Low-resolution Australasian palaeoclimate records of the last 2000 years

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Abstract

Non-annually resolved palaeoclimate records in the Australasian region were compiled to facilitate investigations of decadal to centennial climate variability over the past 2000 years. A total of 675 lake/wetland, geomorphic, marine, and speleothem records were identified. The majority of records are located near population centres in southeast Australia, in New Zealand, and across the maritime continent, and there are few records from the arid regions of central and western Australia. Each record was assessed against a set of *a priori* criteria based on temporal resolution, record length, dating methods, and confidence in the proxy-climate relationship over the Common Era. A subset of 22 records met the criteria, and was endorsed for subsequent analyses. Chronological uncertainty was the primary reason why records did not meet the selection criteria. New chronologies based on Bayesian techniques were constructed for the high quality subset to ensure a consistent approach to age modelling and quantification of age uncertainties. The primary reasons for differences between published and reconstructed age-depth models were the consideration of the non-singular distribution of ages in calibrated ^{14}C dates and the use of estimated autocorrelation between sampled depths as a constraint for changes in accumulation rate. Existing proxies and reconstruction techniques that successfully capture climate variability in the region show potential to address spatial gaps and expand the range of climate variables covering the last 2000 years in the Australasian region. Future palaeoclimate research and records in Australasia could be greatly improved through three main actions: i.) Greater data availability through the public archiving of published records, ii.) Thorough characterisation of proxy-climate relationships through site monitoring and climate sensitivity tests, and iii.) Improvement of chronologies through core-top dating, inclusion of tephra layers where possible, and increased date density during the Common Era.

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1 Introduction

1.1 Background

Elucidation of climate system variability and long-term change requires a spatially and temporally robust baseline of natural climate conditions. This is particularly relevant for Australasia, where climate variability has strong agricultural, socioeconomic, and environmental impacts (Head et al., 2014; Kiem et al., 2016; van Dijk et al., 2013). The Intergovernmental Panel on Climate Change (IPCC) previously supported a two thousand year baseline to establish climate variability for Earth (Masson-Delmotte et al., 2013). This time period is ideal for providing an effective context for three primary reasons: (i) shifts in global boundary conditions are believed to be minor and well-constrained over this time frame; (ii) the last two millennia contains periods of relatively warm and cool climate anomalies, which offers opportunity to study regional responses to global and/or regional climate fluctuations; and (iii) the majority of high-resolution proxy climate records occur within this period, which provides reconstructions of climate at individual sites and across geographic regions with increased chronological certainty (Consortium et al., 2013; Neukom and Gergis, 2012).

The International Geosphere-Biosphere Programme-led Past Global Changes (PAGES) 'Regional 2k' initiative was established in 2008 to coordinate and synthesise regional and continental-scale reconstructions spanning the last 2000 years. This network also provides a way to exchange ideas and test hypotheses about recent palaeoclimates that can be queried using consistent quality controlled datasets. The PAGES initiative encourages use of rigorous, multi-method approaches to compare variability, patterns, and timing of changes across regions (Kaufman, 2014). The 'Aus2k' working group investigates Australasian climate variability over the last 2000 years, hereafter referred to as the Common Era (CE).

Data derived from natural archives for the purpose of investigating climate variability falls into two categories: 'high-resolution' (monthly to annually resolved) and 'low-resolution' (non-annually resolved). High-resolution archives, such as tree-rings, corals, varved sediments, and some ice cores, have been used to reconstruct regional and global temperature trends over the Common Era (Consortium et al., 2013; Gergis et al., 2016; Mann, 2007; Mann and Jones, 2003). In addition to several advantages of using annually resolved data, such as chronological precision and temporal resolution, annually resolved data possess some limitations when examining the past two millennia. These limitations can include the confined spatial coverage inherent to the high-resolution data network, and difficulties in capturing low-frequency variability (Anchukaitis and Tierney, 2012). The limitations of interpreting low-frequency signals in high-resolution archives are exemplified with tree rings, where multiple short, individual series are used to compile longer composite chronologies. The applied standardisation techniques used to construct the composite chronologies can restrict meaningful long-term signal retention, referred to as the 'segment length curse' (Cook et al., 1995).

Due to the limited potential of reconstructing multi-decadal and longer-term variability from high-resolution archives, it is important to complement the resulting reconstructions with non-annually resolved, low-resolution records (Moberg et al., 2005). Previous studies have explored combining high- and low-resolution archives in the Australasian region to investigate a range of climate variables and atmospheric circulation patterns (Goodwin et al., 2013; Goodwin et al.,

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2014; Lorrey et al., 2007; Lorrey et al., 2008). Annually resolved records in the Southern Hemisphere (including Australasia) have been identified, reviewed, vetted, and augmented (Neukom and Gergis, 2012), but no equivalent synthesis of non-annually resolved records in the Australasian region currently exists.

Low-resolution sedimentary archives available within Australasia include lacustrine, fluvial and wetland sediments (including peat), marine sediments, speleothems, and geomorphic features (e.g. moraines, dunes) across diverse climate settings. These archives have multiple strengths for use in palaeoclimate reconstructions. First, the typical length of low-resolution records (>500 years) is longer than many available annually resolved records. Data processing techniques for low-resolution sedimentary archives also tend to preserve low-frequency climate signals, i.e. those over multi-centennial and longer time frames. Second, low-resolution archives have a greater potential to be more widely distributed in comparison to d to annually resolved archives for most regions (Anchukaitis and Tierney, 2012). This is especially true in the ocean-dominated Southern Hemisphere. For example, marine sediment cores can provide records of oceanic variability without the tight climatic and bathymetric constraints of coral records. Other low-resolution archives such as speleothems and lake sediments can provide continuous records from climate regions spanning arid regions (Gliganic et al., 2014; Quigley et al., 2010) to the tropics (Crausbay et al., 2006; Rodysill et al., 2013). Third, the climate signals preserved in low-resolution records can differ from those found in annually-resolved records, meaning that a wider range of long-term climate changes, as well as differing types of climate variability, can be reconstructed through their inclusion in multi-proxy syntheses.

1.2 Aims

To date, Australasia has hundreds of published low-resolution palaeoclimate records. However, a comprehensive palaeoclimate record database has not been compiled and evaluated for suitability to contribute to examination of climate variability during the Common Era. In this study, low-resolution palaeoclimate datasets for Australasia were compiled and assessed for their suitability for quantitative climate reconstruction efforts. Records were assessed against a set of pre-determined quality metrics to develop a subset of suitable records that could then be presented in a flexible, consistent format to facilitate future palaeoclimate investigations in the region. The four objectives of this study are to: (i) identify Australasian palaeoclimate records spanning the last 2000 years; (ii) evaluate each record against the criteria set out by the global PAGES2k network, (iii) recalibrate age-depth models of the resulting subset of records using Bayesian techniques; and (iv) discuss merits and shortcomings of existing palaeoclimate reconstructions while providing recommendations for future palaeoclimate record collection and development for the Australasian scientific community.

The work compliments a recent review of all annually resolved records in the Southern Hemisphere covering the Common Era (Neukom and Gergis, 2012), as well as other sub-region synthesis efforts in Australasia (Freeman et al., 2011; Gouramanis et al., 2013; Lorrey et al., 2007; Lorrey et al., 2008; Lorrey et al., 2010). The outcomes of this study will be helpful to researchers by identifying the most reliable low-resolution records in the Australasian region for climate model-palaeoclimate data intercomparisons in the Southern Hemisphere (Phipps et al., 2013).

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2 Data and Methods

Records published before 2017 were identified through inspection of citation databases, reference lists of past review papers, online public data repositories, personal communication with authors, and a general inquiry to all Australasian Quaternary Association members. Data were retrieved from the National Oceanic and Atmospheric Administration (NOAA) paleoclimate database (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data), the Neotoma database (https://www.neotomadb.org), the PANGAEA data publisher (https://www.pangaea.de/), and directly from record creators.

2.1 Defining Aus2k low-resolution palaeoclimate data criteria

For this study, all assembled records were screened against a set of selection criteria for the purpose of identifying a 'high-quality' subset for the use of the PAGES Aus2k working group. The selection criteria, outlined below, follow those designated by the international PAGES Regional 2k initiative (http://pastglobalchanges.org/ini/wg/2k-network/data). For inclusion, a record was required to meet the following five criteria:

(i) The proxy must be related to one or more climate variables, as stated in a peer-reviewed publication.

(ii) The record must extend continuously for at least 500 years out of the last 2000 years.

(iii) The record must have an age model based on at least two to three chronological anchors.

(iv) The record must have an average sample resolution between 2-50 years per sample or analysis.

(v) The collection location must fall within the region that has been identified by PAGES Aus2k to influence Australasian climate (90°E - 140°W, 10°N - 80°S) (Gergis et al., 2016). The Australasian region includes tropical Southeast Asia because of the dynamical influences of the Indo-Pacific region on the Australasian monsoon (Meehl and Arblaster, 2002), as well as the Australian/New Zealand sector of the Southern Ocean and Antarctica because of oceanographic and atmospheric teleconnections (Hall and Visbeck, 2002; van Ommen and Morgan, 2010).

The application of each criterion was justified on several grounds. First, records must have a published, peer-reviewed interpretation of the relationship between the measured proxy and climate variable(s). This provides quality control through the traditional peer review process by palaeoclimate specialists. Second, the overall length and average sample resolution have been selected for the purpose of reconstructing climate variability at a range of time scales over the Common Era. It is important that the data have sufficient resolution to capture fluctuations at multi-decadal scales, and that they are long enough to capture an appropriate number of cycles in the study period (Chen and Grasby, 2009). Third, the low-resolution records must have reasonable chronological constraints. 'Reasonable' was defined by PAGES2k as containing at least one chronological control point near the youngest part of the record, another near 1CE or the end of the record (whichever is younger), and, for records greater than 1000 years in length, an additional date near the middle of the record. Many records, primarily in the marine realm, extend beyond the Common Era. Dates outside this period were retained to constrain interpolation uncertainties at age-model extremes. The final requirement is that records must be publically available, which contributes towards the transparency and reproducibility of results. All of the records identified within the Aus2k region

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have been previously published, but very few were publically available. One of the tasks undertaken by the Aus2k working group was to ensure that all records were stored in public archives. All Aus2k datasets are available through the NOAA paleoclimate archive or PANGAEA data publisher (https://www.pangaea.de) (Table 1).

Preservation of metadata relating to the Aus2k datasets will assist future computer-driven, multi-record comparisons and reconstructions. One recent initiative of the palaeoclimate community is the development of a 'common language' of palaeoclimatology, where data and metadata are stored in a consistent, machine-readable format (Emile-Geay and Eshleman, 2013; McKay and Emile-Geay, 2015). The Linked Paleo Data (LiPD) framework has been developed with input from the wider scientific community (McKay and Emile-Geay, 2015). The metadata retained for the Aus2k datasets are based on the fields in the LiPD framework. As a part of the metadata, raw age determinations are recorded. Although one approach for the creation of age models is presented in this study, the raw data are available for individuals who wish to apply alternative methods.

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2.2 Past palaeoclimate data syntheses in Australasia

Previous palaeoclimate and palaeoenvironmental reviews have compiled lists of studies and obtained proxy data to address a range of research questions from the Australian and New Zealand sectors. Australian palaeoclimate records containing at least one date in the Holocene were compiled through a partnership between Macquarie University and the New South Wales Department of Environment, Climate Change, and Water (Freeman et al., 2011). The review identified 190 low-resolution records and 51 high-resolution records. Of these 241 records, 141 were classified as 'moderate to high confidence' based on climatic sensitivity, possible non-climatic influences, local forcing, and chronological confidence. Gouramanis et al. (2013) compiled a set of records for a latitudinal transect across the Australian continent, used to compare consistency in climate histories between eastern and western Australia over the past ~8000 years. The datasets were chosen by the reputation of the published records, based on the regularity of citation.

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Other groups within Australasia have previously conducted multi-proxy palaeoclimate syntheses under the banner of AUS-INTIMATE (Australasian INTegration of Ice, MArine, and TErrestrial records). Records identified through this initiative have benefitted the most recent PAGES2k effort to evaluate and update the last 2000 years. AUS-INTIMATE was organised within the International Union for Quaternary Research (INQUA), with two distinct research phases from 2004-2007 and 2008-2011. Both NZ- (New Zealand) and OZ- (Australia) INTIMATE projects focused on the interval 30,000-8,000 years ago (Alloway et al., 2007; Barrell et al., 2013; Bostock et al., 2013; Reeves et al., 2013b); however, many of the compiled records extend to the present. The purpose of AUS-INTIMATE was to integrate available proxy data into climate event stratigraphies. AUS-INTIMATE coverage has been extended from 8000 years ago to present via the Southern Hemisphere Assessment of PalaeoEnvironments (SHAPE) project supported by INQUA since 2013.

New Zealand palaeoclimate proxies covering several late Quaternary intervals, including the last 2000 years, were compiled prior to and during Phase I of Aus2k (Lorrey et al., 2008; Lorrey et al., 2010) to address how regional atmospheric circulation has changed during the late Holocene. The New Zealand data assemblage for the last 2000 years included 35 low-resolution (multi-decadal to centennial) hydroclimatically sensitive records. These data were compiled from a site level up to a homogeneous regional climate district level (Kidson, 2000; Lorrey et al., 2007) from a range of environments that range from temperate subtropical in the far north of New Zealand to glacial in the south. Thirteen temperature-sensitive records were obtained from studies that had undertaken multi-decadal binning of annually resolved temperature reconstructions. There are also several speleothem stable isotope series for New Zealand that cover the Holocene, including the last 2000 years (Lorrey et al., 2008; Lorrey et al., 2010; Lorrey and Bostock, 2017). In addition, two compilations of past Southern Alps glacier activity (summarised from Lorrey et al., 2008 and Schaefer et al., 2009) and a summer mean surface pressure anomaly reconstruction (after Villalba et al., 1997) completed the New Zealand low-resolution dataset that is relevant for Aus2k. In the interest of not duplicating data previously included in the Aus2k high-resolution compilation, the New Zealand tree ring data are excluded here.

Additional global syntheses are also drawn upon in this study. The charcoal database presented by Mooney et al. (2011) is the Australasian subset of a global charcoal database (Power et al., 2010), and contains all datasets (published and unpublished) up until 2011 that include charcoal analyses. The OZ-PACS working group under the Australasian Quaternary Association (AQUA) was created to investigate ecosystem changes and human impact on the landscapes over the last 500 years. One outcome of the initiative was a list of records until 2007 that covered the target period (Fitzsimmons et al., 2007).

2.3 Caveats on resolving changes from low-resolution sedimentary records

Despite the benefits of low-resolution archives, these records often contain relatively large errors associated with radiometric dating techniques (Anchukaitis and Tierney, 2012; Moberg et al., 2005) and uncertainty associated with using age-depth models to predict ages of undated layers (Trachsel and Telford, 2017; Telford et al., 2004). Age ambiguity leads to difficulty in cross-correlating records. These errors can result from three primary complications in radiocarbon dating techniques: dead carbon contamination, multiple possible calibrated ages associated with measured ^{14}C values, and inbuilt ages (McFadgen, 2007).

Radiometrically 'old' or 'dead' carbon derived from groundwater and/or carbonate rocks can drastically alter the apparent ^{14}C age of freshwater bodies (Geyh, 2000) and the organisms that live within or near the water (Beavan-Athfield and Sparks, 2001). The possibility of contamination by old carbon can be minimised through the use of short-lived plant macrofossils (Blois et al., 2011), when present, as well as dating of modern water samples to identify the presence of an old carbon reservoir (e.g. Gouramanis et al., 2010). Fluctuations in atmospheric ^{14}C through time may result from aperiodic changes in ocean-atmosphere-terrestrial radiocarbon partitioning, upper atmosphere radiocarbon production, and oceanic upwelling dynamics (Rodgers et al., 2011) that lead to 'wiggles' in the radiocarbon calibration curve. When this is pared with the measurement uncertainty of radiocarbon samples, it leads to a range of possible calendar dates (Blaauw, 2010). The inbuilt age of samples may have multiple components that influence dating uncertainties. These include incorporated age (i.e. chronologically old material contained in an organism that pre-dates its death, as with long-lived trees) and environmental residence time (also termed 'storage age'), which is the elapsed time between the death of the dated organism

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and deposition of its remains in a dated horizon (McFadgen, 1982). The most common example of this phenomenon is the preservation of long-lived trees in the landscape before deposition in sediment (see Grant, 1985, for an example related to alluvial sedimentation).

