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A mathematical analysis of the divergence problem in dendroclimatology

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Abstract Tree rings provide a primary data source for reconstructing past climates, particularly over the past 1,000 years. However, divergence has been observed in twentieth century reconstructions. Divergence occurs when trees show a positive response to warming in the calibration period but a lesser or even negative response in recent decades. The mathematical implications of divergence for reconstructing climate are explored in this study. Divergence results either because of some unique environmental factor in recent decades, because trees reach an asymptotic maximum growth rate at some temperature, or because higher temperatures reduce tree growth. If trees show a nonlinear growth response, the result is to potentially truncate any historical temperatures higher than those in the calibration period, as well as to reduce the mean and range of reconstructed values compared to actual. This produces the divergence effect. This creates a cold bias in the reconstructed record and makes it impossible to make any statements about how warm recent decades are compared to historical periods. Some suggestions are made to overcome these problems.

1 Introduction

Tree rings have been widely used in recent years for reconstructing past climates, particularly temperature (e.g. Cook et al. 2004; Crowley 2000; Crowley and Lowery 2000; D'Arrigo et al. 2007; Esper et al. 2002; Jones 1998; Jones et al. 1999; Mann and Jones 2003; Mann et al. 1995, 1998, 1999; Overpeck et al. 1997). An analysis of twentieth century tree growth patterns, however, has uncovered what is known

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as the divergence problem (Barber et al. 2000; Briffa 2000; Briffa et al. 1998a, b, 2004; Bungten et al. 2006; Carrer and Urbinati 2006; D'Arrigo et al. 2004, 2007; Driscoll et al. 2005; Feeley et al. 2007; Jacoby and D'Arrigo 1995; Jacoby et al. 2000; Kelly et al. 1994; Lloyd and Fastie 2002; Oberhuber 2004; Pisaric et al. 2007; Vaganov et al. 1999; Wilmking et al. 2004, 2005; Wilson and Luckman 2003; Wilson et al. 2007). This problem is characterized by trees or assemblages of trees that showed a positive response to warming in the early part of the century showing a lessened or even negative response to warming in the period starting in the 1960s to 1980s. Several hypotheses exist to explain this response. The purpose of this study is to provide an explanation for divergence and trace the implications of divergence for reconstructing past climates.

Studies have documented divergence across much of the upper northern hemisphere (but not at all sites), though dendroclimatic studies are rare in warmer climates (see Feeley et al. 2007) so this geographic restriction does not mean it is restricted to the far north. Reduced tree growth in response to warmer temperature was found in Alaska after ~1950 by Lloyd and Fastie (2002), by Wilson and Luckman (2003) in Canada, and in Siberia since ~1970 (Jacoby et al. 2000), among other places. In a recent circumpolar satellite survey covering 1982 to 2003 (Bunn and Goetz 2006), it was found that tundra areas showed increased photosynthetic activity, but forested areas showing a change evinced decreased photosynthesis and this effect was greater where tree density was higher. This effect probably reflects moisture limitations at higher temperatures. In some places trees appear inherently insensitive to temperature (e.g. Berg et al. 2007). Decreased sensitivity to temperature or actual negative responses to warming could result from frost damage (Hänninen 2006), drought stress, change in seasonal patterns of temperature, or changes in snow pack, among other possible causes (D'Arrigo et al. 2007). An upside down quadratic growth response to temperature (Fritts 1991; Vaganov et al. 1990) has been demonstrated experimentally (e.g. Fritts 1976; Kramer and Kozlowski 1979; Gates 1980; Lyr et al. 1992; Schoettle 2004). Field studies have also shown that exceptionally warm years can turn positive responders into negative responders (Case and Peterson 2005, 2007; Oberhuber et al. 2008; Pichler and Oberhuber 2007), which is diagnostic of an upside down quadratic growth response to temperature. In this study it is shown that such nonlinear growth responses can produce the observed divergence and also pose a mathematical quandary for determining an inverse function (temperature as a function of ring width) because the inverse function is nonunique. Although the existence of an upside down quadratic response to temperature has been known for a long time (e.g., Fritts 1976), current tree ring-based reconstructions universally assume that a linear approximation is not problematic, which is equivalent to the assumption that past climates do not deviate far from those in the calibration period, as will be shown. Furthermore, the implications of divergence for reconstructing paleoclimate do not seem to be appreciated or discussed in the literature.

