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Influence of snowfall and melt timing on tree growth in subarctic Eurasia

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The causes of a reduced sensitivity of high-latitude tree growth to variations in summer temperature for recent decades[1,2], compared to earlier this century, are unknown. This sensitivity change is problematic, in that relationships between tree-ring properties and temperature are widely used for reconstructing past climate. Here we report an analysis of tree-ring and climate data from the forest–tundra zone, in combination with a mechanistic model of tree-ring growth, to argue that an increasing trend of winter precipitation over the past century in many subarctic regions[3–5] led to delayed snow melt in these permafrost environments. As a result, the initiation of cambial activity (necessary for the formation of wood cells) has been delayed relative to the pre-1960 period in the Siberian subarctic. Since the early 1960s, less of the growth season has been during what had previously been the period of maximal growth sensitivity to temperature. This shift results not only in slower growth, but also in a reduced correlation between growth and temperature. Our results suggest that changes in winter precipitation should be considered in seeking explanations for observed changes in the timing of the 'spring greening' of high-latitude forests[6], and should be taken into account in the study of the role of the Siberian subarctic forest in the global carbon cycle.

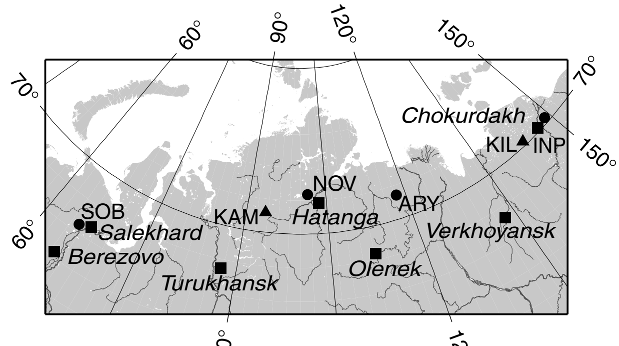

Figure 1 Location of sites and meteorological stations. Squares, meteorological stations; circles, tree-ring width sites; triangles, tree-ring width and tree-ring structure sites.

We used tree-ring measurements of conifers from the Siberian northern timberline (Fig. 1) to define relationships between tree-ring[7] growth and temperatures at different times in the growth season (see Methods). In addition to tree-ring width measurements, maximum late-wood density was used. The most important interval of the growth season—when temperature influences cell production, and hence ring width—is quite short (Fig. 2): four pentads (periods of five contiguous days) (17 June–6 July) with significant