It is not always possible to identify environmental residence time within a radiocarbon sample, and the uncertainty may not be acknowledged within the resulting chronology (McFadgen, 2007). In some cases, anatomical studies may reveal whether incorporated age is large or minimal (e.g. identifying heart wood versus sapwood in tree samples). Methods exist to attempt to classify the relationship of a radiometric age to a horizon of interest, for example: i. a *close age* is a radiocarbon date from within or directly adjacent to the horizon of interest, which is assumed to have a minimal inbuilt age, due to the type of material; ii. a *minimum age* is derived from a sample with a minimal inbuilt age, which has been collected stratigraphically above the horizon or event of interest; and iii. a *maximum age* is derived from a sample with minimal inbuilt age, which has been collected from a horizon below the horizon or event of interest (McFadgen, 2007). Overall, the use of close ages within a horizon of interest, in conjunction with bracketing by minimum and maximum ages, assists in decreasing uncertainty in dating individual events. Estimated inbuilt ages for some common New Zealand plant species have been published (McFadgen, 2007), but less emphasis has been placed on this subject in Australian studies.

Identifying a high-quality subset of records allows both an inter-comparison of records and helps to answer questions of climatic consistency between or within regions (Tyler et al., 2015). Two factors that complicate comparison of published studies are the reliance on calibrated conventional radiocarbon ages (CRAs) and the wide range of methods that are currently used in age-depth modelling. The conversion of CRAs to calendar timescales can have variable results because of updates to the atmospheric radiocarbon calibration curve (Reimer et al., 2013). Furthermore, the calibration curves that are used to convert conventional CRAs to calendar-equivalent time scales have variable precision through time (Reimer et al., 2013). Both factors result in changes to the slope and variability of the calibration curve, so multiple statistically significant calendar age possibilities exist for CRAs on organic material. As such, the probability distribution ranges for calibrated CRAs (and therefore their temporal uncertainty) can be large (>100 calendar years) for some time periods in the last 2000 years (Anchukaitis and Tierney, 2012).

The recalibration of CRAs with the most up to date calibration curve can assist in improving the representation of the uncertainty for radiocarbon dates (Blaauw, 2010). A further source of age model uncertainty comes from the interpolation or modelling of ages between dated layers, an uncertainty that decreases proportionally to the number of age constraints. Traditional age modelling approaches, including linear regression and polynomial equations, treat age uncertainty within dated horizons and interpolated ages between chronological anchors differently. Age model uncertainty can be minimised by overlapping age probability distribution functions through a sedimentary sequence, but this is not always possible due to the cost of radiocarbon dating and availability of suitable material. Current age modelling techniques are capable of quantifying interpolation uncertainty when deriving age-depth relationships (Goring et al., 2012; Blaauw and Christen, 2011; Bronk Ramsey, 2009; Hua et al., 2012). Probability functions at each dated horizon are calculated, and then accumulation behaviour between these horizons is iteratively resampled to create thousands of possible time series. The

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probability distributions allow for the consideration of the non-singular nature of age calibrations for individual radiocarbon dates that form the anchors of a chronology (Hogg et al., 2013; Reimer et al., 2013).

2.4 Age model recalibration

One of the most commonly used software packages for constructing age models is 'BACON' (Bayesian ACcumulatiON histories) (Blaauw and Christen, 2011), which is run through the 'R' statistical package (RCoreTeam, 2015). Within the software, *a priori* information ('priors') informs the outcome of the statistical tests – namely the sampling interval, memory strength, and accumulation rate. Prior values can be set, based on existing knowledge of particular archives and/or study sites (e.g. Hua et al., 2012, Goring et al., 2012), and varied by the program to determine the best fit (Blaauw and Christen, 2011). The sampling interval prior is an estimate of the realistic physical distance over which the accumulation rate can change. It is not possible to know for certain if there are shifts in accumulation rate within one physical sample, so changes are restricted to sampling intervals.

Memory strength refers to the extent to which the accumulation rate of one section relies on that of the previous section (i.e. the degree of autocorrelation), or the likelihood of a rapid shift in the accumulation rate. For example, speleothems are observed to have minimal memory effect (Scholz et al., 2012); therefore, the memory prior should be lowered from the default (Hua et al., 2012). For the Aus2k datasets, accumulation rate has been estimated from the published age-depth model. Even if the published accumulation rate was inaccurate, the program considers how well the priors agree with the accumulation rate suggested by the data. This also allows for non-linear accumulation rates (Goring et al., 2012), which is an important consideration in the Australasian context. For example, a rapid increase in sedimentation rate is known to correspond to European settlement in Australia (Gell et al., 2009) and changes in land cultivation practices in the Malay Archipelago (Gharibreza et al., 2013; Rodysill et al., 2012).

BACON uses student t-distributions for radiocarbon dates, which have wider tales than normal distributions (Blaauw and Christen, 2011). This distribution is chosen with the intention of including the maximum number of dates in an age-depth model and decreasing the need to remove outliers. In this study, decisions of the original authors were upheld in the recalibration of age models, including the exclusion of radiocarbon dates due to inversion or contamination. Radiocarbon dates at terrestrial sites were recalibrated with the SHCal13 calibration curve (Hogg et al., 2013), while marine radiocarbon dates were recalibrated with the Marine13 curve (Reimer et al., 2013). Any radiocarbon reservoir effects identified by the original authors were applied during age-depth model construction. Overall, the approach used in this study maintains the specialist knowledge of the original authors, while updating records using a common statistical method for the development of age models and the calculation of uncertainty estimates.

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3 Results

3.1 General attributes of Australasian palaeoclimate data

The complete compilation of Australasian records contains 675 records (Supplementary Table 1), shown in Fig. 1. The areas of high data availability occur around the coastal population centres of Australia, with density decreasing with increasing distance from cities. The Malay Archipelago has a moderate, yet spatially even coverage. New Zealand has data available across the country, with a majority of records located within the northern and eastern North Island and the western South Island districts (Lorrey et al., 2008; Lorrey et al., 2010). Karst terrain extends in small patches along the length of both main islands in New Zealand. This has resulted in individual and composite speleothem records that have been used to infer past regional climate conditions (Lorrey et al., 2007). The most common source of terrestrial palaeoclimate information for both New Zealand and Australia is pollen, followed by biotic microfossils. Geochemical analysis of foraminifera is the most common proxy in marine cores (Supplementary Table 1). There are a number of study sites where multiple proxies have been analysed, particularly pollen and charcoal in terrestrial cores, and $\delta^{18}O$ and Mg/Ca of foraminifera in marine cores (Supplementary Table 1).

As seen in Fig. 2, the length of records varies dramatically. Some lake sediment records focus on environmental change over decades (e.g. Tibby et al., 2010), while some marine cores extend into the Pleistocene (e.g. Van der Kaars and De Deckker, 2002). For many records, the youngest age is not precisely known, but the original authors assume the core top reflects collect year or ‘present’ (1950CE). Some records are presented as having annual or sub-annual resolution (e.g. Martin et al., 2014); however, many of these records are not constrained by annually resolved markers. These types of records are regarded as non-annually resolved records in this study.

3.2 Results of PAGES Aus2k screening

When the PAGES selection criteria outlined in section 2.1 were applied to all Australasian records, a subset of 22 records met the stringent quality requirements (Table 1). Within this screened Aus2k subset, the two areas with greatest geographical coverage were southeast Australia and the Indonesian Malay Archipelago (Fig. 3). This follows the pattern seen in the complete dataset (Fig. 1). Records from Indonesia are predominantly marine (n=8), but also include four terrestrial records. Eight lake/wetland records are located within southeast Australia, and one speleothem record is located within Western Australia. One record is physically located in New Zealand, but as a record of dust accumulation, it is interpreted to be a proxy for Australian climate (Marx et al., 2009). Lacustrine microfossils are the most common terrestrial proxy in the Aus2k records, while foraminifera geochemistry is the predominant marine proxy. Average sample resolution varies; eight records have resolution less than 10 years/sample, including six lake cores, and two speleothems. Other records resolve decadal to multi-decadal time scales.

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3.3 Age model updates

The age models for all Aus2k records in Table 1 were recalibrated using the techniques outlined in section 2.4. The extent of change in the minimum and maximum ages, as well as timing of anomalous events, varies within the Aus2k datasets (Fig.4, Fig. S2). Examples of recalibrated chronologies are shown in Fig. 4.

4 Discussion

The results presented here are the first comprehensive collection of Australasian sedimentary records that cover the last 2000 years. Few records are currently publically available through the data archives outlined in section 2. There is moderate spatial and temporal coverage of existing records across the geographic network (Fig. 1 and 2), with the exception of poor coverage for arid central and western Australia. Although there are proxies from the arid region that cover longer time frames over the Quaternary (Fitzsimmons et al., 2013), most available records do not have the continuity and resolution to investigate climate variability during the Common Era. The resolution of most Australasian records falls between two and 300 years (Fig. 2), which is suitable for examining variability at multi-decadal to centennial time scales. A low number of radiocarbon dates and/or low confidence in the chronologies are the most common reasons for record exclusion from the Aus2k dataset. Therefore, even if record length and resolution are ideal for examining climate variability over the last 2000 years, age model uncertainties means that it would be difficult to draw conclusions on the timing of events.

4.1 Composition of the low-resolution Aus2k dataset

The 22 records that meet the PAGES2k selection criteria provide a subset of records with robust chronologies, an identified proxy-climate relationship, and sufficient record length and resolution to investigate decadal to centennial variability during the last 2000 years. As seen in Supplementary Table 1 and Fig. 2, the number of high-quality records is very low in comparison to the total number of palaeoclimate records identified and assessed. The low acceptance rate of records into the Aus2k database (3%) may reflect may reflect regionally specific problems of sparse and discontinuous sediment records and poor preservation of macrofossils for radiocarbon dating due to sparse vegetation, in addition to a historical focus on other aspects of Quaternary research in the Australasian region.

The geographic distribution of Aus2k records displays stronger spatial biases than the complete regional database (Fig. 3). Southeast Australia has seven records, likely following the ease of access to locations proximal to major cities with research institutions, and a relative abundance of lakes and wetlands. In contrast, the availability of high quality records in Indonesia relates to global interest in the region as a dynamical 'centre of action' for numerous climate drivers including the El Niño-Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the Australian-Indonesian Summer Monsoon (AISM), resulting in high levels of international funding for research in this area.

While New Zealand has a high number of sites that could potentially contribute more to understanding palaeoclimate of the last 2000 years, many records fail to pass the Aus2k criteria. The main reasons for New Zealand records

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not meeting the selection criteria are: lack of established proxy-climate variable relationship, insufficient sampling resolution, or the use of composite chronologies that require care in interpretation. Nonetheless, it is clear from the New Zealand proxy assemblages that the presence of tephras and pollen markers can improve the chronostratographic constraints associated with ^{14}C dates as applied in many cores. Some sites also show potential to be revisited to improve age controls, sample at higher resolution, and calibrate proxy data against instrumental records to develop a reliable climate reconstruction (Roop et al., 2015).

The subset of 22 high quality records that meet the Aus2k criteria include a range of lacustrine sediment cores, marine cores, speleothems, and two peat cores. These archives are best suited for examining decadal to multi-decadal variability due to their accumulation rate, continuity, preservation, and dating potential. A brief description of archives and their applicability to studying climate variability during the Common Era is provided below.

4.1.1 Lakes, wetlands, and peatlands

The majority of palaeoclimate records in Australasia are sediment cores from lake and wetland environments (Fig. 1, 3). The length of lake and wetland records can vary greatly, including short, high-resolution records that focus on inter-annual changes, and long, low-resolution records that cover hundreds of thousands of years (Fig. 2). Cores are analysed for both biogenic and inorganic proxies. Peat bogs can be ideal sources of sediment cores because of high accumulation rates and the capture of a variety of organic and non-organic components (Barber et al., 1994; Booth et al., 2010). Peat is a promising archive within Australasia due to the large longitudinal coverage; mires are found from tropical locations in Papua New Guinea to the sub-Antarctic islands (McGlone, 2002a; McGlone et al., 2010; Whinam and Hope, 2005). Most peat-based records in Australasia contain pollen and charcoal that may be used for palaeoclimate, palaeoecology, and palaeo-fire reconstructions (Whinam and Hope, 2005; Mooney et al., 2011). Degree of humification has also been applied as a hydroclimate indicator in the late Holocene (Burrows et al., 2014; Wilmshurst et al., 2002) in cores were dating density is sufficient.

A possible limitation in the Australasian context is the assumption of a stable relationship between sediment properties and climate variables over long periods of time. Humans have likely impacted Australian wetland ecosystems for the entire duration of the Holocene (Fletcher and Thomas, 2010b; Black et al., 2007), and impact has been recognised in New Zealand during the last millennium (Horrocks et al., 2007; McGlone and Wilmshurst, 1999b). This anthropogenic influence has intensified across Australasia since the arrival of European settlers (Gell et al., 2007; Bickford and Gell, 2005; McGlone and Wilmshurst, 1999a), which may lead to palaeolimnological signals unrelated to climate. The primary consideration in lake, wetland, or peat-derived climate archives is a clear understanding of the modern proxy-climate relationship, including the geomorphic, hydrological, geochemical, and biological response, most of which are complex and non-linear (Adrian et al., 2009; Winder and Schindler, 2004). Site-specific factors such as sediment accumulation rate, basin morphology, and hydrological balance, may potentially have a strong impact on the preservation of climate signals (Wigdahl et al., 2014). Detailed understanding of these relationships relies on local monitoring programs or comparisons between

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observed proxy behaviour and instrumental records over a sufficient length of time. Development of mechanistic response models is also a priority, in order to quantify the sensitivity of certain proxies to hypothetical changes, as well as to integrate the multiple climate effects upon a particular palaeoclimate record.

The most common approach for characterising modern proxy-limnology-climate relationships in Australia is the 'calibration in space' of lake and wetland derived proxies, where lakes across an environmental gradient are sampled for the purpose of identifying these relationships (Gell, 1997; Saunders, 2011). In addition, 'calibration in time' has been performed, whereby a proxy time series is calibrated with instrumental meteorological timeseries data to produce a predictive transfer function for quantitative reconstruction beyond the calibration period (Larocque-Tobler et al., 2011; von Gunten et al., 2012; Cook et al., 1994). Two studies within the Aus2k dataset have used 20th century instrumental precipitation and temperature data for calibration of longer records of sediment reflection data (Saunders et al., 2013; Saunders et al., 2012).

Ostracods

Ostracods, small carbonate bivalve crustaceans, have been used as palaeosalinity and lake level indicators in southern Australia for over three decades (De Deckker, 1982; Gouramanis, 2009). The regular moulting of valves throughout the organisms' lifetime means that there is a rapid response time of calcite accretion to changes in the lake environment. Originally, observed salinity tolerances of modern species were used to infer palaeosalinity (De Deckker, 1982). More recently, transfer functions have been developed to translate fossil assemblages into quantitative salinity estimates through the use of spatial training sets for sites across southern Australia (De Deckker et al., 2011; Gouramanis et al., 2012; Gouramanis, 2009; Kemp et al., 2012). Reconstructed lake water salinity fluctuations are interpreted to reflect precipitation-evaporation (P/E) balance, assuming minimal groundwater flow into and out of the lake basin.

Geochemical analysis of ostracod valves is another proxy used to reconstruct lake chemistry and water temperature. Monitoring of modern lacustrine systems has led to detailed understanding of controls on ostracod valve chemistry in Australian lakes. Valve Mg/Ca records both lake water Mg/Ca values and temperature (Chivas et al., 1986). For much of the ostracod research in Australia, valve Sr/Ca has been interpreted as a proxy for water Sr/Ca (Chivas et al., 1985; Chivas et al., 1986) with a possible temperature influence (De Deckker et al., 1999). Recent studies argue that alkalinity is also an important influence on valve Sr/Ca (Gouramanis and De Deckker, 2010). Stable isotope analyses are also undertaken on the carbonate valves. Oxygen isotope values reflect the combined influence of the oxygen isotopic composition and temperature of the lake water, while carbon isotopes reflect the isotopic composition of the dissolved inorganic carbon present in the lake system (see Gouramanis et al., 2010 and references therein).

