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Rapid Communication

A strong regional temperature signal in low-elevation Huon pine

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ABSTRACT: We have produced the first annually resolved, centennial-length tree-ring chronologies, based on tracheid radial diameter (TRD) and microfibril angle for south-eastern Australia (SEA) from what would commonly be considered a dendroclimatically suboptimal site. The chronologies exhibit a strong regional temperature signal for the austral summer (nominally November–April) that extends across much of SEA. The strength and spatial extent of the temperature–TRD correlations surpass those between the iconic Tasmanian Mt Read ring-width chronology and austral summer temperatures, and are more time-stable. We demonstrate that the value of wood property chronologies for their ability to improve the both the quality and the quantity of highly climate-sensitive series available for regional annual-resolution climate reconstructions, in data-sparse regions in Australasia and beyond, should be examined. In light of the 'divergence debate', the time-stability of relationships with climate, relative to other tree-ring proxies, also requires further investigation. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS: Australia; microfibril angle; Huon pine; tracheid radial diameter; tree ring.

Introduction

South-eastern Australia (SEA) is home to approximately 57% of Australians and is a critical food production zone. In recent times it has experienced significant rainfall decline, drought, fires and floods consistent with predictions of climate change effects (CSIRO, 2010). The expectation that climate variability will increase under climate change means there is a pressing need to better understand the longer-term climate history of SEA and emphasizes the need for high-resolution climate proxies with regional SEA climate signals. The only annual-resolution record used in its own right to reconstruct regional climate for SEA has been the 3600-year Tasmanian Mt Read Huon pine chronology (Cook *et al.*, 1992, 2000, 2006), which is strongly correlated with sea surface temperatures (SSTs) over the Southern Ocean due west of Tasmania (Cook *et al.*, 2000) during the austral summer (November–April). Although long and well replicated, this reconstruction is based on a single site. A number of other multi-century Tasmanian tree-ring chronologies (Allen *et al.*, 2001) have been used in multi-proxy climate reconstructions for SEA [e.g. Gergis *et al.*, 2011 (precipitation); Gallant and Gergis, 2011 (streamflow)], but these temporally limited (1783–1988) reconstructions have necessarily relied heavily on proxy records outside SEA due to the lack of annually resolved records from the SEA region. It is therefore likely that these reconstructions better reflect impacts of broad-scale variability beyond SEA. Development of additional proxies from SEA with regional climate signals would be invaluable for future climate reconstructions, and for comparison with existing southern hemisphere reconstructions. Substantial asynchronicities among temporally overlapping temperature reconstructions from South America, New Zealand and Tasmania (Mt Read) (Villalba *et al.*, 1997, 2012; Cook *et al.*, 2006) make this all the more important.

To date, it has not been possible to develop a robust temperature reconstruction based on the ring width (RW) chronology from any other single site from Tasmania due to the poorly understood complex climate response of ring widths at these sites (Buckley *et al.*, 1997; Allen *et al.*, 2001, 2011; Cook *et al.*, 2006). Recent work, however, has demonstrated that while low-elevation Huon pine ring width (RW) is not significantly ($P < 0.05$) correlated with local growing season mean temperature, average microfibril angle (MFA) and average tracheid radial diameter (TRD) from low elevation contain a significant ($P < 0.05$) local warm-season temperature signal (Drew *et al.*, 2013). The strength of correlations between local temperature and these wood properties (MFA and TRD) is comparable to that of correlations between the Mt Read chronology and mean temperature over the same months, although the sign of correlations is opposite (Fig. 1). Information about MFA and TRD is available in Donaldson (2008) and Vaganov *et al.* (2006). Sensitivity of wood properties such as MFA and tracheid diameter to local climate (Xu *et al.*, 2010; Drew *et al.*, 2013; Fig. 1) can be explained in terms of adjustments in developmental processes in the developing xylem (Vaganov *et al.*, 2006; Fonti *et al.*, 2010; Drew *et al.*, 2013). Negative correlations between mean temperature and TRD and MFA are probably related to sensitivity of Huon pine to even moderate water deficits (Brodribb and Hill, 1998; Brodribb and Cochard, 2009) and the resultant impacts of drought on xylem differentiation processes (Drew *et al.*, 2013). This provides a strong prima facie case for investigating the value of wood property chronologies (cf. Fonti *et al.*, 2010) for climate reconstructions.

