GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 9, 1296, 10.1029/2001GL013739, 2002

Spatial and temporal oxygen isotope trends at the northern tree-line in Eurasia

Matthias Saurer
Paul Scherrer Institute, Villigen PSI, Switzerland

Fritz Schweingruber
Swiss Federal Research Institute WSL, Birmensdorf, Switzerland

Eugene A. Vaganov
Institute of Forest, Siberian Branch of the Russian Academy of Science, Krasnoyarsk, Russia

Stepan G. Shiyatov
Institute of Plant and Animal Ecology, Ural Branch of the Russian Academy of Science, Ekaterinburg, Russia

Rolf Siegwolf
Paul Scherrer Institute, Villigen PSI, Switzerland

Received 6 July 2001; revised 12 October 2001; accepted 9 November 2001; published 4 May 2002.

[1] The oxygen isotope ratio of ice cores and sea-sediments is an extremely useful source of information on long-term climatic changes. A similar approach has been applied to the oxygen isotope ratio of tree rings to enable a pattern-based reconstruction of the isotope variations on the continents. We present an oxygen isotope map for northern Eurasia spanning from Norway to Siberia, that reflects the isotope distribution in the late 19th century, and compare it with an equivalent map for the present-day situation. The average isotope values of 130 trees show a large east-to-west gradient and are highly correlated with the isotope distribution of precipitation. Surprisingly, the $^{18}O/^{16}O$ ratio of the wood has been decreasing in the interior of the continent since the late 19th century, in contrast to the strong temperature increase recorded by meteorological data. From this isotope trend over time a change in the seasonality of precipitation can be inferred. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 1040 Geochemistry: Isotopic composition/chemistry; 1620 Global Change: Climate dynamics (3309); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology

1. Introduction

[2] The recent climate change involves a complex spatial pattern of temperature and precipitation variations with causes often difficult to discern. The warming trend over the 20th century by about 0.6°C is well established, but the magnitude of the warming is not uniform with respect to different areas of the globe [*Bradley et al.*, 1987; *Jones*, 1994]. Due to an incomplete understanding of the natural climate variability, our ability to project future climate changes at a regional scale is still limited [*Hulme et al.*, 1998]. This necessitates the systematic collection of proxy observations of temperature and precipitation for the detailed reconstruction of natural variability [*Overpeck et al.*, 1997]. Trees as climatic archives are ideal for mapping purposes because they are growing on many land areas and are often precisely datable. Tree-ring density and ring-widths have been successfully used to reconstruct summer temperatures in high-northern latitudes, although a discrepancy between tree-growth and temperature has been found for the recent decades [*Briffa et al.*, 1998]. Oxygen isotopes in tree rings have the potential to extend this approach by reconstructing past spatial variations of ^{18}O in precipitation [*Burk and Stuiver*, 1981]. This method has not yet been fully exploited as not many maps of past ^{18}O distribution exist - a fact which may be rapidly changing due to analytical improvements: the development of on-line measuring techniques for organic matter and the finding that cellulose extraction from wood may not be necessary as the climatic signal is also reflected in the whole wood [*Barbour et al.*, 2001; *Saurer et al.*, 2000].

2. Materials and Methods

[3] We measured the $^{18}O/^{16}O$ ratio for a network of old dominant trees across Eurasia from Norway to Siberia using material from three widely distributed tree genus (*Larix*, *Picea*, *Pinus*) sampled previously for the Northern Eurasian Tree-Ring Project [*Schweingruber*, 1993] (Figure 1a). The sites were selected at the northern timberline of the Eurasian boreal forest where growth is most limited by temperature. We determined the oxygen isotope composition $\delta^{18}O$ on composite wood samples of the period 1861–90 and 1961–90 using a continuous-flow pyrolysis system with a precision of ±0.3‰ [*Saurer et al.*, 1998]. The samples were collected by splitting off sections with 30 rings from wood cores that had previously been used for density measurements (one core per tree, 5 trees per species and site). This approach yields spatially resolved information on a possible shift of the oxygen isotope ratio from the late nineteenth century to the present with a limited number of samples.