Detailed ostracod-based investigations of climatic and environmental change, as well as salinity reconstructions indicative of E/P balance, are available for Blue Lake in South Australia (Gouramanis et al., 2010), Barker Swamp in Western Australia (Gouramanis et al., 2012), Lake Keilambete and Lake Gnotuk in southern Victoria (Wilkins et al., 2013), and lakes in the northern region of Victoria (Kemp et al., 2012). Although the sample resolution at Barker Swamp and Lake Gnotuk precludes the inclusion of the sites in the Aus2k dataset, all of these sites possess a salinity reconstruction. This

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diversity of proxies, as well as the high-resolution sampling of the sediment cores, has allowed for high-quality climate and environmental reconstructions based on Australian ostracod records.

Diatoms

Ecological assemblages of diatoms, siliceous unicellular algae, are used to create quantitative and qualitative climatic and environmental reconstructions for lake and river systems across Australasia. Diatom fossils are well suited to decadal to multi-decadal climate reconstruction because of their short lifespan and sensitivity to subtle changes in their environment. These characteristics facilitate rapid responses to shifts in environmental change and high-resolution sampling in sediment cores. Transfer functions, developed from modern calibration data sets, have been established for numerous aquatic variables in both estuarine (Logan and Taffs, 2013; Tibby and Taffs, 2011) and lacustrine (Gell et al., 2005) settings. Variables include conductivity/salinity (Barr, 2010; Barr et al., 2014; Gell, 1997; Saunders et al., 2007; Saunders et al., 2008; Saunders, 2011), pH (Tibby et al., 2003), and nutrients (Logan and Taffs, 2013; Tibby, 2004). Detailed studies on short time scales have examined pre-European baselines and anthropogenic impact since European settlement in the 19th century through pH (Taffs et al., 2008), salinity, and nutrient (Saunders et al., 2008) reconstructions.

Two diatom-derived conductivity reconstructions for Lake Elingamite and Lake Surprise in western Victoria are included in the Aus2k dataset (Table 1). Transfer functions for the lakes are based on 47 sites across southeast Australia, and reconstructions have been subject to multiple forms of quality control before being interpreted in a climatic framework (Barr et al., 2014). In addition, both sites have chronologies based upon radiocarbon and ^{210}Pb dates that constrain the timing of inferred climatic shifts. Date density along the core, in addition to dates near the bottom of the core, leads to reduced uncertainty for age estimates for each sample (Barr et al., 2014).

Palaeo-water isotopes

Plant wax deuterium (δD), controlled by source water deuterium values, can be preserved in lake and marine sediment cores. Analysis of leaf n-alkanes can assist in the reconstruction of local precipitation δD values if the degree of fractionation between the leaf and water is known (Sachse et al., 2006). Two Indonesian sedimentary records within the Aus2k dataset use δD measurements as a climate proxy: one terrestrial and one marine. Konecky et al. (2013) used terrestrial plant wax compounds in lake sediments to reconstruct rainfall amount, associated with Australian-Indonesian Summer Monsoon intensity. Tierney et al. (2010) analysed leaf waxes in material that had been transported offshore. The same controls on δD were assumed in both settings, with no impact by sediment transport in the marine core.

Lithics

The lithic fraction of sediment cores can provide information about climate driven depositional environmental changes through time. In Australia, grain-size analyses have been used as lake-level indicators in locations where the relationship between sediment size fraction and lake levels is well understood. The most heavily studied example is Lake Keilambete in Victoria (Bowler, 1981; Bowler and Hamada, 1971; Mooney, 1997; Mooney and Dodson, 2001; Wilkins et al., 2013). The Lake Keilambete lake level reconstruction is very commonly used for validation of other palaeoclimate records in the region. Recent high-resolution sampling of new cores, and the examination of new proxies within these cores,

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reinforces the interpretation of the grain size analysis (Wilkins et al., 2013). The dating density is also the highest of any of the Aus2k records, with four new accelerator mass spectrometry (AMS) radiocarbon dates and four optically stimulated luminescence (OSL) dates within the last 2000 years in the most recent chronology (Wilkins et al., 2012).

Changes in transport into a lake, reflected by accumulation rate, can be driven by climatic changes such as surface runoff or wind strength, or changed catchment conditions due to human impact (Sloss et al., 2011; Zhang et al., 2011). A rapid increase in sedimentation rates associated with European settlement is seen across Australia. Studies of wetlands and lakes across southern Australia have revealed increases from two- to eighty-fold between pre-settlement and modern day (Gell et al., 2009; Hollins et al., 2011; Sloss et al., 2011). This phenomenon is important for separating human and climatic influences on sediment cores. The lacustrine records that are available across New Zealand contain evidence for discrete sedimentation events or sedimentation variability. Signatures of acute sedimentation are interpreted as rapid in-washing of coarse loads (Lake Rotonuiaha (Wilmshurst et al., 1997); Lake Tutira (Eden and Page, 1998; Gomez et al., 2012); Round Lake (Chester and Prior, 2004)) that could be influenced by climate and/or seismic variability. Some of the lithological changes observed in lake cores are suggested as a response to climatically driven increases and decreases in lake level (Lake Maratoto (Green and Lowe, 1985); Lake Poukawa (McGlone, 2002b)). Other triggering factors for lake sedimentation that have been hypothesised and/or demonstrated include fluvial undercutting, anthropogenic impacts, weathering, and tectonically induced base level changes (Eden and Page, 1998).

Non-destructive analytical techniques for sediment cores are becoming more widespread in Australasian studies. These techniques, including reflectance spectroscopy (Saunders et al., 2012; Saunders et al., 2013) and X-ray florescence (Fletcher et al., 2014), can be conducted at very high (<1mm) resolution, and are easily combined with other analyses for multi-proxy studies.

Another important component of sediment deposits in Australia is the aeolian dust fraction. Dust deposition rates are a proxy for continental aridity and wind intensity, while spatial differences in deposition rates can suggest shifts in dust transportation pathways (Bowler, 1976; Hesse, 1994; Hesse and McTainsh, 2003). The method for classifying dust varies by site, and depends on the sedimentary environment. For coastal study sites, the local quartz input from sand dunes is ignored, while remaining material is assumed to have been transported to the site via aeolian means (McGowan et al., 2008). For peat bogs, the mineral content is determined as the non-combustible fraction of dry peat mass (Marx et al., 2011; Marx et al., 2009). Mapped and modelled variations in trace element signatures and ratios of 'far-travelled' sediment can elucidate shifts in dust sources and net transport (Marx and Kamber, 2010; Marx et al., 2011; Petherick et al., 2009). Grain size and morphology of quartz grains have also been analysed as proxies for wind speed and aeolian transport pathways (Stanley and De Deckker, 2002). The Aus2k dataset contains two records that analyse the aeolian dust fraction in peat cores (Marx et al., 2009; Marx et al., 2011). In both records, cores were extracted from locations slightly elevated (~1m) in comparison to the surrounding bog. This collection approach is predicted to minimise transport of local sediment and maximise atmospheric deposition. Frozen sediment cores were sampled at multi-decadal resolution. Cores from both sites were examined for trace

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element concentration, which allowed for reconstruction of overall dust deposition as a proxy for continental aridity, as well as contribution of dust from specific source areas (Marx and Kamber, 2010; Marx et al., 2005).

Pollen

Australasia has a rich history of palynological studies, with research extending back to the 1960s (Churchill, 1960; Moar, 1967). Early research focused on reconstructing vegetation diversity at a single site, but approaches have expanded to examine broader environmental questions such as regional vegetation response to climatic shifts (Donders et al., 2007), reconstruction of a specific variable across a region (Fletcher and Thomas, 2010a), recovery from episodes of disturbance such as fire (Lynch et al., 2007), and responses to human impacts in the pollen catchment (Haberle et al., 2006; Horrocks et al., 2001; Leahy et al., 2005).

The investigation of the abundance and ecological assemblage of pollen spores sheds lights on palaeoecological dynamics through time, predominantly driven by changes in climate (Donders et al., 2007; Kershaw et al., 1991) and the impacts by human activity (Lynch et al., 2007). There is an extensive network of well-studied sites centred on the Atherton Tablelands in northern Queensland (Haberle, 2005; Haberle et al., 2006; Kershaw, 1970, 1975, 1983, 1971; Kershaw et al., 2007; Walker et al., 2000), including some of the most highly cited records of Australian-Indonesian Summer Monsoon dynamics and rainforest response to climate variability through time (Kershaw, 1994). The majority of pollen records are restricted to the peripheries of the Australian continent due to the need for water availability in the accumulation and preservation of pollen grains (Fitzsimmons et al., 2013). There have been comparisons of available pollen records for southeast Australia (D'Costa and Kershaw, 1997), and a north-south transect of high-quality pollen records along the east coast of Australia (Donders et al., 2007). New Zealand palynology records cover the entire length of the country, and range in resolution from millennial scale to multi-decadal scale (see references in Lorrey and Bostock, 2017).

While almost all Australasian pollen reconstructions are qualitative in their approach, there have been a small number of quantitative studies. Cook and Van der Kaars (2006) comprehensively outlined early approaches (i.e. single-taxa indicators and modern analogue techniques (MAT)) and their limitations in the Australian context. The same study explored the potential of existing pollen sites to be used for construction of transfer functions, and found that regional transfer functions could be used to associate modern pollen distributions to modern hydroclimate. Herbert and Harrison (2016) conducted a similar review of modern analogue techniques in Australia and suggested that, despite possible limitations in the current sampling density of the continent, MAT can be an appropriate reconstruction technique. Transfer functions have been produced for average annual temperature in Tasmania (Fletcher and Thomas, 2010a) and New Zealand (Wilmshurst et al., 2007), but no quantitative reconstructions that pass the Aus2k criteria encompass the Common Era. Development of training datasets in New Zealand has historically been complicated by deforestation since 750YBP; however, a pre-deforestation dataset developed by Wilmshurst et al. (2007) mitigates this issue for future New Zealand studies.

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The most common approach in Australia is the 'calibration in space' of lake and wetland derived proxies, where lakes across an environmental gradient are sampled for the purpose of establishing modern proxy-limnology-climate relationships (Gell, 1997, Saunders, 2011). Comparisons with instrumental records form the basis of the 'calibration in time' technique, where a proxy time series is calibrated with meteorological data to produce a predictive function for quantitative reconstruction for a longer time series (Larocque-Tobler et al., 2011). Two studies within the Aus2k databset have used 20th century instrumental precipitation and temperature data for calibration of longer records of sediment reflection data (Saunders et al., 2013, Saunders et al., 2012). A possible limitation in the Australasian context is the ... [8]

4.1.2 Marine cores

Marine sediment cores have been collected from the entire perimeter of Australasia, some of which have accumulation rates and chronologies suited to the analysis of the last 2000 years (Fig. 1 and 3). In cores recovered in areas where sediment incorporates terrestrial input, microfossils reflect conditions within defined horizons in the water column and organic biomarkers indicate environmental conditions in the biome of origin (Bradley, 2014). Marine sediments deposited within the last 2000 years are dated through radiocarbon methods and tephrochronology (Mohtadi et al., 2014; Oppo et al., 2009).

There is a dense concentration of marine cores in the Indonesian region, where there are large areas of shallow continental shelves (Reeves et al., 2013a). These areas remained above the lysocline through the recent past and now provide ideal sites for marine sediment core collection. Overwhelmingly the most commonly studied proxy in marine cores is the geochemistry of biogenic material. During recent millennia, oxygen isotopes of planktonic and benthic foraminifera vary as a function of both temperature and δ^{18}O-seawater (Zachos et al., 1994). For some coupled ocean-atmosphere climate modes, such as ENSO and the IOD, the coupled warm/wet and cold/dry conditions influence the δ^{18}O signature in the same direction, thus intensifying the climate signal in the oxygen isotopes (Brijker et al., 2007; Khider et al., 2011).

In places where both temperature and salinity vary on inter-annual time scales, Mg/Ca analyses allow for elucidation of the two components of the δ^{18}O signature. Mg/Ca ratios are controlled by temperature, and are independent of seawater salinity changes (Lea et al., 1999). These independent temperature determinations can then be used to remove the temperature component of δ^{18}O and isolate the salinity component. Therefore, the water temperature and water salinity can be used independently for climate reconstructions (Elderfield and Ganssen, 2000). This has allowed the tracing of the geographic extent, dominant control, and average conditions of the Indo-Pacific Warm Pool through time (Oppo et al., 2009; Stott et al., 2004), as well as connectivity between the Pacific and Indian Oceans through the Indonesian Throughflow (Linsley et al., 2010; Newton et al., 2011). In addition, water-column dynamics have been investigated by reconstructing temperature differences between surface-dwelling and thermocline-dwelling species of foraminifera. This has led to inferences about wind-driven mixing (Steinke et al., 2010) and properties of water masses that upwell in other regions of the globe (Khider et al., 2014).

Alternate isotopic analyses, such as the δD interpretations outlined above, have also been applied to the marine realm (Tierney et al., 2010). In central Indonesia, one study has employed δ^{15}N, controlled by basin ventilation, as a proxy for localised ENSO signatures (Langton et al., 2008). Marine proxies are well established as recorders of climate information over long time scales. Again, sedimentation rate is the primary limitation of marine cores as recorders of Common Era climate. It is also important to separate the atmospheric and oceanographic drivers of variability in sea-surface temperatures and salinity through multi-proxy approaches.

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4.1.3 Speleothems

Over the past half-century, speleothems have emerged as valuable sources of palaeoclimate information because of their potential for preserving precisely dated, multi-proxy, high-resolution records of past climate change (Fairchild et al., 2006). They cover a range of temporal scales across the Holocene, from millennial (Partin et al., 2007) through to monthly to weekly resolution (Frappier et al., 2007; Treble et al., 2003; Treble et al., 2005a). Recent work indicates that Australasian speleothems offer a high-quality source of palaeoclimate information over the Common Era. Young speleothems (up to ~300 YBP) can be dated through high-precision U-Th dating methods, as long as there is sufficient uranium within the calcium carbonate matrix and the growth rate is fast enough to provide sufficient material for dating (Zhao et al., 2009). Resulting dates can have appropriate precision (+/-10-80 years) for reconstructing multi-decadal to centennial climate fluctuations (Zhao et al., 2009). Radiocarbon bomb-spike dating has also been used to date young speleothems when U-Th dating techniques are not appropriate (Hua et al., 2012).

Speleothems fill an important geographic niche in the Australasian region, particularly for Australia, as they can be found in karst regions where a lack of standing surface water precludes the development of lacustrine records. Similar to lake cores, geochemical interpretations are site-specific, with depositional controls varying with bedrock characteristics and local climate. Moreover, the application of multiple proxies contained within speleothems can be used to narrow the range of possible palaeoclimatic and palaeoenvironmental interpretations. The site-specific nature of many reconstructions is reliant on site monitoring, hydrologic modelling, and karst theory (Baker et al., 2014; Fischer and Treble, 2008).

The calcite mineralogy of speleothems means that they are ideal for oxygen and carbon isotope analysis and trace element concentration determinations. The complexity of site-specific controls on oxygen and carbon isotopes is recognised within speleothem studies (Lachniet, 2009); as such, it is necessary to investigate the impact of precipitation geochemistry (Fischer and Treble, 2008), processes in the aerated (vadose) zone above the cave (Dreybrodt and Scholz, 2011), and in-cave conditions (Baldini et al., 2006) on the $\delta^{18}O$ signal preserved in each speleothem. Oxygen isotopes in mid-latitude Australian speleothems primarily record rainfall amount through precipitation isotopic composition (Treble et al., 2005a) or record karst aquifer recharge frequency (Markowska et al., 2016), whereas tropical samples from Indonesia and the monsoonal region of northern Australia are more sensitive to the intensity of precipitation (Denniston et al., 2013; Griffiths et al., 2013). Recent dripwater monitoring has also identified a $\delta^{18}O$ response signal after a bushfire, driven by a change in surface evaporation/precipitation balance (Nagra et al., 2016). In young speleothem records, $\delta^{18}O$ values can be compared to instrumental climate data to identify correlations with temperature and rainfall (Treble et al., 2005a). Where speleothems can be sub-annually resolved, or where a significant seasonal bias can be inferred, excursions in speleothem $\delta^{18}O$ in tropical regions can be related to past cyclone events; this signal has been used to calculate cyclone occurrence over the past millennium (Haig et al., 2014). Early- to mid-Holocene $\delta^{13}C$ in a Tasmanian speleothem record was inferred to reflect productivity and the resulting carbon isotope fractionation in the soil (Xia et al., 2001). This is based on the extent to which atmospheric CO_2 is released into the soil through vegetation breakdown, and is controlled by moisture levels in the soil

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(Goede, 1994). The comparison of $\delta^{13}C$ analyses with trace element analyses may provide clarification of dominant controls on carbon isotopic fractionate at a given study site (Treble et al., 2005b). Treble et al. (2005b) suggest that their 20th century $\delta^{13}C$ record could partially reflect water stress on leaf stomata (Farquhar et al., 1988), based on correlation with Mg concentrations. In Indonesian speleothem records, $\delta^{13}C$ has been found to often co-vary with Mg/Ca and Sr/Ca ratios, suggesting that these proxies respond to prior calcite precipitation (Griffiths et al., 2010; Partin et al., 2013). Prior calcite precipitation (PCP) occurs in dry conditions, when less water is transported or stored in the vadose zone, which leads to degassing of CO_2 into fractures in the bedrock (Fairchild et al., 2000).

