



Broadening the Spatial Applicability of Paleoclimate Information—A Case Study for the Murray–Darling Basin, Australia

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ABSTRACT

Recent advances in the collection and analysis of paleoclimate data have provided significant insights into preinstrumental environmental events and processes, enabling a greater understanding of long-term environmental change and associated hydroclimatic risks. Unfortunately, it is often the case that there is a dearth of readily available paleoclimate data from regions where such insights and long-term data are most needed. The Murray–Darling basin (MDB), known as Australia’s “food bowl,” is an example of such a region where currently there are very limited in situ paleoclimate data available. While previous studies have utilized paleoclimate proxy records of large-scale climate mechanisms to infer preinstrumental MDB hydroclimatic variability, there is a lack of studies that utilize Australian terrestrial proxy records to garner similar information. Given the immediate need for improved understanding of MDB hydroclimatic variability, this paper identifies key locations in Australia where existing and as yet unrealized paleoclimate records will be most useful in reconstructing such information. To identify these key locations, rainfall relationships between MDB and non-MDB locations were explored through correlations and principal component analysis. An objective analysis using optimal interpolation was then used to pinpoint the most strategic locations to further develop proxy records and gain insights into the benefits of obtaining this additional information. The findings reveal that there is potential for the future assembly of high-resolution paleoclimate records in Australia capable of informing MDB rainfall variability, in particular southeast Australia and central-northern Australia. This study highlights the need for further investment in the development of these potential proxy sources to subsequently enable improved assessments of long-term hydroclimatic risks.

1. Introduction

A common limitation in hydroclimatic risk assessment is the lack of suitably long records with which to assess decadal to multidecadal variability (Kiem and Franks 2004; Rutherford et al. 2005; Cook et al. 2006; Verdon-Kidd and Kiem 2010; Gallant et al. 2012). For example, in Australia and much of the Southern Hemisphere, reliable rainfall and streamflow records are limited to the last approximately 90 years at best (with records even shorter for most regions, particularly for streamflow).

This is clearly insufficient to capture variability occurring on a multidecadal time scale or longer. Recent advances in the collection and analysis of paleoclimate information have, however, provided insights into historical environmental events and processes prior to the availability of instrumental records (Bradley and Jones 1995; Cronin 2010). This information has enabled a greater understanding of long-term environmental variability and associated hydroclimatic risks (Mann et al. 1998; Evans et al. 2002; Verdon and Franks 2006; Mann et al. 2009; Gallant and Gergis 2011).

Paleoclimate studies have utilized records collected from sources such as documentary evidence (e.g., Bradley and Jones 1995; Rodrigo et al. 1999; Wang et al. 2001; Gale et al. 2004), corals (e.g., Druffel and Griffin 1999;

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Charles et al. 2003; Lough 2007; Linsley et al. 2008; Gong et al. 2009), ice cores (e.g., Souney et al. 2002; Oerter et al. 2004; Schneider et al. 2006; van Ommen and Morgan 2010), tree rings (e.g., Fritts 1976; Cook et al. 1999; D'Arrigo et al. 2001; Cullen and Grierson 2009), speleothems (cave deposits such as stalagmites, stalactites, and flowstones; e.g., Frisia et al. 2003; Treble et al. 2003; McDonald et al. 2004; Griffiths et al. 2009; Quigley et al. 2010), and freshwater and marine sediments (e.g., Mooney 1997; Overpeck et al. 1997; Barr 2010). It is important to consider, however, that paleoclimate proxies all contain inherent biases and, consequently, climatic interpretations and reconstructions are an extrapolation of the known relationship between the proxy and variable of interest.

Reconstructions of past climate variability have utilized numerous statistical techniques, each with a varying ability to resolve different aspects of the magnitude and frequencies of the climate signal (Mann et al. 2007; Christiansen et al. 2009; Wilson et al. 2010). Despite the intrinsic noise and associated error, paleoclimate data can serve as proxy records of hydroclimatic variables such as rainfall and streamflow, as well as large-scale ocean-atmospheric processes including El Niño-Southern Oscillation (ENSO), the interdecadal Pacific Oscillation (IPO), the Indian Ocean dipole (IOD), and the southern annular mode (SAM).

While significant advances have been made in the development of proxies for large-scale ocean-atmospheric processes and local hydroclimatology, proxy hydroclimatic records are still scarce in some areas where long-term rainfall and streamflow reconstructions are needed. The Murray-Darling basin (MDB) in Australia is one such region where high-resolution paleoclimate proxies that capture continuous records of recent climate variability currently only exist on or beyond the basin's margin. Paleoclimate proxies related to MDB hydroclimatic variability would enable improved estimations and understanding of hydroclimatic risk and variability, which is critical given the region's reputation as Australia's "food bowl." Presently, efforts toward a greater understanding of the hydroclimatic variability of the region are restricted by the relatively short records of available observed instrumental data. Given the immediate need for such records in the MDB, it follows that currently available paleoclimate records, critical to the reconstruction of MDB hydroclimatology, should be identified and utilized in order to garner this information (Lough 2007; Verdon and Franks 2007; Gallant and Gergis 2011; Kiem and Verdon-Kidd 2011; Gallant et al. 2012). The work presented in this paper therefore aims to identify regions in Australia where existing or future developments of paleoclimate proxies

will be of most use in informing MDB hydroclimatic variability.

Thus far, five attempts have been made to develop paleoclimate-informed, high-resolution reconstructions of MDB rainfall or streamflow variability. Verdon and Franks (2007) used reconstructions of the Pacific decadal oscillation (PDO; Mantua et al. 1997), based on a network of tree-ring chronologies, fossil coral records, and ice-core records, to infer rainfall and streamflow variability in the Lachlan River Valley located in the central east of the MDB. McGowan et al. (2009) also utilized a PDO proxy, based on a 530-yr flood and drought record in eastern China, to reconstruct the headwater inflows into the Murray River, located in the southeastern corner of the MDB. The hydroclimate reconstructions by Verdon and Franks (2007) and McGowan et al. (2009) are both based on the relationship between a remote large-scale climate driver, the PDO, and its influence on MDB hydroclimatic variability. In contrast, Gallant and Gergis (2011) reconstructed Murray River flows using a network of nine annually resolved tree-ring and coral paleoclimate proxies from the Australasian region (with all proxy records located outside the MDB). A similar network of paleoclimate proxies with an additional ice-core record from Law Dome, Antarctica, was used by Gergis et al. (2012) to reconstruct rainfall over the southeast Australian region, which approximately includes the lower third of the MDB. In addition to these studies, Vance et al. (2013) used the ice-core record at Law Dome and related summer sea-salt deposition in the ice core with ENSO and rainfall from four stations in eastern Australia, three of which are located in the northern MDB. Although no time series reconstruction was presented, Vance et al. (2013) used the results to assess recent rainfall variability in the context of the previous millennium.

The hydroclimatology of the MDB is highly variable, both spatially and temporally (e.g., Wright 1997; CSIRO 2008; Gallant et al. 2012), primarily as a result of differences in the relative importance of remote large-scale drivers of rainfall (ENSO, IOD, SAM, IPO/PDO, etc.), as summarized in Gallant et al. (2012) and references therein. It is therefore probable that a whole-basin hydroclimate reconstruction will not be particularly useful (in terms of informing hydroclimatic risk assessments for different regions in the MDB). Similarly, individual region-specific reconstructions cannot provide the degree of spatial information required to inform hydroclimatic risk across the MDB. Hence, there is a need for a network of hydroclimate reconstructions in the MDB to be developed.

The aim of this paper is to identify regions where high-resolution paleoclimate information can be utilized to

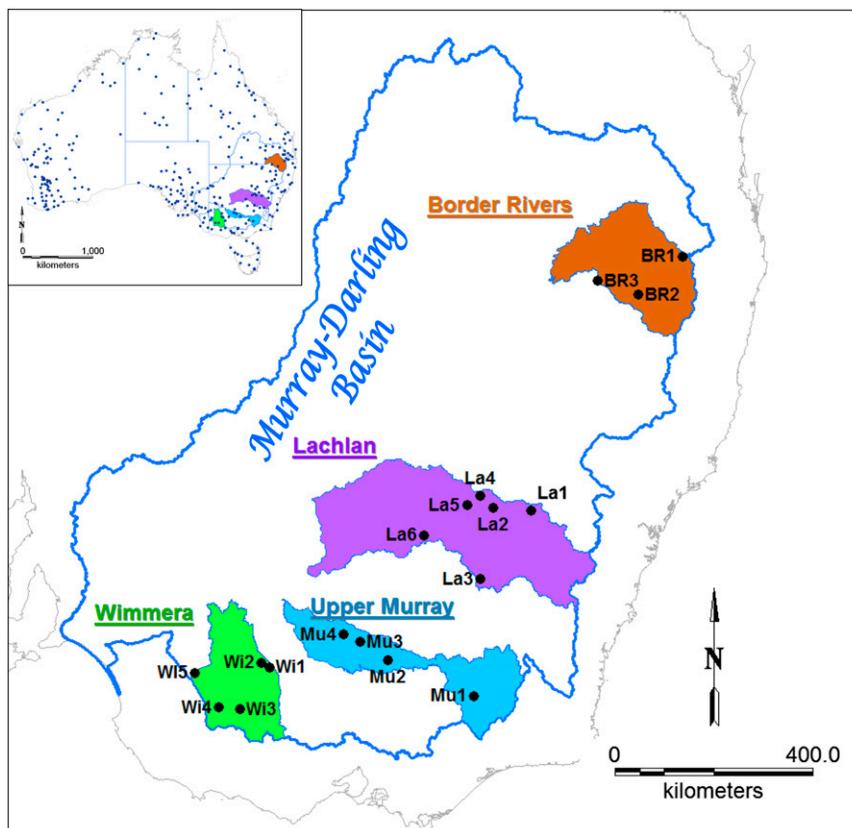


FIG. 1. The Murray–Darling basin, selected subcatchments, and high-quality stations within these subcatchments (see Table 1 for reference numbers) and inset is the Australian high-quality rainfall stations.

inform past changes in MDB rainfall on a regional basis, thereby optimizing the spatial applicability of the existing paleoclimate data. Through the identification of these regions, the findings of this study will also help to direct future paleoclimate investigations to locations where the assembly of paleoclimate records will be of greatest value in understanding long-term MDB hydroclimatology. This will ultimately aid in the development of regionally specific, basinwide hydroclimatic reconstructions for the MDB, thereby improving the robustness of flood and drought risk assessment for the region.

2. Data

a. Rainfall data

Two sets of rainfall data were used in the analyses, both spanning the period from July 1910 to June 2009. The first rainfall dataset, the Australia-wide monthly gauged rainfall data, has been quality tested for length, completeness, and heterogeneities (Lavery et al. 1997) and is referred to as “high quality” data as it is sourced from Australia’s high-quality climate change datasets

(BoM 2011). It has been updated since the publication of Lavery et al. (1997) and contains 307 composited rainfall stations. Of these, 79 are located within the MDB catchment. The second rainfall dataset is the monthly Australian Water Availability Project (AWAP) gridded rainfall dataset, produced through a joint effort by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Marine and Atmospheric Research, the Bureau of Meteorology (BoM), and the Bureau of Rural Science (Jones et al. 2009; Raupach et al. 2009). AWAP gridded rainfall data are interpolated from the BoM’s gauged network of approximately 7500 gauges (both open and closed gauges and including high-quality and non-high-quality data) and provided on 681×841 grids with a cell size of $0.05^\circ \times 0.05^\circ$ ($\sim 5 \text{ km} \times 5 \text{ km}$).