3. Results and Discussion

[4] We found a large east-to-west gradient in the oxygen isotope composition, with the highest values in Norway close to 25‰ and the lowest values in the most continental area at the northern boundary of the investigated area around 16‰. At the sites where more than one species was available the species differences in $\delta^{18}O$ were small, although the values of *Picea* tended to be higher than the values of the other two species: $\delta^{18}O_{Picea} - \delta^{18}O_{Pinus} = 0.74 \pm 1.17‰$ and $\delta^{18}O_{Picea} - \delta^{18}O_{Larix} = 0.86 \pm 1.09‰$. These differ-

0094-8276/02/2001GL013739

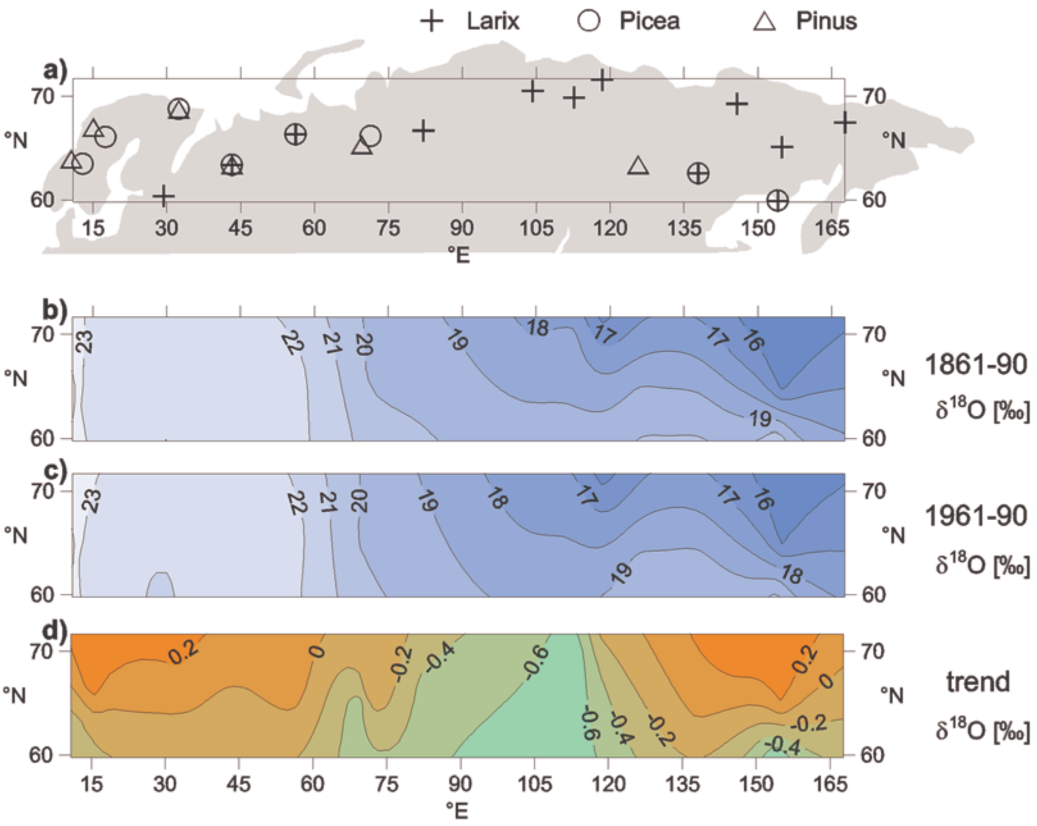

Figure 1. (a) Location of sites and tree species, (b) tree-ring oxygen isotope isolines for the period 1861–90, and (c) for 1961–90, (d) difference plot between (c) and (b), whereby positive values indicate an increasing temporal trend of δ^{18}O. The isolines were calculated

ences are of the same order of magnitude as the average within-site (tree-to-tree) variability, which was ±0.61‰. Accordingly, the values from all species were pooled to calculate isolines of δ^{18}O (Figures 1b and 1c). The maps of δ^{18}O for 1861–90 and for 1961–90 are rather similar, indicating that temporal variations are small compared to spatial variations. This conclusion is in line with results from previous studies with higher temporal resolution [*Robertson et al.*, 2001; *Saurer et al.*, 2000]. Nevertheless, the 19‰-isoline has moved westward. The difference between the two periods is plotted in Figure 1d and shows that δ^{18}O decreased in the interior part of the continent by about 0.5‰, whereas δ^{18}O slightly increased to the east and west of the continent, particularly at latitudes >65°N. This century-scale isotope decrease is significant at $p < 0.05$ in the longitude range from 60°E to 120°E (−0.40 ± 0.16‰; see Table 1, first column).