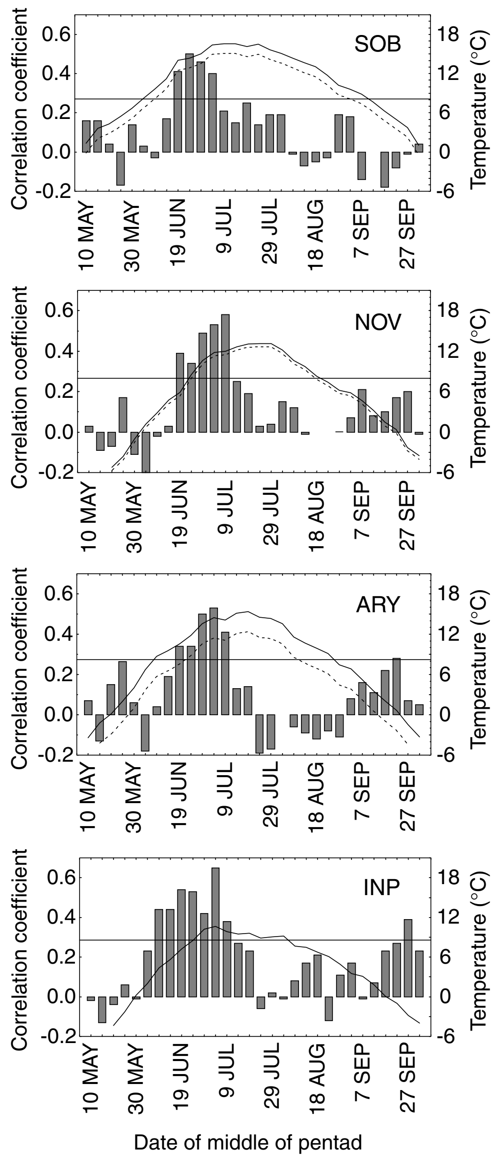

Figure 2 Correlation of the mean temperature of five consecutive days ('pentads') with tree-ring width indices for four sites near the northern timberline. The three-letter codes for each panel indicate the tree-ring site (see Fig. 1). At SOB, meteorological data from Berezovo were used, at NOV, from Hatanga, at ARY, from Olenek, and at INP, from Chokurdakh. Values above the horizontal solid line are statistically significant ($P < 0.05$). Solid line, mean of temperature data (over several years) from meteorological station close to site; dotted line, temperature corrected to the site.

correlation at site SOB in the west, five pentads (17 June–11 July) for sites NOV and ARY, and seven pentads (7 June–6 July) for site INP in the east (station locations are shown in Fig. 1). This interval is essentially the period of the early season temperature increase. The mean temperature (averaged over several years) of the first pentad which shows significant positive correlation with tree-ring width decreases from west to east: 10 °C, 6–7 °C and 4 °C at SOB, NOV and ARY, and INP, respectively. The fraction of the season when tree-ring width and temperature are significantly correlated is much shorter than the period with temperature higher than 5 °C, increasing from 21% at SOB, to 35% at NOV and ARY, to 50% at INP. The period when temperature influences maximum late-wood density is longer; for example, 4 June–2 October at KIL.

The seasonal dynamics of temperature vary to a great extent from year to year. For example, the date after which temperature stays consistently above 0 °C can differ by up to 25–30 days. Data on the physiology of cambial activity indicate that, in conditions where temperature strongly limits the radial growth of trees, the temperature must be higher than some threshold and the thawing of the soil upper layer after snow melt must have begun so that radial growth can commence[8–10]. Therefore, it is not strictly appropriate to correlate tree-ring parameters with temperatures for pentads whose dates are fixed relative to the calendar. Doing this will result, in some years, in tree-ring data being compared with the temperature of a period when there is no growth and, for other years, when growth is in an active, or even a very active, phase. It makes more sense to correlate tree-ring structural parameters with pentad temperatures where the dates of the pentad are fixed relative to the date of cambial initiation, as defined by tree physiology and by climate data. As soil temperature is a very important parameter for tree growth on permafrost soil[11], we attempted to connect the date of the beginning of growth and the date of snow melt.

The date of snow melt was calculated from temperature and winter precipitation data according to simple methods[12]. The dates calculated correlate very well with available observed snow melt data ($n = 16$, $R = 0.82$, $F = 28.8$, $P < 0.0001$) and their standard deviation, maximum and minimum values are very similar. The correlation of temperature with maximum late-wood density changed when pentad dates were fixed relative to snow melt rather than the calendar. For example, the maximum correlation between maximum late-wood density and temperature at KAM was 0.52 when calculated for calendar-related pentads, but was 0.67 when the pentads were related to the date of snow melt. This is consistent with knowledge of the physiology of cell wall growth. The variability of tree-ring width is explained by the temperature of pentads immediately after snow melt (the first part of the growth season)[13–15]. High temperature during the first part of a season leads to formation of a wider cambial zone, higher cell production through the season, and consequently a wider ring[16–18]. Thus, the main controlling factors of seasonal growth and tree-ring structure formation in northern timberline trees are early summer temperature and the date of snow melt, which influences the date of cambial initiation. Multiple regression models of tree-ring width indices, calculated with early summer temperature and snow-melt date as independent variables, show strong agreement with observed data. For KAM, $R^2 = 0.50$, $F = 20.3$ and $P < 0.00001$, and for KIL, $R^2 = 0.54$, $F = 22.8$ and $P < 0.00001$. Comparison of the mean ring widths of years with very early and very late snow melt confirms the influence of snow-melt date on tree-ring width. At KAM, the mean (standard deviation) tree-ring width index for the 12 years of earliest snow melt was 1.25 (0.19), and for the 10 years of latest snow melt was 0.88 (0.25). Similarly at KIL, the means (standard deviations) were 1.06 (0.28) for the 9 earliest years, and 0.92 (0.22) for the 9 latest years. These data indicate that tree-ring width indices are higher in years with earlier snow melt.