As mentioned, both gauged rainfall and AWAP gridded rainfall data were used in this study. This was necessary because gauged data are sparse across many areas of Australia (see Fig. 1 inset) and hence the use of only gauged rainfall would potentially ignore some locations that could yield paleoclimate proxies able to inform MDB rainfall variability. Gridded data have obvious

TABLE 1. Record lengths and locations of high-quality rainfall stations in the MDB case study subcatchments.

| | Station name (BoM station no., reference abbreviation) | Lat (°S) | Lon (°E) | Elev (m) | Period of record |
|---------------|---|----------|----------|----------|---------------------|
| Border Rivers | Passchendaele (041079, BR1) | 28.54 | 151.84 | 914 | 1910–2008 |
| | Wallangra (054036, BR2) | 29.24 | 150.89 | 440 | 1883–2009 |
| | Croppa Creek (053018, BR3) | 28.99 | 150.02 | 222 | 1879–2009 |
| Lachlan | Manildra (065022, La1) | 33.16 | 148.59 | 530 | 1888–2009 |
| | Bogan Gate Post Office (050004, La2) | 33.11 | 147.80 | 240 | 1911–2009 |
| | Temora Agricultural Research Station (073038, La3) | 34.41 | 147.52 | 270 | 1907–2009 |
| | Trundle (050028, La4) | 32.90 | 147.52 | 264 | 1883–2009 |
| | Condoblin Agricultural and Advisory Research Station (050052, La5) | 33.07 | 147.23 | 195 | 1880–2009 |
| Upper Murray | Naradhan (075050, La6) | 33.61 | 146.32 | 192 | 1910–2009 |
| | Mitta Mitta Forestry (082068, Mu1) | 36.53 | 147.37 | 320 | 1909–2009 |
| | Yarroweyah (080065, Mu2) | 35.88 | 145.55 | 115 | 1893–2009 |
| | Deniliquin P. O (074128, Mu3) | 35.55 | 144.95 | 93 | 1870–2009 |
| Wimmera | Wakool (075012, Mu4) | 35.45 | 144.60 | 84 | 1896–2009 |
| | Narraport (077030, Wi1) | 36.01 | 143.03 | 100 | 1886–2009 |
| | Birchip (077008, Wi2) | 35.93 | 142.85 | 100 | 1910–2009 |
| | Drung Drung (079010, Wi3) | 36.78 | 142.40 | 146 | 1905–2009 |
| | Natimuk (079036, Wi4) | 36.74 | 141.94 | 122 | 1906–2009 |
| | Yanac North (078043, Wi5) | 36.11 | 141.42 | 130 | 1897–2009 |

advantages of temporal and spatial completeness because of the interpolation processes used. However, numerous studies (e.g., Tozer et al. 2012) have demonstrated the necessity of using gauged data to verify the results obtained using gridded data (which is essentially modeled data) and to ensure that relationships observed when using gridded data are not simply a result of the interpolation processes used.

All analyses were conducted at an annual resolution as this is currently the resolution most paleoclimate archives are available at (although it should be noted that there are emerging archives at seasonal resolutions). Both sets of rainfall data were aggregated for the typical Australian water year that spans from 1 July to 30 June (BoM 2012).

b. Case study catchments

The Border Rivers, Lachlan, upper Murray, and Wimmera catchments (Fig. 1) were chosen as case study catchments of the MDB on which to develop our rainfall relationships used to locate useful potential/existing paleoclimate data. These catchments represent the northern, central, southeast, and southern MDB regions respectively. Details of the stations located in the case study MDB catchments are shown in Table 1. Although it is highly unlikely that these subcatchments are climatologically independent (i.e., rainfall variability is not confined to these subcatchment boundaries), the separation into hydrological subcatchments was deliberate. This was done to enable the method developed here to produce inputs suitable for hydrological and

environmental impact modeling, which is required at the subcatchment scale.

The Border Rivers catchment (northern MDB) is a summer-dominated rainfall region subjected to strong ENSO influences (CSIRO 2008; Gallant et al. 2012). The central and southeastern MDB regions are represented by the Lachlan and upper Murray catchments respectively. The Lachlan catchment receives similar rainfall in both summer and winter whereas the upper Murray catchment is dominated by winter rainfall. The climate in both catchments ranges from temperate in the east to arid in the west (Peel et al. 2007). Both are seasonally influenced to varying degrees by large-scale climate drivers such as ENSO, IOD, and SAM (Verdon and Franks 2005; Meneghini et al. 2007; Risbey et al. 2009). The Wimmera catchment was chosen to represent the southern MDB (winter-dominated rainfall regime), where the climate is primarily influenced by SAM processes originating from the Southern Ocean (Pook et al. 2006; Meneghini et al. 2007) as well as IOD effects in winter and spring (Ashok et al. 2003; Verdon and Franks 2005; Risbey et al. 2009).

3. Methods

a. Assessing catchment homogeneity

The homogeneity of rainfall within the selected MDB subcatchments was investigated to determine whether remote paleoclimate records (i.e., those obtained from sites situated beyond the basin's margin) may be used to reconstruct rainfall at a subcatchment scale, or whether

location-specific reconstruction methods, based on relationships with remote paleoclimate records, would be required within the subcatchment (attributable to a lack of subcatchment homogeneity). Subcatchment homogeneity was tested using two approaches:

- 1) analyzing the relationships between high-quality rainfall locations within a subcatchment, and
- 2) assessing the similarities and differences between how rainfall in the selected subcatchments relate to rainfall outside the MDB.

The first approach is investigated by calculating correlations between all rainfall stations, at an annual time scale, within each MDB subcatchment. The second approach explored the relationship between rainfall in each of the selected subcatchments and the main modes of rainfall variability outside the MDB through a combination of principal component analysis (PCA) (Jolliffe 2002) and correlations.

PCA was used to transform the rainfall data into a set of uncorrelated principal components (PCs) with each PC being a linear combination of all the rainfall outside the MDB. Lower-order PCs contain most of the variance in the original variables, likely to represent coherent large-scale physical climatic signals, while higher-order PCs mostly contain noise. Therefore, only the lower-order PCs were retained in the analysis. A number of heuristic methods [Kaiser's rule, Jolliffe's modified Kaiser rule, broken stick model, scree graph, log-eigenvalue (LEV) plot, and North's rule of thumb (Jolliffe 2002; Cangelosi and Goriely 2007)] were tested for determining the number of PCs to retain. The use of a stringent PC retention method would result in a smaller number of PCs being retained. To enable higher-order PCs to be investigated for possible connections with MDB rainfall, a conservative approach (i.e., retaining more PCs) using the LEV plot was employed. The retained PCs were then related to rainfall in the selected subcatchments through correlations. If consistent correlations were uniformly found across the subcatchment then the subcatchment was considered to be homogeneous.

The correlation matrix (as opposed to the covariance matrix) was chosen for this analysis for two reasons. First, performing a PCA on the correlation matrix will enable PCA results from both the gridded and gauged datasets to be more comparable given the difference in the number and spatial distribution of variables in each dataset. The second, justification for using a correlation matrix is that the variables are first standardized. Consequently, regions in Australia with comparatively high rainfall variability, such as regions in northeast Australia driven by tropical systems, will not dominate the analysis.

b. Assessing relationships between rainfall stations inside and outside the MDB

Correlations between the representative rainfall stations (or the grid corresponding to the station location) in each of the four case study subcatchments and the gauged and gridded Australia-wide rainfall networks outside the MDB were calculated. The correlation pattern was then interrogated to ascertain the probable origin of the rainfall (Pacific, Indian Ocean, Southern Ocean, etc.) to provide a physical interpretation of the statistical results (and hence improve the reliability of conclusions drawn from these statistics). The relationships between MDB rainfall and Australian rainfall outside the basin were further tested using correlations between MDB rainfall at the representative station locations and the PCs of Australian rainfall outside the MDB (as determined in part 2 of section 2b). The spatial loadings of a PC found to be significantly correlated with MDB rainfall indicate regions where paleoclimate proxies may capture these modes of variability and thereby inform long-term MDB rainfall variability.

c. An objective method of identifying potential and existing paleoclimate proxy sites useful for informing long-term MDB hydroclimatic variability

In a hypothetical scenario where all locations in Australia had the potential to yield paleoclimate proxies at suitable resolutions, the question would arise as to which network of proxies would be best able to inform long-term MDB rainfall variability. The above methods provide an indication of regions highly correlated to MDB rainfall (with the potential to remotely inform long-term variability). However, a network of individually highly correlated remote sites would not necessarily provide the best network with which to reconstruct MDB rainfall variability. Of greater value would be the inclusion of sites able to resolve different features of MDB rainfall variability without each site necessarily being highly correlated to MDB rainfall. A similar scenario was posed by Evans et al. (1998), who selected sites from a network of existing and unrealized coral-based paleoclimate proxies in order to reconstruct various aspects of global sea surface temperatures. The method used by Evans et al. (1998) is known as optimal interpolation (OI), a data assimilation technique commonly used in meteorology, originally derived by Eliassen (1954). It was described by Evans et al. (1998, p. 503) as "an inverse technique of finding the best-fit field, in a least-squares sense, to both a sparse observational network of data and a description, or model, of how the field varies."

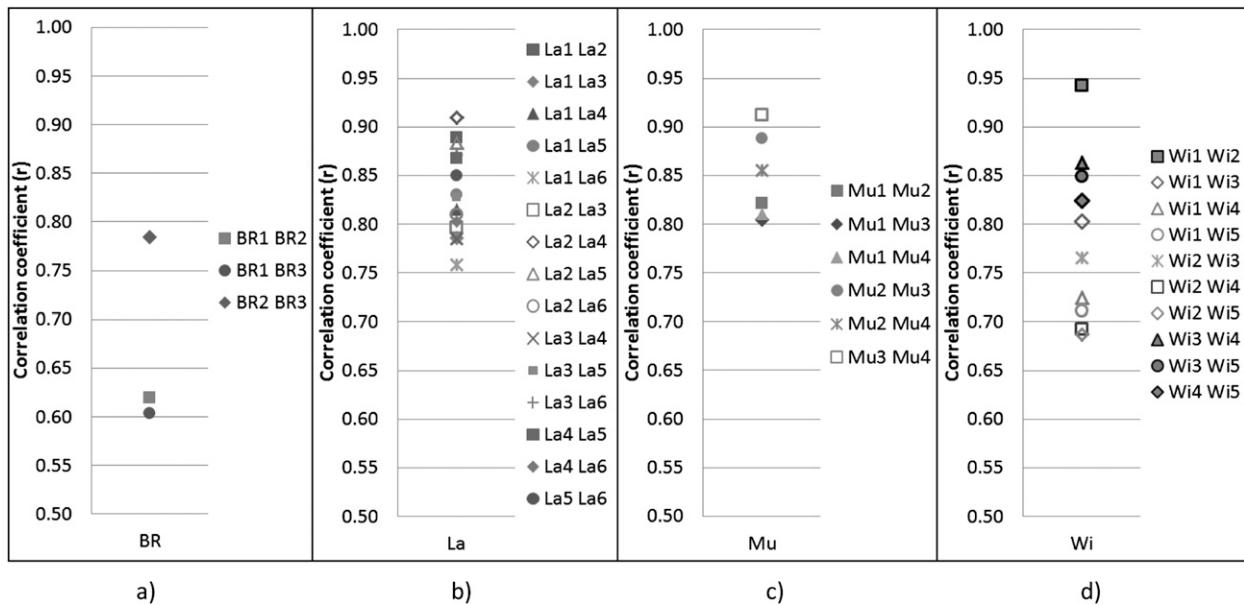


FIG. 2. Testing subcatchment homogeneity using annual rainfall correlations between gauged rainfall stations in the (a) Border Rivers, (b) Lachlan, (c) upper Murray, and (d) Wimmera catchments. All correlations were significant at the 99th percentile.