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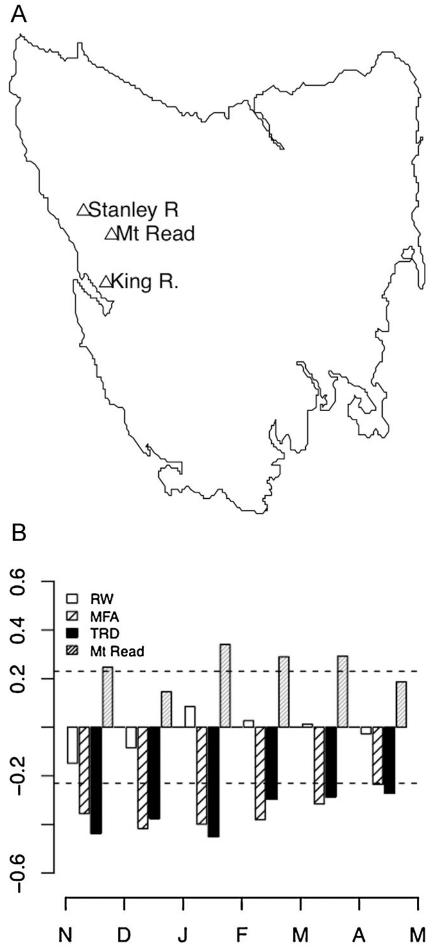

Figure 1. (A) Location of King River site, the low-elevation Stanley River site that has produced a multi-millennial chronology, and the high-elevation Mt Read site from which the 3600-year chronology and mean temperature reconstruction has been produced. (B) Monthly correlations between mean temperature (warm season months) and the King River ring-width (RW), tracheid radial diameter (TRD) and microfibril angle (MFA) chronologies, and between the Mt Read RW chronology and mean warm-season temperature.

While the strong correlations between wood properties and climate suggest the possibility for development of a robust local climate reconstruction across a wider range of Tasmanian sites, it remains unclear whether the low-elevation wood property chronologies might also provide a broader, regional climate signal for SEA. In this paper we focus on the regional relevance of our wood property chronologies. We ask two specific questions. First, is there evidence for a regional climate signal in low-elevation Huon pine MFA and TRD chronologies? Second, how does any regional climate signal compare with the spatial extent and strength of the temperature signal in the high-elevation Mt Read RW chronology?

Materials and methods

The King River site is located in low-elevation (60 m above sea level) temperate rainforest adjacent to the King River in western Tasmania, Australia (Fig. 1). Mean annual summer (December–March) and winter (June–August) temperatures are 14.5 and 8.1 °C, respectively. Mean annual rainfall is ~2400 mm, falling mostly in the winter and spring months.

Two 12-mm-diameter cores were extracted from each of 15 (100–300 years old) Huon pine trees and a single core of the same diameter extracted from each of another three trees using a motorized corer. We used SilviScan (Evans, 1994), an integrated X-ray diffractometry and densimtometry platform, to measure wood properties at high spatial resolution in each core. Average tracheid radial diameter was measured on the transverse surface at a sampling interval of 25 μm. Wood density was measured at the same resolution using X-ray densitometry. Microfibril angle measurements, obtained through X-ray diffractometry, were made at a sampling interval of 100 μm, using a 200-μm primary beam. Manual ring-allocations based on density and fibre diameter profiles were checked against RW profiles based on standard dendrochronological techniques (Stokes and Smiley, 1968; Drew *et al.*, 2013). Subsequently, visual cross-dating of wood properties was checked using the standard dendrochronological data quality control software tool COFECHA (Holmes, 1994). Signal-free chronologies (Melvin and Briffa, 2008) for MFA, TRD and RW were developed and standardized using the Friedman 'super-smoother' (Friedman, 1984). An updated Mt Read chronology (unpublished data), consistent with the previously published chronology (Cook *et al.*, 2000), was also developed using the signal-free framework.