In the New Zealand setting, many different factors are demonstrated to influence stable isotope signals in speleothems (Williams et al., 2010). Previous studies, which are largely theoretical, have indicated that $\delta^{13}C$ variations can be used to interpret climate changes in the form of local water balance (Lorrey et al., 2008). Including the aforementioned idiosyncrasies for cave environments and processes, local water balance has been largely assumed to represent effective precipitation in New Zealand. Therefore, past research has exploited $\delta^{13}C$ as a proxy for hydroclimatic variability related to precipitation amount. That reasoning has been employed to make inferences from speleothems about regional atmospheric circulation, which controls climate regimes and regional-scale precipitation (Lorrey et al., 2007). This synoptic approach allows the integration of co-varying, spatially heterogeneous responses of several speleothem environments to surface climate, which is forced by orographic circulation and advection related to base climate state shifts (Lorrey et al., 2008; Lorrey et al., 2014; Lorrey et al., 2012).

In the Australian setting, Mg/Ca in speleothems has been shown to be a reliable recorder of effective rainfall (Fairchild and Treble, 2009; Treble et al., 2003; McDonald et al., 2004) because longer water residence times increase the Mg/Ca in speleothem drip water (Fairchild et al., 2000; Fairchild and McMillan, 2007). This relationship has been supported by comparison of recent speleothem records to instrumental datasets (Treble et al., 2003). In addition, Australian studies of Sr/Ca has found the ratios to represent temperature-regulated fluctuations in terrestrial productivity above the cave (Desmarchelier et al., 2006) or the combined effect of PCP and/or growth rate, depending on the time scale examined (McDonald et al., 2004; Treble et al., 2003). Multiple nutrients in dripwaters, including Cl, Mg, and Sr, were impacted by bushfires in Western Australia, driven by removal by fire processes, and subsequent changes in surface evaporation (Nagra et al., 2016). Indonesian studies suggest that drip rate and residence time influence Mg/Ca and Sr/Ca ratios in locations where PCP is not a constant driver (Partin et al., 2013). P/Ca has been suggested to be a palaeorainfall proxy (Fairchild et al., 2001; Treble et al., 2003) because of the release of phosphorous from soils and subsequent transport and incorporation associated with heavy rainfall events.

The only speleothem record in the Aus2k dataset is from Liang Luar Cave, a tropical $\delta^{18}O$ record that expresses precipitation intensity above the cave (Griffiths et al., 2016; Griffiths et al., 2009). The very fine sampling interval means that the average sample resolution is high (8 years/sample).

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4.2 Discussion of age modelling approaches

The recalibrated age-depth models developed in this study have variable agreement with the originally published models (Figure 4, Figure S2). Most studies previously published in the Australasian region have constructed chronologies through linear interpolation between median calibrated ages. Blaauw (2010) stresses the hazard of ignoring the non-singular age distribution of calibrated radiocarbon dates because of obscured error in the age depth models when date distributions are not properly acknowledged. The Aus2k records use variable construction methods for the published chronologies and variable methods of estimating and acknowledging errors. This is the primary reason for recalibrating existing Australasian age models and comparing the outcome of updated approaches to the published models.

Chronologies for most marine sediment cores are based on fitting a linear age-depth relationship across the set of dates. The results of BACON-derived age models moderately support the application of linear accumulation for this archive, with the ages of young/shallow samples more likely to match between the two approaches in comparison to samples from deeper in the core. The disparity between published and reconstructed ages for marine records increases back through time. This is most likely related to date density through individual cores, as well as periods of interpolation between dated horizons. Indonesian marine cores use the 1815 Tambora tephra as a chronological anchor, which decreases age uncertainty near the present, but date density further back in time varies between records.

The published Snowy Mountain core had age model difficulty, with two possible age models with similar r^2 values (Marx et al., 2011). The self-adjusting Monte-Carlo approach within the BACON software clearly favoured one model over the other (Supplementary Fig. 1). The BACON-derived age model showed greater agreement with the published age model built upon more dates. This is likely driven by acknowledgement of the probability distributions of calibrated radiocarbon dates, as well as estimated autoregression between sampled (but undated) depths.

Advances have been made with publically accessible statistical age modelling software over the past decade. The 'CLAM' (CLassical Age Modeling) software package facilitates age modelling through combining classical statistics with calibrated radiocarbon dates within a Monte-Carlo framework (Blaauw, 2010). This approach incorporates realistic probability distributions for calibrated radiocarbon dates, and can calculate age uncertainty through thousands of Monte Carlo iterations. However, the underlying statistical methods within and between classical and Bayesian approaches vary greatly (Blaauw, 2010; Blaauw and Christen, 2011; Bronk Ramsey, 2009). In the 'CLAM' software, the creator choses the type of relationship used to predict ages between chronological anchors (e.g. linear interpolation, polynomial regression, or smoothing splines), and then the program calculates likely age distributions based upon the chosen type of relationship. Blaauw (2010) suggests that Bayesian approaches construct more realistic age-depth models due to their incorporation of observed or predicted sediment behaviour; however, the simplicity of the classical approach means that it is arguably easier to construct age models, and the method remains transparent.

Two study sites in southern Australia (Barr et al., 2014) were originally published with chronologies constructed using CLAM. The Bayesian age models, based on the same radiocarbon and 210Pb dates, produced similar maximum and

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minimum ages and timing of events within the record, however notable differences are also visible, particularly for the Lake Elingamite record between 100-50YBP and between 1300-1200YBP (Supplementary Fig. 2). Differing age-depth model behaviour within these periods generally reflects differences in the degree of rigidity in the modelling approaches. That is, BACON age models appear more resistant to shifts in accumulation rate, even when low memory strength is implied within the prior settings. By contrast, CLAM allows the user to fit age models that respond more readily to changes in sediment accumulation rate. Rigidity is not a benefit or weakness of any given approach, but is a characteristic to be considered during age model construction. The literature suggests that Bayesian approaches still incorporate more site-specific information than classical methods; however, consistency in determining age uncertainties and objectivity in age modelling is arguably more important for regional comparisons (Blaauw, 2010).

The strongest predictors for the error envelope at the oldest/1CE sample are: (i) the distance between the oldest/1CE sample depth and the nearest age anchor, and (ii) the 95% confidence interval at the nearest dated horizon. The records that have the greatest departure from the published age models are those that have the smallest number of chronological anchors. The international PAGES working group established a criterion of two dates for records <1000 years and three dates for records between 1000-2000 years in length. However, the outcomes of this study demonstrate that this criterion is still too relaxed for robust investigation of decadal to multi-decadal climate variability in the Common Era. For example, the age model for the one Makassar Strait record (Tierney et al., 2010) is based on six dates and one tephra layer across two cores covering the past 2000 years. The number of dates present is much higher than that suggested by PAGES2k, but dating density in this record still results in an average 95% confidence envelope for sample ages that is greater than 100 years. Therefore, the outcome of age model recalibration in this study suggests that the criterion of two or three dates within 2000 years is not nearly stringent enough to provide robust chronologies for examining climate dynamics over sub-centennial time scales. Based on the outcomes presented here, the authors propose at least one date every 200 years, with at least one date near the top of the core, and another near the oldest sample/1CE.

It can be argued that the Bayesian methods applied in this study represent the current state of the art with regards to age-depth modelling of Quaternary sediment sequences. Nevertheless, due to the on-going development of radiocarbon calibration and modelling techniques, the age models generated here should not be viewed as permanent optimized chronologies. Radiocarbon calibration and chronology construction methods are likely to improve through time. Therefore, continuous updates of age modelling approaches could be assisted via provision of raw dates and complete chronological metadata in publications and public data repositories.

4.3 Aus2k dataset limitations, potential, and recommendations

Identification and assessment of existing Australasian palaeoclimate records have highlighted limitations in the current data network. These constraints are outlined and discussed in the following section. This review also highlights additional action items that may be undertaken to improve the data network in the Australasian region. Expansion of the Aus2k palaeoclimate

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data network in a geographically large, but institutionally limited region is a considerable undertaking. Therefore, a concerted community effort is required to coordinate the collection of new palaeoclimate data.

4.3.1 Climate variables and relationships

One reason for identifying and assessing low-resolution records in Australasia is to determine what climate variables are represented in the high-quality subset. A distinct skew is evident for the types of climate variables currently available. New Zealand is biased towards temperature interpretations, with many of the existing low-frequency records having been constructed through multi-decadal binning of annual data (not discussed within this study). On the other hand, climate variables currently represented in the high quality Aus2k subset are heavily skewed towards hydroclimate indicators, as reconstructed by the diverse proxies outlined in section 4.1.

Only one low-resolution terrestrial temperature reconstruction exists in the Aus2k dataset: the Duckhole Lake record (Saunders et al., 2013). A range of proxies has been used in other regions of the world to reconstruct terrestrial palaeotemperatures in low-resolution records (Marcott et al., 2013); however, they have not yet been applied to Australasian sites at the time scales examined here. Lake temperatures have been reconstructed through chironomid transfer functions on the east coast of Australia (Chang et al., 2015), Tasmania (Rees and Cwynar, 2010), and the South Island of New Zealand (Vandergoes et al., 2008; Woodward and Shulmeister, 2007) at time scales beyond the Common Era. Modern training sets exist for additional locations in Tasmania (Rees et al., 2008) and an additional location on South Island, New Zealand (Dieffenbacher-Krall et al., 2007). All of these transfer functions have the potential of being applied to the Common Era, thus providing quantitative reconstructions from sub-tropical and temperature climate zones of Australasia.

Another temperature proxy applied to Australasian sites is the distribution of branched glycerol dialkyl glycerol tetraethers (GDGTs) in membrane lipids in sediments (Prahl and Wakeham, 1987). This proxy has been used to reconstruct mean annual temperature in Lake Pupuke in New Zealand (Heyng et al., 2015) and Lake Mackenzie in Australia (Woltering et al., 2014). Both temperature and aridity have been reconstructed for Onepoto Maar by combining analysis of fatty acid $\delta^{13}C$, biomass-burning biomarkers, and pollen abundances calibrated to mean annual temperatures (Sikes et al., 2013). The use of GDGTs and other lipid biomarkers has great potential for reconstructing Australasian temperatures during the Common Era, however it faces significant challenges too, including non-systematic uncertainties of ~1ºC which may obscure the magnitude of temperature change during the last 2000 years, in addition to much greater systematic uncertainties related to the origin of the biomarkers and the type of calibration used (Woltering et al. 2014).

Borehole-derived ground surface temperature reconstructions from across the Australian continent show strong agreement with high-resolution palaeoclimate datasets (Appleyard, 2005; Cull, 1982; Huang et al., 2000; Pollack et al., 2006; Suman et al., 2016). However, the temperature estimates derived from boreholes reflect long-term, low-frequency trends that fall outside the desired sample resolution of this study (Pollack et al., 2006).

A requirement of all palaeoclimate research is a thorough understanding of the relationship between climate variability and the geochemical, sedimentological, or biological composition of any record. To address these questions,

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researchers are employing long-term monitoring strategies to develop a detailed understanding of local conditions required for calibrating palaeoclimate archives (Markowska et al., 2016; Treble et al., 2003). In some cases, monitoring outcomes can lead to some palaeoclimate records being excluded on the basis of hitherto unknown complications; conversely, modelling the response of palaeoclimate tracers to climate change can lead to more rigorous quantitative constraints on past climates (Jones et al., 1998; Jones et al., 2001). Developing modern monitoring strategies should sit prominently in the collective community goal of generating more reliable regional palaeoclimate records. Site-specific monitoring projects are particularly important in the Australian region, where shortcomings in the gridded instrumental meteorological dataset are observed in rural areas and areas of steep climatic gradients (Jones et al., 2009; Tait et al., 2006).

4.3.2 Chronology

The most important characteristic that a record must possess for inclusion in the 'high quality' dataset is a robust chronology, accompanied by acknowledgement and estimation of possible sources of uncertainty. Many older publications have a small number of dates due to the high cost of radiocarbon analysis in past decades. There are now low-cost commercial services, and institutional dating operations have endeavoured to match the costs of the competitive commercial market. These developments mean new, more cost-effective dating strategies can be employed to create new well-dated records, as well as renewed efforts to revisit former sites to improve the original chronologies.

There are also important caveats with composite records that cover the last 2000 years (see speleothem data presented in Lorrey et al., 2008). For example, composite data may be subject to distortion because of inconsistencies in the methods used to compile overlapping series into a longer, continuous record. From this perspective, potential issues could be inherited from changes in sampling interval, as well as resultant mean and variance shifts across transitions where individual series are spliced into longer records (Lorrey et al., 2010). A similar perspective can also be applied to irregular event-based records, such as alluvial sediments (Grant, 1985) that are bracketed by tephras and/or radiocarbon ages, or compilations of geochronology dates on moraine emplacement. In these types of cases, further work could help to evaluate the veracity of composite low-resolution records, and also determine protocols on how the development and interpretation of "master records" (e.g. isotope chronologies from several speleothems in one cave) could be improved. Inevitably, a multi-proxy approach for corroborating interpretations is warranted.

It is possible for local factors to limit optimal dating materials or complicate the interpretation of radiocarbon dates (e.g. Rodysill et al., 2013). However, use of tephrostratigraphy as chronological has commonly been applied in New Zealand records (Lowe et al., 2013), has been employed in initial syntheses (Lorrey et al., 2008, Lorrey et al., 2010), and has equivalent potential in most Malay Archipelago records. The only eruption used as an anchor in the Aus2k dataset is Tambora (1815CE) in the Malay Archipelago records. Additional New Zealand tephras have been identified and characterised within the Common Era (Lowe et al., 2013), and a previously unutilised tephra in the Malay Archipelago has been characterised (Alloway et al., 2017). Identification of additional eruptions, even in the form of cryptotephra (non visible tephra layers), is a potential source of chronological tie points where datable material for radiocarbon analyses can be scarce

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(Gehrels et al., 2006; Gehrels et al., 2008). For example, the discovery of both basaltic and silicic glass shards in the Holocene sediments of Lake Keilambete, Victoria, highlights the potential of using cryptotephra to constrain chronologies and correlate records across southeastern Australia and potentially between Australia and New Zealand (Smith et al., 2016).

When possible, conducting core-top radionuclide analyses, such as ^{210}Pb and ^{137}Cs (Appleby and Oldfield, 1978) can offer greater confidence in the age at the top of the core, as well as any significant impacts on the site by the arrival of Europeans (Sloss et al., 2011; Rodysill et al., 2013; Roop et al., 2016). A robust 'young' chronology derived from the most recent section of cores may also allow comparison of lower resolution records to instrumental observations for quantitative calibration. Future work on geochronology best practice for the Aus2k region will help to define relevant protocols and establish potential chronologic tie points.

4.3.3 Climate teleconnections

Previously, annually-resolved palaeoclimate records from one location within the Australasian region have demonstrated statistically significantly relationships with climatic conditions at distant locations within the same geographic area (Gallant and Gergis, 2011; Gergis et al., 2012; Ho et al., 2013). These climate teleconnections have been utilised to expand spatial coverage of palaeoclimate reconstructions within Australasia (Ho et al., 2013). However, recent modelling and examination of documentary evidence have indicated that the climate teleconnection between Australian climate and remote drivers, such as temperatures in the western Pacific Ocean, have varied on multi-decadal to centennial time scales (Ashcroft et al., 2016; Brown et al., 2016; Hope et al., 2016; Lewis and LeGrande, 2015).

Multiple approaches for integrating Australasian palaeoclimate data have recognised the importance of teleconnection stability and how varying teleconnection strength through time may impact on reconstruction interpretations (Gergis et al., 2012; Gallant et al., 2013; Goodwin et al., 2013; Lorrey et al., 2014; Goodwin et al., 2014; Gergis et al., 2016). All of the approaches are potentially limited by the short length and quality of calibration time scales, uncertainties in proxy archive dating, regional biases from uneven spatial coverage, seasonal sensitivity, and in some cases multiple influences on proxy archive interpretation (i.e. potential distortion effects from other environmental processes). One Principal Component Regression (PCR) ensemble method uses Monte Carlo simulations of analytical parameters such as principal component truncation, proxy selection, and variations in the length of calibration/verification interval to estimate reconstruction uncertainty. The ensemble spread of possible outcomes is then used as a quantitative estimate of uncertainty, which may contain a component of variability related to teleconnection instability (Gergis et al., 2012, Gergis et al., 2016).