The OI method used in Evans et al. (1998) was adapted for this study. A model of rainfall field variability was developed using PCA on the correlation matrix to decompose the gridded Australian rainfall data, including MDB rainfall, into the main modes of annual rainfall variability. The heuristic approaches used in section 2b were replicated to determine the number of PCs to retain for the optimal interpolation with discarded higher-order PCs accounted for in the error term. Rainfall in each of the four case study catchments was used as the target field in four separate OI analyses. We consecutively selected 10 locations from all the grids available (a total of 243 053 grids) located in Australia outside the MDB [see Evans et al. (1998) for detailed methods]. Only 10 locations were chosen because of the trade-off between computational time required by OI and the desire to resolve subcatchment specific variability within the MDB. Although Evans et al. (1998) explored a range of observational or proxy errors between 0.1° and 1.0°C , we assumed “perfect proxies” (i.e., with an observational error of approximately zero). While this is an unrealistic expectation, given that all paleoclimate proxies are inherently noisy, an improved estimate of the proxy error could not be justified as the type and quality of the as-yet-unrealized proxies are unknown. Furthermore, the results presented by Evans et al. (1998) detailed how the OI selection process would respond to increasingly noisy proxy records by resampling the crucial sites that would, hypothetically, enable the observational error to be

reduced. As an additional test of the robustness of the method and its ability to identify real physical relationships, we eliminated the 10 grid points first identified by OI (i.e., the 10 non-MDB locations that explain most of the within-MDB variability) and repeated the OI analysis to select another 10 points. The OI method can be considered robust for our case study if the majority of the 10 points selected on the second application of OI are located close to the first 10 selected.

4. Results

a. Assessing catchment homogeneity

1) RAINFALL–RAINFALL RELATIONSHIPS WITHIN A CATCHMENT

All annual rainfall (gauged) data within each subcatchment were significantly correlated at the 99th percentile (Fig. 2). Correlations between stations located either east and west or north and south of a subcatchment are slightly lower, though still statistically significant. The MDB becomes increasingly dry toward the west, and rainfall becomes more winter-dominated toward the south (CSIRO 2008; Gallant et al. 2012), possibly accounting for the slight difference seen between north–south and east–west stations. Given that correlations between all stations are statistically significant at the annual scale within each subcatchment, it is reasonable to employ a single rainfall reconstruction model, based on remote paleoclimate records, across the entire

subcatchment to inform preinstrumental rainfall variability. As paleoclimate proxies are inherently noisy, differences in subcatchment rainfall variability are likely to be smaller than the errors associated with the climate reconstruction process.

2) ASSESSING CATCHMENT HOMOGENEITY THROUGH RELATIONSHIPS WITH THE MAIN MODES OF RAINFALL VARIABILITY OUTSIDE THE MDB

The ultimate purpose of investigating catchment homogeneity is to determine whether rainfall at different locations in a subcatchment correlate with rainfall outside the MDB in a similar way. Consequently, in addition to assessing MDB subcatchment homogeneity through rainfall relationships within a subcatchment (detailed above), we also investigate catchment homogeneity through correlations between rainfall in every grid in the four case study MDB subcatchments and time-varying amplitudes of the retained PCs (using the conservative LEV method) representing the main modes of rainfall variability outside the MDB. Only gridded data results are shown in Fig. 3 for results significant at the 99th percentile. Table 2 summarizes these correlations for rainfall grids that correspond to the gauged data used in this study showing only PCs that are significantly correlated at the 90th percentile.

The emphasis on the analysis here is to assess how MDB subcatchment rainfall relates to modes of rainfall variability outside the MDB and whether the relationship is homogeneous across the subcatchment. Statistically significant correlations at the 99th percentile were identified for regions within the four case study subcatchments: these are PCs 1–8, 10, 14, 15, and 19, shown in Fig. 3 (corresponding PC loading patterns are shown in Fig. 5). In some cases, these correlations are near-uniform across the subcatchments such as Border Rivers with PC2, Lachlan with PC1 and PC2, upper Murray with PC2 and PC4, and Wimmera with PC1 and PC4. Uniform or near-uniform statistically significant results across a subcatchment suggest a similarity in how rainfall throughout a subcatchment relates to different modes of rainfall variability outside the MDB. However, similar to the results obtained when comparing stations within the catchment, a north to south divide is seen in both the Border Rivers and Wimmera catchments (characterized by a decrease or increase in the size of the correlation coefficient) with some PCs (i.e., PCs 1, 3, and 10 and PCs 2, 3, and 7, respectively). A similar spatial divide is evident between the east and west in the Lachlan (PC3 and PC10) and upper Murray (PC7 and PC10).

Figure 3 confirms that stations found to be similar within a subcatchment also appear to relate to modes of

rainfall variability outside the basin in a similar manner (although for some catchments the strength of the relationship differs on either an east–west or north–south basis). Importantly, the east–west divides in both the Lachlan and upper Murray catchments, the northeast–southwest divide in the Wimmera and the north–south divide in the Border Rivers catchment are again evident (Figs. 2 and 3). These results (along with the earlier correlation analysis carried out within each catchment) therefore suggest that future hydroclimatic reconstructions for the case study subcatchments may need to consider the spatial divides identified above (i.e., proxy records developed at a single location cannot necessarily be considered representative of the entire subcatchment although, as previously stated, the differences in subcatchment rainfall variability are likely to be small in comparison to climate reconstruction errors).

b. Assessing relationships between rainfall inside and outside the MDB

Both PCA and rainfall–rainfall correlations were used to examine the relationships between MDB and Australia-wide rainfall. Rainfall–rainfall correlations provided a preliminary insight into rainfall regions that relate to MDB rainfall (Fig. 4 shows results for the station with the longest and most complete record in each subcatchment). Correlations to the north of the MDB suggest an influence of tropical rainfall processes. These influences decrease toward the south of the basin. Pacific Ocean influences can be detected by significant correlations on the east coast of Australia, a relationship that is particularly evident for the Border Rivers, Lachlan, and upper Murray catchments. In addition, cloud bands originating in the eastern Indian Ocean transport moisture to east (and southeast) Australia (e.g., Wright 1997; Verdon and Franks 2005). The Indian Ocean influence can be implied by significant correlations in regions northwest of the MDB. Significant correlations with regions across southern Australia (e.g., southwest Western Australia, the south coast of central Australia, south of the basin, and Tasmania) suggest an influence of Southern Ocean processes. Southern Ocean processes appear to influence the Lachlan, upper Murray, and Wimmera catchments.

The patterns of significant correlations are similar between the subcatchments, in particular the Lachlan and upper Murray results (Figs. 4b,c). The similarities suggested that a more sophisticated identification method was required to identify the different sources of rainfall influence in each subcatchment. Such a step is crucial as changes in the spatial and temporal variability of rainfall

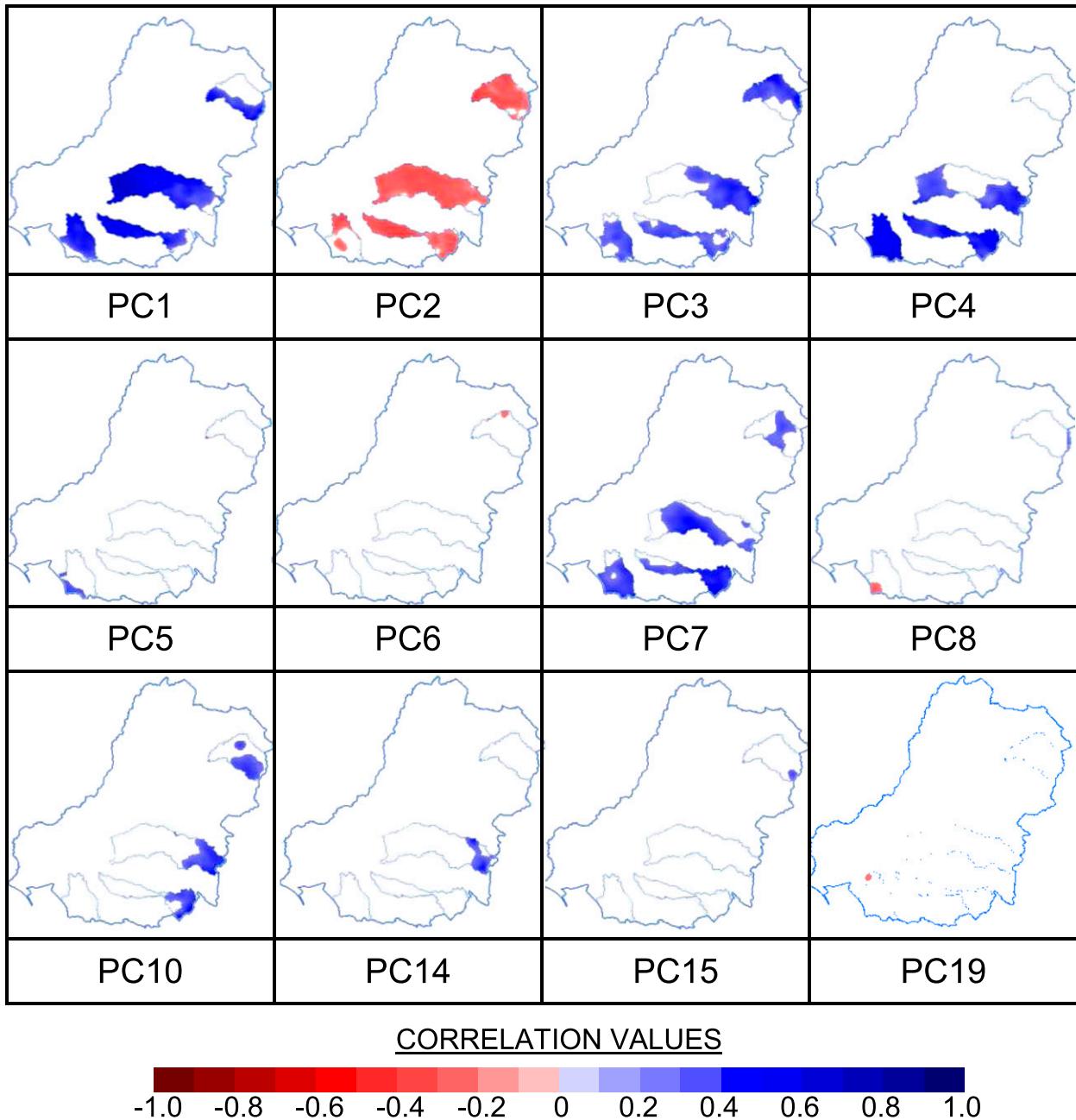


FIG. 3. Correlations between rainfall in the four MDB case study subcatchments and the retained PCs showing correlations significant at the 99th percentile. PCs that do not result in correlations significant at the 99th percentile with rainfall in any of the subcatchments are omitted.

