The *'Divergence Problem'* in tree-ring research

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Introduction

Evidence for reduced sensitivity of tree growth to temperature has been reported from multiple forest sites along the mid to high northern latitudes and from some locations at higher elevation. This alleged large-scale phenomenon reflects the inability of temperature sensitive tree-ring width and density chronologies to track increasing temperature trends in instrumental measurements since around the mid-20th century. In addition to such low-frequency trend offsets, resulting in warmer instrumental and cooler reconstructed temperatures, the potential inability of formerly temperature sensitive trees to reflect high-frequency climate signals derives from some boreal and alpine sites. These two observations have recently been introduced as the *'Divergence Problem'* (DP), with causes and scales being discussed in a variety of recently published high-ranking peer-review articles. If the DP turns out to be a real and widespread phenomenon, and the result of anthropogenic-indiced global warming, it would not only have a substantial effect on biomass productivity rates, with serious implications on carbon sequestration, but it would further question the overall ability of tree ring-based temperature reconstructions to capture earlier periods of putative warmth, such as the so-called Medieval Warm Period, and subsequently to model possible reactions of forest ecosystems in a warming world.

Here we synthesize the main points of a *Podium Discussion* that took place during the international conference TRACE (April, 2008), which stressed the DP from different perspectives: ecology, climatology, and methodology. The existing body of literature related to the DP is briefly reviewed, while highlighting regional-scale evidence for and against the phenomenon and discussing main sources of uncertainty that contribute towards complicating the issue.

Definition

D'Arrigo et al. (2008) recently defined the DP as: "the tendency for tree growth at some previously temperature-limited northern sites to demonstrate a weakening in mean temperature response in recent decades, with the divergence being expressed as a loss in climate sensitivity and/or an offset in trend". To expand on this definition, we should clarify that the DP is actually expressed in two ways in the *dendrochronological* literature: 1) a 'response related' divergence between tree ring-based reconstructed temperatures and actual measured temperatures, and 2) a 'growth divergence' (GD) that has been reported for some high-latitude and high-elevation sites, where formerly homogeneous sites show emergent subpopulations of trees with diverging growth patterns during the late 20th century (Wilmking et al. 2005; Pisaric et al. 2007; Zhang et al. 2008). This divergence is found between subsets of trees within one study site and commonly indicates different longer-term growth trends. The former ‘flavor’ of DP can be thought of as a *dendroclimatological* expression, while the latter reflects a *dendroecological* perspective.

Evidences

The existence of the DP is not spatially complete and appears to be more prevalent to some areas. Evidence for a potential DP was first noted in Alaska (Jacoby and D’Arrigo 1995; Taubes 1995), which appears to be a specifically sensitive region to the phenomenon (Barber et al. 2000; Jacoby et al. 2000; Lloyd and Fastie 2002; Davi et al. 2003 (for ring-width); Wilmking et al. 2004, 2005; D’Arrigo et al. 2005; Driscoll et al. 2005). However, using a large northern hemisphere network of maximum latewood density chronologies with regional composites across northern North America, Northern Europe and Siberia, Briffa et al. (1998) demonstrated widespread evidence for the DP. Despite this apparent large-scale distribution of the phenomenon, at a site or regional level, the DP is not observed at all studied locations (e.g., Jacoby et al. 1996; D'Arrigo et al. 2000, 2001; Wilson and Luckman 2002; Cook et al. 2003; Davi et al. 2003 (for density); Wilson and Topham 2004; Büntgen et al. 2005, 2006a, 2007, 2008b; Frank and Esper 2005; Luckman and Wilson 2005; Youngblut and Luckman 2008; Wilson et al. 2007). Moreover, the current body of literature reveals that the DP does not exist at lower latitudes (Briffa et al. 1998; Cook et al. 2004; Büntgen et al. 2008a). Therefore, the DP should not be thought of as an endemic large-scale phenomenon with one overriding cause, but rather a local- to regional-scale phenomenon of tree-growth responses to changing environmental factors including multiple sources and species-specific modification (Table 1).

Table 1 *Overview of available publications sorted by tree species that provide possible ecological explanations for the DP (only first author mentioned) when studying ring-width data only. All studies represent northern mid- to high-latitude or -altitude environments and demonstrate either a changing relationship over time between climate and radial tree growth (climate/TRW), show emergent subpopulation behavior (GD), physiological growth thresholds (differing growth responses to certain climatic thresholds), or age/size effects (differing age or tree size classes denoting different growth responses to climate). All of these phenomena possibly contribute in various ways to the DP.*

Species	**Climate/ TRW**	**GD**	**Thresholds**	**Age/size effects**
Abies alba	Smith 1999			
Abies alba	Wilson 2004			
Larix dahurica	Wilmking 2005			
Larix deciduas	Carrer 2006		Rossi 2007	Carrer 2004
Larix deciduas				Rossi 2008
Larix gmelinii	Lloyd 2007			
Larix sibirica	Wilmking 2005			
Larix sibirica	Lloyd 2007			
Picea abies	Wilson 2004		Rossi 2007	Rossi 2008
Picea abies	Büntgen 2006			

