Increased temperature sensitivity and divergent growth trends in circumpolar boreal forests

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[1] Tree rings have been used to both reconstruct past climate, and to estimate and project carbon uptake of forest ecosystems. Here we show that large groups of trees of the dominant tree species within widely-distributed circumpolar forest sites show opposing growth trends during recent warming. These opposing growth trends are present at a sub-chronology level and, if averaged into chronologies, may have contributed to the widely reported overall decreased temperature sensitivity of high-latitude chronologies over recent decades. Unlike previous studies, we find that temperature sensitivity has actually increased for most individual trees at these sites. This recent, widespread divergence in growth response seems unique over the past three centuries, and may relate to different microsite responses of individual trees to temperature-induced drought stress or other factors. This divergence needs to be taken into account in dendroclimatic reconstructions, estimations of global warming impacts, and carbon uptake projections. **Citation:** Wilmking, M., R. D'Arrigo, G. C. Jacoby, and G. P. Juday (2005), Increased temperature sensitivity and divergent growth trends in circumpolar boreal forests, *Geophys. Res. Lett.*, *32*, L15715, doi:10.1029/2005GL023331.

1. Introduction

[2] Understanding forest growth responses to recent warming is critical for projections of future global change. Previous tree-ring studies demonstrated widespread declines of temperature sensitivity in northern high-latitude forests with significant implications for paleoclimatic reconstructions [*Jacoby and D'Arrigo*, 1995; *Briffa et al.*, 1998; *Vaganov et al.*, 1999] and carbon uptake projections [*Sitch et al.*, 2003]. These studies relied either on chronologies representing averages of many trees at a given site [*Jacoby and D'Arrigo*, 1995; *Vaganov et al.*, 1999], or on data-sets based on many chronologies [*Briffa et al.*, 1998]. The search for the mechanism leading to this decline in temperature sensitivity is ongoing [e.g., *Briffa et al.*, 2004].

[3] In a recent study of treeline sites in northern Alaska [*Wilmking et al.*, 2004], where pronounced warming has taken place in recent decades [*Hansen et al.*, 1999], we systematically sampled 1558 white spruce (*Picea glauca*) at thirteen sites in the Brooks Range and the Alaska Range. Opposing types of tree growth response (positive or negative) to temperature were demonstrated, with both types of trees occurring within a given sample site. In such cases, some individual tree-ring series contributed to a statistically significant relationship of the chronology with a particular predictive function of climate, while others degraded it. Even though these opposing growth responses were present in all sampled sites, their relative proportion varied between sites following patterns of regional and local moisture availability [*Wilmking and Juday*, 2005]. Here we present evidence that this phenomenon is not a regional abnormality, but is operating in several dominant tree species in forests across the circumpolar North (Figure 1).

2. Building Responder Chronologies Instead of Site Chronologies

[4] The development of dendrochronological time series or chronologies usually involves the sampling of multiple trees at a site, and the precise dating and measurement of wood samples. The series are then detrended to account for age-related bias of the tree-ring parameter of interest (usually ring width or density). Finally, individual series measurements are averaged (standardized) to form a chronology [*Cook and Kairiukstis*, 1990; *Briffa et al.*, 1998], and this chronology is then analyzed for a relationship to climate (e.g. temperature). In this study, however, we have analyzed growth trends and climate relationships for each individual tree-ring series prior to grouping trees with similar trends and climate-growth relationships into what we have termed "responder-chronologies".

[5] Raw tree ring series were obtained from the International Tree Ring Data Bank (MK, MC, PU, TK in Figure 1) and from the authors' collections (AL, CM, LB, SD in Figure 1). We selected sites which had a) been used in published climate studies and b) included as many series as possible. Tree-ring series were cross-dated using COFECHA [*Holmes*, 1983] and individually detrended using ARSTAN [*Cook and Kairiukstis*, 1990] with negative exponential or straight-line curve fits. After averaging series from within the same tree, we built responder chronologies by grouping individual trees from each site that had similar growth patterns and climate-growth relationships in recent decades. Grouping of trees was performed following *Wilmking et al.* [2004], where we first employed a cluster analysis to search for growth patterns shared by groups of trees within the data set. We then selected the monthly mean temperature variables with the highest correlation scores to the different clusters to calculate the correlation score with each individual cluster member. All trees with a significant positive correlation to site-specific mean monthly temperatures were grouped into