(or lack thereof) are impacted by differences in the rainfall source (Verdon-Kidd and Kiem 2009b). Consequently, identifying the different sources of rainfall is vital to understanding rainfall variability and is a step toward understanding the mechanisms behind nonstationary climate and rainfall relationships (not addressed in this study). For this reason, PCA was employed to further explore MDB rainfall influences. PC loadings of

Australian rainfall outside the MDB show the different weights assigned to rainfall at different locations, which are combined to calculate the PC (Fig. 5 shows only PCs significantly correlated at the 99th percentile to MDB rainfall). These maps indicate regions of greatest influence for the given mode of variability and are interpreted in the context of determining the probable large-scale climate mechanisms driving the variability.

TABLE 2. Correlations between PCs and MDB rainfall, summaries for rainfall grids corresponding to high-quality station locations (only showing PCs found to have significant correlations to MDB subcatchment rainfall at the 90th, 95th, and 99th percentiles are shown in italic, lightface, and boldface roman font, respectively).

| | Border Rivers | | | | | Lachlan | | | | | Murray | | | | | Wimmera | | | | |
|------|---------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--|--|
| | BR1 | BR2 | BR3 | La1 | La2 | La3 | La4 | La5 | La5 | Mu1 | Mu2 | Mu3 | Mu4 | Wi1 | Wi2 | Wi3 | Wi4 | Wi5 | | |
| PC1 | 0.23 | 0.32 | 0.35 | 0.40 | 0.44 | 0.34 | 0.46 | 0.41 | 0.44 | 0.30 | 0.37 | 0.47 | 0.51 | 0.39 | 0.38 | 0.30 | 0.23 | 0.30 | | |
| PC2 | -0.26 | -0.31 | -0.36 | -0.29 | -0.33 | -0.30 | -0.31 | -0.36 | -0.35 | -0.28 | -0.40 | -0.39 | -0.37 | -0.26 | -0.24 | -0.26 | -0.23 | -0.22 | | |
| PC3 | 0.34 | 0.24 | 0.27 | 0.33 | 0.32 | 0.31 | 0.29 | 0.27 | 0.23 | 0.28 | 0.28 | 0.29 | 0.26 | 0.29 | 0.29 | 0.24 | 0.21 | 0.24 | | |
| PC4 | — | — | — | 0.22 | 0.20 | 0.32 | 0.17 | 0.17 | 0.23 | 0.36 | 0.38 | 0.33 | 0.32 | 0.46 | 0.44 | 0.48 | 0.49 | 0.44 | | |
| PC5 | — | — | -0.17 | — | — | — | — | — | — | — | — | — | — | — | 0.25 | 0.29 | 0.27 | 0.27 | | |
| PC7 | 0.23 | 0.27 | 0.25 | 0.22 | 0.17 | 0.35 | 0.17 | 0.23 | 0.39 | 0.36 | 0.30 | 0.24 | 0.22 | 0.34 | 0.35 | 0.32 | 0.31 | 0.32 | | |
| PC8 | 0.22 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | -0.22 | | |
| PC10 | 0.22 | 0.33 | 0.20 | 0.28 | 0.21 | 0.23 | 0.25 | 0.24 | 0.18 | 0.24 | — | — | — | — | — | -0.24 | -0.29 | -0.22 | | |
| PC14 | — | — | 0.24 | 0.32 | 0.17 | — | — | — | — | — | — | — | — | — | — | — | 0.17 | — | | |
| PC19 | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | -0.17 | | |

Border Rivers rainfall is characterized by wet-season rainfall originating from tropical systems or their interactions with midlatitude systems in the Pacific Ocean (Sturman and Tapper 2006; Gallant et al. 2012). The Pacific Ocean influence is evident in significant correlations between Border Rivers rainfall and PC2 (Fig. 3), a pattern representing the difference in rainfall variability between the east and west of Australia (Fig. 5). Likewise, the tropical rainfall influence is also evident in the significant correlations with PC3 (Fig. 3), a mode associated with rainfall variability in tropical and eastern Australia (Fig. 5). Although Indian Ocean influences account for 30%–40% of northern MDB dry season (April–October) rainfall (Pook et al. 2006), this influence was not evident in the PC–rainfall correlations.

Lachlan rainfall is significantly correlated with PC2 and PC3 (Fig. 3), suggesting an influence of tropical and Pacific Ocean weather systems on the central eastern MDB (Fig. 5). This influence could be explained by the increased impact of the South Pacific convergence zone (SPCZ) on the Lachlan catchment, particularly during La Niña and cool IPO events when the SPCZ is positioned closer to Australia (Folland et al. 2002). Correlations with PCs 4, 7, and 10 show a distinct variation in coefficient values across the catchment. Rainfall across southern Australia dominates these modes of variability (Fig. 5), suggesting a spatially varied response within the Lachlan catchment to SAM influences (the dominant climate mode in the Southern Ocean).

Significant correlations exist between the upper Murray catchment and PC4 and PC7 (Fig. 3), suggesting that rainfall in the upper Murray is primarily influenced by Southern Ocean processes (e.g., cold fronts and cut-off lows that move across southern Australia; Pook et al. 2006). Significant correlations are also seen with PC2 and PC3, likely attributable to the moisture delivered via heat troughs running north–south across the MDB, a phenomenon that often occurs during summer (Sturman and Tapper 2006), via the southeast trade winds from the Pacific Ocean (Rakich et al. 2008).

The Wimmera catchment experiences a winter-dominated rainfall regime (CSIRO 2008) with rain-bearing weather systems tending to originate from the midlatitudes (~40°–60°S) (Pook et al. 2006; Risbey et al. 2009; Verdon-Kidd and Kiem 2009a). This is consistent with the correlations with modes of variability highly influenced by southern Australian rainfall (PC4 and PC7). Cloud bands originating from the Indian Ocean have also been shown to deliver rainfall to the Wimmera catchment primarily in winter and spring (Verdon and Franks 2005; Risbey et al. 2009). This mechanism is reflected in the significant correlations with PC5, a mode that shows a distinctive northwest–southeast band.

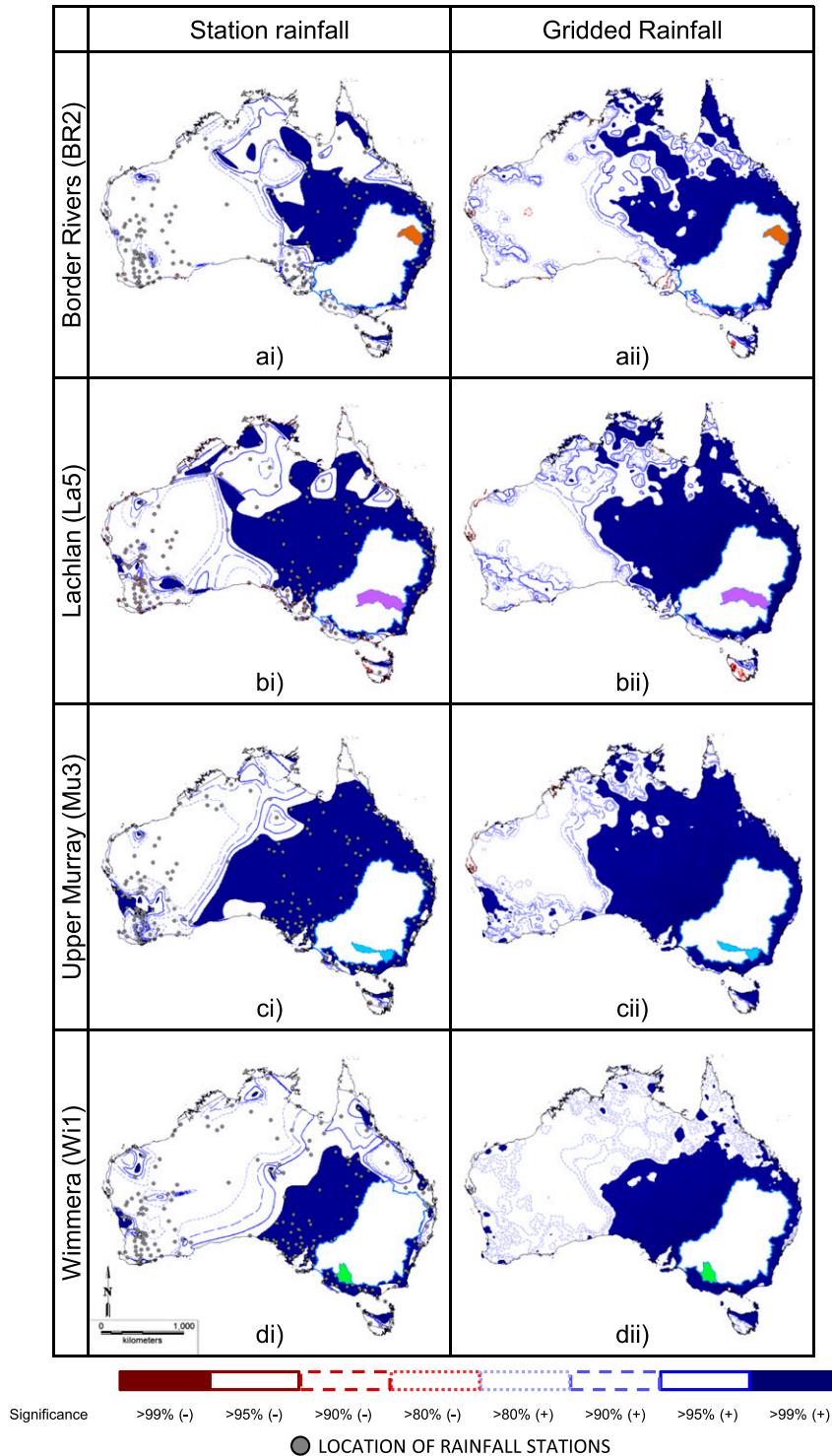


FIG. 4. Significance of annual correlations between Australia-wide rainfall outside the MDB and the representative (left) station and (right) gridded rainfall in the (a) Border Rivers (orange), (b) Lachlan (purple), (c) upper Murray (cyan), and (d) Wimmera (green) catchments. Significance values for station-based results are interpolated using triangulation. Blue (red) indicates positive (negative) correlations.

