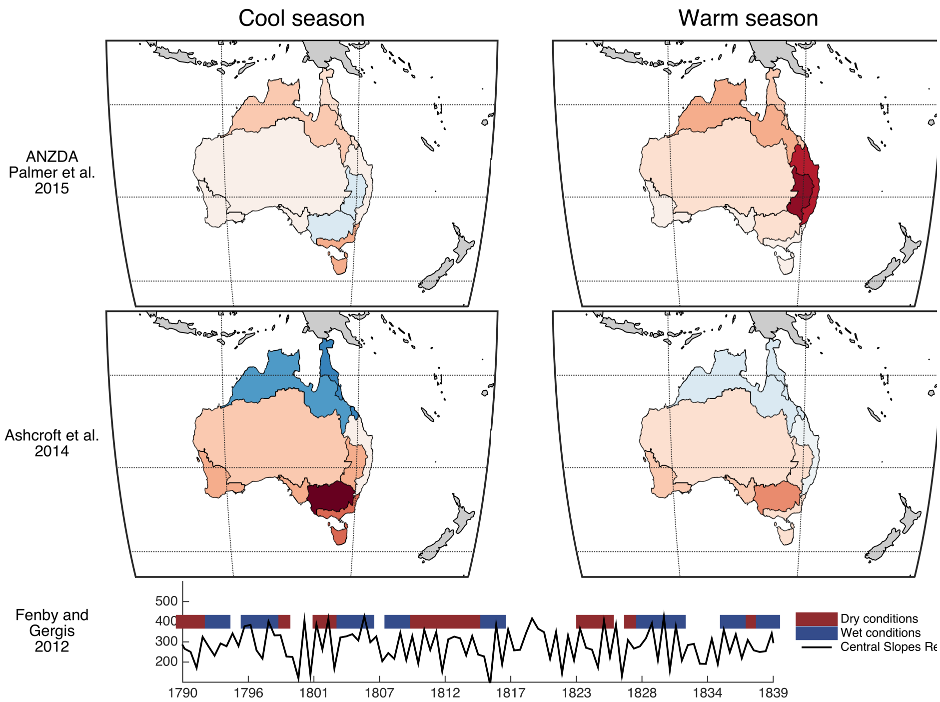

Figure 9. Comparison with published studies. Spatial correlation plot of regional NRM rainfall reconstruction and published studies on drought and rainfall. Spatial maps show region-wise correlation with the summer Australia New Zealand drought atlas (ANZDA) prior to instrumental period (1600-1899) (Palmer et al., 2015), season-wise correlation with high-quality observational data from southeast Australia (Ashcroft et al., 2014) from 1832-1859 and a quantitative/visual comparison with pre-instrumental documentary sources compiled by (Fenby and Gergis, 2012) for southeast Australia (Central Slopes reconstruction from this study).

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SE Drought

Settlement Drought

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1836-1845

1790-1793