Another approach has applied atmospheric regimes in order to avoid climate proxy teleconnection dependencies (Kidson, 2000; Lorrey et al., 2007; Goodwin et al., 2013). Emphasis is placed on maximising agreement between locally derived palaeoclimate signals that are influenced by physical factors such as site-specific orography, advection, and wind stress. In that situation, local climates are assumed to respond consistently through time to synoptic-scale atmospheric circulation. In the absence of other main forcing mechanisms like volcanism, solar variability, greenhouse gases, and insolation changes, atmospheric regime frequency shifts are implicated for causing local anomalies (Goodwin et al., 2013;

Jiang et al., 2013; Lorrey et al., 2014; Lorrey et al., 2007; Lorrey et al., 2008; Lorrey et al., 2010). Past climate interpretations using this approach remain heavily reliant on modern observations, palaeoclimate reconstructions that have been calibrated to local climate data, sufficient palaeodata network density, and understanding how other forcing mechanisms operated and impacted local climates in the past.

One high quality record located in the South Island of New Zealand indicates dust accumulation in a peat bog may be used as a proxy for aridity on the Australian continent (Marx et al., 2009). This interpretation has been supported by modern (1989-2001) dust provenance identification through trace element signatures (Gingele et al., 2007; Marx et al., 2005; McGowan et al., 2005). In that case, a physical process (represented by a unique dust signature) supports a plausible link to a direct, long-distance, synoptically driven transport process and, therefore, a dynamical association with remote climate forcing.

The use of 'upstream' sites could assist in improving the skill of reconstructions for a particular proxy at locations of interest. The utilisation of high-quality sites near to, but outside, the location of interest may lead to regional reconstructions with higher statistical skill, as they may preserve signals of large-scale circulation patterns rather than local climate features (Gallant and Gergis, 2011; Gergis et al., 2012; Gergis et al., 2016; Ho et al., 2013). In Australia, sites along the southern coast of South Australia and Victoria are impacted by a similar atmospheric circulation features and remote climate drivers as major cities and agricultural centres of southern Australia (Murphy and Timbal, 2008), lending the potential to use palaeoclimate records from near the coast to infer patterns of change inland (Ho et al., 2013).

Overall, the diversity of reconstruction methods applied to the Australian region, which either do or do not estimate uncertainty associated with teleconnection instability, provides opportunities to test and compare methods, examine reconstruction assumptions, and to reconstruct climate for areas where there may be limited opportunity for data collection. The fact that many of these approaches result in the generation of spatial fields means that there is potential to utilise their collective outputs as an ensemble, forward model, or as prospecting guidance to target and collect new records in Australasia. In particular, the resulting spatial fields and climate metrics (indices, archetypal patterns) that are able to be generated from the current range of approaches used by the Aus2k group have offered opportunities to explain how local signals in a regional palaeoclimate network simultaneously arise in a dynamical context. In many cases, the different approaches have been used as tools to explore hypotheses and reconcile apparently conflicting climate signals (spatial heterogeneity) in the Southern Hemisphere data network (Goodwin et al., 2013, Goodwin et al., 2014, Lorrey et al., 2013, Lorrey et al., 2007, Lorrey et al., 2008).

Finally, the approaches employed thus far demonstrate potential for up-scaling local palaeoclimate data assemblages to be more comparable with global climate model simulations (Ackerley et al., 2011; Lorrey et al., 2012). A recent high-resolution reconstruction of Australian temperature over the last millennium demonstrates the regionally specific timing and magnitude of temperature fluctuations that can be directly compared to climate model simulations to determine dynamical influences (see studies listed in section 4a of Gergis et al., 2016). Overall, understanding of regional climate variability is important for using palaeoclimate data to evaluate possible responses to future climate change.

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4.3.4 Recommendations

The following recommendations for future low-resolution palaeoclimate research of the Common Era are provided to help improve the coverage and quality of the Australasian data network:

1. The primary difficulty in establishing a basis for data comparison is a lack of publically available data. Although there are multiple public data archives available (e.g. NOAA National Centers for Environmental Information, Pangaea, Neotoma), few low-resolution records from Australasia are formally archived. It is of vital importance for continuation of data comparison in climate research that those creating records archive their existing and future data with at least one of those repositories. Future application and comparison of published data would benefit from additional metadata included in publications. Useful metadata fields include: raw geochronological data, archive collection dates, sampling interval, temporal resolution, and the method (and data) by which the proxy-climate relationship has been established.

2. Site monitoring (Treble et al., 2013; Roop et al., 2015; Tibby et al., 2003), climate sensitivity studies (Bertrand et al., 2002; Neukom and Gergis, 2012), and proxy systems models (Dee et al., 2016; Evans et al., 2013) are approaches that increase confidence in the type and strength of climate signal expressed by a proxy. These approaches would also help to improve the interpretation of previously published work in Australasia. Site monitoring and the development of transfer functions to help develop frameworks for dynamical interpretation would also improve the quality of mechanistic models and quantitative climate reconstructions. Support for augmentation of global reanalysis datasets (i.e. 20CR) (Compo et al., 2011) via data rescue activities (e.g. Atmospheric Circulation Reconstructions across Earth; OldWeather, etc) (Allan et al., 2011; Allan et al., 2016; Brohan et al., 2012) to extend calibration series would provide large benefits to the palaeoclimate research community. Comprehensive understanding of site-specific climate-proxy relationships strengthens confidence that palaeoclimate records are expressing climate variability through time without modification of signals by human activities in the catchment.

3. Robust chronologies are of utmost importance in understanding the frequency of climate fluctuations, defining the timing of events, and testing for synchronicity of events between sites. These questions cannot be confidently answered without rigorous chronological control. Reliable chronologies require multiple dates within the past 2000 years, a date near the top and bottom of the core or near 1CE, and sufficient density of dates (at least 1 date per 200 years) across the Common Era to identify possible changes in timing within the past ~2000 years. Furthermore, although the use of cryptotephra to correlate sedimentary records has rapidly developed over the last decade, its application to Australasian (particularly Australian) records has been notably slow to take off, despite considerable potential for constraining chronologies for the last 2000 years (Davies, 2015; Smith et al., 2016). Generation of the Bayesian age models presented here suggests that classical statistics (i.e. linear interpolation or spline smoothing) might not fully capture complex depositional pattern changes in the Australasian region.

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5 Conclusions

Within this study, 675 non-annually resolved palaeoclimate records across the Australasian region were identified and assessed. Of these, the majority are sediment cores from lakes and wetlands, with pollen ecological assemblages and invertebrate fossil geochemistry as the most common proxies. Of the large number of records identified, a subset of only 22 records met the international PAGES2k selection criteria to be classified as 'high-quality' records. This dataset contains good examples of what characteristics are necessary for the investigation of climate variability during the Common Era. Additional records of similar quality are needed to further expand the spatial coverage and diversity of climate variables within the Aus2k record network.

For each of the 22 records that were identified in this study, new age-depth models were constructed using consistent Bayesian age modelling approach. Comparison between published and BACON-derived age models suggests that age modelling has a strong influence on the timing of events within and between records. Overall, three recommendations are presented to improve the quality of future low-resolution climate reconstructions and syntheses. Public availability of data and metadata will facilitate record comparison, updates, and assessment. Thorough characterisation of proxy-climate relationships could be achieved through site monitoring, climate signal characterisation through model comparison, and development and evaluation of new biological/sedimentological transfer functions. Finally, chronologies must be greatly improved for confident characterisation of Common Era climate variability. Increased numbers of dates, core-top dating, incorporation of sediment behaviour and site idiosyncrasies in age-depth model construction, and acknowledgement of age uncertainties are necessary.

The relatively low number of high quality, low-resolution records in comparison with other regions of the world highlights the progress that is needed to improve reconstructions of the climate of the past 2000 years in Australasia. However, the existing high-quality records demonstrate the potential of sites within this region to provide well-dated records with recognised connections to climate variables. In addition, a range of reconstruction techniques applied to other regions and time scales have the potential to expand the spatial coverage and range of climate variables in Australasia.

Data availability

Originally published and BACON-derived recalibrated age-depth models are archived through the NOAA paleoclimate archive [ftp://ftp.ncdc.noaa.gov/pub/data/paleo/pages2k/dixon2017australasia/].

Author contributions

B.C. Dixon identified and assessed the palaeoclimate Australian and Malay Archipelago records and wrote the manuscript with the assistance of J.J. Tyler, who conducted the initial database collation. A.M. Lorrey identified and assessed the New Zealand records. I.D. Goodwin oversaw the construction of the joint report between Macquarie University and New South

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Wales Department of Environment, Climate Change, and Water, which was the inspiration and a major data source for this paper. J. Gergis instigated and directed the initial stages of the Aus2k low-resolution data initiative. All coauthors contributed to discussion of the content and the writing of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

Special issue statement

This is a submission for the PAGES2k special issue.

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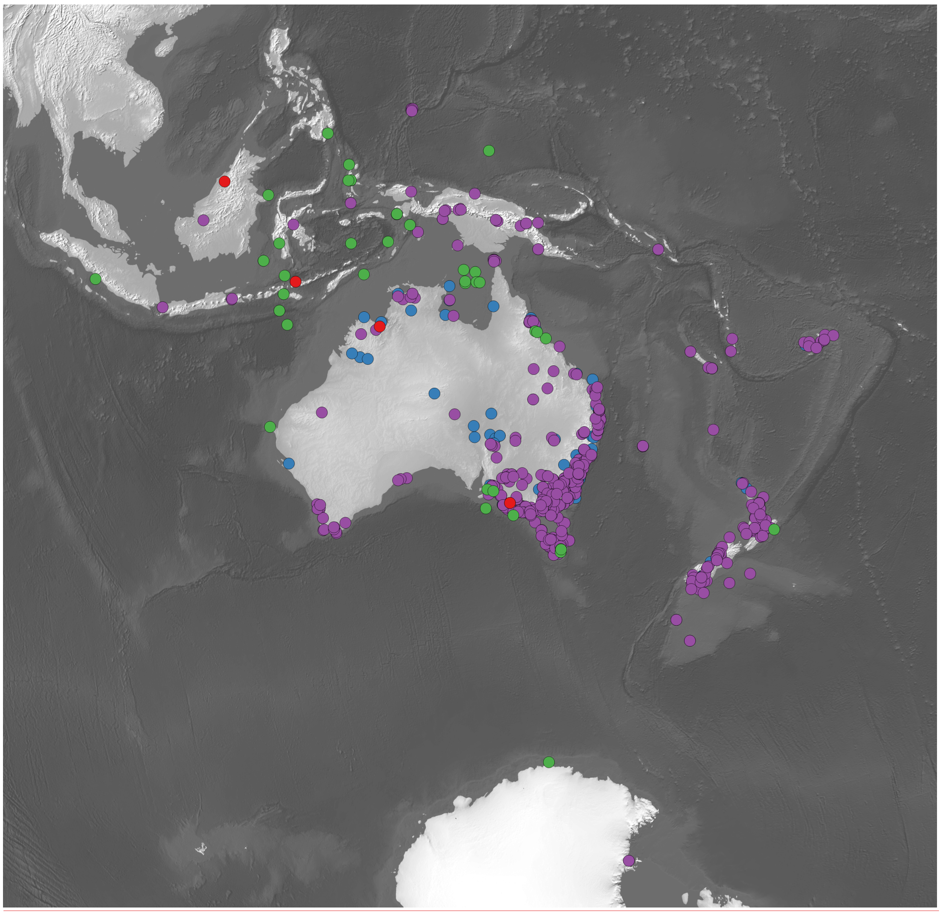

Figure 1. Map of all Australasian records identified. Each marker represents one record location. Archive types are represented by colour for lake/wetland/peat (purple), marine (green), speleothem (red), and geomorphic (blue) archive types.

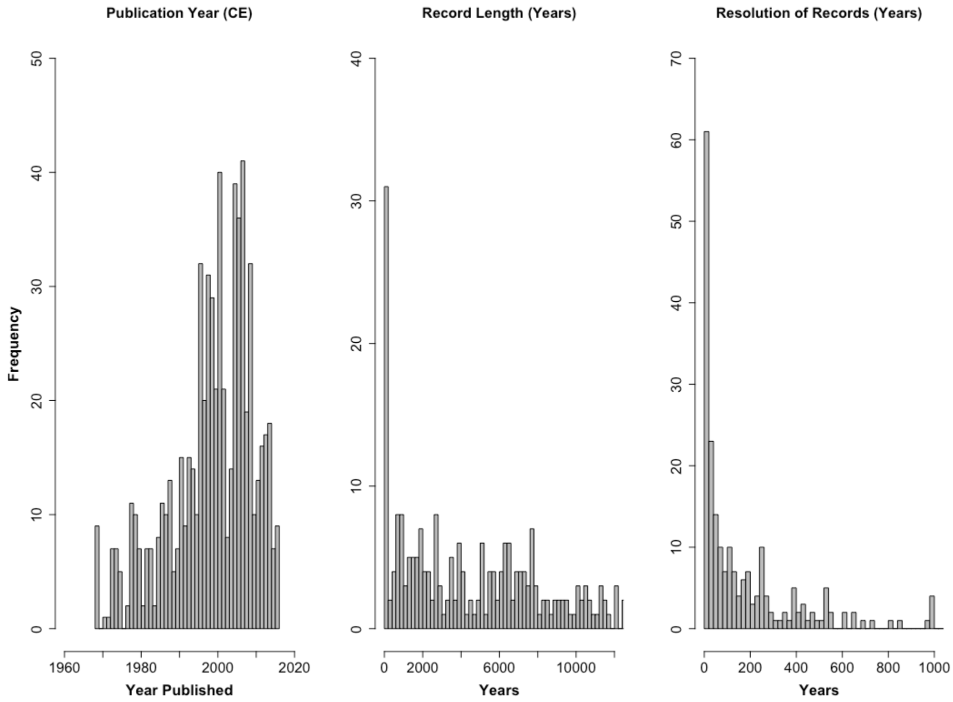

Figure 2. Metadata for all Australasian records. Data are presented for a.) Publication year for most recent presentation of each record; b.) length of time between oldest and youngest sample (where possible to calculate); and c.) sampling resolution (years/sample) of record (where possible to calculate for lake/wetland, speleothem, and marine records).

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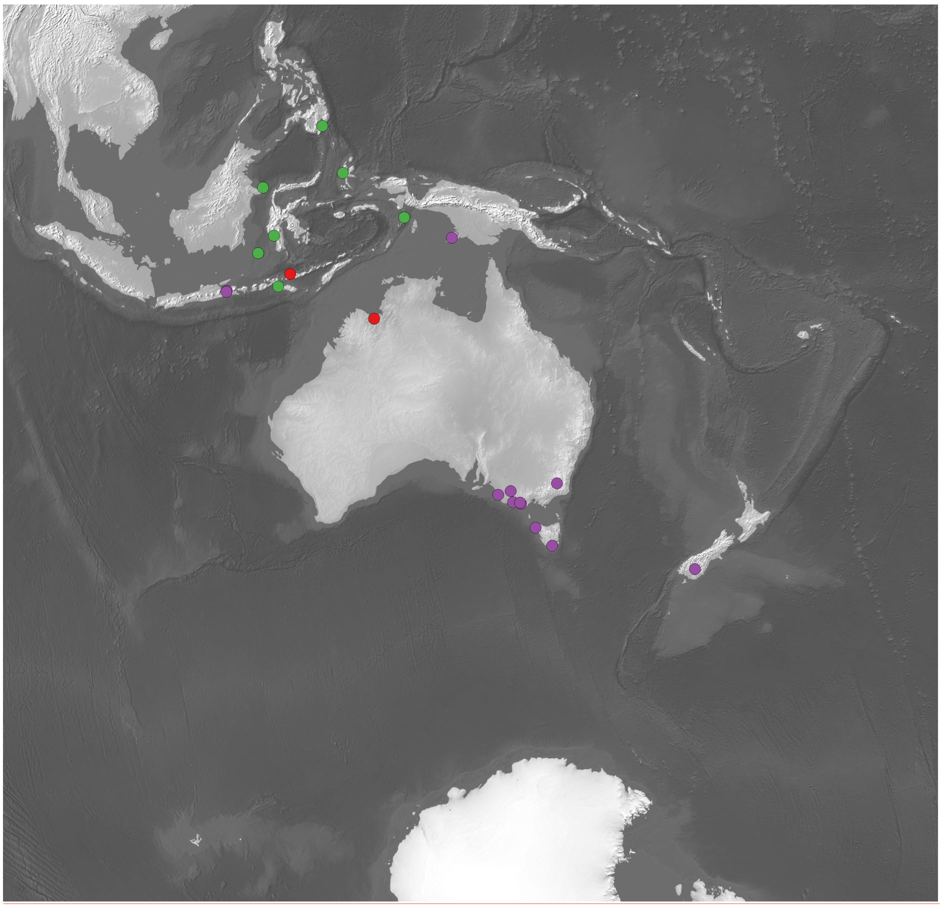

Figure 3. Locations of high quality Aus2k records. Each marker represents one record location. Archive types are represented by colour for lake/wetland (purple), marine (green), speleothem (red), and geomorphic (blue) archive types.

