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Opinion Paper

Concord and discord among Northern Hemisphere paleotemperature reconstructions from tree rings

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ABSTRACT

We review the current generation of large-scale, millennial-length temperature reconstructions derived from tree rings and highlight areas of agreement and disagreement among these state-of-the-art paleotemperature estimates. Although thousands of tree ring-width chronologies are now available from temperate and boreal forest sites across the Northern Hemisphere, only a small fraction of those records are suited as proxies for surface temperature. Maximum latewood density is clearly a superior temperature proxy but is less available, with few densitometric records that are both long and up-to-date. Compared to previous efforts, the newest generation of tree-ring reconstructions correlate more strongly against hemispheric summer temperatures and show better performance in tracking decadal/multi-decadal variability and year-to-year fluctuations. They also fit the observed memory structure of instrumental temperatures more closely than their predecessors. These new estimates still show signs of the so-called ‘divergence problem’ (the apparent loss of temperature sensitivity under recent warming), but do not extend after 2004 and cannot be used to evaluate the impact of the past decade's warming on northern temperature-limited forests. We caution against averaging together the latest hemispheric-scale reconstructions because they have each been constructed to suit different purposes and share much of the same underlying tree-ring data, especially prior to CE 1500. Past temperatures are recorded more clearly in maximum latewood density than total ring-width, so we recommend the Northern Hemisphere densitometry network be modernized through a new round of field collections and observations.

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Much of what we know regarding large-scale variations in Earth's mean near-surface summer temperatures during the past millennium comes from tree rings. The first attempts using tree rings by themselves to reconstruct Northern Hemisphere temperatures over the entire past millennium were based on a relatively small number of long records from high-elevation and latitudinal treeline sites in Eurasia and North America (14 or fewer; Briffa, 2000; Esper et al., 2002). D'Arrigo et al. (2006) increased the scope of the underlying tree-ring network by combining dozens of chronologies of varying lengths from high-elevation and latitudinal treeline to construct regional-, continental-, and hemispheric-scale composites. This first generation of paleotemperature reconstructions all indicated the 20th century was the warmest during the most recent millennium, but disagreed about the total amplitude of past temperature change and had relatively modest calibration and verification statistics (e.g, correlations with instrumental temperatures that ranged between 0.4 and 0.5; Esper et al., 2018). After a hiatus that lasted roughly a decade, a new cohort of Northern Hemisphere reconstructions were produced that used either a much larger compilation of mid- and high-latitude tree-ring chronologies (Wilson et al., 2016; hereafter Wil16; Stoffel et al., 2015; hereafter Sto15), or a select number of the very longest wood density chronologies (Schneider et al., 2015; hereafter Sch15). Because of the continuing importance of tree-ring records within paleoclimatology, here we briefly review the current generation of large-scale, millennial-length temperature reconstructions derived solely from this archive and highlight areas of agreement and disagreement among these state-of-the-art paleotemperature estimates.

Globally, the most common variable measured from tree rings is total ring-width (TRW), but only a small fraction of records constructed from that parameter are well suited as proxies for surface

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temperature. Although thousands of TRW chronologies (composite series that describe mean growth among two or more dozen trees within a forest stand) are now available from temperate and boreal sites across the Northern Hemisphere, a clear majority of these data come from xeric or near-xeric environments and as a result primarily reflect the influence of precipitation or drought stress (Babst et al., 2013; St. George, 2014). Many of those chronologies also exhibit an inverse response to warm summer temperatures, but because this association is a secondary effect of moisture stress these data should not be used to provide estimates of past temperatures (Emile-Geay et al., 2017). By contrast, TRW chronologies containing a strong positive temperature signal are much less common and are largely restricted to high-latitude and high-elevation forests (St. George, 2014; Esper et al., 2016, Fig. 1a). For trees in these cold forests, warm weather during the growing season acts to enhance photosynthesis and extends the period of cambial activity, which causes TRW to encode information on summer temperatures. But because tree growth is also influenced by strong biological memory due to needle retention and carbohydrate storage (Matalas, 1962; Franke et al., 2013; Frank and Esper, 2005), temperature reconstructions derived from TRW often exhibit unrealistically strong persistence (first-order autocorrelation; Esper et al., 2015, 2018).