Although Drew *et al.* (2013) produced a number of wood property chronologies, we focus on average TRD and average MFA due to the relative novelty and high quality of these chronologies and the strength of correlations between them and mean temperature over the November–April period (Fig. 1) that was used as the basis for the Mt Read temperature reconstruction. Spatial correlations between first-differenced (to remove trend) November–April mean temperatures (CRU TS3.1) and each of the first-differenced TRD, MFA, RW and Mt Read chronologies were calculated for all grid points centred on land in the 25–44.5° S and 130–155° E box. This chosen region conformed to the spatial extent of climate correlations between mean temperature and Mt Read previously shown (Cook *et al.*, 1996). Three periods were examined: the entire period of available climate data (1901–2009) and two 54-year periods (1901–1954 and 1955–2009). To test the validity of these spatial correlation fields we generated 1000 synthetic series from random numbers for each grid cell, each containing an autoregressive AR(1) process and AR coefficient the same as the tree-ring chronology (≈0.4). These series, like the actual chronologies, were first-differenced and the 2.5th and 97.5th percentiles for each grid cell were calculated for each of the three periods. The 2.5th (TRD/MFA/RW) or the 97.5th (Mt Read) percentiles used to check whether the correlations between mean temperatures and TRD, MFA and Mt Read were more extreme than 97.5% of values obtained through the correlation of synthetic series with mean temperature for each grid point. The Supporting information (Appendix S1) contains further methodological detail.

Results

All four chronology time series examined here differed from one another over the 20th century (Fig. 2A,C). An upward trend in the Mt Read RW series since the 1950s was matched by a decline in the TRD chronology. RW exhibited an almost monotonic decrease over the 20th century. After detrending, correlations between TRD and MFA, TRD and Mt Read, and between mean temperatures and each of TRD, MFA and Mt Read (Table 1) remained significant ($P < 0.05$). Correlations between TRD and MFA, TRD and Mt Read, and TRD and November–April temperatures were higher for detrended data than for non-detrended data (Table 1).

The pattern of spatial correlations ($P < 0.1$) between RW and regional temperature was not consistent across the three periods, nor was the centre of correlation consistently over