2 Climate reconstruction

Divergence can emerge as a simple mathematical consequence of nonlinear tree growth responses to temperature. It is useful to start with the simple case of no divergence. It is generally assumed that trees respond in a linear fashion to temperature in some critical season(s) (leaving aside the question of precipitation, discussed later):

$$r = mT + b \tag{1}$$

where r is ring property (width or density), T is temperature, and m and b are parameters. If we assume a temperature history (Fig. 1) and model tree growth using Eq. 1, the resulting ring width series (Fig. 2) has the identical shape, but with a simple change of scale. Use of a linear combination of different months or seasons in the regression does not change this result.

Standard practice, given the series in Fig. 2, is to pick a time period for which temperatures are known, compile an age-corrected series for a group of trees, plot temperature vs. ring width, and fit a linear response model of ring width by regression (see e.g. Esper et al. 2002). In the absence of noise (measurement error, extraneous influences on growth), the linear model for temperature as a function of tree growth will be simply the inverse of Eq. 1:

$$\begin{aligned} T &= \frac{r-b}{m} \\ &= \frac{1}{m}r - \frac{b}{m} \\ &= m'r - b' \end{aligned} \tag{2}$$

The reconstructed temperature obtained by running the ring width timeseries (Fig. 2) through Eq. 2 will be exactly the original in the absence of noise. This simple predictive process breaks down when tree growth response is not linear.

Even for this simple case, there are a few points worth mentioning. As with any regression, the parameters of Eq. 2 will be estimated more reliably if a wider range of yearly weather values (and hence ring widths) have been sampled. It is also worth noting that the relationship does not require a warming period for estimation. A cooling period or even fluctuating temperatures will work just as well because the regression model captures the relationship between ring width and temperature. Time is not a variable in the model. Finally, one of the variables could be scaled

Fig. 1 Hypothetical historical temperature series (arbitrary scale)

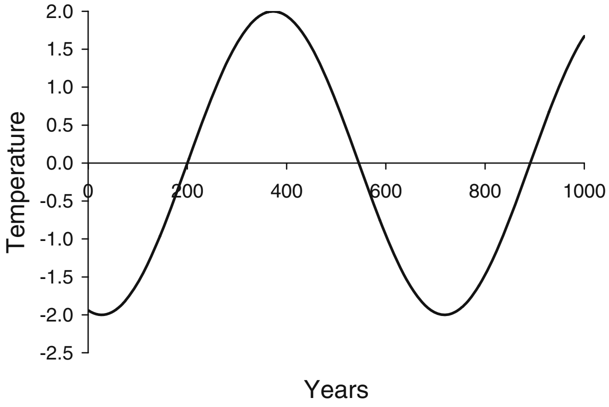
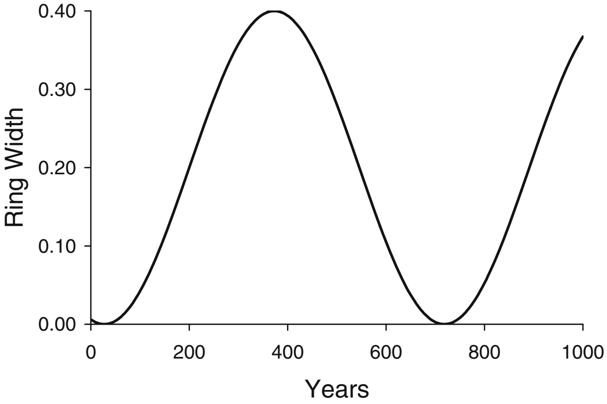


Fig. 2 Tree ring width assuming the linear relation from Eq. 1 (arbitrary scale)



by a logarithmic or other transformation without affecting the predictive power or the model linearity.