Picea abies	Lloyd 2007			
Picea glauca	Jacoby 1995	Wilmking 2005	D'Arrigo 2004	Szeicz 1994
Picea glauca	Wilmking 2005	Driscoll 2005	Wilmking 2004	
Picea glauca	Driscoll 2005	Pisaric 2007		
Picea glauca	Lloyd 2007			
Picea mariana	Lloyd 2007			Wilmking 2008
Picea mariana	Wilmking 2008			
Picea obovta	Lloyd 2007			
Picea rubens	Smith 1999			
Picea sitchensis	Lloyd 2007			
Pinus banksiana	Lloyd 2007			
Pinus cembra	Oberhuber 2007		Rossi 2007	Rossi 2008
Pinus sibirica	Wilmking 2005	Wilmking 2005		
Pinus sylvestris	Linderholm 2004			Linderholm 2004
Pinus sylvestris	Wilmking 2005			
Pinus sylvestris	Lloyd 2007			
Pinus tabulaeformis	Zhang 2008	Zhang 2008		
Sabina przewalski	Zhang 2008	Zhang 2008		Yu 2007
Tsuga mertensiana	Biondi 2000			
Tsuga mertensiana	Lloyd 2007			

Causes

A discussion of candidate reasons for the DP is detailed in D'Arrigo et al. (2008), which we briefly summarize here: Potential causes at the local- to regional-scale include recently occurring temperature-induced late summer drought-stress (Jacoby and D'Arrigo 1995; Barber et al. 2000; Lloyd and Fastie 2002; Büntgen et al. 2006b), complex non-linear growth responses to changing climatic and/or ecological settings (Vaganov et al. 1999; D'Arrigo et al. 2004; Wilmking et al. 2004), the utilization of an imprecise instrumental target for calibration (e.g., maximum temperatures may be more appropriate than mean temperatures – Wilson and Luckman 2002, 2003; Büntgen et al. 2008a; Youngblut and Luckman 2008), and affects of airborne pollution (Yonenobu and Eckstein 2006). At larger spatial scales, changes in stratospheric ozone concentration (Briffa et al. 1998, 2004) and/or effects of global dimming on photosynthesis rates (D'Arrigo et al. 2008) have also been proposed, but have not yet been robustly tested.

Superimposed on these biological and ecological related issues are methodological-induced uncertainties (see Büntgen et al. 2008b for an overview) including the tree-ring detrending methods applied during the standardization process and 'end-effect' issues emerging from different techniques of chronology development (Cook and Peters 1997; Melvin 2004). Further biases may emerge from the calibration technique applied (e.g., regression versus scaling) and calibration interval used (Esper et al. 2005), as well as the time-series smoothing practice performed (Mann 2004).

This concert of tree ring related uncertainties is complemented by potential sources of instrumental station error, e.g., the homogenization technique applied, 'micro-site' effects and effects gained from 'urban heat islands' (Frank et al. 2007). Such limitations of the target data, multivariate growth/climate interactions, and methodological issues can systematically bias inferred relationships with tree growth.

It should also be noted that several recent studies observed a similar phenomenon observed in chronologies from low-elevation drought sensitive tree-ring sites that express a loss or weakening of the growth/climate response with instrumental precipitation sums and/or drought metrics in the post-1970s (e.g., Brazdil et al. 2002; Wilson and Elling 2004; Wilson et al. 2005; Zhang et al. 2008). Potential reasons for the observed late 20th century discrepancy include pollution effects for the Central to Eastern European region. A systematic and sophisticated analysis based on a complete and updated data collection is, however, still missing.

Solutions

As there are likely multiple causes for the DP, which are not only tied to a certain species and region, but may also be related to methodological issues (e.g., detrending and chronology development), there is simply not one uniform solution to overcome the DP. On the contrary, the issue must be systematically studied on a site-by-site basis or within climatically homogenous regions where a network of sampling sites and reliable long-term instrumental measurements are available. Consequent testing for the ability of ring-width and density data to track temperatures during the exceptional recent warmth is necessary to understand the reliability of long-term climate reconstructions. Such tests are, however, complicated, as a variety of environmental factors including climate, ecology, stand structure and competition, forest history, and human influences simultaneously impact tree-growth. Therefore, well-replicated temperature sensitive tree-ring data and carefully homogenized meteorological target data, which both extend back into the 19th and forward into the 21st century facilitate a more robust study of the DP. Both conditions, as well as an unprecedented warming trend since the past ~150 years, exist for the European Alps. Accordingly, Büntgen et al. (2008b) compiled a unique network of the main Alpine conifer species larch and spruce. TRW measurements from 124 sites were aggregated, carefully detrended, and resulting chronologies compared with well-documented and homogenized climate data from numerous high-elevation instrumental stations. The TRW data were first analyzed to emphasize common growth trends and climate responses as a function of site elevation, location and species. Split period correlations were then used to assess proxy/target relationships over time. That is, a subset of TRW chronologies was calibrated to summer temperatures over the early 1864-1933 period and subsequently helped assessing their (independent) ability to track late 20th century warming. In this regard, however, it should be emphasized that the current quality level of instrumental measurements recorded across the Greater Alpine Region is exceptional and not reached in other parts of the globe. Subsequently, it is highly recommended to apply quality controls via outlier tests, such as the one introduced by Alexandersson (1986). The corresponding open source software (*AnClim*; Štěpánek 2007) should be mentioned. Moreover, in the light of reducing potential station measurement inconsistency, consideration of area means is recommended – more is always better. Investigations on the DP should not only be based on ‘standard’ climatic parameters, but also on extreme values and more complex indices including drought metrics, radiation duration, ozone and airborne pollution.