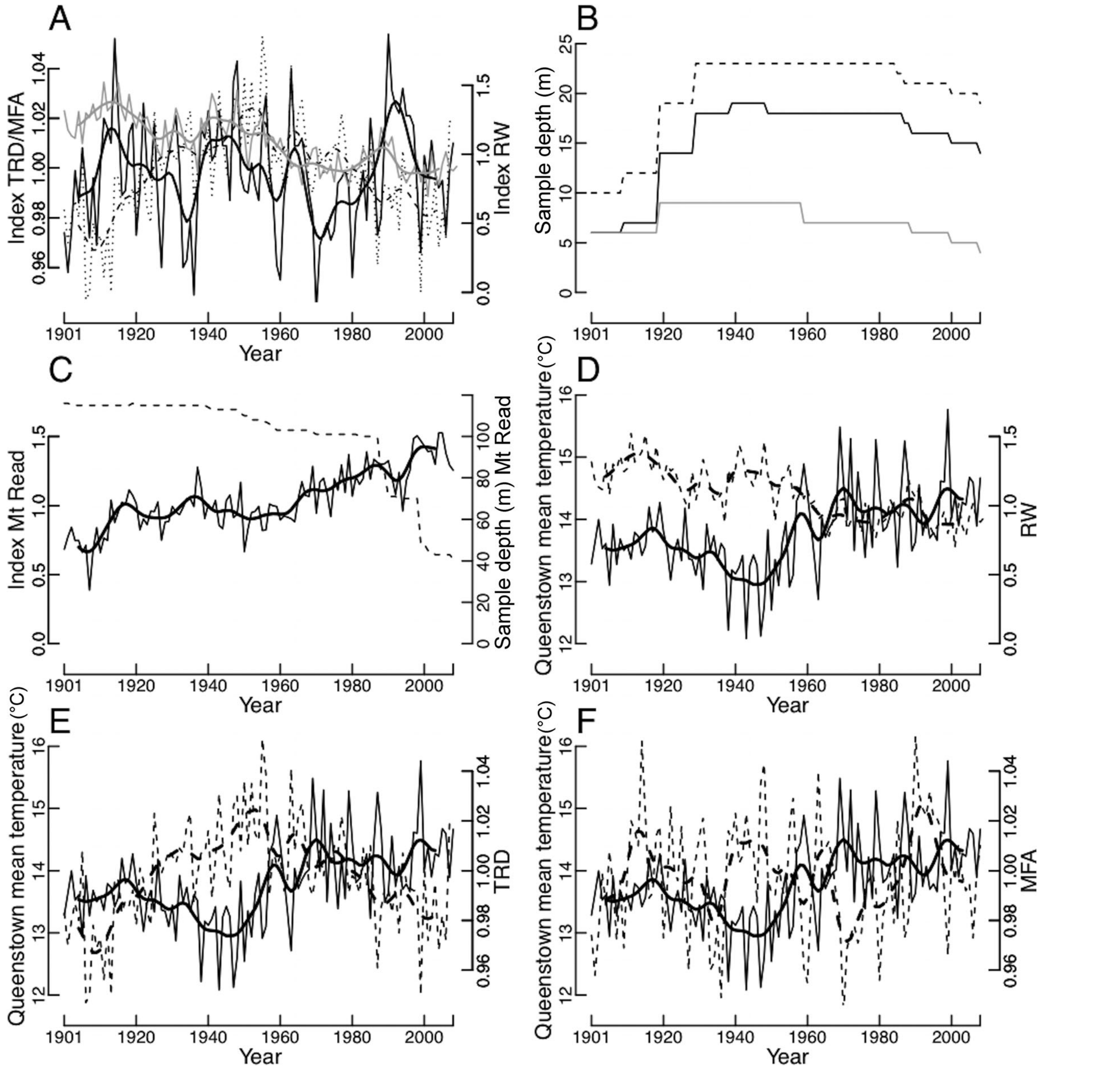

Figure 2. (A) Chronology plots for three King River chronologies, 1901–2009. Black solid line is MFA; black dashed line is TRD and grey line is RW chronology. RW is plotted on the right axis. A 9-year Gaussian filter has been used to smooth the data. (B) Sample depth for the King River TRD, MFA and RW chronologies: black solid line is MFA, black dashed line is TRD and grey line is RW. (C) Mt Read chronology (left axis) and sample depth (right axis). (D) RW (dashed) and mean warm-season temperatures (solid). (E) TRD (dashed) and mean warm-season temperatures (solid). (F) MFA (dashed) and mean warm-season temperatures (solid). A 9-year Gaussian filter has been fitted to the data for plots D–F.

southern SEA (Fig. 3). In contrast, correlations between regional mean temperature and each of TRD and Mt Read each possessed relatively consistent patterns with strongest correlations centred on southern SEA. In addition, a large proportion of the areas of significant correlation ($P < 0.1$) for TRD and Mt Read also had correlations that exceeded 97.5% of correlations with synthetic data (Fig. 3). Although the spatial extent of significant correlations between MFA and

Table 1. Correlations between the various chronologies and between chronologies and mean temperature and chronologies.

	RW	MFA	TRD	Mt Read	Mean warm-season (November–April) temperatures
RW	1	0.13 (0.06)	−0.39** (−0.12)	−0.5** (0.00)	−0.32** (–0.01)
MFA		1	0.26* (0.58**)	0.02 (0.01)	−0.43** (–0.44)**
TRD			1	−0.08 (−0.3**)	−0.41** (–0.56**)
Mt Read				1	0.47** (0.4**)

Data in parentheses are for detrended series. Asterisks indicate significant correlations at: *$P < 0.05$; **$P < 0.01$. Correlations between RW and each of TRD, mean temperature and Mt Read become non-significant after detrending while those between MFA and TRD, and between mean temperatures and each of TRD, MFA and Mt Read remain significant ($P < 0.05$). All correlations between non-detrended series cover the period 1901–2009 and correlations between detrended series cover the period 1902–2009.