Since parameters are never estimated precisely, it is important to evaluate the effect of parameter error on hypothesis tests. In this case, a critical hypothesis concerns the extent to which recent warming exceeds past warm episodes. In Eq. 2, if m' is underestimated, reconstructed timeseries will show damped amplitudes compared to actual. If m' is overestimated, the amplitudes will be exaggerated. Using parametric confidence intervals from the regression (creating many reconstructions by sampling "m" and "b" from their uncertainty distributions), it should be possible to make an assessment of the accuracy of reconstructed past extreme warm peaks, though this is not how confidence intervals have been computed in most published reconstructions.

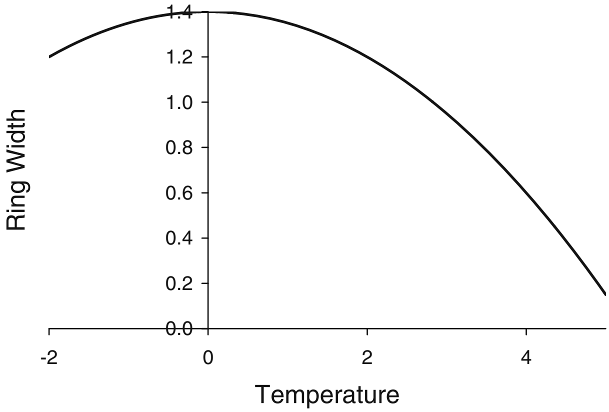
We can now assess the effects of nonlinear growth responses. I assume here the often observed upside-down quadratic (though see below also):

$$r = p - c\,(T - k)^2 \tag{3}$$

where in the particular case simulated (Fig. 3), $p = 1.4$, $c = 0.05$, and $k = 0$ and parameters can refer to either a single tree or a group mean response. This is merely the simplest model compatible with the data and is used for illustrative purposes only. In this model p controls the largest r value, c controls the tightness of the quadratic, and k gives the threshold temperature at which r begins to decline. Linear regression is again used to estimate a linear model for temperature as a function of ring width. In this case the years 75 to 175 were picked for calibration in Fig. 1. A period with cooler temperatures was picked to test whether higher temperatures over the period could be properly predicted by the model. Because a nonlinear response is being estimated by a linear model, the fit over the calibration interval is not perfect but is still quite good at $R^2 = 0.978$. The ring width history generated from Eq. 3 and Fig. 1 is then used with the linear response function (2), as is usual practice, to reconstruct temperature (Fig. 4). The exact shape of the reconstructed curves will depend on parameters.

There are some interesting features of the reconstruction (Fig. 4). The peak historical temperature values are not merely truncated but are converted into troughs. Thus the quadratic growth response will cause past (or future! i.e., divergence) warm

Fig. 3 Example upside-down quadratic growth response function (arbitrary scale)

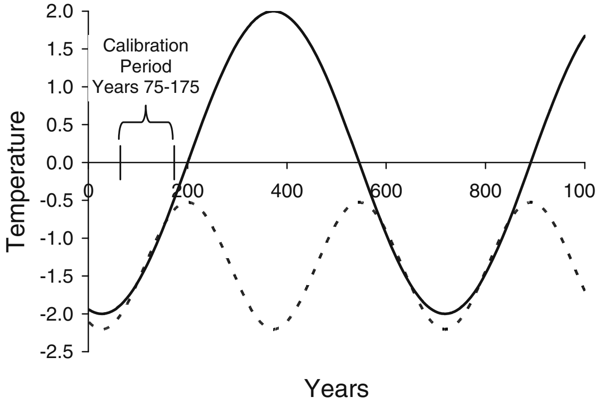


intervals to be filtered out. The remaining signal is damped (lower amplitude or peak minus trough values) and has a lower mean value. The bottom of the troughs is also lower than actual. This last effect is smaller than the other biases and will vary depending on where on the quadratic curve the linear model is fit. The reconstruction shows the features of divergence: under conditions warmer than the calibration period, the model under-predicts temperature.

It might seem logical that the linear approximation should be okay if the threshold k is not exceeded. However, staying below the threshold does not eliminate the problem. In Fig. 5, a temperature series is simulated that comes up to but does not exceed the temperature threshold in Eq. 3. While temperatures are more accurately matched by the linear model ($R^2 = 0.99$) for the calibration period, as the threshold is approached the reconstructed curve flattens out. Thus, temperature peaks are still truncated for values below the threshold, though troughs are not created.