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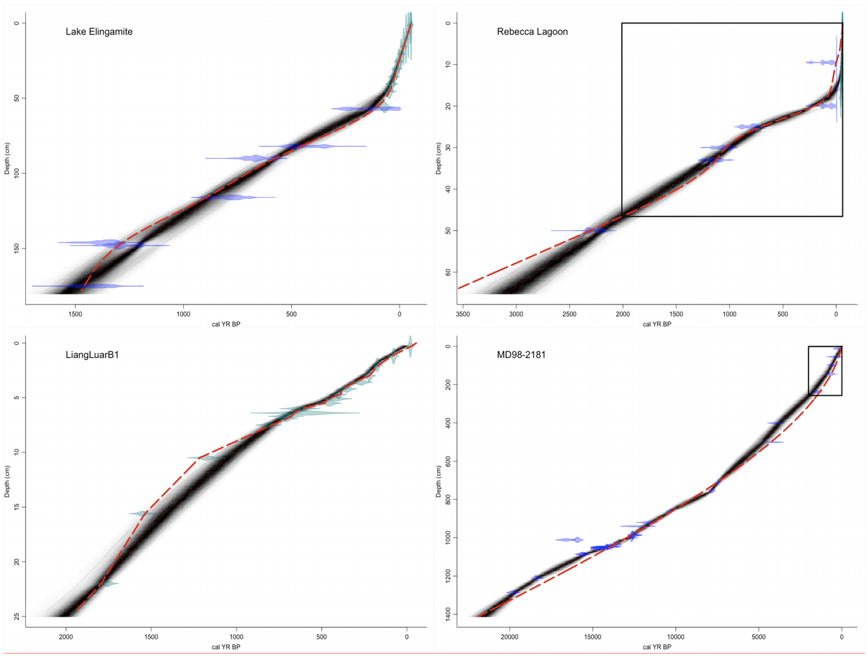

Figure 4. Examples of BACON outputs for recalibrated age-depth models for a.) Lake Elingamite; b.) Rebecca Lagoon; c.) Liang Luar Cave; d.) Marine core MD98-2181. Originally published age-depth relationships were retrieved from public archives (Table 1) and are displayed by a dashed red line. The Common Era is highlighted by a black rectangle in records that extend beyond the last 2000 years.

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Table 1. Australasian records identified as high quality, according to the PAGES2k evaluation criteria, and associated metadata. Column titles indicate: Political state where site is located (VIC=Victoria, INDO=Indonesia, SA=South Australia, WA=Western Australia, NSW=New South Wales, TAS=Tasmania, NZ=New Zealand), Latitude, Longitude, Elevation (metres above sea level), Classification of archive, Source of core, Description of archive, proxies measured within core, published interpretation of climate proxy (E/P=Evaporation/Precipitation balance), author of most recent publication, most recent publication year, length of record, year of oldest sample (including uncertainty), year of youngest sample (including uncertainty), average sampling resolution according to published chronology (years/sample).

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Low-resolution Australasian palaeoclimate records of the last 2000 years

Bronwyn C. Dixon[1], Jonathan J. Tyler[2], Andrew M. Lorrey[3], Ian D. Goodwin[4], Joëlle Gergis[5], Russell N. Drysdale[1]

Response to Reviewer 1

General comments

A huge effort would have gone into compiling these records and the manuscript represents an important contribution to the PAGES2K network and the palaeoclimate community more generally.

My main comments relate to providing some additional information so readers can more easily assess old vs. new age-depth models and reproduce them, together with more of a critique about causes of differences and factors to be aware of. At present this is not possible, which detracts from the value of the paper. It would also be helpful to include direct links to each record that has been archived (see 2 below).

Response:

This identification and assessment of non-annually resolved Australasian palaeoclimate records has been underway since 2009, and has been the focus of both post-doctorate research and a PhD project. We are pleased to present the outcomes of more than eight years of work, and hope that the scientific community can benefit. Original and updated age models and datasets will be available through NOAA World Data Center at:

ftp://ftp.ncdc.noaa.gov/pub/data/paleo/pages2k/dixon2017australasia/

This link will become publicly available upon publication of this manuscript.

Specific comments

Abstract

* Include briefly: where the best and worst coverage of sites is; the main reason(s) for the differences between old and new age-depth models; and summary of recommendations.

Response: The abstract was revised as suggested and now reads as follows:

'Non-annually resolved palaeoclimate records in the Australasian region were compiled to facilitate investigations of decadal to centennial climate variability over the past 2000 years. A total of 675 lake/wetland, geomorphic, marine, and speleothem records were identified. The majority of records are located near population centres in southeast Australia, in New Zealand, and across the maritime continent, and there are few records from the arid regions of central and western Australia. Each record was assessed against a set of *a priori* criteria based on temporal resolution, record length, dating methods, and confidence in the proxy-climate relationship over the Common Era. A subset of 22 records met the criteria, and was endorsed for subsequent analyses. Chronological uncertainty was the primary reason why records did not meet the selection criteria. New chronologies based on Bayesian techniques were constructed for the high quality subset to ensure a consistent approach to age modelling and quantification of age uncertainties. The primary reasons for differences between published and reconstructed age-depth models were the consideration of the non-singular distribution of ages in calibrated ^{14}C dates and the use of estimated autocorrelation between sampled depths as a constraint for changes in accumulation rate. Existing proxies and reconstruction techniques that successfully capture climate variability in the region show potential to address spatial gaps and expand the range of climate variables covering the last 2000 years in the Australasian region. Future palaeoclimate research and records in Australasia could be greatly improved through three main actions: i.) Greater data availability through the public archiving of published records, ii.) Thorough characterisation of proxy-climate relationships through site monitoring and climate sensitivity tests, and iii.) Improvement of chronologies through core-top dating, inclusion of tephra layers where possible, and increased date density during the Common Era.'

2 Data and Methods

* As it is stated that many of the records were not publically available, were some obtained by personal communication with the original authors? If so, this should be noted in addition to NOAA and Neotoma databases.

Response: Sources of pre-existing records have been updated to include 'a general inquiry to Australasian Quaternary Association members' and 'personal communication with authors'

* Can links to the NOAA database for each dataset in Table 1 be included? This means readers can go directly to the relevant record.

Response: Links to the NOAA URL for originally published datasets are now included in Table 1. A link to the comparison of originally published and updated age models are also included in the 'Data availability' section at the end of the manuscript.

3.3 Age model updates and 4.2 Discussion of age modelling approaches

* It would be helpful if the BACON settings for each model are provided (e.g. in supplementary material). This would ensure people can reproduce the age-

depth models exactly. For example, values specified for thickness, accumulation mean and memory strength influence the output, and these are determined based on prior knowledge of the core and site as the authors highlight on page 8. If this information is not included others will not necessarily be able to reproduce the chronologies.

Response: A supplement of all code and settings used to construct updated age models are now included in the supplementary information, for the purpose of transparency and reproducibility of methods presented in this study

* In Figure 4, can the original age-depth models be plotted on top of the new BACON-derived outputs (or at least side by side as done in Figure S2) so readers can see the differences between old and new? At present it is not possible to make this assessment. It would also be helpful if examples were provided of cores where new and old age-depth models are quite similar, and some examples where there are notable differences, together with a critique as to why.

Response: Figure 4 has been updated to show the four example age-depth models side-by-side with the originally published age models so that differences can be observed. Each pair of old/new age models has been provided in the supplementary information, so that readers can see examples of similar and divergent age models. Further discussion of reasons for differences in age model outcomes has been included within section 4.2, which now reads: 'Chronologies for most marine sediment cores are based on fitting a linear age-depth relationship across the set of dates. The results of BACON-derived age models moderately support the application of linear accumulation for this archive, with the ages of young/shallow samples more likely to match between the two approaches in comparison to samples from deeper in the core. The disparity between published and reconstructed ages for marine records increases back through time. This is most likely related to date density through individual cores, as well as periods of interpolation between dated horizons. Indonesian marine cores use the 1815 Tambora tephra as a chronological anchor, which decreases age uncertainty near the present, but date density further back in time varies between records.

The published Snowy Mountain core had age model difficulty, with two possible age models with similar r^2 values (Marx et al., 2011). The self-adjusting Monte-Carlo approach within the BACON software clearly favoured one model over the other (Supplementary Fig. 1). The BACON-derived age model showed greater agreement with the published age model built upon more dates. This is likely driven by acknowledgement of the probability distributions of calibrated radiocarbon dates, as well as estimated autoregression between sampled (but undated) depths.'

* While the authors state that the decisions by the original authors regarding exclusion of radiocarbon dates were upheld, was this also the case for the Lake Elingamite record (Figure S2)? The CLAM-model shows three dates (in red) that do not appear to be in the BACON model output. If these were treated as outliers

by Barr et al. (2014) but still plotted, which is an option in CLAM, this should be noted in the figure caption to explain why the number of dates is different.

Response: The dates presented in red in Barr et al., (2014) have indeed been excluded by this study because of their previous identification as outliers. Figure S2 has been updated to compare original and BACON age models for all records in the Aus2k dataset.

4.1.1 Lakes and wetlands.

* The authors list the common factors that can have an impact on preservation of the climate signal (e.g. sediment accumulation rate, basin morphology, page 11, line 4). Human impacts, particularly since European settlement can also override potential climate signals. This can complicate the development of transfer functions/modern analogue technique models and calibration in time. This is highlighted in the 'lithics' section, but is relevant to biological proxies too.

Response: The information on biological proxies in section 4.1.1. has updated to appropriately communicate the impact of site-specific feature and land use change on biological proxies in Australasia. Relevant supporting literation has also been included.

* Page 14, lines 8-10 and Supplementary Fig. 1: State which age model the BACON-derived one supports and why.

Response: This section has clarified and expanded upon to indicate which published model is preferred, as indicated by the BACON-derived age model, and why BACON is a useful tool for choosing appropriate age models. It now reads: 'The published Snowy Mountain core had age model difficulty, with two possible age models with similar r^2 values (Marx et al., 2011). The self-adjusting Monte-Carlo approach within the BACON software clearly favoured one model over the other (Supplementary Fig. 1). The BACON-derived age model showed greater agreement with the published age model built upon more dates. This is likely driven by acknowledgement of the probability distributions of calibrated radiocarbon dates, as well as estimated autoregression between sampled (but undated) depths.'

* Page 15, lines 14-19: This paragraph is better suited near the start of the section before discussing the different proxies as it is general. Some references would be beneficial, in particular in relation to proxies being complex and non-linear. In addition, using a multi-proxy approach is important for being able to potentially discern climate vs. human impact vs. within lake signals.

Response: This paragraph has shifted to the beginning of the section (page 11, lines 23-33), and will be edited to prevent repetition with the existing introductory paragraph. Supporting literature has been added to support the complex and non-linear nature of palaeoclimate proxies in lake and wetland environments.

* Page 15, line 24: von Gunten et al. (2012) is an additional reference as it describes the calibration in time approach using case studies based on biogeochemistry (von Gunten L, Grosjean M, Kamenik C, Fujak M, Urrutia R (2012) Calibrating biogeochemical and physical climate proxies from non-varved lake sediments with meteorological data: methods and case studies. J Paleolimnol DOI 10.1007/s10933-012-9582-9).

Response: Information from this reference has been incorporated into page 12, line 6-8, and the paper has been added to the reference list.

*Page 19, lines 4-7: the difference between the oldest/closest to 1 CE dates are also likely due to the amount of extrapolation between it and the previous 14C date, not just the density of dates through the core. In addition to having at least one date near the top of the core (line 8), ideally 210Pb and/or 137Cs would be used if the sedimentation rate is fast enough.

Response: The degree of interpolation will be discussed in the possible reasons for large chronological uncertainties. References will be supplied to support this point. The authors agree that ^{210}Pb and/or ^{137}Cs would be ideal for constraining the top of sediment cores in Australasia, and these radionuclides have has been used in previous studies. The use of 210Pb dating for constraining upper-core ages is included in the 'chronology' section of the discussion (page 23, lines 4-9).

Figures and Tables

* **Figures 1 and 3:** What symbol marks peat records?
Response: Peat records are included in the lake/wetland category, which is represented by the purple markers. The figure captions have been changed to clarify the types of proxies included within each archive category.

* **Tables:** It is not clear how studies are ordered, which makes it hard to search through them (also applies to Table S1)

Response: Records within all tables in the main text and supplementary section have been reordered by archive type (i.e. lake/wetland, marine, speleothem, marine), then by state/country, for the sake of easy searching by readers.

*** Table 2**
Just presenting the difference between top and base years in the old compared to new chronologies is useful, but does not necessarily illustrate the actual differences between the age-depth models. For example, if the lowermost 14C date is above the bottom of the core, which means the age-depth models are extrapolated, this may lead to a larger apparent difference in ages than might be the case for most of the core. To address this, figures of each site with old and new age-depth models could be included. All new age-depth model figures should already be available as part of BACON output. Doing this means the settings could be incorporated into each figure (see comment 3.3 above). Ideally the original age-depth models would be plotted on top to best illustrate

differences and similarities. If this is not possible, then at least provide them side-by-side. This would help readers assess the differences for themselves, identify common patterns and assist their decision making when investigating these records and developing chronologies for other sites.

Response: Comparison figures displaying overlain old and new age models for each of the 22 sites are now included in the supplementary material in Supp Fig. 2. Table 2 has been removed from the main text and readers now directed to the supplementary Table S2.

<u>* Technical corrections:</u> There are a number of typographical errors in the text. I have listed the ones I found, but recommend the authors do a thorough check. This includes the order of references within the text, which are not always consistent (e.g. Marx et al., 2011, Marx et al., 2009, page 13, line 32).

*Page 1, lines 15-16: A high quality subset of 22 records across Australasia met the criteria and they are **were** endorsed for subsequent analyses

Response: Revised to read: 'A subset of 22 records met the criteria, and was endorsed for subsequent analyses.'

*Page 2, line 30: Low-resolution sedimentary archived **archives** available within Australasia include lacustrine…

Response: The text now reads: 'Low-resolution sedimentary archives available within Australasia include lacustrine, fluvial and wetland sediments (including peat), marine sediments, speleothems, and geomorphic features (e.g. moraines, dunes) across diverse climate settings.' (Page 3, lines 4-6)

* Page 3, line 13: state the most recent year of publication of the records so it is clear until when the database is up to date. This is important because new records are being published (e.g. comments by Rouillard).

Response: The text now reads 'Records published before 2017 were identified through inspection of citation databases, reference lists of past review papers, online public data repositories, personal communication with authors, and a general inquiry to all Australasian Quaternary Association members.' (Page 4, lines 2-4)

* Page 4, line 12: a reference is needed at the end of the sentence The Australasian region includes tropical Southeast Asia because of the dynamical influences of the Indo-Pacific region on the Australasian monsoon. As two Antarctic sites appear to be included, the reason why stated.

Response: References have been added to this section, and the text now reads: 'The Australasian region includes tropical Southeast Asia because of the dynamical influences of the Indo-Pacific region on the Australasian monsoon (Meehl and Arblaster, 2002), as well as the Australian/New Zealand sector of the Southern Ocean and Antarctica because of oceanographic and atmospheric teleconnections

(Hall and Visbeck, 2002; van Ommen and Morgan, 2010).' (Page 4, lines 17-20)

Page 4, line 19: 'Reasonable' was defined as **by** PAGES2k as containing at least one…

Response: The correction has been made, and the text now reads: ''Reasonable' was defined by PAGES2k as containing at least one chronological control point near the youngest part of the record, another near 1CE or the end of the record (whichever is younger), and, for records greater than 1000 years in length, an additional date near the middle of the record.' (Page 4, lines 27-29)

* Page 5, line 1: …approach for the creation of age models in presented in this study…

Response: This sentence has been clarified, and the text now reads: 'Although one approach for the creation of age models is presented in this study, the raw data are available for individuals who wish to apply alternative methods.' (Page 5, lines 9-11).