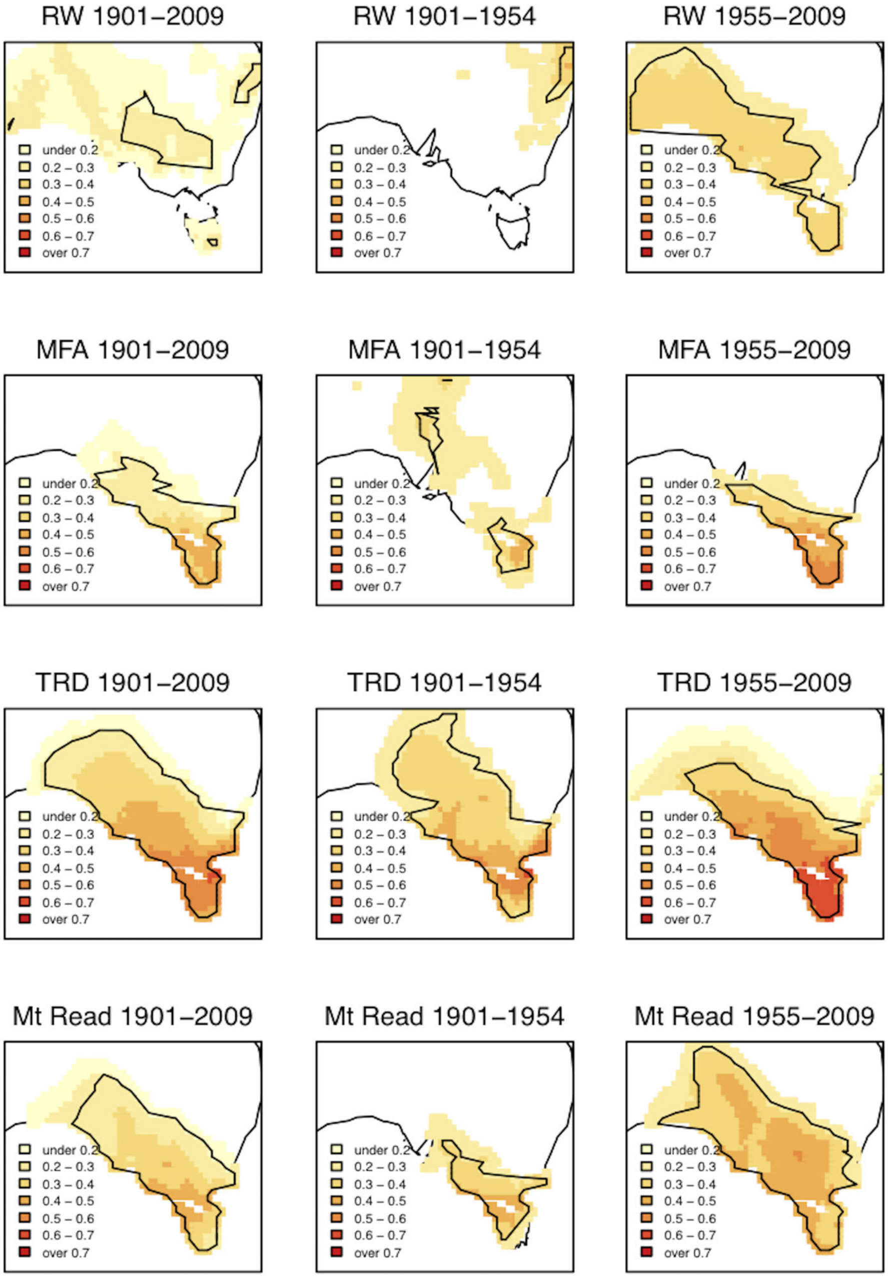

Figure 3. Spatial correlations between first-differenced mean warm-season temperature (November–April CRU TS 3.1 average) and the three first-differenced chronologies. Sign of correlations for MFA and TRD have been reversed to more readily enable comparison with the Mt Read correlations. Only correlations significant at $P < 0.1$ are shown. Top: King River tree-ring width (RW); second row microfibril angle (MFA); third row tracheid radial diameter (TRD); bottom: Mt Read. Left column is 1901–2009, middle column is 1901–1954 and right column is 1955–2009. Areas outlined in black include those grid points for which the correlation value of the chronology with mean temperature was more extreme than 97.5% of all correlations between the synthetic series and mean temperature. Plots were generated in the R-environment. This figure is available in colour online at wileyonlinelibrary.com.

mean warm-season temperatures varied widely across the three periods, strongest correlations occurred over Tasmania for all three periods. Spatial correlation patterns for MFA, TRD and Mt Read were consistently weaker in the 1901–1954 period than the 1955–2009 period (Fig. 3). Atmospheric circulation changes may be responsible for weaker early-period correlations (Larsen and Nicholls, 2009), although poorer quality and fewer meteorological recording stations in the earlier period may also have played an important role.

The spatial extent of the regional signal of the low-elevation TRD chronology is greater than that of the high-elevation Mt Read RW chronology for both the 1901–2009 and the 1901–1954 periods (Fig. 3). The TRD correlations, however, were stronger than those for Mt Read for all three periods.

Discussion

The first annually resolved, climatically sensitive, centennial-length chronologies based on the wood properties MFA and TRD, from what would be considered a dendroclimatically suboptimal site, contain a strong regionally coherent signal. The regional relationship between TRD/MFA and mean temperatures is significant and consistently focused on SEA (Fig. 3). The spatial extent of the regional relationship is consistent with that between the Mt Read RW chronology and mean warm-season temperatures (Fig. 3). The strength of the TRD–mean warm-season temperature relationship, however, exceeds that between the Mt Read chronology and mean warm-season temperatures. Notably, the temporal stability of the regional footprint of the TRD relationship is greater than that of Mt Read.