The effect of an upside-down quadratic growth response is thus to truncate the range of temperatures in the reconstruction (reducing variance and lowering the mean and maximum values) as well as possibly introducing spurious temperature lows at exactly the true peaks. These effects are in spite of a fit of the linear model

Fig. 4 Reconstructed temperature (arbitrary scale) (*dotted line*) vs. actual (*solid line*) using a linear approximation to the quadratic from Fig. 3. Temperatures larger than the threshold become inverted



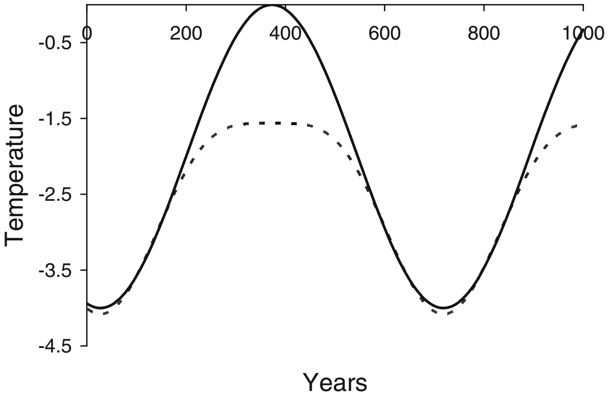


Fig. 5 When temperatures (*solid line*) rise up to but do not exceed the threshold of the quadratic growth response, there is a better estimation of temperature (*dotted line*) but peaks are still suppressed

of 0.978 in Fig. 4 and 0.999 in Fig. 5, values never achievable using real tree ring data (Bürger 2007). In the case of a peak such as the Medieval Warm Period, such reconstructions will say it did not occur, but incorrectly so.

Will actual temperature reconstructions be this bad? It is impossible to say without testing. An appropriate test would be to compare modeled temperature to measured temperature at some time when measured temperature is known and is higher than during the calibration period. Such tests are difficult to perform before 1900 because "true" temperatures then are not known (which is why these proxies are being developed in the first place). For the 1980s and 1990s, where data exist (not all tree ring data include recent decades) the divergence problem is often observed, which means they fail this test. If divergence results from nonlinear growth response, then this indicates that the models do not in fact detect warmer temperatures than the calibration period very well, just as hypothesized here.

It has been argued (D'Arrigo et al. 2007) that divergence may in large part be due to moisture limitation as either warmer temperatures increase evapotranspiration or the precipitation regime changes, or both. Can there be divergence on very moist sites? It has been argued (Loehle 1998, 2000) that trees have a maximum potential growth rate. It can easily be seen in the greenhouse that better conditions will increase plant growth but only up to a point, which is determined by the species. White spruce, for example, can not be induced to grow as fast as bamboo. For trees not limited by moisture the growth rate should flatten out at higher temperatures as trees reach their maximum growth rate (Fig. 6). If this situation is simulated as before with a linear response to a maximum of $r = 0.3$ (Fig. 6), it is seen that again the temperature peaks are truncated (Fig. 7). Thus while trees from drier and wetter sites may evince different divergence responses to warming (Fig. 3 vs Fig. 6), the effect on time series reconstruction is similar—peaks are chopped off, the mean is reduced, and variance is damped.

It has been shown that a simple upside-down quadratic model can be used to mimic ring width series with some skill (Evans et al. 2006). It was suggested that this approach could be used to model paleoclimates. Although this approach is limited because it requires precipitation as an input (which is not available for prehistorical periods), it is more fundamentally impossible to incorporate nonlinear growth responses. This is because a nonlinear function of this type creates an inverse

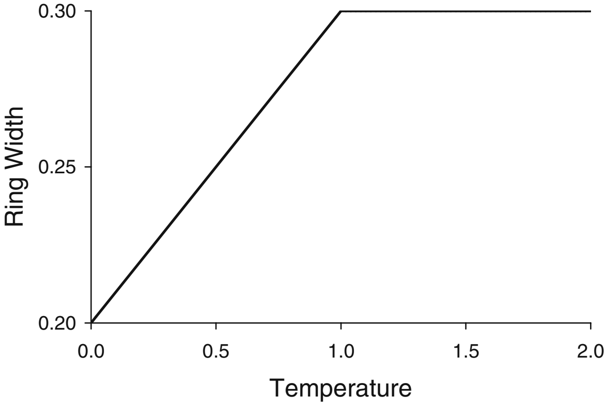


Fig. 6 Linear growth response up to some maximum level, at which other factors become limiting

with nonunique solutions. Consider the upside-down quadratic growth response model (3). Solving for T (temperature) as a function of r (ring property), we get

$$T = k \pm \sqrt{\frac{p-r}{c}} \tag{4}$$

which for any given r has two solutions (defined by a horizontal line in Fig. 3 intersecting the growth curve).