Ultimately, from a *dendroclimatic* point of view, we need to be very careful which chronologies we actually use for deriving spatiotemporal forceful reconstructions. While being an important (and credent) sub-community within the grand *Global Climate Change Consortium*, we should not forget the main principles of *dendrochronology*, and one cannot overemphasize the importance of careful site selection. If the aim of a study is to reconstruct temperature, then sites from near the latitudinal or upper treelines are most likely ideal – general assumptions, however, cannot be made! One should not be surprised that growth/climate relationships may be weak or variable if a site is represented by a few individuals sampled far away from the temperature controlled forest boundaries. Dendrochronologists should be very cautious about finding apparent divergence between their proxy chronologies and instrumental target values if the data considered were located in an area that would not be expected to be climatically sensitive and where correlations between tree parameter (TRW or MXD) indices are relatively weak (i.e., $r < \sim 0.45$) even in the periods when chronologies apparently show a climate signal. Certainly, a myriad of non-climatic factors could influence individual trees, individual sites or even regions. However, if the trees/sites are sampled from carefully selected locations in a climatically homogenous area, the common forcing signal (presumably climate) will dominate the chronology signal, if a sufficient number of trees is collected from multiple sites – again, more is always better.

In some respects, there is a clash of methodological approaches that dendro-climatologists or -ecologists need to keep in mind. A dendroecologist might be more interested in small-scale processes and growth responses of individual trees or populations to environmental changes, whereas a dendroclimatologist is generally interested in the mean response of many trees (and many sites) to an overriding larger scale forcing which more often than not will be climate related. This has also implications for the use of tree-ring data taken from freely available data pools (e.g., ITRDB) for large-scale modeling purposes: Before being included in climate modeling studies, metadata about the specific sampling strategies for an underlying tree-ring data set should carefully be considered. Nevertheless, as both approaches are built upon similar ecological principles, it might be worthwhile to better synthesize the different research agendas in the face of today's apparent unprecedented rates of climate and ecological change.

Conclusions

From our brief synthesis of a *Podium Discussion* that took place at the international conference TRACE (April, 2008), it is clear that there is NO systematic DP affecting all conifer sites over vast areas of the Northern Hemisphere and that there is also NO single causal mechanism superimposed on the relationship between tree growth and temperature.

This review reveals that future dendroclimatic research should not ignore potential complex and nonlinear growth responses to a changing climate system, which may challenge the current interpretation of the principle of uniformity as well as methodological biases that emerge from tree-ring detrending and chronology development. Possible directions to reduce uncertainties related to the DP should include:

(i) Sampling strategies at the site level that improve not only the selection of location (i.e., tree-line environments where the probability of only one climatically driven limiting factor is greater) but also increase the number of trees which should be up to an order of magnitude greater than the "traditional" amount of 15-20 individuals.

(ii) Sampling of different age-classes to avoid sub-population biases instead of focusing only on the oldest trees within a population.

(iii) Sampling more than one single site to represent and assess different ecological settings at the regional-scale, such as altitudinal gradients, various substrate types, different slope exposition and inclination, as well as inter-species variety.

Moreover, methodological recommendations related to the DP include:

(i) Exploring chronology development techniques that reduce artificial variance changes through time.

(ii) Utilizing detrending methods that allow possible low-frequency information to be obtained, and diminish 'end-effect' problems coinciding with the recent warming trends.

(iii) Selecting representative subsets of homogenized instrumental target data.

(iv) Scaling instead of regressing, although calibration/verification statistics are poorer after scaling. Regression becomes always critical when the target data have values well above or below the mean of the calibration period.

(v) Reducing of end-effect amplification due to the smoothing technique applied.

(vi) Omitting simple site deviation into 'responders' and 'non-responders' (those data that do or do not correlate with climate) without considering independent screening (calibration/verification) periods.

(vii) Understanding the DP – including high frequency loss in climate sensitivity and/or low-frequency trend offset – at the local to regional level, before drawing conclusions for larger-scales.

Finally, we should underline that the DP *'hype'* is very much dendro-centric while representing one potential 'problem' for dendroclimatology, and needs to be overcome if we aim to have faith in tree-ring derived climate reconstructions. Therefore, the term DP should be devalued towards something more appropriately called the "*Divergence Challenge*". The raised issue actually provides an opportunity to re-assess established assumptions, principles, sampling strategies and methods rather than debunking dendroclimatic expertise. Hence, we recommend picking up this challenge in a productive way to deepen our understanding of tree growth responses to various environmental factors and to develop new techniques or to improve established approaches of tree-ring data processing. In this case, the DP might stimulate and improve our discipline.

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