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EDITORIAL

# Divergence pitfalls in tree-ring research

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In this issue of Climatic Change, Loehle (2009) reports on a technique to calibrate tree-ring data against temperature time series. Such methods are commonly used to transfer ring width, density, or stable isotope measurement from mm, g/mm$^3$, and ‰ into degrees Celsius—forming the cornerstone for proxy reconstructions (Cook and Kairiukstis 1990). The specific subject of the Loehle (2009) contribution is on non-linear calibration techniques, which have been considered when proxy data indicate inconsistent responses to medium and extreme temperature deviations. Non-linear calibration has a long-standing history in tree-ring research (see Fritts 1976 for an introduction), and variants of non-linear response models have been applied in a variety of tree-ring analyses over the past decades (e.g., Carrer and Urbinati 2001; Fritts 1969; Graumlich and Brubaker 1986; Woodhouse 1999). So, while approaches to tackle non-linear tree-ring/climate associations are relevant when dealing with proxy data, it is, however, the motivation that called for re-attention to these techniques that is of particular interest: the divergence phenomenon (DP) in tree-ring research.

DP was first described over a decade ago by Jacoby and D'Arrigo (1995) and since then has been reported from a variety of sites mainly concentrated towards the Northern Hemisphere boreal forest zone (see D'Arrigo et al. 2008 for a review). DP effectively describes a disassociation of late twentieth century (typically post-1960) tree growth parameters, such as ring width or maximum latewood density, from regional temperature trends. This disassociation does not necessarily comprise a weakening of the high-frequency climate signal. That is, inter-annual tree-ring variation may be predominantly controlled by temperatures, but the long-term

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warming trend is not (fully) retained in the tree-ring time series. Such a situation is of importance, as it limits the suitability of tree-ring data to reconstruct long-term climate fluctuations, particularly during periods that might have been as warm or even warmer than the late twentieth century.

As DP is perceived as a major challenge of dendroclimatology, and given the wide use of tree-ring data in temperature reconstructions of the past millennium (Esper et al. 2004), of high-resolution paleoclimatology as a whole, a number of potential reasons causing this disassociation have been put forward (see D'Arrigo et al. 2008 for an overview). Rather than re-iterating these arguments, or adding on non-linear statistics or other methodologies to 'handle' DP, we wish to take a step back to the basics and describe a number of pitfalls that may be encountered when processing and analyzing tree-ring and temperature data, and that can lead to an accidental detection of DP. That is, observance for DP would not have been made if a particular data handling procedure—or combinations of them—would have been carried out differently. The most relevant pitfalls are displayed as a cartoon effectively summarizing the experiences and mistakes we made over the past years when sampling and measuring tree-ring data, developing chronologies, and reconstructing climate fluctuations. Avoidance of these pitfalls might help in preventing from erroneous detection of DP.

One of the more important pitfalls is related to tree-ring detrending. Application of detrending techniques is generally necessary to remove tree age related (biological) trends from width or density data, before these can be averaged to meaningful chronologies (Cook and Kairiukstis 1990; Fritts 1976). There are numerous ways to detrend tree-ring data, and selection of an appropriate method is largely determined by the objective of a particular analysis. Recent work (e.g., Cook et al. 1995), however, showed that retaining lowest frequency, centennial scale trends—just as contained in many regional temperature time series—is one of the key challenges of high-resolution paleoclimatology (Esper et al. 2002). Methods to preserve such long-term variance in tree-ring time series require large sample collections and specific age-structures of the data combined in mean chronologies (Briffa et al. 1996; Cook et al. 1995; Esper et al. 2003, 2008). These data requirements and consideration of specific methods to preserve low frequency trends are, however, frequently not met in studies analyzing DP (e.g., Briffa et al. 1998). These situations can cause divergence between long-term increasing temperatures and tree-ring time series for which the long-term climatic trends were not well preserved due to the applied detrending (Fig. 1a). Dendrochronological assessments might particularly be prone to this pitfall, if measurement series were relatively short (e.g., <200 years) and/or where the series have been individually detrended, using flexible growth curves (e.g., splines) or curves that may remove long-term positive trends (e.g., Hugershoff).