There are at least three important implications of our work. First, relationships between climate variables and a RW/density chronology that substantially weaken ('the divergence problem') or strengthen through time are examples of unstable climate–chronology relationships (e.g. Peterson *et al.*, 1990; Briffa *et al.*, 2004; Büntgen *et al.*, 2008; D'Arrigo *et al.*, 2009; Salzer *et al.*, 2009; Benito *et al.*, 2010). Instability in the relationship between a climate variable and RW/density over time result in greater uncertainty in reconstructions than do stable relationships. The more stable response of low-elevation TRD to temperature suggests that a temperature reconstruction for SEA based on it will contain less inherent uncertainty than that based on the Mt Read RW chronology. This, however, requires further investigation using much longer series.

Secondly, multi-proxy archives from corals (Gagan *et al.*, 2000), speleothems (Baker *et al.*, 2008) and tree rings (Hughes *et al.*, 2011) are now quite commonly used to elicit more detailed climatic information available from a single archive (cf. Sidorova *et al.*, 2012). Our results indicate that a wider variety of proxies in tree rings than has currently been exploited is available for development of climate-sensitive chronologies. There is a relative wealth of long-lived species available from SEA, including celery top pine (Allen *et al.*, 2001), pencil pine, King Billy pine (Allen *et al.*, 2011) and lower elevation Huon pine (Buckley *et al.*, 1997). The vast amount of woody material available for analysis from these species archives in SEA has enormous potential to become the basis of a robust and detailed temperature reconstruction for the SEA region based on wood properties.

Thirdly, development of wood property chronologies with regional climate signals from sites where it has not been possible to develop climate-sensitive RW chronologies due to poor cross-dating or complicated climate signals may be possible. This is critical, especially in the southern hemisphere, because additional chronologies in data-sparse regions are required for the improvement and verification of reconstruction quality (Cook *et al.*, 2000; Esper *et al.*, 2002; Jones *et al.*, 2009; Fonti *et al.*, 2010). Wood property chronologies may also be the key to very long annually resolved regional temperature records for SEA based largely on material from the Stanley River archive.

Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's web-site.

Appendix S1. Additional methodological information.

Please note: This supporting information is supplied by the authors, and may be re-organized for online delivery, but is not copy-edited or typeset by Wiley-Blackwell. Technical support issues arising from supporting information (other than missing files) should be addressed to the authors.

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Abbreviations. MFA, microfibril angle; RW, ring width; SEA, south-eastern Australia; TRD, tracheid radial diameter

References

Allen KJ, Cook ER, Francey RJ, *et al.* 2001. The climatic response of *Phyllocladus aspleniifolius* (Labill.) Hook. F. in Tasmania. *Journal of Biogeography* **28**: 305–316.

Allen KJ, Ogden J, Buckley BM, *et al.* 2011. The potential to reconstruct broadscale climate indices associated with Australian droughts from *Athrotaxis* species, Tasmania. *Climate Dynamics* **37**: 1799–1821.

Baker A, Smith CL, Jex C, *et al.* 2008. Annually laminated speleothems: a review. *International Journal of Speleology* **37**: 193–206.

Benito DM, del Rio M, Cañellas I. 2010. Black pine (*Pinus nigra* Arn.) growth divergence along a latitudinal gradient in Western Mediterranean mountains. *Annals of Forest Science* **67**: 401–413.

Briffa KR, Osborn TJ, Schweingruber FH. 2004. Large-scale temperature inferences from tree rings: a review. *Global and Planetary Change* **40**: 11–26.

Brodribb T, Hill RS. 1998. The photosynthetic drought physiology of a diverse group of Southern Hemisphere conifer species is correlated with minimum seasonal rainfall. *Functional Ecology* **12**: 465–471.

Brodribb TJ, Cochard H. 2009. Hydraulic failure defines the recovery and point of death in water-stressed conifers. *Plant Physiology* **149**: 575–584.

Buckley BM, Cook ER, Peterson MJ, *et al.* 1997. A changing temperature response with elevation for *Lagarostrobos franklinii* in Tasmania, Australia. *Climatic Change* **36**: 477–498.

Büntgen U, Frank D, Wilson R, *et al.* 2008. Testing for tree-ring divergence in the European Alps. *Global Change Biology* **14**: 2443–2453.

Cook ER, Bird T, Peterson M, *et al.* 1992. Climate change over the last millennium reconstructed from tree-rings. *Holocene* **2**: 205–217.

Cook ER, Buckley BM, D'Arrigo RD, *et al.* 2000. Warm-season temperatures since 1600 BC reconstructed from Tasmanian tree rings and their relationship to large-scale sea surface temperature anomalies. *Climate Dynamics* **16**: 79–91.

Cook ER, Buckley BM, Palmer JG, *et al.* 2006. Millennia-long tree-ring records from Tasmania and New Zealand: a basis for modelling climate variability and forcing, past, present and future. *Journal of Quaternary Science* **21**: 688–699.

Cook ER, Francey RJ, Buckley BM, *et al.* 1996. Recent increases in Tasmanian Huon pine ring widths from a subalpine stand: natural climate variability, CO_2 fertilisation, or greenhouse warming? *Papers and Proceedings of the Royal Society of Tasmania* **130**: 65–72.

CSIRO. 2010. Climate Variability and Change in South-Eastern Australia A Synthesis of Findings from Phase 1 of the South Eastern Australian *Climate Initiative (SEACI)*. Commonwealth Scientific and Industrial Research Organisation.

D'Arrigo RD, Jacoby GC, Buckley BM, *et al.* 2009. Tree growth and inferred temperature variability at the North American Arctic tree line. *Global and Planetary Change* **65**: 71–82.

Donaldson L. 2008. Microfibril angle: measurement, variation and relationships – a review. *IAWA Journal* **29**: 345–386.