[5] The basis for the climatic dependence of the ^{18}O/^{16}O ratio are the temperature-dependent fractionation processes during evaporation and condensation in the hydrological cycle, leading to a close relationship between δ^{18}O of precipitation and annual mean surface air temperature [*Dansgaard*, 1964]. Further, changes in source area and in the flow path of moisture affect ^{18}O in precipitation [*Rozanski et al.*, 1993]. The oxygen isotope ratio in cellulose [*Roden and Ehleringer*, 1999] as well as in whole wood [*Saurer et al.*, 2000] of tree rings has been shown to

Table 1. Comparison of Measured and Calculated Isotope Trends

Region Longitude °E	$\Delta\delta_{tree\text{-}ring}$[a] [‰]	$\delta_{w\text{-}precip}$[b] [‰]	$\delta_{s\text{-}precip}$ [‰]	P_w/P_{year}[c] 1901–30 [‰]	P_w/P_{year} 1961–90 [‰]	$\Delta\delta_{precip}$[d] [‰]
0°–60°	0.03±0.10	−14.57	−8.96	44.7	46.4	−0.09
60°–120°	−0.40±0.16	−22.52	−12.39	31.3	36.1	−0.48
120°–180°	−0.20±0.13	−22.93	−15.50	29.6	34.0	−0.33

[a] $\Delta\delta_{tree\text{-}ring}$ is the measured oxygen isotope trend in the tree rings, i.e. the difference between 1861–90 and 1961–90 (mean ± se).

[b] $\delta_{w\text{-}precip}$ and $\delta_{s\text{-}precip}$ are the winter (October–March) and summer (April–September) isotopic values of precipitation calculated from the gridded GCM-isotope data [*Hoffmann et al.*, 1998] for the present day situation. All values are averages for the 60°–70°N latitude band.

[c] P_w/P_{year} is the relative contribution of winter precipitation to whole year precipitation amount (for 1901–30 and 1961–90, respectively) calculated from meteorological data [*Hulme et al.*, 1998].

[d] $\Delta\delta_{precip}$ is the calculated change in whole year isotopic composition of precipitation from 1901–30 to 1961–90: $\Delta\delta_{precip} = \delta_{w\text{-}precip}(P_w/P_{year\ 1961-90} - P_w/P_{year\ 1901-30}) + \delta_{s\text{-}precip}(P_s/P_{year\ 1961-90} - P_s/P_{year\ 1901-30})$, where $P_s/P_{year} = 1 - P_w/P_{year}$. This equation is derived from the amount-weighted means for two different time periods. Only the influence of changing seasonality of precipitation is considered, neglecting possible shifts in $\delta_{w\text{-}precip}$ and $\delta_{s\text{-}precip}$. There is a highly significant correlation between $\Delta\delta_{precip}$ and $\Delta\delta_{tree\text{-}ring}$ ($r^2 = 0.98$; $p < 0.01$).

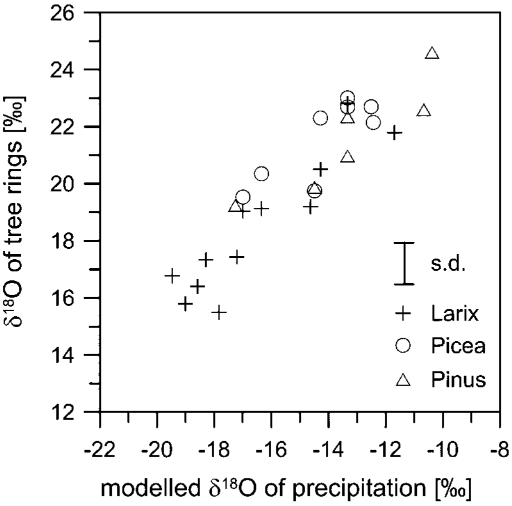

Figure 2. Correlation of GCM-calculated oxygen isotope data of precipitation [*Hoffmann et al.*, 1998] with tree ring isotope values of 1961–90. The precipitation values are weighted annual means of the steady-state present-day model run provided at a grid resolution of 3.75° × 3.75°. The standard deviation (s.d.) indicates the average tree-to-tree variability within a site.

reflect the isotopic composition of precipitation, although a humidity signal is superimposed [*Edwards and Fritz*, 1986]. Regarding spatial patterns, the isotope composition of precipitation is decreasing with distance to the coast, denoted as continentality effect [*Rozanski et al.*, 1993]. Based on the Raleigh-distillation model, the positive correlation between $\delta^{18}O$ in precipitation and local temperature is due to the ongoing isotopic depletion of cloud water during loss of water, which is assumed to be caused by cooling-driven condensation. Over the continents, the situation is complicated by the water stemming from transpiration, which is relatively enriched [*Gat*, 1980]. Nevertheless, the slope for the spatial correlation between precipitation $\delta^{18}O$ and temperature for northern Eurasia is 0.59‰/°C (isotope precipitation data available eastward up to Irkutsk, 104°E [*IAEA/WMO*, 1998]), almost identical to the value reported by Dansgaard for northern coastal stations.