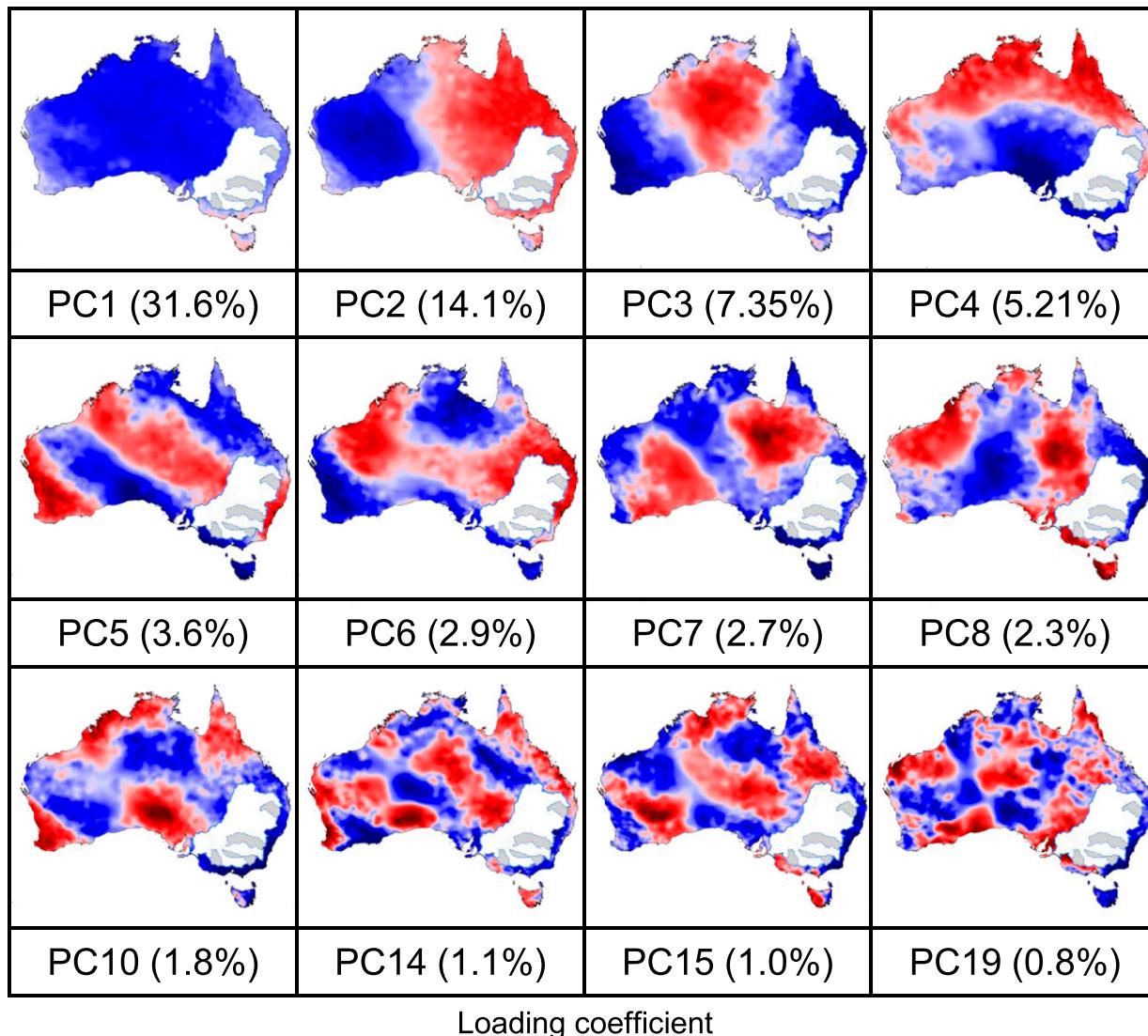


FIG. 5. PC loadings of Australian gridded rainfall outside the MDB that are significantly correlated to MDB rainfall at the 99th percentile.

c. Identification of potential and existing paleoclimate proxy sites useful for informing long-term MDB hydroclimatic variability using optimal interpolation

Optimal interpolation was used to sequentially select 10 sites located outside the MDB that capture the greatest amount of rainfall variability for each of the case study catchments (Fig. 6). The sites were selected from the AWAP gridded rainfall dataset by using a model of Australia-wide rainfall variability based on the first 14 PCs, selected using Kaiser’s rule, which account for almost 80% of the variance. A more stringent approach was used to select the number of PCs to retain for the OI

given the results in section 4a, which verified that the higher-order, noisy PCs were not significantly related to MDB rainfall. The corresponding errors associated with each additional site selected for each subcatchment are shown as a percentage of the signal in Fig. 7a. Although an observational error of zero was implemented in this study (see section 3), it is expected that for increased values of observational errors, resampling of a proxy site would be required to improve the estimate of the variance (as per Evans et al. 1998).

In the upper Murray and Wimmera catchments, the selection of four points was able to reduce the error to less than 10% of the signal (i.e., four sites were able to

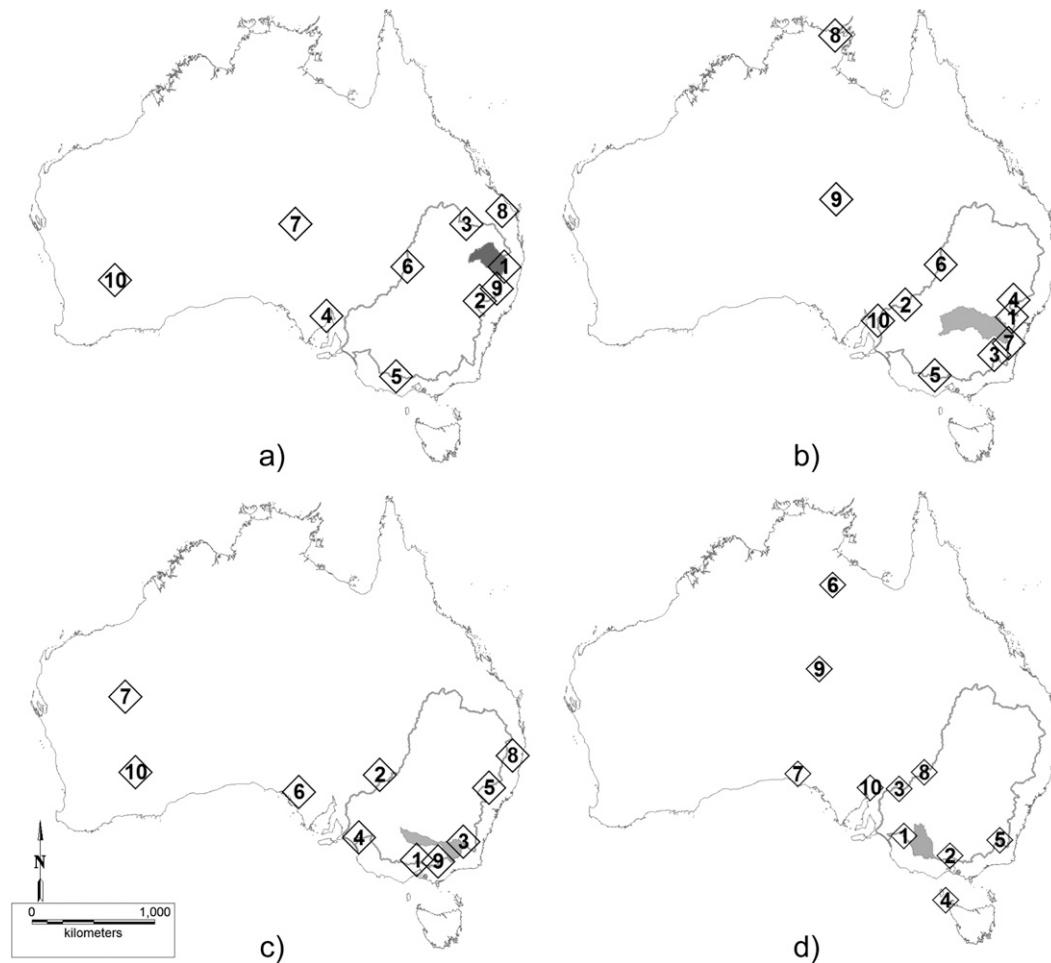


FIG. 6. First 10 sequentially selected sites using OI for period 1910–2009 for the (a) Border Rivers, (b) Lachlan, (c) upper Murray, and (d) Wimmera catchments.

capture over 90% of the variance of the signal in the retained PCs). The Border Rivers and Lachlan catchments required eight sites and six sites respectively in order to resolve 90% of the signal. This finding indicates

that additional paleoclimate proxy archives may be required for some catchments in order to resolve a similar degree of rainfall variability. For all four MDB catchments, the first site selected is located adjacent to the

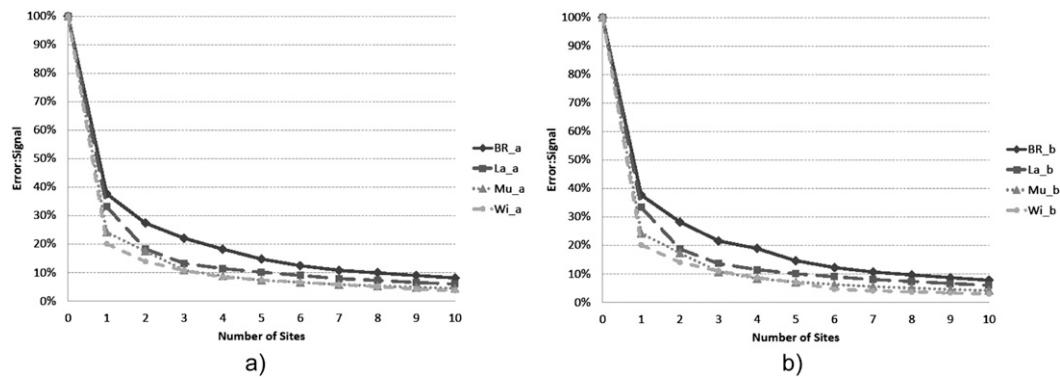


FIG. 7. Decreasing error to signal ratio with the selection of sequential sites using OI for (a) the original 10 sites selected and (b) the reselected 10 sites for each of the four MDB subcatchments.

respective subcatchment (Fig. 6). The selection of the first site is likely to represent rainfall that is most similar to the overall rainfall across the subcatchment. Subsequent sites were selected from spatially differing regions resulting in error reductions with each additional site (Fig. 7a).

The first two sites for the Border Rivers catchment are clustered near central-eastern Australia and suggest dominance of ENSO influences. The third site is located north of the MDB and likely captures variability associated with tropical rainfall systems that impact on this region that were not resolved by the first two points (Fig. 6a).

The second site selected for the Lachlan catchment is located to the west of the MDB (Fig. 6b), likely capturing additional variability associated with Indian Ocean-influenced rainfall. The next two sequentially selected sites are in the same region as the first site and marginal reductions in analysis error are made with sites 3 and 4 (Fig. 7a). Further error reductions are achieved with the addition of sites located in the southern-central and northern regions of Australia, which likely captures the Southern Ocean influence (which was particularly evident for the west of the catchment; see section 4b) and tropical rainfall variability influence on the Lachlan catchment.

The locations of the 10 sites selected for the upper Murray catchment are predominantly located in southern Australia. Many of the sites appear to resolve rainfall variability associated with Southern Ocean weather influences (e.g., points 1, 3, 4, 6, and 9). The selection of the second site on the western border of the MDB suggests that modes of rainfall variability originating from the Indian Ocean are critical in the upper Murray catchment.

A similar dominance of rainfall variability in south-east Australia is seen for the Wimmera catchment with the first five sites located in this region. The selection of sites 7 and 10 suggests a strong Southern Ocean influence in this catchment. Sites 6 and 9 are located to the northwest of the MDB around northern-central Australia, likely resolving Wimmera rainfall variance associated with cloud bands and Indian Ocean variability.

d. Validation of OI results

It is expected that regions where rainfall is interpolated should exhibit similar records because of the nature of gridded data. Consequently, the recalculation of the OI, excluding the selection of the 10 original grid points, should select points in similar regions. The 10 new points for each subcatchment are shown as red circles in Fig. 8 (note that the previously selected points are also shown as black diamonds). In all the subcatchments, the first point resolves between 60% and 80% of

the variability in the signal captured by the retained PCs. As all of the first reselected points were within one grid space of the original site, the reselection process indicates a robust result. In addition, the error to signal ratio for all reselected points differed by less than 1% in comparison to the original points selected (Fig. 7b). A slight difference is seen in the order in which points are selected for higher-order points but the locations remain similar, again implying robustness of the sites originally selected. The reselection process highlights that paleoclimate records at the locations selected would be useful for understanding preinstrumental rainfall variability in the MDB.