The same problem occurs with the ramp function (Fig. 6). For any point above the asymptote, r is at a maximum c:

$$r = c + aT \tag{5}$$

where a is 0. The inverse function to find T is

$$T = \frac{c-r}{a} \tag{6}$$

but since $a = 0$, this is undefined (infinite).

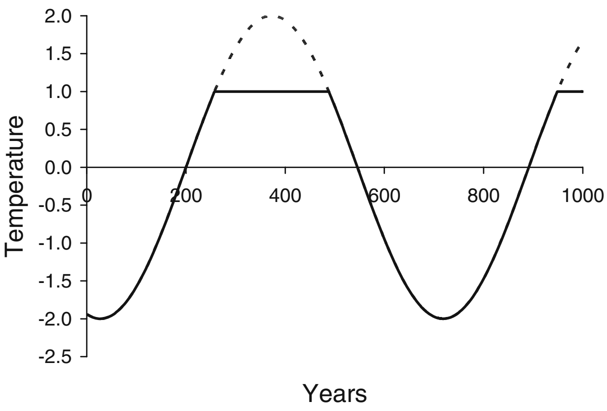


Fig. 7 If tree growth response is linear up to some maximum level (see Fig. 6), the reconstruction of climate from tree rings is truncated. *Dotted line* is temperature; *solid line* is reconstructed temperature (arbitrary scale)

Because of this problem, increasing model realism (e.g. Deslauriers et al. 2007) will not produce valid paleoclimate reconstructions. The nonlinear nature of the growth responses means that a given level of growth is not uniquely identified with a given temperature. In addition, more realistic models need precipitation as an input, but precipitation records are not usually available for past periods.

3 Discussion

In dendroclimatology studies, the raw data consist of tree ring series for many trees. Of these, some trees show a positive response to temperature, and these (or sites showing generally more response) are the ones generally used for reconstruction. However, many trees also show a negative response or are "nonresponders." These latter trees appear to be further to the right on the quadratic or ramp function growth curve. That is, under the growing conditions for that tree either temperature is not a limiting factor or further temperature increases cause drought (or other) stress. The fact that divergence has been so widely observed across tree species and regions indicates that choosing positive responders (or responsive sites) does not guarantee linearity of response.

The mathematical consequence of a nonlinear growth response is to (1) lower the mean reconstructed temperature, (2) damp out or truncate reconstructed peaks or even turn them into troughs, and (3) narrow the range of values (minimum to maximum) of the reconstruction (reduce variance). These qualitative results hold for any linear reconstruction model and quadratic or ramp growth response function. These effects are consistent with data showing more visible historical temperature peaks observed over the past 2,000 years with non-tree ring proxies such as borehole (e.g. Beltrami 2002; González-Rouco et al. 2003; Huang et al. 2000; Pollack and Huang 2000; Pollack and Smerdon 2004) or stalagmite (e.g. Tan et al. 2006) reconstructions (and others) compared to tree ring reconstructions (reviewed in Loehle 2006, 2007; Loehle and McCulloch 2008; Soon and Baliunas 2003), which also seem to have anomalously low variance.

