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Wood density provides new opportunities for reconstructing past temperature variability from southeastern Australian trees

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ABSTRACT

Tree-ring based climate reconstructions have been critical for understanding past variability and recent trends in climate worldwide, but they are scarce in Australia. This is particularly the case for temperature: only one tree-ring width based temperature reconstruction – based on Huon Pine trees from Mt Read, Tasmania – exists for Australia. Here, we investigate whether additional tree-ring parameters derived from *Athrotaxis cupressoides* trees growing in the same region have potential to provide robust proxy records of past temperature variability. We measured wood properties, including tree-ring width (TRW), mean density, mean cell wall thickness (CWT), and tracheid radial diameter (TRD) of annual growth rings in *Athrotaxis cupressoides*, a long-lived, high-elevation conifer in central Tasmania, Australia. Mean density and CWT were strongly and negatively correlated with summer temperatures. In contrast, the summer temperature signal in TRW was weakly positive. The strongest climate signal in any of the tree-ring parameters was maximum temperature in January (mid-summer; $JanT_{max}$) and we chose this as the target climate variable for reconstruction. The model that explained most of the variance in $JanT_{max}$ was based on TRW and mean density as predictors. TRW and mean density provided complementary proxies with mean density showing greater high-frequency (inter-annual to multi-year) variability and TRW showing more low-frequency (decadal to centennial-scale) variability. The final reconstruction model is robust, explaining 55% of the variance in $JanT_{max}$, and was used to reconstruct $JanT_{max}$ for the last five centuries (1530–2010 C.E.). The reconstruction suggests that the most recent 60 years have been warmer than average in the context of the last ca. 500 years. This unusually warm period is likely linked to a coincident increase in the intensity of the subtropical ridge and dominance of the positive phase of the Southern Annular Mode in summer, which weaken the influence of the band of prevailing westerly winds and storms on Tasmanian climate. Our findings indicate that wood properties, such as mean density, are likely to provide significant contributions toward the development of robust climate reconstructions in the Southern Hemisphere and thus toward an improved understanding of past climate in Australasia.

1. Introduction

Tree-ring based reconstructions of climate have been critical for understanding past climate variability and placing recent climatic trends in a long-term context. However, for most of the Southern Hemisphere, including Australia, there are few tree-ring based climate reconstructions, which constrains our understanding of recent and potential future climatic changes. In Australia, the limited number of tree-ring based climate reconstructions is largely attributable to a lack of tree species that are suitable for dendrochronology. The dominant angiosperm genera do not generally produce visually distinct or strictly annual rings suitable for dendrochronological methods (Schweingruber, 1992), but recent progress points to the potential some of these genera may hold (Brookhouse and Brack, 2006; Brookhouse et al., 2008; Heinrich et al., 2009; Whinder et al., 2013).

In addition to this, the primary focus of Australian dendrochronology has been on tree-ring width (TRW) – the most commonly used tree-ring parameter in chronology development globally – which has failed to provide clear climatic signals in many of the species and sites examined to date. Recent successes in the reconstruction of past rainfall and/or drought indices have used TRW measurements from the mainland conifer *Callitris columellaris* (including the previously named *C. intratropica*, Farjon, 2005) in the north and west of the continent (Cullen and Grierson, 2009; D'Arrigo et al., 2008; O'Donnell et al., 2015). However, to date, the only temperature reconstruction derived from TRW is based on Huon Pine (*Lagarostrobos franklinii*) from one high-elevation site (Mount Read, 900 m.a.s.l.) in Tasmania (Cook et al., 1991; Cook et al., 1992; Cook et al., 2000). Globally, this is also one

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of the longest tree-ring based climate reconstructions (1600 B.C.E.–1991 C.E.). Despite considerable efforts over the past two decades, high-quality reconstructions of temperature based on low-elevation Huon Pine TRW (Buckley et al., 1997) and TRW of other long-lived conifer species i.e., Pencil Pine (*Athrotaxis cupressoides*, Allen et al., 2011) and Celery Top Pine (*Phyllocladus aspleniifolius*, Allen et al., 1999) in Tasmania have so far been unsuccessful.

Other physical wood properties (i.e., density, cell wall thickness (CWT), tracheid radial diameter (TRD), and microfibril angle (MFA); e.g., Drew et al., 2013) as well as chemical wood properties (i.e., stable isotope concentrations, e.g., Treydte et al., 2006; Brienen et al., 2012, and trace element concentrations, e.g., Poussart et al., 2006) are also known to record climatic information. In particular, strong temperature signals have been identified in the wood density of conifers across Europe (e.g., Briffa et al., 2002; Büntgen et al., 2010; Trouet, 2014) and North America (e.g., Briffa et al., 1992; D'Arrigo et al., 1992; Davi et al., 2003; Luckman and Wilson, 2005; Wilson et al., 2007). In many cases, wood density, particularly maximum latewood density (MXD), has been more strongly correlated with temperature and over a longer summer season than TRW (Briffa et al., 2002; Grudd, 2008; Tuovinen et al., 2009; Trouet et al., 2012). Consequently, MXD has been widely used in the Northern Hemisphere to build temperature-sensitive chronologies (e.g., Schweingruber and Briffa, 1996; Frank and Esper, 2005; Grudd, 2008) and to reconstruct summer temperatures over the last several centuries to millennia (e.g., Briffa et al., 1992; Luckman and Wilson, 2005). Recent work has also demonstrated the potential of various wood properties (e.g., CWT, TRD, MFA, and mean ring density) of several long-lived Tasmanian conifers as sources of past climatic information (Allen et al., 2012; Drew et al., 2013; Allen et al., 2013) and for reconstructing stream flow (Allen et al., 2015). Despite this potential, temperature reconstructions based on these wood properties have not yet been developed.