* Page 5, line 8: Or **Of** these 241 records…

Response: The correction has been made, and the text now reads: 'Of these 241 records, 141 were classified as 'moderate to high confidence' based on climatic sensitivity, possible non-climatic influences, local forcing, and chronological confidence.' (Page 5, lines 17-18)

* Page 5, line 27: Should temperature be temperate?

Response: This correction has been made, and the text now reads: 'These data were compiled from a site level up to a homogeneous regional climate district level (Kidson, 2000; Lorrey et al., 2007) from a range of environments that range from temperate subtropical in the far north of New Zealand to glacial in the south.' (Page 6, lines 1-3)

Page 6, line 27: …residence time within a radiocarbon samples…

Response: The correction has been made, and the text now reads: 'It is not always possible to identify environmental residence time within a radiocarbon sample, and the uncertainty may not be acknowledged within the resulting chronology (McFadgen, 2007).' (Page 7, lines 4-5)

* Page 7, lines 26-27: Sentence is not necessary – In this study, one focus is to generate new age models for records that meet the PAGES2k selection criteria, providing consistency in the approach to age determination and uncertainty estimates.

Response: This sentence has been removed from the manuscript.

* Page 7, lines 27-29: Sentence is not necessary as it overlaps with the end of the previous paragraph. Combine it with the previous paragraph so the references are included. This study applies Bayesian age modelling across the Aus2k records, a decision that follows the initiative of the wider palaeoclimate community (e.g. Anchukaitis and Tierney, 2012, Goring et al., 2012, Hua et al., 2012).

Response: This sentence has been removed, and the references were added to the previous paragraph.

* Page 9, lines 13-14: Sentence not necessary – 661 Australasian sedimentary records spanning the Common Era were systematically reviewed for their suitability for reconstructing regional climate dynamics over the last 2000 years.

Response: Sentence was removed.

* Page 9, lines 21-22: Sentence is a repeat of the previous section – Lacustrine microfossils are the most common terrestrial proxy in the Aus2k records, while foraminifera geochemistry is the predominant marine proxy.

Response: This sentence discusses the composition of the vetted Aus2k dataset, rather than the complete regional dataset.

* Page 10, line 5: Missing word: A low number **of** radiocarbon dates…

Response: The missing word was added to the sentence. The text now reads: 'A low number of radiocarbon dates and/or low confidence in the chronologies are the most common reasons for record exclusion from the Aus2k dataset.' (Page 10, lines 12-14)

* Page 10, line 11: …resolution to intestigate **investigate** decadal…

Response: The typo was corrected, and the text now reads: 'The 22 records that meet the PAGES2k selection criteria provide a subset of records with robust chronologies, an identified proxy-climate relationship, and sufficient record length and resolution to investigate decadal to centennial variability during the last 2000 years.' (Page 10, lines 17-19)

* Page 10, line 15 paragraph: This appears to be a contradiction to the start of the Discussion where the authors comment there is widespread spatial and temporal coverage of existing records across the geographic network (page 10, line 1). Please reword to clarify what is meant.

Response: This section discusses the vetted Aus2k dataset, rather than the regional dataset. This has been clarified in the text, which now reads: "The geographic distribution of Aus2k records displays stronger spatial biases than the complete regional database (Fig. 3).' (Page10, lines 24-25)

* Page 10, lines 18-19: …climate drivers including **the** El Niño-Southern

Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the Australian-Indonesian Summer Monsoon…

Response: The sentence has been revised, and the text now reads: 'In contrast, the availability of high quality records in Indonesia relates to global interest in the region as a dynamical 'centre of action' for numerous climate drivers including the El Niño-Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the Australian-Indonesian Summer Monsoon (AISM), resulting in high levels of international funding for research in this area.' (Page 10, lines 26-29)

*Page 10, line 32: Climate **Common** Era

Response: The text was corrected and now reads: 'A brief description of archives and their applicability to studying climate variability during the Common Era is provided below.' (Page 11, lines 9-10)

* Page 11, line 2: Core**s**

Response: The correct form of the word has been added to the text.

* Page 11, line 23: Chivas et al., 1985**, Chivas et al., 1985**

Response: The reference has been corrected in the text and in the reference list.

* Page 11, line 25: Oxygen isotopes values…

Response: The text has been corrected and now reads: '. Oxygen isotope values reflect the combined influence of the oxygen isotopic composition and temperature of the lake water, while carbon isotopes reflect the isotopic composition of the dissolved inorganic carbon present in the lake system (see Gouramanis et al., 2010 and references therein).' (Page 12, lines 26-28)

* Page 12, line 5: Transfer functions built upon **developed from** modern calibration…

Response: The text has been clarified and now reads: 'Transfer functions, developed from modern calibration data sets, have been established for numerous aquatic variables in both estuarine (Logan and Taffs, 2013; Tibby and Taffs, 2011) and lacustrine (Gell et al., 2005) settings.' (Page 13, lines 8-9)

* Page 12, line 20: … because of the their…

Response: The text has been corrected and now reads: 'Over the past half-century, speleothems have emerged as valuable sources of palaeoclimate information because of their potential for preserving precisely dated, multi-proxy, high-resolution records of past climate change (Fairchild et al., 2006).' (Page 17, line 2-3)

* Page 12, line 22: …both with on biological and statistical grounds…

Response: This sentence has been removed to improve the clarity of this section.

Page 12, lines 22-23: this sentence is misleading (Nevertheless, the ecological dynamics of lakes are clearly governed by climate conditions) because the ecological responses in some lakes are influenced more by humans than climate (e.g. damming), or changes in the catchment that are not climate-driven (e.g. land clearing), or could just vary internally.

Response: These two sentences have been removed. The consideration of the limnology-proxy-climate connection is now discussed in section 4.1.1.

Page 12, line 23: …this lake microfossils… – should 'this' be 'thus'?

Response: This sentence has been removed to improve the clarity of this section.

Page 12, line 31: … analysed lead waxes… – should 'lead' be 'leaf'?

Response: The text has been corrected and now reads: 'Tierney et al. (2010) analysed leaf waxes in material that had been transported offshore.' (Page 13, line 26)

Page 13, line 5: Does not make sense – The Lake Keilambete grain-size derived is very commonly used for validation and comparison of palaeocliamte **palaeoclimate** records in the region

Response: This sentence has been clarified and corrected, and the text now reads: 'The Lake Keilambete lake level reconstruction is very commonly used for validation of other palaeoclimate records in the region.' (Page 13, lines 33-34)

Page 13, line 8: …accelerator mas**s** spectrometry…

Response: The typo has been corrected, and the text now reads: 'The dating density is also the highest of any of the Aus2k records, with four new accelerator mass spectrometry (AMS) radiocarbon dates and four optically stimulated luminescence (OSL) dates within the last 2000 years in the most recent chronology (Wilkins et al., 2012).' (Page 14, lines 1-3)

Page 13, line 18: …could be influences**d** by climate…

Response: The correct word has been substituted here, and the text now reads: 'Signatures of acute sedimentation are interpreted as rapid in-washing of coarse loads (Lake Rotonuiaha (Wilmshurst et al., 1997); Lake Tutira (Eden and Page, 1998; Gomez et al., 2012); Round Lake (Chester and Prior, 2004)) that could be influenced by climate and/or seismic variability.' (Page 14, lines 10-12)

Page 13, line 19: …lake core**s** are…

Response: The typo has been corrected, and the text now reads: 'Some of the lithological changes observed in lake cores are suggested as a response to climatically driven increases and decreases in lake level (Lake Maratoto (Green and Lowe, 1985); Lake Poukawa (McGlone, 2002b)).' (Page 14, lines 12-14)

Page 13, line 31: …assumed to be have been…

Response: This sentence has been clarified and now reads: 'For coastal study sites, the local quartz input from sand dunes is ignored, while remaining material is assumed to have been transported to the site via aeolian means (McGowan et al., 2008).' (Page 14, lines 24-25)

Page 14, lines 11-17: This paragraph does not belong here as is discusses an archive, not a proxy. It would be more suitable at the start of section 4.1.1. and the title adjusted to include peat.

Response: This paragraph has been added to the beginning of section 4.1.1.

Page 14, line 27: …impact**s**…

Response: The text has been corrected, and now reads: 'Early research focused on reconstructing vegetation diversity at a single site, but approaches have expanded to examine broader environmental questions such as regional vegetation response to climatic shifts (Donders et al., 2007), reconstruction of a specific variable across a region (Fletcher and Thomas, 2010a), recovery from episodes of disturbance such as fire (Lynch et al., 2007), and responses to human impacts in the pollen catchment (Haberle et al., 2006; Horrocks et al., 2001; Leahy et al., 2005).' (Page 15, line 5-9)

Page 14, line 29: …highly cites**d** records…

Response: The typo has been corrected, and the text now reads: 'There is an extensive network of well-studied sites centered on the Atherton Tablelands in northern Queensland (Haberle, 2005; Haberle et al., 2006; Kershaw, 1970, 1975, 1983, 1971; Kershaw et al., 2007; Walker et al., 2000), including some of the most highly cited records of Australian-Indonesian Summer Monsoon dynamics and rainforest response to climate variability through time (Kershaw, 1994).' (Page 15, lines 12-15)

Page 15, line 7: Herber**t**

Response: The typo has been corrected (Page 15, line 25)

Page 16, line 9: …this intensifying… – should 'this' be 'thus'?

Response: The typo has been corrected and the text now reads: 'For some coupled ocean-atmosphere climate modes, such as ENSO and the IOD, the coupled warm/wet and cold/dry conditions influence the $\delta^{18}O$ signature in the same direction, thus intensifying the climate signal in the oxygen isotopes (Brijker et al., 2007; Khider et al., 2011)' (Page 16, lines 11-13)

Page 16, line 26: …in seas-surface…

Response: The typo has been corrected, and the text now reads: '. It is also important to separate the atmospheric and oceanographic drivers of variability in sea-surface temperatures and salinity through multi-proxy approaches.' (Page 16, line 29-30)

Page 17, line 24: records

Response: The typo has been corrected and the text now reads: 'Early- to mid-Holocene $\delta^{13}C$ in a Tasmanian speleothem record was inferred to reflect productivity and the resulting carbon isotope fractionation in the soil (Xia et al., 2001).' (Page 17, lines 31-32)

Page 18, line 8: cli**m**ate

Response: The typo has been corrected and the text now reads: 'This synoptic approach allows the integration of co-varying, spatially heterogeneous responses of several speleothem environments to surface climate, which is forced by orographic circulation and advection related to base climate state shifts (Lorrey et al., 2008; Lorrey et al., 2014; Lorrey et al., 2012).' (Page 18, lines 14-17)

Page 18, line 11: shows**n**

Response: The typo has been corrected and the text now reads: 'In the Australian setting, Mg/Ca in speleothems has been shown to be a reliable recorder of effective rainfall (Fairchild and Treble, 2009; Treble et al., 2003; McDonald et al., 2004) because longer water residence times increase the Mg/Ca in speleothem drip water (Fairchild et al., 2000; Fairchild and McMillan, 2007).' (Page 18, lines 18-20)

Page 19, line 33: …number **of** chronological…

Response: The word has been added, and the text now reads: 'The records that have the greatest departure from the published age models are those that have the smallest number of chronological anchors.' (Page 20 lines 11-12)

Page 20, line 20: …demonstrate that that **this** criterion…

Response: The typo has been corrected and the text now reads: 'However, the outcomes of this study demonstrate that this criterion is still too relaxed for robust investigation of decadal to multi-decadal climate variability in the Common Era.' (Page 20, lines 14-15)

Page 20, line 10: …with regards **to** age-depth…

Response: The sentence was corrected and the text now reads: 'It can be argued that the Bayesian methods applied in this study represent the current state of the art with regards to age-depth modelling of Quaternary sediment sequences.' (Page 20, line 23-24)

Page 20, lines 17-18: Sentence is not necessary

Response: This sentence has been removed for the clarity of the section.

Page 20, line 32: record**s**

Response: The typo has been corrected. The text now reads 'Only one low-resolution terrestrial temperature reconstruction exists in the Aus2k dataset: the Duckhole Lake record (Saunders et al., 2013).' (Page 21, lines 10-11)

Page 21, line 6: …this providing… – should 'this' be 'thus'?

Response: The typo has been corrected and the text now reads: 'All of these transfer functions have the potential of being applied to the Common Era, thus providing quantitative reconstructions from sub-tropical and temperature climate zones of Australasia.' (Page 21, lines 17-18)

Page 21, line 6: D**ei**ffenbacher-Krall et al., 2007 should be D**ie**ffenbacher

Response: The reference typo has been corrected.

Page 21, line 9: …used to **re**construct…

Response: The typo has been corrected and the text now reads: 'This proxy has been used to reconstruct mean annual temperature in Lake Pupuke in New Zealand (Heyng et al., 2015) and Lake Mackenzie in Australia (Woltering et al., 2014).' (Page 21, lines 20-22)

Page 21, line 25: …unknown complications; C**c**onversely, modelling…

Response: The capitalisation has been removed (Page 22, line 3)

Page 22, line 17: Sentence starting 'However' is not clear.

Response: The sentence has been clarified and the text now reads: 'There are now low-cost commercial services, and institutional dating operations have endeavoured to match the costs of the competitive commercial market. These developments mean new, more cost-effective dating strategies can be employed to create new well-dated records, as well as renewed efforts to revisit former sites to improve the original chronologies.' (Page 22, lines 12-15)

Page 22, line 19: …used **as** an anchor…

Response: The text has been corrected and now reads: 'The only eruption used as an anchor in the Aus2k dataset is Tambora (1815CE) in the Malay Archipelago records.' (Page 22, lines 29-30)

Page 22, lines 27-29: Provide an Australian and ideally New Zealand reference at the end of the sentence.

Response: Australian and New Zealand references have been added and the text now reads: 'When possible, conducting core-top radionuclide analyses, such as ^{210}Pb and ^{137}Cs (Appleby and Oldfield, 1978) can offer greater confidence in the age at the top of the core, as well as any significant impacts on the site by the arrival of Europeans (Sloss et al., 2011; Rodysill et al., 2013; Roop et al., 2016).' (Page 23, lines 4-6)

Page 23, line 12: ...limited by **the** short length...

Response: The sentence has been corrected and the text now reads: 'All of the approaches are potentially limited by the short length and quality of calibration time scales, uncertainties in proxy archive dating, regional biases from uneven spatial coverage, seasonal sensitivity, and in some cases multiple influences on proxy archive interpretation (i.e. potential distortion effects from other environmental processes).' (Page 23, lines 21-23)

Page 23, line 26: ...reconstructions w**h**ere proxies...

Response: The text has been clarified and now reads: 'Past climate interpretations using this approach remain heavily reliant on modern observations, palaeoclimate reconstructions that have been calibrated to local climate data, sufficient palaeodata network density, and understanding how other forcing mechanisms operated and impacted local climates in the past.' (Page 24, lines 1-4)

Page 24, lines 2-4: Sentence starting 'For example' is not clear.

Response: The text has been clarified and now reads: 'The use of 'upstream' sites could assist in improving the skill of reconstructions for a particular proxy at locations of interest. The utilisation of high-quality sites near to, but outside, the location of interest may lead to regional reconstructions with higher statistical skill, as they may preserve signals of large-scale circulation patterns rather than local climate features (Gallant and Gergis, 2011; Gergis et al., 2012; Gergis et al., 2016; Ho et al., 2013). In Australia, sites along the southern coast of South Australia and Victoria are impacted by a similar atmospheric circulation features and remote climate drivers as major cities and agricultural centres of southern Australia (Murphy and Timbal, 2008), lending the potential to use palaeoclimate records from near the coast to infer patterns of change inland (Ho et al., 2013).' (Page 24, lines 11-17)

Page 24, line 14: ...signals in **a** regional palaeoclimate...