Drew DM, Allen KJ, Downes GM, *et al.* 2013. Wood properties in a long-lived conifer reveal strong climate signals where ring-width series do not. *Tree Physiology* **33**: 37–47.

Esper J, Cook ER, Schweingruber FH. 2002. Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* **295**: 2250–2253.

Evans R. 1994. Rapid measurement of the transverse dimensions of tracheids in radial wood sections from *Pinus radiata*. *Holzforschung* **48**: 168–172.

Fonti P, von Arx G, García-González I, *et al*. 2010. Studying global change through investigation of the plastic responses of xylem anatomy in tree rings. *New Phytologist* **185**: 42–53.

Friedman JH. 1984. *A Variable Span Scatterplot Smoother*. Standford University Technical Report No. 5.

Gagan MK, Ayliffe AK, Beck JW, *et al*. 2000. New views of tropical palaeoclimates from corals. *Quaternary Science Reviews* **19**: 45–64.

Gallant AJE, Gergis J. 2011. An experimental streamflow reconstruction for the River. Murray, Australia, 1783–1988. *Water Resources Research* **47**: [doi: 10.1029/2010/WR009832.]

Gergis J, Gallant A, Braganza K, *et al*. 2011. On the long-term context of the 1997–2009 'Big Dry' in south-eastern Australia: insights from a 206-year multi-proxy rainfall reconstruction. *Climatic Change* **111**: 923–944.

Holmes R. 1994. *Dendrochronology Program Manual*. Laboratory of Tree Ring Research: Tucson, AZ.

Hughes MK, Swetnam TW, Diaz HF. (eds). 2011. *Dendroclimatology: Progress and Prospects*. Springer: New York.

Jones PD, Briffa KR, Osborn TS, *et al*. 2009. High resolution palaeoclimatology of the last millennium: a review of current status and future prospects. *Holocene* **19**: 3–49.

Larsen SH, Nicholls N. 2009. Southern Australian rainfall and the subtropical ridge: variations, interrelationships and trends. *Geophysical Research Letters* **36**: [DOI: 10.1029/2009GRL037786.]

Melvin TM, Briffa KR. 2008. A 'signal-free' approach to dendroclimatic standardisation. *Dendrochronologia* **26**: 71–86.

Peterson DL, Arbaugh MJ, Robinson LJ, *et al*. 1990. Growth trends of whitebark pine and lodgepole pine in a subalpine Sierra Nevada forest, California, U.S.A. *Arctic and Alpine Research* **22**: 233–243.

Salzer MW, Hughes MK, Bunn AG, *et al*. 2009. Recent unprecedented tree-ring growth in bristlecone pine at the highest elevations and possible causes. *Proceedings of the National Academy of Sciences of the USA* **106**: 20348–20353.

Sidorova OV, Saurer M, Myglan VS, *et al*. 2012. A multi-proxy approach for revealing recent climatic changes in the Russian Altia. *Climate Dynamics* **38**: 175–188.

Stokes MA, Smiley TL. 1968. *Introduction to Tree-Ring Dating*. University of Chicago Press: Chicago.

Vaganov EA, Hughes MK, Shashkin AV. 2006. Radial cell enlargement. In *Growth Dynamics of Conifer Tree Rings: Images of Past and Future Environments*, Caldwell MM, Heldmaier G, Jackson RB, Lange OL, Mooney HA, Schulze E-D, Sommer U (eds). Springer: New York; 105–134.

Villalba R, Cook ER, D'Arrigo RD, *et al*. 1997. Sea-level pressure variability around Antarctica since A.D. 1750 from subantarctic tree-ring records. *Climate Dynamics* **13**: 375–390.

Villalba R, Lara A, Masiokas MH, *et al*. 2012. Unusual Southern Hemisphere tree growth patterns induced by changes in the Southern Annular Mode. *Nature Geocisences* **5**: 793–798.

Xu J, Lu J, Bao F, *et al*. 2010. Cellulose microfibril angle variation in *Picea crassifolia* tree rings improves climate signals on the Tibetan plateau. *Trees* **726**: 1007–1016.