We examined the dynamics of early summer temperature, winter precipitation and calculated dates of snow melt for some meteorological stations in the study region, and for others located a

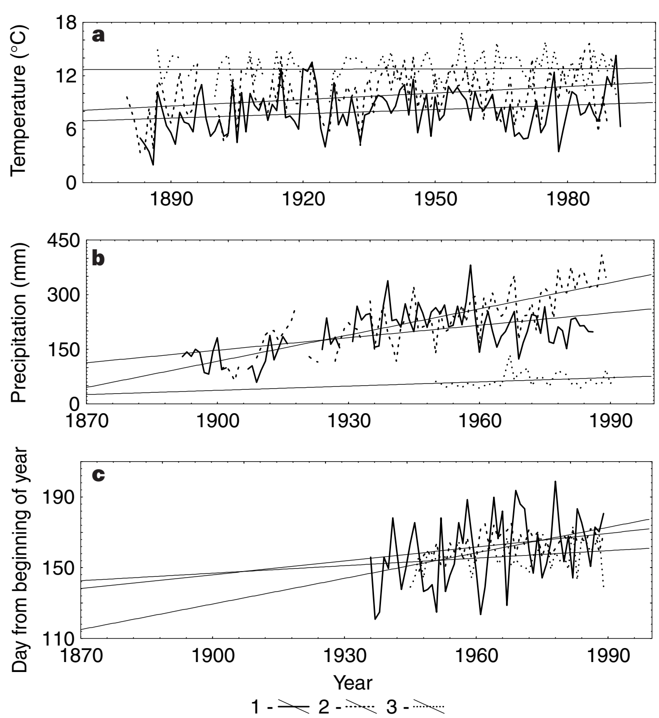

Figure 3 Meteorological time series. Variability of **a**, early summer temperature, **b**, winter precipitation and **c**, calculated dates of snow melting over several years. Data are from meteorological stations as follows: Salekhard, solid line ('1' in key), Turukhansk, broken line (2) and Verkhoyansk, dotted line (3). In each case, as well as the meteorological time series, a straight line shows the trend over the period of record. Differences in ending dates of time series relate to data availability.

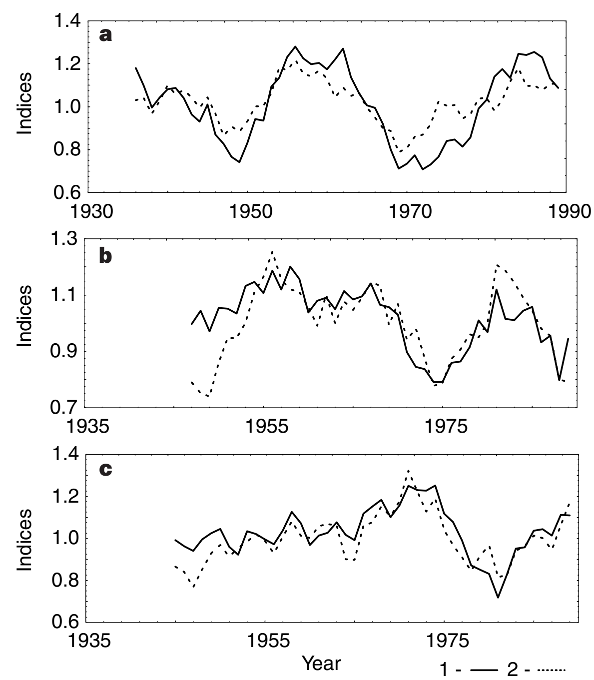

Figure 4 Tree-ring width dynamics at three sites: (**a**), SOB; **b**, NOV; **c**, INP. Solid line ('1' in key), measurements, dashed line (2), simulation model. Data are smoothed by 5-year averaging. The vertical axis represents dimensionless indices derived by detrending the individual tree-ring width series and, in the case of the measured data, calculating a site mean.