As a surrogate for summer temperatures, wood density is superior to TRW in nearly every respect. An integrated measure of several properties including cell wall thickness, lumen diameter, and duct size and frequency, wood density reaches its peak late in the growing season when trees form small cells with thick walls (Rathgeber, 2017). Compared to TRW measurements generated from the same trees, maximum latewood density (MXD) chronologies are more highly correlated with nearby instrumental temperature records (Wilson et al., 2016), track temperatures over a longer portion of the growing season, and show more consistent associations with temperatures across a wide range of latitudes (Briffa et al., 1998a; Björklund et al., 2017). And because wood density is less affected by biological persistence, the statistical properties of MXD chronologies (particularly the first-order autocorrelation) are in general more similar to instrumental temperature observations (Esper et al., 2015). The main limitation of MXD is its restricted availability. There are fewer than a dozen laboratories worldwide that conduct traditional x-ray densitometry on tree rings and the International Tree-Ring Data Bank (ITRDB; Grissino-Mayer and Fritts, 1997) only holds 575 sets of MXD measurements compared to more than 4200 sets of TRW measurements, with fewer than a dozen densitometric series extending back to CE 1000 or earlier. Over the past decade the blue intensity technique (BI; Campbell et al., 2007, 2011), which is based on the correspondence between the degree of lignification of latewood cells and the intensity of visible blue light reflected off the wood surface, has emerged as a low-cost alternative to MXD. But although BI has been shown to be an effective summer temperature proxy (e.g., Rydval et al., 2014; Wilson et al., 2014), it also exhibits non-climatic biases at centennial timescales caused by tree-to-tree differences in staining due to extractives (Björklund et al., 2014) that may complicate its integration into multi-century long proxy temperature estimates.

All three latest millennial-length temperature reconstructions from tree rings are constructed upon a foundation of ring-width and density records but they differ in the approach used to select data, estimate and remove age-size trends, and convert tree-ring measurements into paleotemperature estimates. The Sch15 reconstruction incorporated the very longest MXD records available, so featured only 15 chronologies from Asia, North America, and Europe. In contrast, Sto15 had TRW and MXD chronologies prescreened to be sensitive to summer (June-to-August) temperatures, and Wil16 used either published temperature reconstructions from