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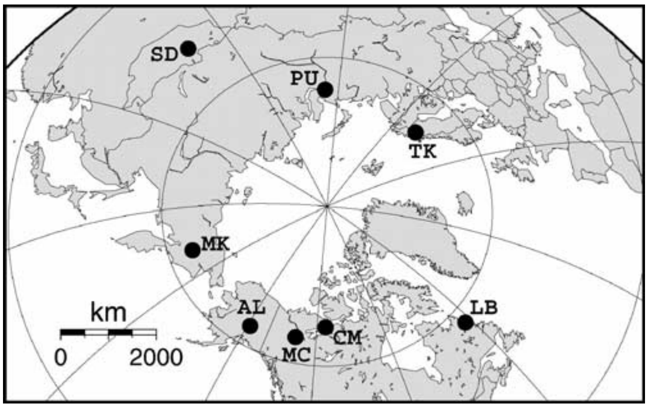

Figure 1. Tree-ring sites analyzed for this study from circumpolar treeline locations. LB: Labrador composite from Salt Water Pond, Nutak, Medusa Bay and Okak (*Picea glauca*), CM: Coppermine (*Picea glauca*), MC: MacKenzie Mountains (*Picea glauca*), AL: Alaska Range (*Picea glauca*), MK: Markovo (*Larix dahurica*), SD: Mongolia composite from Tarvagatay Pass, Sologotyin Davaa and Suleen Bagtraa (*Pinus sibirica*), PU: Polar Urals (*Larix sibirica*), TK: Tornetraesk (*Pinus sylvestris*).

''responder chronology A''. All tree ring series with a statistically significant negative correlation to a site-specific mean monthly temperature (mostly July; an indication of drought stress) were grouped into what we call ''responder chronology B''. Trees could only be members of one responder chronology, and possible overlaps occurred only very infrequently. Trees with no significant correlation with the main climate indices were excluded from further analysis (for number of trees in each group; see Table 1).

[6] Climate-growth relationships (Pearson correlations) of the resulting responder-chronologies were calculated for two periods: 1) 1961 to last year of growth; 2) 1920–1960 (Table 2). We used climate data from those stations closest to the sampling site from the Global Historical Climate Network (GHCN from the GISS database) with continuous records of mean monthly temperatures from 1920 onwards (Table 3) to calculate shifts in temperature sensitivity (exceptions: Coppermine, 1933 onwards; Goose, 1941 onwards). Missing data was very minimal and was usually confined to the period before 1960 and was estimated using the mean of the years before and after the missing data point. Two or more consecutive years of missing data led to the elimination of these years in the climate growth correlation. Temperature indices used in Table 2 were calculated for the current year of growth (May–August, March–April) and the prior winter (November–February).

Table 2. Five Year Filtered Correlation Scores of Responder-Chronologies (A = red chronology in Figure 2, B = blue chronology) With Three Temperature Indices of Local Climate Stations Between Periods 1921–1960 (Pre) and 1961–2000 (Post)[a]

		Nov–Feb		Mar–Apr		May–Aug	
Site	Time Period	A	B	A	B	A	B
LB	Pre	n.s.	n.s.	n.s.	0.53	n.s.	0.42
LB	Post	n.s.	n.s.	n.s.	−0.32	n.s.	−0.42
CM	Pre	n.s.	−0.37	n.s.	−0.54	n.s.	n.s.
CM	Post	0.46	−0.64	0.71	−0.33	0.64	−0.48
MC	Pre	n.s.	n.s.	0.62	0.59	n.s.	n.s.
MC	Post	0.91	−0.30	0.46	−0.52	0.80	−0.77
AL	Pre	n.s.	−0.50	n.s.	n.s.	−0.44	n.s.
AL	Post	0.48	−0.34	0.79	−0.80	0.47	−0.78
MK	Pre	n.s.	−0.30	n.s.	−0.30	n.s.	n.s.
MK	Post	n.s.	n.s.	0.36	n.s.	0.82	−0.33
SD	Pre	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
SD	Post	0.65	−0.55	0.66	−0.50	0.56	−0.49
PU	Pre	−0.41	−0.33	−0.78	−0.78	0.61	0.63
PU	Post	n.s.	n.s.	−0.34	−0.57	n.s.	0.55
TK	Pre	−0.35	0.44	n.s.	n.s.	n.s.	n.s.
TK	Post	n.s.	0.75	−0.64	n.s.	0.51	0.46