Here, we investigate the potential of several of these wood properties for reconstructing past temperatures in Australia. We focus on the native conifer, *Athrotaxis cupressoides* (Pencil Pine), which is endemic to high-elevation (700–1300 m.a.s.l.) areas of Tasmania (Farjon, 2005). In addition to TRW, we measured mean density, TRD, and CWT. Given the strength of climatic signals previously identified in these wood properties, we expect that chronologies based on wood properties, particularly mean density, will allow us to produce the first robust *A. cupressoides*-based temperature reconstruction in Tasmania.

2. Methods

2.1. Site description

We collected *A. cupressoides* samples at two high elevation sites (~1200 m.a.s.l.) in central Tasmania, Australia (41.742°S, 146.703°E; Fig. 1a). The first site is adjacent to Pine Lake. The other site is on a southwest-facing slope adjacent to Mickey Creek. These two sites are ca. 1.5–2 km apart on Tasmania's Central Plateau. The Pine Lake-Mickey Creek (PLMC) site is approximately 100 km east of the Mt Read site (~900 m.a.s.l.) that was sampled to develop the only existing tree-ring based temperature reconstruction in Australia (Cook et al., 1991; Cook et al., 1992; Cook et al., 2000). Climate at the PLMC site is characterised by cold and wet conditions in the winter and spring months (May–Oct) and comparatively warmer and drier conditions in the summer and autumn months (Nov–Apr; Fig. 1b).

2.2. Sample collection and preparation and chronology development

2.2.1. TRW

A total of 57 cores (5-mm diameter) were collected from 20 trees from the Mickey Creek site in April 2010. Wherever possible, three cores per tree were collected. We also obtained 29 cores from 19 trees from the Mickey Creek site (collected in 1990) directly from the collectors, E. Cook and B. Buckley. Cores were prepared according to standard dendrochronological techniques (Stokes and Smiley, 1968) and visually crossdated before TRW was measured. This TRW data set was complemented with 27 TRW series from 27 trees collected by LaMarche and Campbell in 1975 (LaMarche et al., 1979) from the Pine Lake site (accessed from: https://www.ncdc.noaa.gov/paleo/study/3844; January 2009). In total 112 series from 66 trees were included in the final TRW chronology.

We used signal-free methods (Melvin and Briffa, 2008) and an age-dependent spline (Melvin et al., 2007) to detrend each of the TRW series. We chose this method to retain a trend in the most recent part of the chronology that is similar to and likely related to a trend in observed temperatures over the same period. We used the RCSigFree program (http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software) to detrend the TRW series and calculated indices as residuals from power-transformed ring widths (Cook and Peters, 1997).

2.2.2. Wood properties

SilviScan-3, a rapid-assessment, high-resolution technology, which includes an image analyser, X-ray densitometer and X-ray defractometer that was developed by the Commonwealth Scientific and Industrial Research Organisation, Australia (Evans, 1994), was used to measure mean density and TRD. In order to obtain measurements that are as accurate as possible, SilviScan-3 requires samples with minimal ring curvature. In addition, samples that have been heavily sanded such that relatively little of an original 5 mm core remains are not suitable for processing. Based on these constraints, a subset of 23 cores (15 trees) from the Mickey Creek 2010 collection and 6 cores (6 trees) from the Mickey Creek 1990 collection were selected for measurement of wood properties. These cores were cut into strips of 2 mm thickness in the tangential direction. For each core, mean density was measured by X-ray densitometry at 25 μm intervals. TRD was also measured at 25 μm intervals by image analysis of the transverse surface. CWT was derived from TRD and mean density. All variables were averaged over individual growth rings to provide mean density, mean TRD, and mean CWT for each year. The final mean density chronology included all 29 series from 21 trees. Some of the CWT series were excluded because they were not significantly correlated with the sample population; consequently the final CWT chronology included 24 series from 16 trees. The TRD series did not show a coherent growth signal so could not be used to develop a robust chronology and were not included in further analyses.

Unlike the TRW series, there were no apparent trends in the recent decades of the mean density or CWT series and we detrended these series using the locally-adaptive Friedman variable span smoother (Friedman, 1984) in the ARSTAN program (Cook and Krusic, n.d.). We calculated mean density and CWT indices as ratios because they showed stronger reconstruction skill compared with indices calculated using the residual method (data not shown; Cook and Peters, 1997). For further analyses, we used the ARSTAN chronologies (pooled autocorrelation added back into the residual chronology; Cook 1985). To assess the quality of our chronologies over time, we used the average correlation between series (RBAR) and expressed population signal (EPS) (Wigley et al., 1984). A minimum EPS value of 0.85 is generally accepted as a reasonable threshold for a reliable chronology.

2.3. Climate data

Instrumental climate records in central Tasmania are sparse and often temporally short or discontinuous, particularly at high altitudes. The Australian Bureau of Meteorology (BOM) lists only two weather stations with temperature records within 100 km of the PLMC site and at comparable elevations (i.e., >1000 m.a.s.l.): Liawenee (1985–2013 C.E., with a discontinuity in 2001–2003 C.E. when the station was moved) at 17 km and Mt Read (1996–2014 C.E.) at 97 km. The time series at these two stations are thus short and long-term temperature records for the PLMC site are limited to gridded data sets