5. Implications of findings

The previous sections have detailed our investigations into regions located outside of the MDB that can potentially provide insight into past MDB rainfall variability in the absence of local (within the basin) reconstructions. As an example of the possible applications of this study, this section of the paper links the first few sites able to resolve over 90% of the signal, referred to here as key regions, identified in section 3 with existing paleoclimate data available in Australia (Fig. 9). All paleoclimate archives contain records of past environmental variability at differing temporal resolutions and record length. For the purposes of water resource management and hydroclimatic risk assessments, high-resolution (annual or at least subdecadal) paleoclimate archives with multi-centennial record lengths are required (Jones and Mann 2004). Paleoclimate archives in this category include tree-rings, speleothems, lake sediments, coral, and ice-core records.

While ice cores and corals can contain high-resolution records, they do not provide a direct land-based proxy of rainfall in Australia. However, they have been used in previous studies by Lough (2007), van Ommen and Morgan (2010), and Vance et al. (2013) to infer high-resolution long-term hydroclimatic variability around Australia. Consequently, currently available reconstructions of Australian rainfall using remote ice-core and coral records are considered as potential contenders when being matched to our key regions for each catchment.

The resolution of paleoclimate proxies found in lake sediments is dependent on the nature of the proxies, the sedimentation rate, the disturbance of the sediments after deposition, the seasonal variability to delineate annual varves, and the climatic sensitivity of the lake (Lotter and Birks 1997). Many biota found in lake deposits in the MDB, such as diatoms and ostracods, are highly sensitive to changes in water chemistry and are

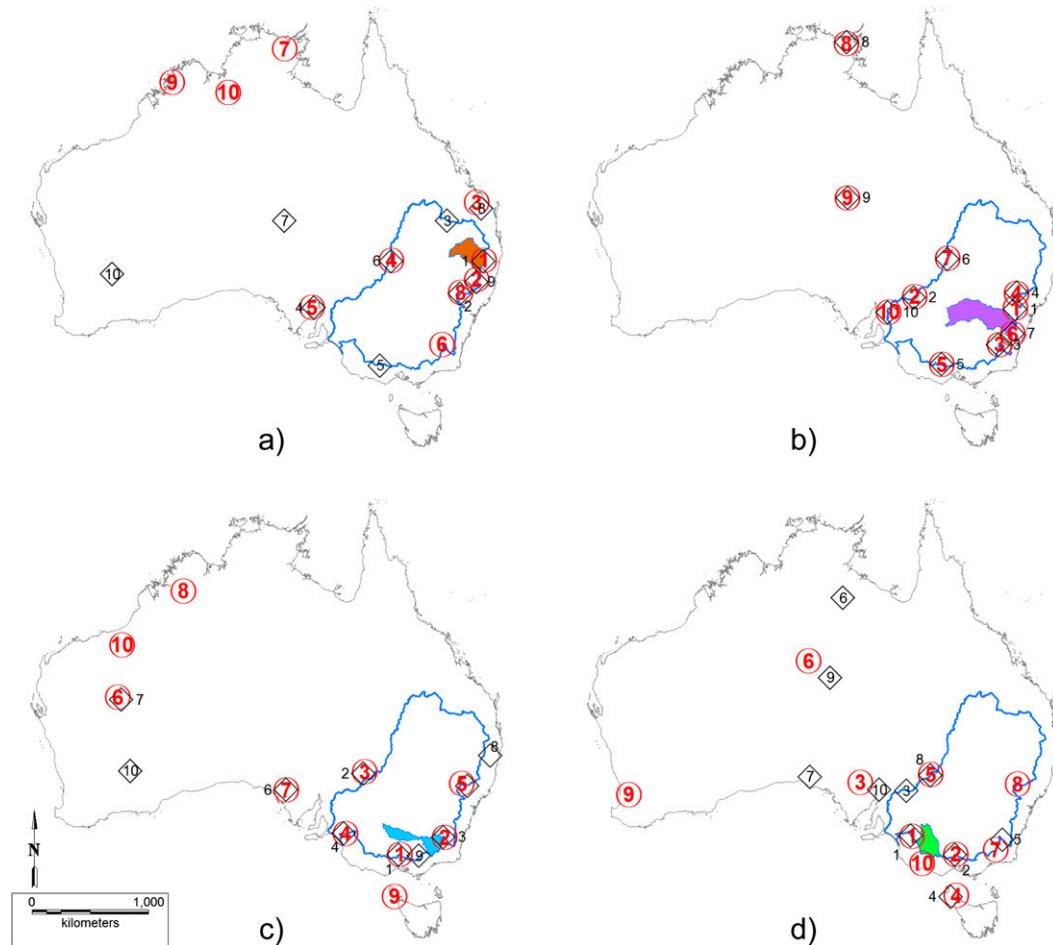


FIG. 8. Results for reselection of 10 sequentially selected sites using OI (shown in red circles) for period 1910–2009 for the (a) Border Rivers, (b) Lachlan, (c) upper Murray, and (d) Wimmera catchments. The 10 original sites are shown with black diamonds.

therefore suitable proxies for investigating high-resolution changes in climate (Mooney 1997; Barr 2010). However, typical sedimentation rates in Australian lakes were relatively low prior to European settlement and subsequent land clearances around the late eighteenth century (Harle et al. 2005). In addition, high-resolution varves can only be obtained when there is minimal bioturbation. Consequently, such a lake would be required to exhibit anoxic, or near anoxic, conditions at the lake bottom. With regard to the climatic sensitivity of a lake, lakes with a small catchment area are preferred to avoid capturing signals of distant climate processes, (a requirement that excludes many MDB lakes; Gell et al. 2009). Consequently, it has been difficult to identify lakes in Australia (particularly in the MDB) to date that are able to yield proxies at the high resolution (from annual to subannual) necessary for investigating hydroclimatic variability in the MDB. Therefore, in this paper we have not included reconstructions based on

lake sediments when matching the available data to the key regions for each catchment given our constraints of focusing on annual resolution, multicentennial, continuous proxy records. It should be noted, however, that lake-based paleoclimate proxy records could, in the future, yield findings that would be suitable for use in studies of hydroclimatic variability.

Dendrochronology studies in Australia are complicated because of a dominance of tree species that do not display distinct annual rings as well as the highly variable Australian climate characterized by extended periods of wet or dry conditions (Gell et al. 2009). At present, tree-ring records in Australia have been limited to conifers in Tasmania (Cook et al. 1992), southern Western Australia (Cullen and Grierson 2009), and northern Australia (Baker et al. 2008) and red cedars (*Toona ciliata*) in Queensland (Heinrich et al. 2009). However, preliminary work has been conducted into snow gums (*Eucalyptus pauciflora*) in the MDB (Brookhouse et al.

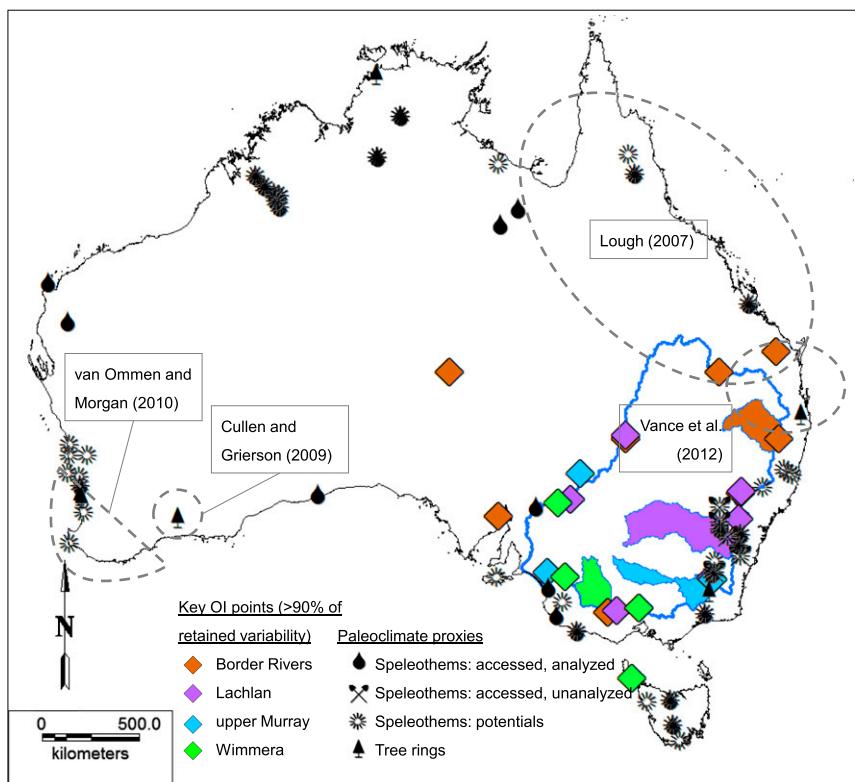


FIG. 9. Key locations selected by OI that resolve $>90\%$ of the variability in the retained PCs for each subcatchment with the location of some suitable paleoclimate proxy archives (only showing tree-ring and karst data). Gray-dashed shapes show regions where existing paleoclimate-informed rainfall reconstructions are located. Accompanying boxes show references for the published reconstructions.

2008), the results of which could provide significant insights into long-term MDB hydroclimatology if the samples are rainfall sensitive, of high resolution, and can be accurately dated. Given the high-resolution and multicentennial records afforded by dendrochronology, it follows that paleoclimate-proxy information yielded from tree rings may be utilized to reconstruct MDB hydroclimatology.

Speleothems (cave deposits) are formed by the accumulation of calcium carbonate (usually calcite) from water drips. The formation of speleothems is related to surface hydrological processes and thus they preserve high-resolution records of precipitation. In addition, there are many karst sites that are as yet unexplored for paleoclimate research. Therefore, there is much potential for the development of paleoclimate rainfall-proxy records derived from speleothems.

The primary aim of this paper was to identify existing and potential networks of paleoclimate data that are useful for reconstructing MDB hydroclimatology and to implement a method that could quantify the additional variability resolved by the inclusion of additional

paleoclimate sites. Figure 9 displays the first few locations selected using OI (chosen as together they resolve over 90% of the rainfall variability) for the four subcatchments alongside the locations of karst sites (explored and analyzed, explored and unanalyzed, and unexplored potential karst sites) and analyzed tree-ring records and regions where rainfall reconstructions exist based on ice cores and corals. These maps may be used to direct future investigations that will yield the most useful paleoclimate records that will inform long-term MDB climate variability.

Speleothems previously used as proxies for other climate variables (flood and drought identification, ENSO, etc.) from caves such as those at Jenolan and Wombeyan in New South Wales and Chillagoe and Mount Etna in Queensland, have the potential to be further developed as rainfall proxies. Similarly, speleothems collected from caves at Wellington on the east coast of Australia are currently under investigation, and could yield important rainfall proxy data. These caves are located in regions identified as important for providing information relating to all four case study subcatchments (Fig. 9). The

extensive collection of dendrochronology studies in Tasmania could also inform long-term climate variability in the Wimmera region if accurately dated hydrological proxies are developed from these archives. The karst of the southwest Western Australia region has already shown excellent potential for rainfall reconstruction (Treble et al. 2003), while the Kimberleys (northern Western Australia) and Kangaroo Island (southern Australia) have the potential for containing hydroclimate archives. Archives from such regions could provide additional information that would enable a greater degree of understanding into long-term MDB hydroclimatic variability in the four target catchments considered in this work (Fig. 6).