[6] The tree-ring $\delta^{18}O$ data in this study reflect the continentality effect and are highly correlated to yearly mean isotope composition of precipitation calculated by the ECHAM General Circulation Model [*Hoffmann et al.*, 1998] (Figure 2; $r^2 = 0.84$). Modelled data are used to enlarge the range for $\delta^{18}O$ of precipitation to Siberia. The slope of the regression line is close to unity (0.88 ± 0.08‰/‰), showing that the spatial variations of $\delta^{18}O$ in precipitation are faithfully recorded in the whole wood of the trees. Across the continent there is also a strong gradient in mean annual temperature. Accordingly, the isotope ratios of the trees are closely related to annual temperature ($r^2 = 0.80$, slope = 0.33‰/°C for *Larix*; $r^2 = 0.80$, slope = 0.23‰/°C for *Picea*; $r^2 = 0.87$, slope = 0.31‰/°C for *Pinus*; temperature data used were global climate normals, National Climate Data Center, USA). No correlation to summer temperature, however, was observed (Figure 3). This latter fact might be explained by the relatively long residence time of rainwater in the soil in the permafrost area and thus by the uptake of water by the roots from the whole year rather than summer only. $\delta^{18}O$ of summer precipitation also exhibits a smaller gradient with increasing continentality, consistent with a lower temperature gradient [*Rozanski et al.*, 1993]. The slope for the temperature-tree-ring relation (0.35‰/°C; species pooled) is lower than for the temperature-precipitation relation (0.59‰/°C), indicating a dampening effect. Because of long-term means studied here, this cannot be due to mixing in the soil or use of carbohydrate reserves, but could point to the incorporation of oxygen with a fixed isotope ratio, namely atmospheric O_2 [*Farquhar et al.*, 1998]. Humidity changes might indirectly influence the isotope ratio in the tree rings via leaf water enrichment [*Edwards and Fritz*, 1986]. However, multiple linear regression analysis with temperature and humidity data as variables did not significantly improve the above correlation. This indicates a strong dampening of the isotopic leaf water signal in the stem cellulose, as is also suggested by other recent results [*Saurer et al.*, 1997].

[7] The centennial ^{18}O-decrease in the interior of the continent (Figure 1d) is surprising because the temperature increased since the late 19th century, and even particularly strong at high latitudes in Eurasia [*Jones*, 1994]. Based on the positive (spatial) temperature-isotope-relationship (see above) there seems to be an inconsistency. One has to be cautious, however, when applying spatial calibrations for temporal changes. The small inter-decadal isotope variations may also be related to changes in atmospheric circulation and seasonality [*Jouzel et al.*, 1997]. Indeed, precipitation amount has increased in this area in the 20th century, particularly in winter [*Bradley et al.*, 1987]. This effect could lower the amount-weighted annual mean of the $^{18}O/^{16}O$ ratio because in winter the heavy isotope is strongly depleted (Table 1). We calculated the effect of the changing seasonality in the 20th century for the regions 0–60°E, 60–120°E and 120–180°E, using a combination of climatic and GCM-calculated isotope data (Table 1). We found no effect of the changing seasonality on the isotopes in the eastern range, a moderate decrease in the 120°–180° range, whereas the strongest effect is found in the interior of the continent. Although small, these calculated changes correspond well with the measured changes in the tree rings, both regarding the regional differences and the sign and magnitude of the shift (considering also that precipitation measurements from 1901–30 were used because reliable precipitation data for the period 1861–90 were not available in this area). From the isotope data alone, we can only calculate the fraction of winter precipitation to whole-year precipitation, while assuming that there were no major changes in the summer precipitation. However, the presented evidence including climate data strongly supports the view that the observed $^{18}O/^{16}O$-decrease in the tree rings is related to the increase of winter precipitation. Based on the measured isotope change of 0.4‰, we estimate the contribution of wintertime precipitation to whole year precipitation to have increased from 32% in 1861–90 to 36% in 1961–90 in the 60°–120° longitude band. This finding is supported by the result