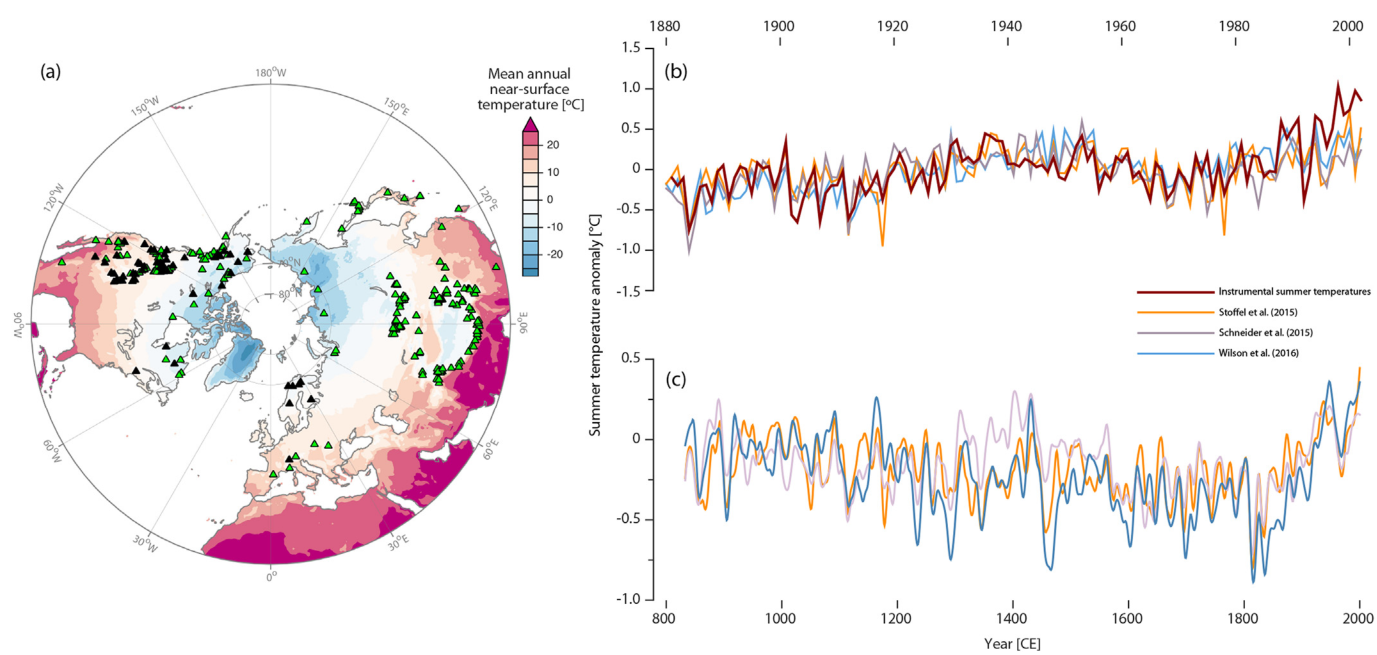

Fig. 1. (A) Map showing temperature-sensitive tree-ring width (green triangles) and maximum latewood density (black triangles) in the Northern Hemisphere. Data were obtained from the global multiproxy database for temperature reconstructions of the Common Era generated by the PAGES 2k Consortium (Emile-Geay et al., 2017). The colored shading represents mean annual near-surface temperatures from instruments over the 1901 to 2016 period (Harris and Jones, 2017). (B) The three state-of-the-art 'tree-ring only' paleotemperature reconstructions (Schneider et al., 2015; Stoffel et al., 2015; Wilson et al., 2016) compared against mean June-July-August instrumental temperatures averaged over 30–70°N land areas (Harris and Jones, 2017). (C) The three tree-ring temperature reconstructions shown over the past millennium, following smoothing with a 25-year filter. All reconstructions are scaled against 30–70 °N JJA temperatures during the common 1881–1992 period, and expressed as anomalies with respect to the 1961–1990 mean (c.f. Esper et al., 2018). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

tree-rings or the tree-ring chronologies used to produce those reconstructions. Because Sto15 and Wil15 did not impose a length criterion, those reconstructions were based on much larger datasets (233 and 54 series, respectively). All three studies applied age-size detrending methods intended to preserve as much low-frequency variability as possible, but while Sch15 used only the regional curve standardization method (Briffa et al., 1992), Sto15 and Wil16 also brought to bear negative exponential curves (D'Arrigo et al., 2006), adaptive regional growth curves (Nicault et al., 2010), and signal-free detrending (Melvin and Briffa, 2008). The detrended tree-ring data were then combined into geographic clusters (to reduce bias towards commonly sampled places), and then either scaled to Northern Hemisphere temperatures (Sch15, Wil16) or used as predictors in a linear regression (Sto15). Because the number of available tree-ring chronologies decreases back in time, all the reconstructions adopted an iterative nested procedure wherein the analysis was repeated with a reduced predictor set whenever a site chronology dropped out. Finally, although all three studies produce estimates of mean summer temperatures across the Northern Hemisphere extratropics, their specific seasonal and geographic targets are not exactly the same (Sto15: June–August and 40º-90ºN; Sch15: June–August and 30º-90ºN; Wil16: May–August and 40º-75ºN).

There are two main areas where the most recent generation of temperature reconstructions distinguish themselves from earlier tree-ring estimates. First, the new reconstructions all correlate more strongly against summer (June to August) Northern Hemisphere (30° to 70ºN) mean temperatures and show better performance in tracking both decadal and multi-decadal variability and year-to-year fluctuations (Esper et al., 2018). Whereas the earlier generation of hemispheric-scale reconstructions (Briffa, 2000; Esper et al., 2002; D'Arrigo et al., 2006) focused on annual mean temperatures, Sch15, Sto15, and Wil16 targeted mean summer temperatures because tree-ring records typically respond to growing-season conditions (St. George, 2014; Anchukaitis et al., 2017). Second, unlike their predecessors, which overestimated considerably the temporal autocorrelation of Northern Hemisphere temperatures, the Sch15 and Wil16 reconstructions fit the observed memory structure of instrumental temperatures much more closely. However, because it was constructed to emphasize the climate response at inter-annual timescales, the Sto15 reconstruction has the opposite problem (too little first-order autocorrelation) and instead gives greater emphasis to high-frequency variability.