Response: The sentence has been corrected and now reads: 'In particular, the resulting spatial fields and climate metrics (indices, archetypal patterns) that are able to be generated from the current range of approaches used by the Aus2k group have offered opportunities to explain how local signals in a regional palaeoclimate network simultaneously arise in a dynamical context.' (Page 24, lines 23-25)

Page 24, line 30: …vital importantce for…

Response: The typo has been corrected and the text now reads: 'It is of vital importance for continuation of data comparison in climate research that those creating records archive their existing and future data with at least one of those repositories.' (Page 25, lines 6-8)

Page 25, line 4: …strength of **a** climate…

Response: This sentence reads in the way that the authors intended. No change made.

Page 25, line 24: diervisty **diversity**

Response: The typo has been corrected and the text now reads: 'Additional records of similar quality are needed to further expand the spatial coverage and diversity of climate variables within the Aus2k record network.' (Page 26, lines 7-8)

Page 25, line 25: …Aus2k records network.

Response: The typo has been corrected (Page 26, lines 7-8)

Page 25, line 31: …model comparison**,** and…

Response: The Oxford comma has been added to the sentence. The text now reads: 'Thorough characterisation of proxy-climate relationships could be achieved through site monitoring, climate signal characterisation through model comparison, and development and evaluation of new biological/sedimentological transfer functions.' (Page 26, lines 13-15)

Page 26, line 3: 'for Common Era research' is not necessary

Response: 'For Common Era research' has been removed.

Page 26, lines 6-7: Do the authors mean 'high-resolution' or 'low resolution'?

Response: 'High resolution' has been removed for clarity of the section. The text now reads: 'However, the existing high-quality records demonstrate the potential of sites within this region to provide well-dated records with recognised connections to climate variables.' (Page 26, lines 21-22)

Page 26, line 7: …recogniz**s**ed…

Response: The American spelling has been replaced with British spelling and is now in line with the rest of the document.

Response: Thank you for the careful editorial reading of our work. All typographic errors were corrected as suggested

Supplementary material
Figure S1: Make axes the same units and scales
Figure S2: Make axes the same units and scales

Response: The axes and scales for figure S1 have been equalized.

References
There are a number of references missing from the reference list or text. Below are the ones I found. I recommend the authors check through all text, references and supplementary material to make sure all references are included and there are no typographical errors.

The following references are missing from the reference list:
Browning and Goodwin 2014
De Deckker et al. 2011
Emile-Geay and Eshleman, 2013
Gingele et al., 2007
Goring et al. 2012
Gouramanis et al. 2010
Grant 1985
Jones et al. 1998, 2001
Kershaw 1982
Martin et al. 2014
R Development core team 2013
Schaefer et al., 2009

Response: Each in-text reference was checked to ensure that it appears correctly in the reference list.

<u>* In the reference list:</u>

Typo: Bowler, J. M. & Hamada, T. 1971. Late Quaternary stratigraphy and radiocarbon chronology of water level fluctuations in Lake Keilambete, Victoria. Nature, 232, 330**-&.**
Please recheck the references for the correct format of surnames. Below are the ones I noticed.
D’costa should be D’Costa
McTainsh (Hesse, P. P. & **Mctainsh**, G. H. 2003. Australian dust deposits: modern processes and the Quaternary record. Quaternary Science Reviews, 22, 2007-2035)
Mcdonald should be McDonald

Mcfadgen should be McFadgen
Mcglone should be McGlone
Mckay should be McKay
McMillan (Fairchild, I. J. & Mc**m**illan, E. A. 2007. Speleothems as indicators of wet and dry periods. International Journal of Speleology, 36, 69-74)
LeGrande (Lewis, S. C. & Le**g**rande, A. N. 2015. Stability of ENSO and its tropical Pacific teleconnections over the Last Millennium. Climate of the Past, 11, 1347-1360)

Response: All references have been checked and now comply with the journal's style requirements.

Low-resolution Australasian palaeoclimate records of the last 2000 years

Bronwyn C. Dixon[1], Jonathan J. Tyler[2], Andrew M. Lorrey[3], Ian D. Goodwin[4], Joëlle Gergis[5], Russell N. Drysdale[1]

Response to Reviewer 2

General comments

This is a very clearly written manuscript, making a convincing case for compiling multiple low-resolution archives of past environmental/climate change in the Australasian region. The paper could be useful for future palaeo-studies in the region and could inspire research teams to produce similar compilations for other regions.

Specific comments

* Which calibration curve was used for the terrestrial sites, SHCal13? Make this clear within the methods.

Response: SHCal13 was used for terrestrial sites, and Marine13 was used for marine sites. This selection is now clarified in the 'data and methods' section, page 8, lines 24-26: 'Radiocarbon dates at terrestrial sites were recalibrated with the SHCal13 calibration curve (Hogg et al., 2013), while marine radiocarbon dates were recalibrated with the Marine13 curve (Reimer et al., 2013).'

* For the marine sites, how were marine dR values and their uncertainties estimated, e.g. using http://calib.org/marine/ ? Which data-points were used to estimate dR values for each site? Please provide this information as supplementary information or at your NOAA archive, so that others can replicate your findings.

Response: Marine dR values and uncertainties were taken from the original publications. This is now clarified in the 'data and methods' section on page 8 lines 26-27: 'Any radiocarbon reservoir effects identified by the original authors were applied during age-depth model construction.'

An additional column now appears in Table 1 to provide links to the NOAA archive of the original publication, so that others can easily find the original dR values.

* p1 line 16, what are progressive Bayesian techniques?

Response: The word 'progressive' has been removed for improved clarity of the abstract. The text has been amended to read: 'New chronologies based on Bayesian techniques…'

* p2 line 4, but one could argue that during this recent time, human impact might have affected more of the proxy records. Could this potentially be a problem in some of your sites?

Response: Yes, it is possible that human impact has affected the proxy records during this time. This point is now clarified on page 11, lines 23-28 of the manuscript: 'A possible limitation in the Australasian context is the assumption of a stable relationship between sediment properties and climate variables over long periods of time. Humans have likely impacted Australian wetland ecosystems for the entire duration of the Holocene (Fletcher and Thomas, 2010b;Black et al., 2007), and impact has been recognised in New Zealand during the last millennium (Horrocks et al., 2007;McGlone and Wilmshurst, 1999b). This anthropogenic influence has intensified across Australasia since the arrival of European settlers (Gell et al., 2007;Bickford and Gell, 2005;McGlone and Wilmshurst, 1999a), which may lead to palaeolimnological signals unrelated to climate.'

However, there is potential for human impact at longer time scales, particularly in regions of the world with long occupation histories. Chronological constraints available for palaeoclimate records during the last 2000 years provide a vital opportunity to investigate potential human impacts at individual sites as well as investigation of climate signals within the records.

Within New Zealand, human impact is only recognised during the last millennium (e.g. Horrocks et al., 2007, McGlone and Wilmshurst, 1999). For this reason, comparison of records from the first millennium CE versus the second millennium CE could highlight potential human impact on palaeoclimate proxies.

One of the selection criteria for high-quality records in this study is 'a demonstrated relationship between the proxy(ies) and at least one climate variable, as stated in a peer reviewed publication'. It is the assumption of this study that this criterion will identify the records where the climate signal is stronger than any potential human impact. In many records, the climate signal and human impact can be independently identified through a multi-proxy approach and/or lab-based theoretical investigations of proxy-climate relationships. The high quality records are available in their entirety on the NOAA data center. Individual researchers may make the choice to exclude the most recent section of any given record, which is the time period most likely to have human impacts.

The use of site monitoring, climate sensitivity studies, and proxy system modelling are highlighted as methods to investigate possible human impact on record sites. This is expressed on page 25 lines 20-22.

* p6 line 12: don't forget to list the error associated with having non-dated levels, and thus requiring an age-model that provides realistic estimates of uncertainties (as you explain later, on p7 lines 16-24). Perhaps cite Bennett, K.D. 1994 (The Holocene 4, 337-348), Telford et al. 2004 (Quat. Sci. Rev. 23, 1-5), and Trachel & Telford 2016 (The Holocene doi:10.1177/0959683616675939).

Response: A sentence discussing the age uncertainties in sedimentary records, as contained within undated layers, and the need for age modelling to estimate interpolation uncertainty has been added to page 6 lines 18-19: 'Despite the benefits of low-resolution archives, these records often contain relatively large errors associated with radiometric dating techniques (Anchukaitis and Tierney, 2012;Moberg et al., 2005) and uncertainty associated with using age-depth models to predict ages of undated layers (Trachsel and Telford, 2017;Telford et al., 2004). '

The suggested references are now cited in page 6 line 19.

* Perhaps cite Flantua et al 2016 (Climate of the Past 12, 387-414) for another recent compilation of regional chronologies.

Response: Although there is some similarity between the approaches, the authors feel that Flantua et al., (2016) does not support any of the specific points made in this paper. Future work could discuss the similarities and differences between the PAGES2k regions, but such a comparison is outside the scope of this paper.

* p8, line 18, Bacon does not exclude outliers but deals with them through using student-t distributions for all dates as default (not student-t tests) - these distributions look much like normal distributions but have wider tails. As a result even dates that seem outlying to our eyes (i.e. lying far away from the model and neighbouring dates) will often still fit the age-model (probability distribution >0 at the age-model at the depth of said date).

Response: We acknowledge the incorrect and unclear information concerning the identification and treatment of outliers within the BACON package. This section has been updated and clarified for more correct information about outliers in this study. Text in section 2.4, page 8 line 21-24 now reads: 'BACON uses student t-distributions for radiocarbon dates, which have wider tales than normal distributions (Blaauw and Christen, 2011). This distribution is chosen with the intention of including the maximum number of dates in an age-depth model and decreasing the need to remove outliers. In this study, decisions of the original authors were upheld in the recalibration of age models, including the exclusion of radiocarbon dates due to inversion or contamination.'

Language

* p12 lines 22-24, check sentence

Response: This sentence has been removed, and the information has been expressed in section 4.1.1.

*p13 line 12, associated & line 18, influenced

Response: The words 'associated' and 'influenced' have been corrected.

* p17 line 29, Indonesian

Response: 'Indonesia' has been corrected to 'Indonesian'.

* p18 line 11, shown

Response: 'shows' has been corrected to 'shown'

* p22 line 4, renewed efforts to renewed efforts to

Response: Revised to read: 'These developments mean new, more cost-effective dating strategies can be employed to create new well-dated records, as well as renewed efforts to revisit former sites to improve the original chronologies.'

* p25 line 24, diversity

Response: The spelling of 'diversity' has been corrected.

* p26 line 25, Past Global Changes (not glocal)

Response: The spelling of 'Global' has been corrected.

References:

Horrocks, M., Nichol, S. L., Augustinus, P. C. & Barber, I. G. 2007. Late Quaternary environments, vegetation and agriculture in northern New Zealand. Journal of Quaternary Science, 22, 267-279.

Mcglone, M. S. & Wilmshurst, J. M. 1999. Dating initial Maori environmental impact in New Zealand. Quaternary International, 59, 5-16.

Low-resolution Australasian palaeoclimate records of the last 2000 years

Bronwyn C. Dixon[1], Jonathan J. Tyler[2], Andrew M. Lorrey[3], Ian D. Goodwin[4], Joëlle Gergis[5], Russell N. Drysdale[1]

Response to Short Comment 1

Dear Dr. Rouillard,

Response: The authors of "Low-resolution Australasian palaeoclimate records of the last 2000 years" thank you for bring additional publications to our attention. As you say, there is a paucity of records in western/northern Australia. For this reason, it is important to include all available records in our reference list.

The references you suggested have been added to the reference list, and the record sites within these papers will be added to our results. Unfortunately, none of the record meet all of the criteria necessary for inclusion in the 'high quality' dataset. The reason(s) for exclusion are listed after each reference.

Again, we thank you for your assistance to ensuring all records are available for future consideration by the palaeoclimate community.

Dear authors,
Considering the relative paucity of records in the Western and Northern parts of Australia, I would like bring to your attention the following recently published low resolution records for these regions, with respective references, for addition to Figure 1 & Figure 2.

Black Springs Lake Wetland McGowan et al., 2012
King River LakeWetland Proske et al., 2014
Fortescue Marsh LakeWetland Rouillard et al., 2016a, b

McGowan, H. et al. (2012) Evidence of ENSO mega-drought triggered collapse of prehistory Aboriginal society in northwest Australia. Geophysical Research Letters 39, L22702, 1–5

Response: This record is excluded from the 'high quality' record list because of an insufficient number of dates within the past 2000 years, as well as too low resolution. The PAGES selection criteria require at least three dates within the past 2000 years if the record is longer than 1000 years.

Proske, U. et al. (2014) A Holocene record of coastal landscape dynamics in the eastern Kimberley region, Australia. Journal of Quaternary Science 29, 163–174

Response: This record is excluded from the 'high quality' record list because of an insufficient number of dates within the past 2000 years.

Rouillard, A. et al. (2016a) Evidence for extreme floods in arid subtropical northwest Australia during the Little Ice Age chronozone (CE 1400–1850). Quaternary Science Reviews 144, 107 – 122

Response: This record is excluded from the 'high quality' record list because of uncertainty in the age model, possible discontinuity in the sedimentary sequence, and an uncertain climatic control on the measured proxies. The record is suitable for qualitative comparison of climate regimes within Australasia, but does not meet the needs of the PAGES Aus2k initiative.

Rouillard, A. et al. (2016b) Interpreting vegetation change in tropical arid ecosystems from sediment molecular fossils and their stable isotope compositions: A baseline study from the Pilbara region of northwest Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 459, 495–507

Response: This record is excluded from the 'high quality' record list because of uncertainty in the age model, and possible discontinuity in the sedimentary sequence. The record is suitable for qualitative comparison of climate regimes within Australasia, but does not meet the needs of the PAGES Aus2k initiative.

Kind Regards,
Alexandra Rouillard, PhD

Low-resolution Australasian palaeoclimate records of the last 2000 years

Bronwyn C. Dixon[1], Jonathan J. Tyler[2], Andrew M. Lorrey[3], Ian D. Goodwin[4], Joëlle Gergis[5], Russell N. Drysdale[1]

Response to Short Comment 2

Dear Dr. Kaufman and 2k Special Issue Data Review Team,

Thank you for your comments on 'Low-resolution Australasian palaeoclimate records of the last 2000 years'. The authors look forward to working to ensure correct data archiving is achieved.

Essential additions for this paper:

* 1) Expand the "Data Availability" section to include a URL to a landing page for the data compilation in this paper. The landing page should list the 22 individual datasets that were selected for this study (Table 1) plus those that were considered but not selected (Table S1).

Response: The following URL will become active upon publication of this manuscript:

ftp://ftp.ncdc.noaa.gov/pub/data/paleo/pages2k/dixon2017australasia/

Age control information, the original published age-depth model, the updated age-depth model, and the previously published time series for each of the 22 'high quality' data sets will be available at this URL.

Raw datasets for each of the publications in table S1 have not been collected. If the data team would prefer, it is possible to include table S1 in spreadsheet form in the online data folder.

* 2) Add Data Citations/URLs (in addition to publication citations) for each of the 22 datasets selected for this compilation. For those data not already in a persistent public repository, submit essential metadata along with the proxy time series itself and add the Data Citation/URL in Table 1.

Response: A column has been added to table 1, which contains data URL(s) for each of the 22 'high quality' datasets.

* 3) Include the 14C and other age control for each of the 22 records, plus the age ensembles (a primary outcome of this study), within the publicly archived files (LiPD format is recommended).

Response: Currently published age control information is available at the individual data URLs mentioned in the previous comment. The BACON age-depth models will be available at:

ftp://ftp.ncdc.noaa.gov/pub/data/paleo/pages2k/dixon2017australasia/

* 4) If any of the records used in this study were also used in previous PAGES 2k databases (temperature or isotopes), please include cross references to those IDs in Table 1.

Response: Data IDs of records used in previous PAGES2k databases have been included in a 'Data ID' column in Table 1 in the online material.

Strongly recommended:

* 5) Table S1 is a major resource for the paleoclimate community. Its value would be increased by: (a) Stating the criterion (or criteria) that was not met for each of the records that did not make the final cut. This will enable future users to easily cull the records that meet other criteria (e.g., lower resolution). (b) Naming the archive and proxy type for each record (as in Table 1). (c) Replacing the "NA" with the actual data or explain the purpose/meaning of the "NA".

Response: Table S1 has been updated to include the archive and proxy for each record. 'NA' was used when it was not possible to calculate the field (i.e. resolution) and/or when it was not possible to access the dataset. This will be clarified in the table caption.

* Please also note the supplement to this comment:

http://www.clim-past-discuss.net/cp-2017-31/cp-2017-31-SC2-supplement.pdf