[a]Significance was established with the unfiltered pairings of tree growth and climate, non significant correlations are marked n.s. ($p > 0.05$). This table is intended to give an overview about the possible range, scale and direction of correlation scores using a coherent method for all calculations, thus should not be interpreted as the ideal representation of a climate-growth relationships for these sites. Individual correlation scores could be maximized using 1) individual mean monthly temperatures, 2) combination of individual months, 3) different time frames.

3. Results

[7] After building responder chronologies for each site, we compared their growth trends over the last four centuries (Figure 2). During most of the past 300 years, growth trends were similar, both in relative magnitude and direction. Recently, however, growth trends of responder-chronologies diverge markedly and, within most sites, now display opposing directions. The divergent response of growth trends becomes important at decadal time scales, and thus could not be easily detected using ''Gleichlaeufigkeit'', which is calculated on an annual basis [*Schweingruber*, 1988].

[8] This feature of diverging growth trends is apparent in all but one site, Labrador. This coincides with the fact that the northern Atlantic region experienced a cooling anomaly

Table 1. Number of Trees in Responder Chronologies[a]

Site ID	Tree species	n A	n B	n n.s.
LB	*Picea glauca*	43	14	14
CM	*Picea glauca*	31	38	30
MC	*Picea glauca*	8	21	13
AL	*Picea glauca*	207	223	170
MK	*Larix dahurica*	13	3	2
SD	*Pinus sibirica*	16	17	0
PU	*Larix sibirica*	11	17	29
TK	*Pinus sylvestris*	8	10	0

[a]Number (n) of trees in red chronologies (A) (column 3), blue chronologies (B) (column 4), and with no significant (n.s.) ($p > 0.05$) correlation to climate (column 5). Color and site identifiers (ID) same as in Figures 1 and 2.

Table 3. List of Climate Stations Used to Calculate Correlation of Temperature and Ring Width (from GHCN)[a]

Site ID	Station Name	Lat.	Long.	Record
LB	Goose, Nfl.	53.3′N	60.4′W	1941–2005
CM	Coppermine	67.8′N	115.1′W	1930–2005
MC	Ft. Good Hope	66.3′N	128.6′W	1898–1989
	Norman Wells	65.3′N	126.8′W	1943–2005
AL	Fairbanks	64.8′N	147.9′W	1906–2005
MK	Anadyr	64.8′N	177.6′E	1898–2005
SD	Irkutsk	52.3′N	104.3′E	1882–2005
PU	Berezovo	63.9′N	65.0′E	1881–1990
TK	Sodankyla	68.4′N	26.6′E	1908–2005

[a]Climate record used for MC is composite of Ft. Good Hope and Norman Wells. Site ID same as in Figures 1 and 2.

in the last decades, whereas all other treeline sites that we studied show warming anomalies during the same period [*Hansen et al.*, 1999].

[9] Contrary to the published literature [*Jacoby and D'Arrigo*, 1995; *Briffa et al.*, 1998; *Vaganov et al.*, 1999; *Barber et al.*, 2000], we find that the temperature sensitivity of individual trees and thus responder-chronologies actually *increases* in a large portion of the samples after 1960 compared to the period before (Table 2). In ~8% of the cases (4 out of 48) climate-growth responses actually switched sign from positive sensitivity before 1960 to negative after 1960 or vice versa. Our results therefore suggest that the previously reported decrease in overall temperature sensitivity of ring-width chronologies [*Jacoby and D'Arrigo*, 1995, *Briffa et al.*, 1998; *Vaganov et al.*, 1999] might have been partly due to how they were developed.