Despite their improved fidelity as hemispheric temperature surrogates, the current generation of tree-ring reconstructions also still show signs of the so-called ‘divergence problem’. This issue, which was first identified in Alaska (Jacoby and D'Arrigo, 1995) and then subsequently at many boreal forest sites (Briffa et al., 1998b), refers to a loss of sensitivity exhibited by some temperature-limited tree-ring chronologies starting in the latter half of the 20th century. Filtering the three latest reconstructions to emphasize variability at decadal scales or longer (Esper et al., 2018) does indeed show they do not track the sharp post-1990 increase in Northern Hemisphere temperatures, and it is evident even in the annual (unfiltered) series that the reconstructions reproduce (incorrectly) only modest warming during this interval (Fig. 1b). If the cause of the divergence phenomenon was not unique to the past few decades, that sort of censored temperature response could cause an underestimation of the magnitude of earlier warm periods and produce biased estimates of climate sensitivity (Hegerl et al., 2006; Jungclaus et al., 2017). More than ten hypotheses have been put forward to explain divergence including (i) the confounding influence of other aspects of environmental change such as drought stress (Barber et al., 2000; Barichivich et al., 2014), melt timing (Vaganov et al., 1999), light availability (Stine and Huybers, 2014), and CO_2 fertilization (Briffa et al., 1998a) or (ii) sampling issues related to tree age (Carrer and Urbinati, 2004; Esper et al., 2008) or stand composition (Driscoll et al., 2005). Unfortunately, because many of the tree-ring records used in paleotemperature studies were collected in the late 1980s and early 1990s (St. George, 2014), even these very newest reconstructions extend no later than 2004, which means we are not able to use them to evaluate the impact of the most recent decade's warming on northern temperature-limited forests.

The paleoclimate histories outlined by the three state-of-the-art tree-ring reconstructions share several of the same major features, but do differ on the timing and duration of major centennial-scale warm and cool events (Fig. 1c). All reconstructions show the 20th was the warmest century during the past 1100 years. They also all present early medieval warmth followed by several centuries of cooling, although the reconstructions disagree about the onset and maximum severity of that prolonged chill. In Sto15 and Wil16, the 900s and 1000s are comparatively warm and the transition to cold conditions occurs midway through the 13th century. Although the Sch15 record also has the 10th century being warm, that reconstruction shows a return to warmer temperatures during the 14th and 15th century, which causes the transition into the putative ‘Little Ice Age’ (Matthews and Briffa, 2005) to be delayed until the 1600s (three centuries later than the other two reconstructions). Sto15 and Sch15 indicate the 17th century was the coldest of the past millennium, while Wil16 suggest hemispheric temperatures did not reach their nadir until the 19th century, at the very end of the Little Ice Age.

It might seem best to split the difference between these estimates, but we recommend against simply averaging together the three reconstructions because they have each been constructed to suit different purposes. The Sto15 reconstruction was developed specifically to examine the climate response at inter-annual timescales, while the extensive tree-ring network in Wil16 has been used as the foundation for a climate field reconstruction of warm season temperatures across the Northern Hemisphere extratropics (Anchukaitis et al., 2017). And because Sch15 incorporates only the very longest MXD chronologies as inputs, that reconstruction may be better able to preserve centennial- or multi-centennial variability by minimizing the loss of low-frequency signals caused by the splicing together of short segments (Cook et al., 1995). The centennial-scale patterns in Sch15 are indeed different from those present in the other two reconstructions (particularly, the later start to the Little Ice Age it implies), but it remains an open question which of these histories provides the most accurate representation of low-frequency climate variability throughout the entire period. Furthermore, because all three reconstructions share much of the same underlying tree-ring data, averaging them together would effectively give undue emphasis to those very longest chronologies. For the simple reason that the same few key records make up most (or all) of the input data farther back in time, we should expect paleotemperature estimates from tree rings to resemble each other during the first half of the second millennium. But because the three reconstructions display the opposite behavior — becoming less similar to each other prior to CE 1400 (Esper et al., 2018), it's more likely that differences in reconstruction methodology rather than choice of proxy data are the cause of their disagreement earlier on.

More than a decade ago, leading members of the dendroclimatology community recommended that temperature-sensitive tree-ring records be updated in order to perform more reliable comparisons with instrumental records and address the emerging issue of divergence (D'Arrigo et al., 2006). Since then the construction of new TRW records has continued apace, but density has lagged behind: The ITRDB currently hosts more than two hundred TRW collections that extend to 2010 or later, but does not have even one MXD record that spans the same interval. And there remains very few MXD chronologies with strong replication early in the second millennium or earlier, which limits our ability to evaluate medieval-era warming (Christiansen and Ljungqvist, 2017). Because thermal history is written more clearly in wood quality than wood quantity, we argue it is imperative to prioritize the development of new, long and up-to-date MXD chronologies. As Briffa (2000) predicted, during the past two decades the field of dendroclimatology has made substantial progress towards a more complete understanding of the climate of the past millennium. But in order to make future advancements within this particular branch of paleoclimatology, our first order of business should be the modernization of the Northern Hemisphere densitometry network through a new round of field collections and observations.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2018.11.013.

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