6. Conclusions

Successful management and risk assessment of water resources requires comprehensive analysis of long-term (i.e., interdecadal and decadal) hydroclimatic variability. Given the brevity of hydroclimatic records in Australia the use of paleoclimate proxies to inform preinstrumental hydroclimate variability is very attractive. Unfortunately, there is a shortage of such records in locations where extensive hydroclimatic records are most required such as the MDB, a region crucial to primary food production in Australia. The MDB is particularly problematic as it not only lacks existing high-resolution paleoclimate data, but sites where such data could be obtained in the future. Furthermore, there is limited development of accurately dated rainfall proxies in Australia thus far (Cullen and Grierson, 2009). Consequently, we have presented a foundation for developing long-term records in the MDB by highlighting key remote regions around Australia that may contain suitable paleoclimate archives that will, if developed, provide a network of data to inform future MDB hydroclimatic reconstructions.

Our findings show changes in the dominance of various local and large-scale climate systems between the different subcatchments suggesting that MDB rainfall reconstructions will need to be unique for each subcatchment and that even higher spatial resolutions may be required to resolve the variability seen in all subcatchments (e.g., the east–west divide seen in the Lachlan). In terms of water resource management, speleothems and tree rings are likely to provide the most useful terrestrial records for practical application (because of record length and resolution). Encouragingly, as we have shown in Fig. 9, there is much untapped potential for such data sources in Australia, highlighting the need for further investment in the development of these potential proxy sources.

This paper has focused on highlighting regions beyond the MDB where potentially useful paleoclimate rainfall records could be assembled. The purpose of the focus on rainfall, as opposed to streamflow, is that variations in streamflow are dependent on more forcing factors than rainfall such as changing environmental conditions (Chiew et al. 1998; Kiem and Verdon-Kidd 2010; Gallant and Gergis 2011) and changes in flow resulting from anthropogenic regulations (e.g., extractions, diversions, retention structures, and interceptions; Gallant and Gergis 2011). Future rainfall reconstructions, based on the methods presented in this paper, can be used to investigate preinstrumental streamflow variability through the use of existing rainfall–runoff models [such as the simple rainfall–runoff model (SIMHYD) and Sacramento]. Subsequent results may then be used to validate and/or extend the findings of previous MDB streamflow reconstructions such as those of Verdon and Franks (2007), McGowan et al. (2009), and Gallant and Gergis (2011).

We have highlighted regions where existing or future developments of high-resolution paleoclimate information can be utilized as remote indicators of rainfall in the MDB that will subsequently enable improved assessments of long-term hydroclimatic risks. These multicentennial rainfall records will enable our understanding of baseline risks associated with natural climate variability in the MDB to be improved. This work has relevance for increasing our understanding of historic climate variability through setting the groundwork for a new approach to reconstructing MDB hydroclimatic variability. Future work will consequently improve current MDB water management practices (which are currently based on a relatively wet flood-dominated climate regime; Vivés and Jones 2005) and enable future climate scenarios to be adequately constrained, validated, and placed in perspective of long-term natural climatic variability. Moreover, our methodology is not restricted to MDB or Australian applications; the methodology presented in this paper may be applied to any region lacking local preinstrumental hydroclimatic information.

Finally, while the results presented here are based on precipitation teleconnections witnessed over Australia in the modern instrumental era, it is unlikely that these relationships were stable during prehistory or will remain stable in the future. Rather than making the method and results presented here redundant, such nonstationarity only highlights the importance of using paleoclimate information to gain a better understanding into the full spectrum of hydroclimatic variability that is possible—and where the instrumental record (on which all hydroclimatic risk assessment and planning in most countries is currently based) fits into that.

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REFERENCES

- Ashok, K., Z. Guan, and T. Yamagata, 2003: Influence of the Indian Ocean dipole on the Australian winter rainfall. *Geophys. Res. Lett.*, **30**, 1821, doi:10.1029/2003GL017926.
- Baker, P. J., J. G. Palmer, and R. D'Arrigo, 2008: The dendrochronology of *Callitris intratropica* in northern Australia: Annual ring structure, chronology development and climate correlations. *Aust. J. Bot.*, **56**, 311–320, doi:10.1071/BT08040.
- Barr, C., 2010: Droughts and flooding rains: A fine-resolution reconstruction of climatic variability in western Victoria, Australia, over the last 1500 years. Ph.D. dissertation, School of Social Sciences, The University of Adelaide, 324 pp. [Available online at <http://digital.library.adelaide.edu.au/dspace/handle/2440/65582>.]
- BoM, cited 2011: Australia's high-quality climate change datasets. Bureau of Meteorology. [Available online at <ftp://ftp.bom.gov.au/anon/home/ncc/www/change/HQmonthlyR/>.]
- , cited 2012: Australian Water Information Dictionary. Bureau of Meteorology. [Available online at <http://www.bom.gov.au/water/awid/id-644.shtml>.]
- Bradley, R. S., and P. D. Jones, 1995: *Climate since A.D. 1500*. Routledge, 706 pp.
- Brookhouse, M., J. Lindesay, and C. Brack, 2008: The potential of tree rings in *Eucalyptus pauciflora* for climatological and hydrological reconstruction. *Geogr. Res.*, **46**, 421–434, doi:10.1111/j.1745-5871.2008.00535.x.
- Cangelosi, R., and A. Gorieli, 2007: Component retention in principal component analysis with application to cDNA microarray data. *Biol. Direct*, **2**, doi:10.1186/1745-6150-2-2.
- Charles, C. D., K. Cobb, M. D. Moore, and R. G. Fairbanks, 2003: Monsoon–tropical ocean interaction in a network of coral records spanning the 20th century. *Mar. Geol.*, **201**, 207–222, doi:10.1016/S0025-3227(03)00217-2.
- Chiew, F. H. S., T. C. Piechota, J. A. Dracup, and T. A. McMahon, 1998: El Niño/Southern Oscillation and Australian rainfall, streamflow and drought: Links and potential for forecasting. *J. Hydrol.*, **204**, 138–149, doi:10.1016/S0022-1694(97)00121-2.
- Christiansen, B., T. Schmith, and P. Thejll, 2009: A surrogate ensemble study of climate reconstruction methods: Stochasticity and robustness. *J. Climate*, **22**, 951–976, doi:10.1175/2008JCLI2301.1.
- Cook, E. R., T. Bird, M. J. Peterson, M. Barbetti, B. M. Buckley, R. D. D'Arrigo, and R. Francey, 1992: Climatic change over the last millennium in Tasmania reconstructed from tree-rings. *Holocene*, **2**, 205–217, doi:10.1177/095968369200200302.
- , D. M. Meko, D. W. Stahle, and M. K. Cleaveland, 1999: Drought reconstructions for the continental United States. *J. Climate*, **12**, 1145–1162, doi:10.1175/1520-0442(1999)012<1145:DRFTCU>2.0.CO;2.
- , B. M. Buckley, J. G. Palmer, P. Fenwick, M. J. Peterson, G. Boswijk, and A. Fowler, 2006: Millennia-long tree-ring records from Tasmania and New Zealand: A basis for modelling climate variability and forcing, past, present and future. *J. Quat. Sci.*, **21**, 689–699, doi:10.1002/jqs.1071.
- Cronin, T. M., 2010: *Paleoclimates: Understanding Climate Change Past and Present*. Columbia University Press, 441 pp.
- CSIRO, 2008: Water availability in the Murray-Darling Basin. Australian Government for the CSIRO Murray-Darling Basin Sustainable Yields Project Rep., 67 pp.
- Cullen, L. E., and P. F. Grieron, 2009: Multi-decadal scale variability in autumn-winter rainfall in south-western Australia since 1655 AD as reconstructed from tree rings of *Callitris columellaris*. *Climate Dyn.*, **33**, 433–444, doi:10.1007/s00382-008-0457-8.
- D'Arrigo, R., R. Villalba, and G. Wiles, 2001: Tree-ring estimates of Pacific decadal climate variability. *Climate Dyn.*, **18**, 219–224, doi:10.1007/s003820100177.
- Druffel, E. R. M., and S. Griffin, 1999: Variability of surface ocean radiocarbon and stable isotopes in the southwestern Pacific. *J. Geophys. Res.*, **104** (C10), 23 607–23 613, doi:10.1029/1999JC900212.
- Eliassen, A., 1954: Provisional report on calculation of spatial covariance and autocorrelation of the pressure field. *Dynamic Meteorology: Data Assimilation Methods*, L. Bengtsson, M. Ghil, and E. Källén, Eds., Springer-Verlag, 319–330.
- Evans, M. N., A. Kaplan, and M. A. Cane, 1998: Optimal sites for coral-based reconstruction of global sea surface temperature. *Paleoceanography*, **13**, 502–516, doi:10.1029/98PA02132.
- , —, and —, 2002: Pacific sea surface temperature field reconstruction from coral $\delta^{18}\text{O}$ data using reduced space objective analysis. *Paleoceanography*, **17**, 1007, doi:10.1029/2000PA000590.
- Folland, C. K., J. A. Renwick, M. J. Salinger, and A. B. Mullan, 2002: Relative influences of the interdecadal Pacific oscillation and ENSO on the South Pacific convergence zone. *Geophys. Res. Lett.*, **29**, 1643, doi:10.1029/2001GL014201.
- Frisia, S., A. Borsato, N. Preto, and F. McDermott, 2003: Late Holocene annual growth in three Alpine stalagmites records the influence of solar activity and the North Atlantic Oscillation on winter climate. *Earth Planet. Sci. Lett.*, **216**, 411–424, doi:10.1016/S0012-821X(03)00515-6.
- Fritts, H. C., 1976: *Tree Rings and Climate*. Academic Press, 567 pp.
- Gale, S. J., R. J. Haworth, D. E. Cook, and N. J. Williams, 2004: Human impact on the natural environment in early colonial Australia. *Arch. Oceania*, **39**, 148–156.
- Gallant, A. J. E., and J. Gergis, 2011: An experimental streamflow reconstruction for the River Murray, Australia, 1783–1988. *Water Resour. Res.*, **47**, W00G04, doi:10.1029/2010WR009832.
- , A. S. Kiem, D. C. Verdon-Kidd, R. C. Stone, and D. J. Karoly, 2012: Understanding hydroclimate processes in the Murray-Darling Basin for natural resource management. *Hydrol. Earth Syst. Sci.*, **16**, 2049–2068, doi:10.5194/hess-16-2049-2012.
- Gell, P., and Coauthors, 2009: Palaeoclimate studies relevant to natural resource management in the Murray-Darling Basin. Murray-Darling Basin Authority Rep., 72 pp. [Available online at http://climatehistory.com.au/wp-content/uploads/2010/01/Gell-et-al_MDBA_Palaeo_Review.pdf.]
- Gergis, J., and Coauthors, 2012: On the long-term context of the 1997–2009 'Big Dry' in south-eastern Australia: Insights from a 206-year multi-proxy rainfall reconstruction. *Climatic Change*, **111**, 923–944, doi:10.1007/s10584-011-0263-x.