If dendrochronological sampling sites are not restricted to temperature limited forest boundaries, or trees are disturbed by other factors influencing growth—such as fires, insects, geomorphic events, etc. (see Schweingruber 1996 for an overview )—these conditions will result in weak climate signals contained in mean chronologies (Fig. 1b). Consideration of tree-ring data that lack a clear temperature signal, however, also means that offset between tree-ring and temperature data occurs regularly and might accidentally be interpreted as DP (e.g., Barber et al. 2000). To avoid such situations, it would not only be useful to restrict DP analyses to sites that contain strong climatic signals, but also to consider a variety of such sites (and

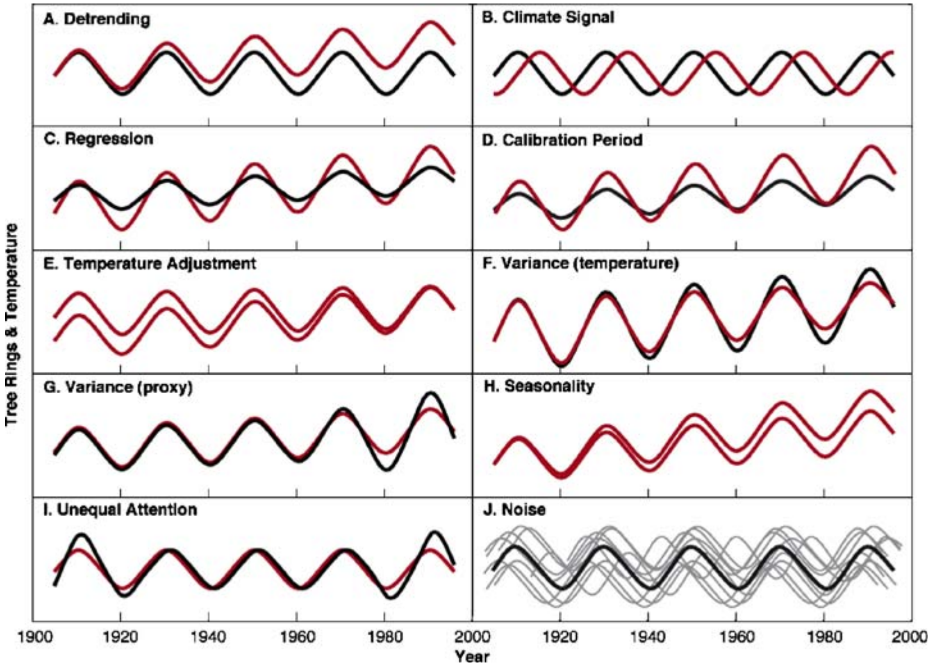

**Fig. 1** Divergence pitfalls. The plates show schematic illustrations of factors that can lead to an erroneous detection of divergence. *Black curves* are mean tree-ring chronologies, *red curves* are temperature time series, *thin grey curves* (in **j**) are single tree-ring measurement series. **a** While the temperature time series shows a long-term increase over the twentieth century, the tree-ring data were detrended so that no centennial scale variance is retained in the chronology. **b** The tree-ring and temperature time series share no variance in common. **c** The tree-ring chronology was regressed against temperatures considering the full period of overlap. **d** The tree-ring chronology was calibrated over a reduced, early period of overlap. **e** The temperature data were adjusted back in time. **f** The variance of the temperature data increases back in time. **g** The variance of the tree-ring chronology increases towards present. **h** Different seasonal means of the temperature data (e.g., June–August and April–September) contain differing twentieth century trends. **i** Divergence appears repeatedly during the period of overlap. **j** The chronology is a mean time series of noisy single measurement series

perhaps even species) in a particular region. Such a sampling strategy would help ensure that offset is systematic and distinct towards present.

Methodological choices that promote DP detection include situations when tree-ring chronologies are regressed against temperatures (Fig. 1c) and/or calibrated over some early (e.g., pre-1960) period of overlap with instrumental data (Fig. 1d). Commonly applied regression techniques reduce the variance of the tree-ring predictor by the fraction of unexplained variance (Esper et al. 2005), and this variance deficit is most noticeable for temperatures further away from the calibration period mean. Given the general warming trend during the instrumental period, offset is often concentrated towards the ends of the period of overlap between the proxy and temperature data (e.g., Briffa et al. 2001). This problem can be mitigated if the tree-ring data are scaled to the temperatures, i.e. mean and variance are adjusted to equal those of the target data. Calibration over only an early period of overlap again minimizes the difference between proxy and temperature data over this period, and allows offset to appear only in the most recent decades (e.g., Jacoby et al. 2000). Both of these factors can contribute to erroneous DP detection, but the combination of regression and early calibration seems particularly dangerous, especially if the target temperatures indicate substantial warming.