4. Discussion and Conclusions

[10] This phenomenon of a divergent response to climate in circumpolar treeline forests, overlapping the general northern hemisphere warming trend of recent decades [*Overpeck et al.*, 1997; *Hansen et al.*, 1999], has several important implications for studies of climate change. One is that researchers need to be more aware of the degree of consistency in tree growth response to climate of individual trees included in a given chronology prior to use in, or interpretation of, dendroclimatic reconstructions [*Cook and Kairiukstis*, 1990]. Selection of cores that have a coherent and consistent relationship with the climate variable of interest [e.g., *Jacoby et al.*, 2000] can thus greatly improve the accuracy of past temperature estimates. If this phenomenon is as widespread as our results suggest, it might help explain some of the differences observed between recent large-scale temperature reconstructions [*Mann et al.*, 1999; *Esper et al.*, 2002] due to the possible inclusion of mixed-response chronologies calibrated over recent decades. Building responder-chronologies could also highlight episodes of high divergence in the past and thus identify periods with higher probability of error in dendroclimatic reconstructions (e.g. opposing growth trends of some responder-chronologies in the early 1600s; Figure 2).

[11] The observed widespread divergence appears to be a unique feature of forest growth at these sites over the past three centuries. Only three of the eight sites have records dating back more than 300 years. All of these records show some divergence during the early 1600s (Figure 2), which most likely relates to lower sample size, but could be indicative of a change in growing conditions during that time. Our interpretation is that, due to recent warming (except for the Labrador site [*Hansen et al.*, 1999]), trees have become more sensitive to microsite differences which could cause some but not all trees at a given site to be stressed by drought or other factors.

[12] There are also important considerations of these observations for global carbon cycle research. If divergent growth responses to temperature are not taken into account, estimates of future atmospheric CO_2 based on carbon cycle models [*Ciais et al.*, 1995; *Sitch et al.*, 2003] could be significantly in error. Divergent growth responses to temperature may increase as temperatures pass recently discovered critical physiological thresholds without a concomitant increase in moisture availability [*Wilmking et al.*, 2004; *D'Arrigo et al.*, 2004]. Growth increases and decreases appear in some of our samples above specific temperature index values (thresholds), which occurred more frequently in the 20th century [*Wilmking et al.*, 2004]. Without

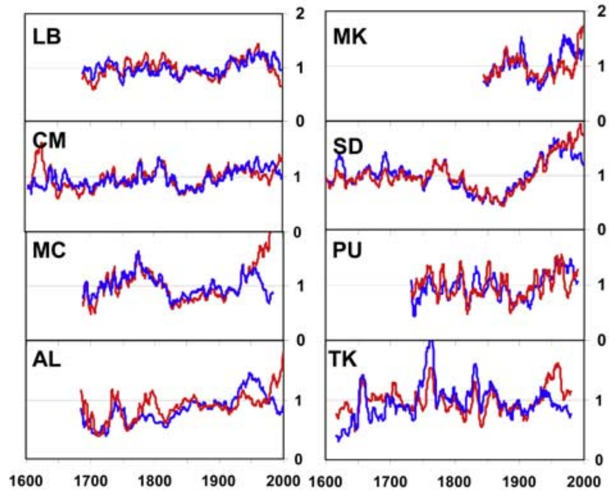

Figure 2. Growth trends of responder-chronologies within each site (5 year filtered) are highly correlated with each other during most of the last 300 years. In recent decades, however, growth trends diverge in opposite directions concurrent with an increase in temperature sensitivity of each responder-chronology (Table 1). Climate-growth relationships can be found in Table 1 (red responder-chronologies in columns labeled A, blue responder chronologies in columns labeled B). All series have been standardized to a mean of 1.

accounting for these opposite responses and temperature thresholds, climate reconstructions based on ring width will miscalibrate past climate, and biogeochemical and dynamic vegetation models will overestimate carbon uptake and treeline advance under future warming scenarios. Our findings suggest that the observed divergent response to climate at circumpolar treeline, overlapping the warming of recent decades, could be important for a significant proportion of the circumpolar forests and their dominant tree species. A more comprehensive analysis is planned to explore this possibility.

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