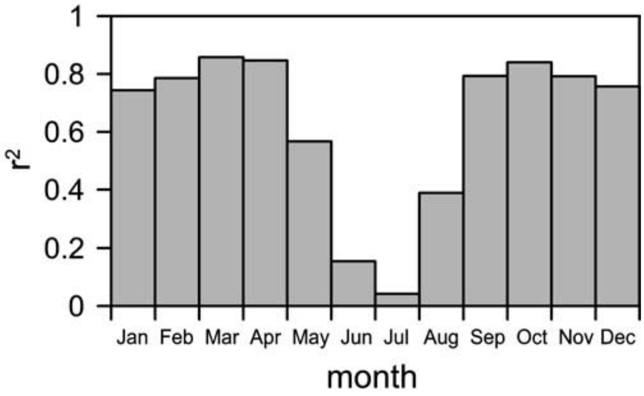

Figure 3. Squared correlation coefficient (r^2) for the correlation between tree ring $\delta^{18}O$ and monthly values of temperature. For this analysis the 1961–90 isotope values (all species pooled) were correlated to the 1961–90 global climate normals (National Climate Data Center, USA).

that tree growth in permafrost areas with increasing winter precipitation is hampered by the delayed snow melt and subsequent delayed initiation of cambial activity [*Vaganov et al.*, 1999].

[8] The relatively low δ^{18}O in recent decades may not only be related to increasing winter precipitation but also to the observed strengthening of the Arctic oscillation, which results in more frequent than average Westerlies carrying moisture into the Eurasian continent in winter [*Thompson and Wallace*, 1998]. Mapping of δ^{18}O in this area may therefore be a unique tool for the reconstruction of past long-term variations in the Arctic oscillation. Global climate change has a significant impact on the hydrological cycle, possibly resulting in long-term changes of humidity, and oxygen isotopes may be one of the few proxy parameters enabling us to document such changes over the last centuries. Biological factors cannot completely be ruled out influencing the oxygen isotope ratios in the trees, for instance ageing effects, although grouping of trees into different age classes did not affect the results. The highly significant correlation with modelled δ^{18}O of precipitation, the similarity of the results for different species - these are all facts strengthening the approach of oxygen isotopes in wood of trees as a reliable proxy for the large scale-mapping of past variations of δ^{18}O in precipitation.

[9] **Acknowledgments.** We would like to thank Theo Forster for helping in tree ring preparation and Georg Hoffmann for making available his numerical experiments on global isotope distribution of precipitation.

References

Barbour, M. M., T. J. Andrews, and G. D. Farquhar, Correlations between oxygen isotope ratios of wood constituents of *Quercus* and *Pinus* samples from around the world, *Australian Journal of Plant Physiology*, *28*, 335–348, 2001.

Bradley, R. S., H. F. Diaz, J. K. Eischeid, P. D. Jones, P. M. Kelly, and C. M. Goodess, Precipitation fluctuations over Northern Hemisphere land areas since the mid-19th century, *Science*, *237*, 171–175, 1987.

Briffa, K. R., F. H. Schweingruber, P. D. Jones, T. J. Osborn, S. G. Shiyatov, and E. A. Vaganov, Reduced sensitivity of recent tree-growth to temperature at high northern latitudes, *Nature*, *391*, 678–682, 1998.

Burk, R. L., and M. Stuiver, Oxygen isotope ratios in trees reflect mean annual temperature and humidity, *Science*, *211*, 1417–1419, 1981.

Dansgaard, W., Stable isotopes in precipitation, *Tellus*, *16*, 436–468, 1964.

Edwards, T. W. D., and P. Fritz, Assessing meteoric water composition and relative humidity from ^{18}O and ^{2}H in wood cellulose; paleoclimatic implications for southern Ontario, Canada, *Applied Geochemistry*, *1*, 715–723, 1986.

Farquhar, G. D., M. M. Barbour, and B. K. Henry, Interpretation of oxygen isotope composition of leaf material, in *Stable Isotopes, Integration of Biological, Ecological and Geochemical Processes*, edited by H. Griffiths, pp. 27–62, Bios Scientific Publishers, Oxford, 1998.