- Gong, D.-Y., S.-J. Kim, and C.-H. Ho, 2009: Arctic and Antarctic Oscillation signatures in tropical coral proxies over the South China Sea. *Ann. Geophys.*, **27**, 1979–1988, doi:10.5194/angeo-27-1979-2009.
- Griffiths, M. L., and Coauthors, 2009: Increasing Australian–Indonesian monsoon rainfall linked to early Holocene sea-level rise. *Nat. Geosci.*, **2**, 636–639, doi:10.1038/ngeo605.
- Harle, K., and Coauthors, 2005: Building a future on knowledge from the past: What palaeo-science can reveal about climate change and its potential impacts in Australia. Australian Greenhouse Office Rep., 46 pp.
- Heinrich, I., K. Weidner, G. Helle, H. Vos, J. A. Lindesay, and J. C. G. Banks, 2009: Interdecadal modulation of the relationship between ENSO, IPO and precipitation: Insights from tree rings in Australia. *Climate Dyn.*, **33**, 63–73, doi:10.1007/s00382-009-0544-5.
- Jolliffe, I. T., 2002: *Principal Component Analysis*. 2nd ed. Springer-Verlag, 487 pp.
- Jones, D. A., W. Wang, and R. Fawcett, 2009: High-quality spatial climate data-sets for Australia. *Aust. Meteor. Oceanogr. J.*, **58**, 233–248. [Available online at <http://www.bom.gov.au/amm/docs/2009/jones.pdf>.]
- Jones, P. D., and M. E. Mann, 2004: Climate over past millennia. *Rev. Geophys.*, **42**, RG2002, doi:10.1029/2003RG000143.
- Kiem, A. S., and S. W. Franks, 2004: Multi-decadal variability of drought risk, eastern Australia. *Hydrol. Processes*, **18**, 2039–2050, doi:10.1002/hyp.1460.
- , and D. C. Verdon-Kidd, 2010: Towards understanding hydroclimatic change in Victoria, Australia—Preliminary insights into the “Big Dry.” *Hydrol. Earth Syst. Sci.*, **14**, 433–445, doi:10.5194/hess-14-433-2010.
- , and —, 2011: Steps toward “useful” hydroclimatic scenarios for water resource management in the Murray-Darling Basin. *Water Resour. Res.*, **47**, W00G06, doi:10.1029/2010WR009803.
- Lavery, B., G. Joung, and N. Nicholls, 1997: An extended high-quality historical rainfall dataset for Australia. *Aust. Meteor. Mag.*, **46**, 27–38.
- Linsley, B. K., P. Zhang, A. Kaplan, S. S. Howe, and G. M. Wellington, 2008: Interdecadal-decadal climate variability from multicorall oxygen isotope records in the South Pacific convergence zone region since 1650 A.D. *Paleoceanography*, **23**, PA2219, doi:10.1029/2007PA001539.
- Lotter, A. F., and H. J. B. Birks, 1997: The separation of the influence of nutrients and climate on the varve time-series of Baldeggersee, Switzerland. *Aquat. Sci.*, **59**, 362–375, doi:10.1007/BF02522364.
- Lough, J. M., 2007: Tropical river flow and rainfall reconstructions from coral luminescence: Great Barrier Reef, Australia. *Paleoceanography*, **22**, PA2218, doi:10.1029/2006PA001377.
- Mann, M. E., R. S. Bradley, and M. K. Hughes, 1998: Global-scale temperature patterns and climate forcing over the past six centuries. *Nature*, **392**, 779–787, doi:10.1038/33859.
- , S. Rutherford, E. Wahl, and C. Ammann, 2007: Robustness of proxy-based climate field reconstruction methods. *J. Geophys. Res.*, **112**, D12109, doi:10.1029/2006JD008272.
- , and Coauthors, 2009: Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science*, **326**, 1256–1260, doi:10.1126/science.1177303.
- Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, 1997: A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Amer. Meteor. Soc.*, **78**, 1069–1079, doi:10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2.
- McDonald, J., R. Drysdale, and D. Hill, 2004: The 2002–2003 El Niño recorded in Australian cave drip waters: Implications for reconstructing rainfall histories using stalagmites. *Geophys. Res. Lett.*, **31**, L22202, doi:10.1029/2004GL020859.
- McGowan, H. A., S. K. Marx, J. Denholm, J. Soderholm, and B. S. Kamber, 2009: Reconstructing annual inflows to the headwater catchments of the Murray River, Australia, using the Pacific decadal oscillation. *Geophys. Res. Lett.*, **36**, L06707, doi:10.1029/2008GL037049.
- Meneghini, B., I. Simmonds, and I. N. Smith, 2007: Association between Australian rainfall and the southern annular mode. *Int. J. Climatol.*, **27**, 109–121, doi:10.1002/joc.1370.
- Mooney, S., 1997: A fine-resolution palaeoclimatic reconstruction of the last 2000 years, from Lake Keilambete, southeastern Australia. *Holocene*, **7**, 139–149, doi:10.1177/095968369700700202.
- Oerter, H., W. Graf, H. Meyer, and F. Wilhelms, 2004: The EPICA ice core from Dronning Maud Land: First results from stable-isotope measurements. *Ann. Glaciol.*, **39**, 307–312, doi:10.3189/172756404781814032.
- Overpeck, J., and Coauthors, 1997: Arctic environmental change of the last four centuries. *Science*, **278**, 1251–1256, doi:10.1126/science.278.5341.1251.
- Peel, M. C., B. L. Finlayson, and T. A. McMahon, 2007: Updated world map of the Köppen–Geiger climate classification. *Hydrol. Earth Syst. Sci.*, **11**, 1633–1644, doi:10.5194/hess-11-1633-2007.
- Pook, M. J., P. C. McIntosh, and G. A. Meyers, 2006: The synoptic decomposition of cool-season rainfall in the southeastern Australian cropping region. *J. Appl. Meteor. Climatol.*, **45**, 1156–1170, doi:10.1175/JAM2394.1.
- Quigley, M. C., T. Horton, J. C. Hellstrom, M. L. Cupper, and M. Saniford, 2010: Holocene climate change in arid Australia from speleothem and alluvial records. *Holocene*, **20**, 1093–1104, doi:10.1177/0959683610369508.
- Rakich, C. S., N. J. Holbrook, and B. Timbal, 2008: A pressure gradient metric capturing planetary-scale influences on eastern Australian rainfall. *Geophys. Res. Lett.*, **35**, L08713, doi:10.1029/2007GL032970.
- Raupach, M. R., P. R. Briggs, V. Haverd, E. A. King, M. Paget, and C. M. Trudinger, 2009: Australian Water Availability Project (AWAP): CSIRO marine and atmospheric research component: Final report for phase 3. Australian Water Availability Project (AWAP), CAWCR, 67 pp.
- Risbey, J. S., M. J. Pook, P. C. McIntosh, M. C. Wheeler, and H. H. Hendon, 2009: On the remote drivers of rainfall variability in Australia. *Mon. Wea. Rev.*, **137**, 3233–3253, doi:10.1175/2009MWR2861.1.
- Rodrigo, F. S., M. J. Esteban-Parra, D. Pozo-Vázquez, and Y. Castro-Diez, 1999: A 500-year precipitation record in southern Spain. *Int. J. Climatol.*, **19**, 1233–1253, doi:10.1002/(SICI)1097-0088(199909)19:11<1233::AID-JOC413>3.0.CO;2-L.
- Rutherford, S., M. E. Mann, T. J. Osborn, K. R. Briffa, P. D. Jones, R. S. Bradley, and M. K. Hughes, 2005: Proxy-based Northern Hemisphere surface temperature reconstructions: Sensitivity to method, predictor network, target season, and target domain. *J. Climate*, **18**, 2308–2329, doi:10.1175/JCLI3351.1.
- Schneider, D. P., E. J. Steig, T. D. van Ommen, D. A. Dixon, P. A. Mayewski, J. M. Jones, and C. M. Bitz, 2006: Antarctic temperatures over the past two centuries from ice cores. *Geophys. Res. Lett.*, **33**, L16707, doi:10.1029/2006GL027057.
- Souney, J. M., P. A. Mayewski, I. D. Goodwin, L. D. Meeker, V. Morgan, M. A. J. Curran, T. D. van Ommen, and A. S. Palmer, 2002: A 700-year record of atmospheric circulation

- developed from the Law Dome ice core, East Antarctica. *J. Geophys. Res.*, **107**, 4608, doi:10.1029/2002JD002104.
- Sturman, A., and N. Tapper, 2006: *The Weather and Climate of Australia and New Zealand*. Oxford University Press, 541 pp.
- Tozer, C. R., A. S. Kiem, and D. C. Verdon-Kidd, 2012: On the uncertainties associated with using gridded rainfall data as a proxy for observed. *Hydrol. Earth Syst. Sci.*, **16**, 1481–1499, doi:10.5194/hess-16-1481-2012.
- Treble, P., J. M. G. Shelley, and J. Chappell, 2003: Comparison of high resolution sub-annual records of trace elements in a modern (1911–1992) speleothem with instrumental climate data from southwest Australia. *Earth Planet. Sci. Lett.*, **216**, 141–153, doi:10.1016/S0012-821X(03)00504-1.
- Vance, T. R., T. D. van Ommen, M. A. J. Curran, C. T. Plummer, and A. D. Moy, 2013: A millennial proxy record of ENSO and eastern Australian rainfall from the Law Dome ice core, East Antarctica. *J. Climate*, **26**, 710–725.
- van Ommen, T. D., and V. Morgan, 2010: Snowfall increase in coastal East Antarctica linked with southwest Western Australian drought. *Nat. Geosci.*, **3**, 267–272, doi:10.1038/ngeo761.
- Verdon, D. C., and S. W. Franks, 2005: Indian Ocean sea surface temperature variability and winter rainfall: Eastern Australia. *Water Resour. Res.*, **41**, W09413, doi:10.1029/2004WR003845.
- , and —, 2006: Long-term behaviour of ENSO: Interactions with the PDO over the past 400 years inferred from paleoclimate records. *Geophys. Res. Lett.*, **33**, L06712, doi:10.1029/2005GL025052.
- and —, 2007: Long-term drought risk assessment in the Lachlan River Valley—A paleoclimate perspective. *Aust. J. Water Res.*, **11**, 145–152.
- Verdon-Kidd, D. C., and A. S. Kiem, 2009a: On the relationship between large-scale climate modes and regional synoptic patterns that drive Victorian rainfall. *Hydrol. Earth Syst. Sci.*, **13**, 467–479, doi:10.5194/hess-13-467-2009.
- , and —, 2009b: Nature and causes of protracted droughts in southeast Australia: Comparison between the Federation, WWII, and Big Dry droughts. *Geophys. Res. Lett.*, **36**, L22707, doi:10.1029/2009GL041067.
- , and —, 2010: Quantifying drought risk in a nonstationary climate. *J. Hydrometeor.*, **11**, 1019–1031, doi:10.1175/2010JHM1215.1.
- Vivés, B., and R. N. Jones, 2005: Detection of abrupt changes in Australian decadal rainfall (1890–1989). CSIRO Atmospheric Research Tech. Paper 73, 54 pp.
- Wang, S., D. Gong, and J. Zhu, 2001: Twentieth-century climatic warming in China in the context of the Holocene. *Holocene*, **11**, 313–321, doi:10.1191/095968301673172698.
- Wilson, R., E. Cook, R. D'Arrigo, N. Riedwyl, M. N. Evans, A. Tudhope, and R. Allan, 2010: Reconstructing ENSO: The influence of method, proxy data, climate forcing and teleconnections. *J. Quat. Sci.*, **25**, 62–78, doi:10.1002/jqs.1297.
- Wright, W. J., 1997: Tropical–extratropical cloudbands and Australian rainfall: I. Climatology. *Int. J. Climatol.*, **17**, 807–829, doi:10.1002/(SICI)1097-0088(19970630)17:8<807::AID-JOC162>3.0.CO;2-J.