As DP depends upon the fit between tree-ring and instrumental data, properties of temperature data used for calibration might also result in divergence. These include trend adjustments (Fig. 1e) that are often not well supported in areas where the density of long-term station records is low (Karl and Knight 1994), and changes in the variance of temperature time series (Fig. 1f) that may be intrinsic to such records (Della-Marta et al. 2007). The latter even appears in compilations that were specifically treated to stabilize variance trough time (Brohan et al. 2006), and could promote misfits towards present when the instrumental data are less variable (though we don't know of an example here). Trend adjustments are typically applied towards the beginning of the time series, and can alter the overall warming signal in a particular region (Peterson et al. 1998). If homogenization approaches are poorly supported via comparison with neighboring stations, for example, due to data sparseness—as is characteristic for the boreal forest zone—interpretation of the DP should be made with caution (e.g., D'Arrigo et al. 2004). If a certain bias, however, affected all station data in a region, as has recently been reported for the entire European Alps where all early summer temperature readings had been affected by sunlight (Frank et al. 2007a; Böhm et al. 2009), calibration will be particularly challenging.

Also the variance of tree-ring chronologies might be subject to biases related to the coherence and number of the underlying data (Frank et al. 2007b). Relevant to DP detection can be changes in sample replication over recent decades, which often appear when data from different sources are combined (e.g., Cook et al. 2004). Most tree-ring datasets were developed after the early 1970's, i.e. the end dates of these compilations typically range over two to three decades. The combination of such data often creates a characteristic decline in sample replication towards present or may involve biases related to changes in chronology representation. Consequences may include inflated variance or jumps related to dataset changes and contribute to accidental DP detection (Fig. 1g).

Consideration of varying seasonal means (e.g., June–August, April–September, annual temperatures) might influence DP detection (Fig. 1h). This appears particularly to be relevant in regions where reported summer warming, as is the case in most areas of the northern boreal forest zone, is less pronounced than warming in spring, fall or winter. High-frequency based calibration statistics might not clearly distinguish the seasonal temperatures controlling tree growth with various seasonal means, including or excluding spring or fall months, correlating arguably as well as peak summer temperatures. Inclusion of these contiguous months can increase the warming trend in the target time series and thus advance DP emergence (e.g., Wilson et al. 2007).

And finally, we also note cases where attention was paid to "divergence" in recent years and offset of similar magnitude at different periods neglected (Fig. 1i, e.g., Wilmking and Singh 2008). Similarly, it is not unexpected that a fraction of data selected on the basis of recent low-frequency trends or fit with instrumental records (i.e., "responders") will agree more closely with the instrumental target or warming trends than the remaining fraction of data (“non-responders”; e.g., Pisaric et al. 2007). Application of such splitting procedures might be prone to circular reasoning and just emphasize the variance of measurement series around a mean chronology (Fig. 1j) in recent times.

Even though the sketches of these pitfalls in Fig. 1 might promote a somewhat fragmented view of possible ways that divergence may emerge, in practice, most (if not all) of these considerations are challenged simultaneously when detrended tree-ring data (Fig. 1a, b, j) are fit (C, D, F, G) to selected instrumental data (E, H) in assessing DP (I) and developing climatic reconstructions. The often subtle nature and interactions between these various pitfalls makes a ranking of importance highly speculative. However, in our estimation, a number of studies addressing DP seem to be affected by at least one of the above listed pitfalls, which presents difficulties to conclude on the spatial extent of DP and the relevance of the phenomenon as a whole.

With reference to DP, a number of high-resolution temperature reconstructions were specifically not calibrated against post-1960 temperature data. While this limitation is currently widely perceived and potential consequences discussed (e.g., IPCC 2007), we here suggested that a number of pitfalls might be encountered when collecting, processing and calibrating tree-ring data, and that inattention to these might result in an artificial offset between proxy and target time series. A recent study of a large network of tree-ring sites in the European Alps (Büntgen et al. 2008) partially validated this conclusion, as it demonstrated the sensitivity of (accidental) DP-notion to the methods chosen for detrending. Similar tests of the pitfalls detailed here could perhaps help to validate the significance of DP in other regions.

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