Gat, J. R., The isotopes of hydrogen and oxygen in precipitation, in *Handbook of Environmental Isotope Geochemistry*, edited by P. F. Fritz, and J. Ch., pp. 21–47, Elsevier, Amsterdam, Oxford, New York, 1980.

Hoffmann, G., M. Werner, and M. Heimann, Water isotope module of the ECHAM atmospheric general circulation model: A study on timescales from days to several years, *Journal of Geophysical Research Atmospheres*, *103*, 16,871–16,896, 1998.

Hulme, M., T. J. Osborn, and T. C. Johns, Precipitation sensitivity to global warming: Comparison of observations with HadCM2 simulations, *Geophysical Research Letters*, *25*, 3379–3382, 1998.

IAEA/WMO, *Global Network for Isotopes in Precipitation GNIP Database*, Int. Atomic Energy Agency, 1998.

Jones, P. D., Hemispheric surface air temperature variations: A reanalysis and an update to 1993, *Journal of Climate*, *7*, 1794–1802, 1994.

Jouzel, J., R. B. Alley, K. M. Cuffey, W. Dansgaard, P. Grootes, G. Hoffmann, S. J. Johnsen, R. D. Koster, D. Peel, C. A. Shuman, M. Stievenard, M. Stuiver, and J. White, Validity of the temperature reconstruction from water isotopes in ice cores, *Journal of Geophysical Research Oceans*, *102*, 26,471–26,487, 1997.

Overpeck, J., K. Hughen, D. Hardy, R. Bradley, R. Case, M. Douglas, B. Finney, K. Gajewski, G. Jacoby, A. Jennings, S. Lamoureux, A. Lasca, G. MacDonald, J. Moore, M. Retelle, S. Smith, A. Wolfe, and G. Zielinski, Arctic environmental change of the last four centuries, *Science*, *278*, 1251–1256, 1997.

Robertson, I., J. S. Waterhouse, A. C. Barker, A. H. C. Carter, and V. R. Switsur, Oxygen isotope ratios of oak in east England: Implications for reconstructing the isotopic composition of precipitation, *Earth and Planetary Science Letters*, *191*, 21–31, 2001.

Roden, J. S., and J. R. Ehleringer, Hydrogen and oxygen isotope ratios of tree-ring cellulose for riparian trees grown long-term under hydroponically controlled environments, *Oecologia*, *121*, 467–477, 1999.

Rozanski, K., L. Araguas, and R. Gonfiantini, Isotopic patterns in modern global precipitation, *Geophysical Monograph*, *78*, 1–36, 1993.

Saurer, M., K. Aellen, and R. Siegwolf, Correlating δ^{13}C and δ^{18}O in cellulose of trees, *Plant Cell and Environment*, *20*, 1543–1550, 1997.

Saurer, M., P. Cherubini, and R. Siegwolf, Oxygen isotopes in tree rings of *Abies alba*: The climatic significance of interdecadal variations, *Journal of Geophysical Research Atmospheres*, *105*, 12,461–12,470, 2000.

Saurer, M., I. Robertson, R. Siegwolf, and M. Leuenberger, Oxygen isotope analysis of cellulose: An interlaboratory comparison, *Analytical Chemistry*, *70*, 2074–2080, 1998.

Schweingruber, F. H., Dendrochronological sampling strategies for radiodensitometric networks in northern hemisphere subalpine and boreal zones, in *Paläoklimaforschung 9*, edited by B. Frenzel, pp. 205–209, Fischer, G., New York, 1993.

Thompson, D. W. J., and J. M. Wallace, The Arctic Oscillation signature in the wintertime geopotential height and temperature fields, *Geophysical Research Letters*, *25*, 1297–1300, 1998.

Vaganov, E. A., M. K. Hughes, A. V. Kirdyanov, F. H. Schweingruber, and P. P. Silkin, Influence of snowfall and melt timing on tree growth in subarctic Eurasia, *Nature*, *400*, 149–151, 1999.

M. Saurer and R. Siegwolf, Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland. (matthias.saurer@psi.ch)

F. Schweingruber, Swiss Federal Research Institute WSL, CH-8903 Birmensdorf, Switzerland.

E. A. Vaganov, Institute of Forest, Siberian Branch of the Russian Academy of Science, Krasnoyarsk 660036, Russia.

S. G. Shiyatov, Institute of Plant and Animal Ecology, Ural Branch of the Russian Academy of Science, Ekaterinburg 620219, Russia.