Table 1 Parameters of trends

Region	Temperature* trend (°C per 10 yr)		Precipitation† trend (mm per 10 yr)		Date of snow melting trend (d per 10 yr)	
	Whole period	1981–90	Whole period	1981–90	Whole period	1981–90
Salekhard	+0.15	+0.13	+11.4	−36.3	+3.7	+14.1
Hatanga	+0.25	−0.70	+22.6	+22.2	+2.6	−0.3
Chokurdakh	+0.03	+0.14	+3.9	+18.0	+1.4	−3.3

* Early summer temperature.
† Winter precipitation (October–April).

short distance to the south which had a longer period of record (Fig. 3). Early summer temperature has a clear positive trend during the past century: winter precipitation also shows a positive trend. These two processes with different directions (temperature accelerates growth, winter precipitation shifts the start of cambial activity to later dates) lead to later activation of tree growth. Further, the higher the values of winter precipitation are, the greater is their influence. In the wet western and middle regions of the Siberian subarctic, the shift of snow-melt dates is larger than in the dryer eastern regions (Table 1).

To test further the combined roles of the timing of cambial initiation (linked to the date of snow melt and hence winter precipitation[19]) and early summer temperature in controlling tree-ring width in the subarctic, we use a simulation model[20–22]. The model uses daily temperature, precipitation and light data to calculate seasonal tree-ring growth and cell production, taking snow melt and soil thawing into account. The model has a specific block devoted to soil thawing dynamics, so that, for example, it takes into account such possibilities as frequent refreezing and thawing. The modelled date of the first cell divisions depends on the estimated dates of the end of constant snow cover and threshold values of air temperature and effective temperature sum. Chronologies generated using this model are very similar to those collected and measured for three sites spread across the region, with correlations between modelled and observed values of 0.86 (1936–89), 0.84 (1947–89) and 0.71 (1945–89) respectively (Fig. 4). We note that these relationships do not deteriorate after 1960. This lends strong support to the hypothesis that delayed cambial activation connected with later snow melt is the real reason for observed weakening of the relationship between summer temperature and tree-ring width dynamics in the forest–tundra zone of the Siberian subarctic. There is reason to believe that these relationships may well apply through much of this vast zone, as tree-ring series are very strongly correlated over great distances in this region. In a study[23] of 65 time series derived from well replicated tree-ring widths from near the northern tree limit throughout the Siberian subarctic, over a 300-year period, pairs of tree-ring series up to 300 km apart had correlation coefficients between 0.7 and 0.8. Series from sites up to 800 km apart correlated at between 0.4 and 0.6.

Our results have implications for the study of both natural and anthropogenic variability in the subarctic. They provide an improvement of the understanding of the biological basis of summer temperature reconstructions from subarctic tree-ring variables, especially in the forest–tundra zone. Similarly, our results lead to a testable working hypothesis for the earlier and increased 'spring greening' of the boreal forest seen in remotely sensed primary productivity for the period 1981–90 (ref. 6). This in turn has implications for the study of the global carbon cycle, and the changes it may undergo in a changing climate. In particular, possible future changes in winter precipitation (as well as changing growth season temperatures) need to be taken into account in the development of models and climate scenarios concerning the role of the Siberian subarctic forest in the carbon cycle. □

Methods

Material from six sites near the northern timberline was analysed (Fig. 1). The choice of these sites was defined by the presence of long records of daily temperature data. Dendroclimatic analysis of standardized tree-ring width chronologies[23] was performed for four sites. For two other sites, in addition to tree-ring width, maximum late-wood density was measured by means of X-ray microdensitometry[24]. Local chronologies were calculated by averaging measurements made for individual trees (12–19 trees—for tree ring width, 15–20—for maximum late-wood density), and chronology statistics calculated. Correlation coefficients of the chronologies with pentad temperatures were calculated. Long instrumental records (1936–90) of daily temperature from nearby meteorological stations (Berezovo, Khatanga, Olenek and Chokurdakh) were used. In addition, monthly temperature and precipitation data available for a longer period (1887–1990) from other meteorological stations (Salekhard, Turukhansk and Verkhoyansk) were used.

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