The nonlinear response of trees to temperature, which can produce divergence, makes it difficult to detect past climate episodes warmer than those occurring during the calibration period. If all trees grow at temperatures far below the inflection point of the growth curve (Fig. 3) during the calibration period, then it may be possible to detect warmer past temperatures, but this will not be known a priori from the data or the fit statistics. That is, one can not tell if a given tree or composite proxy is able to detect past temperatures warmer than those present in the calibration data, though it might. Thus it is fundamentally impossible using tree ring data to say that recent decades are warmer than any time in the past n years because temperatures warmer than those of the first half of the twentieth century are likely to be suppressed by the method used for reconstruction. In addition to this problem, it has been shown that various other issues such as age detrending, regression method, and scaling period can affect the amplitude of past reconstructions, in most cases damping the signal (Esper et al. 2004, 2005a, b, 2007; von Storch et al. 2004). Loehle (2005) also showed that when multiple proxies with dating error are combined, the effect on a reconstruction is to damp the signal (because peaks do not line up). Thus there are multiple factors contributing to difficulties with reconstructing the amplitudes of past temperature fluctuations.

Limited evidence has been cited (D'Arrigo et al. 2007) suggesting that divergence is unique somehow to recent decades. One unique factor of the late twentieth century is rising carbon dioxide levels, but this should cause positive divergence (increased growth relative to warming), not negative (e.g. Idso 1989). The results of a study by Wilson et al. (2007) are also relevant. In this study, tree ring series were selected for model development that extended into the 1990s (more recent than in past studies) and only sites showing a strong temperature response at the local scale were chosen. In this case much less divergence was found, suggesting that there is nothing unique about recent decades. By picking sites that show a response in recent decades, this study shifts the temperature over which calibration is performed, but cannot show that temperatures warmer than this range can be detected in the past.

A study by Grudd (2008) using trees updated to 2004 also found little divergence and showed a warm Medieval Warm Period. It is worth noting that divergence is also evident during the calibration period (first half of the twentieth century) in most cases in the form of individual trees that respond negatively to higher temperatures (Driscoll et al. 2005; Wilmking et al. 2005), though these trees or sites are often not used. Thus, divergence can not easily be attributed to something occurring uniquely in recent decades, though this remains a possibility. Thus to continue using linear temperature extrapolations it is necessary to show that divergence is *not* caused by the growth responses documented here and that divergence *is* caused by something unique to recent decades. That is, when there is a potentially serious confounding factor in a (simplified linear) model, that factor must be proven not to be operative under the conditions in question in order to validly use the model.

Extant reconstructions thus provide no basis for statements about how unique recent high temperatures have been. Calibration fit statistics (Bürger 2007) are meaningless if the growth model (linear in this case) is mis-specified, as argued here. Even when other proxies have been included in the reconstructions, the tree ring data have usually been heavily weighted and/or the other proxies have been "rescaled" in some way (e.g. as in Moberg et al. 2005).

There are some things that could be done to mitigate this problem. First, it should be recognized that trees near northern or upper elevational range limits can still exhibit warming-induced growth declines (D'Arrigo et al. 2004; Lloyd and Fastie 2002) and thus are not automatically good proxies. High elevation sites, for example, often have very thin soils prone to drying. Trees in very moist sites may give better response. Second, if some trees in a stand or nearby are showing a damped or negative response to warming, then the trees in the area may be close to the peak of the quadratic response curve. Third, for trees that are truly not moisture limited it would be useful to check how close growth is to the maximum possible for the species. The trees will not show any response for temperatures above those that give maximum growth. In these three situations the reliability of reconstructions will be questionable.

More specific tests are also possible. If a reconstruction already shows divergence, it is an indication that recent temperatures are already in the nonlinear zone. Such reconstructions should not be used for evaluating past climates. Another method of testing is to cross-validate against other local proxy data, where available. In certain

European countries, for example, lake sediments, caves, and nearby ocean sediments all provide proxy data for comparison.

Finally, a promising new method is the use of δ^2H isotope ratios in wood (Keppler et al. 2007). These isotope ratios can be calibrated to the temperature of rain water and can at the same time be precisely dated by the tree rings.

In conclusion, the nonlinear response of trees to temperature explains the divergence problem, including cases where divergence was not found. The analysis here also shows why non-tree ring proxies often show the Medieval Warm Period but tree ring-based reconstructions more often do not. While Fritts (1976) notes the parabolic tree growth response to temperature, recent discussions of the divergence problem have not focused on this mechanism and climate reconstructions continue to be done using a linear response model. When the divergence problem clearly indicates that the linearity assumption is questionable, it is not good practice to carry on as if linearity is an established fact.

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