JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, G02019, doi:10.1029/2007JG000473, 2008

Isotopic composition (δ^{13}C, δ^{18}O) in wood and cellulose of Siberian larch trees for early Medieval and recent periods

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Received 26 April 2007; revised 4 December 2007; accepted 11 February 2008; published 6 May 2008.

[1] We related tree ring width (TRW) and isotopic composition (δ^{13}C, δ^{18}O) of wood and cellulose from four larch trees (*Larix cajanderi* Mayr.) to climate parameters. The material was sampled in northeastern Yakutia [70°N–148°E] for the recent (AD 1880–2004) and early Medieval (AD 900–1000) periods. During the recent period June, July, and August air temperatures were positively correlated with δ^{13}C and δ^{18}O of wood and cellulose, while July precipitation was negatively correlated. Furthermore, the vapor pressure deficit (VPD) of July and August was significantly correlated with δ^{13}C of wood and cellulose, but VPD had almost no influence on δ^{18}O. Comparative analyses between mean isotope values for the (AD 900–1000) and (AD 1880–2004) periods indicate similar ranges of climatic conditions, with the exception of the period AD 1950–2004. While isotopic ratios in cellulose are reliably related to climatic variables, during some periods those in whole wood showed even stronger relationships. Strong positive correlations between δ^{18}O of cellulose and Greenland ice-core (GISP2) data were detected for the beginning of the Medieval period ($r = 0.86$; $p < 0.05$), indicating the reliability of isotope signals in tree rings for large-scale reconstructions.

Citation: Sidorova, O. V., R. T. W. Siegwolf, M. Saurer, M. M. Naurzbaev, and E. A. Vaganov (2008), Isotopic composition (δ^{13}C, δ^{18}O) in wood and cellulose of Siberian larch trees for early Medieval and recent periods, *J. Geophys. Res.*, *113*, G02019, doi:10.1029/2007JG000473.

1. Introduction

[2] Mean Northern Hemisphere temperatures are reported to be rising over the last 100 years, especially in the last decade, when changes have been particularly marked at high latitudes [*IPCC*, 2001, 2007; *Bradley*, 2000; *Brohan et al.*, 2006]. This is highly relevant for Siberian forest ecosystems because of their sensitivity to both climate change and the potential direct effects on tree physiology caused by a change of the atmospheric concentration of carbon dioxide [*Vaganov and Shiyatov*, 1999; *Körner*, 2000; *IPCC*, 2001, 2007]. Thawing of permafrost, which characterizes most of these high latitude regions (playing a key role in stabilizing the climatic system) [*Pozdnyakov*, 1983], would drastically change the energy and water balance, and as a consequence shift the tree-line further north.

[3] A variety of natural archives contain temperature proxy records in Arctic and Subarctic regions. They have different temporal resolutions and cover a variety of time-scales. Annual layers are well defined in tree rings, ice cores and lake sediments [*Fritts*, 1976; *Bradley*, 1999; *Alley*, 2000]. Of these proxies, tree ring chronologies are the most reliable and precise (annual and seasonal resolution), providing distinct quantitative archives for studies on climatic variability on inter-annual to multi-centennial time scales throughout the last few millennia.

[4] The remains of dead trees (exceeding 1000 years in lifespan) from Eurasian forests, preserved in the permafrost, allow the development of tree ring chronologies for much of the Holocene [*Schweingruber*, 1996; *Vaganov et al.*, 2000; *Sidorova et al.*, 2005a, 2005b]. These studies improve our knowledge about climate change in the past and help us to place the recent dramatic temperature increase at the global scale in a longer perspective. However, the problem of long-term climate change is directly linked with multiple responses of woody plants to natural and anthropogenic environmental variability and changes (e.g. increasing amounts of greenhouse gases). Thus it is difficult to extract pure and unbiased climatic information from tree rings or any other archive based on biological systems, in particular regarding the low-frequency variations [*Bradley*, 2000; *Briffa et al.*, 2001; *Esper et al.*, 2002].

[5] The use of stable isotopes can potentially help to distinguish long-term climatic changes. Stable isotopes in tree rings provide an additional proxy for paleoclimate reconstruction with the same precise annual resolution and statistically defined confidence limits around mean values, as in hundreds of records based on ring width and maximum latewood density [*Hughes*, 2002]. These can be translated into confidence intervals around quantitative paleoclimate estimates [*McCarroll and Loader*, 2004]. Few stable isotope studies have been carried out for the northern boreal forests [*Barber et al.*, 2000; *Arneth et al.*, 2002; *Kagawa et al.*,

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a)

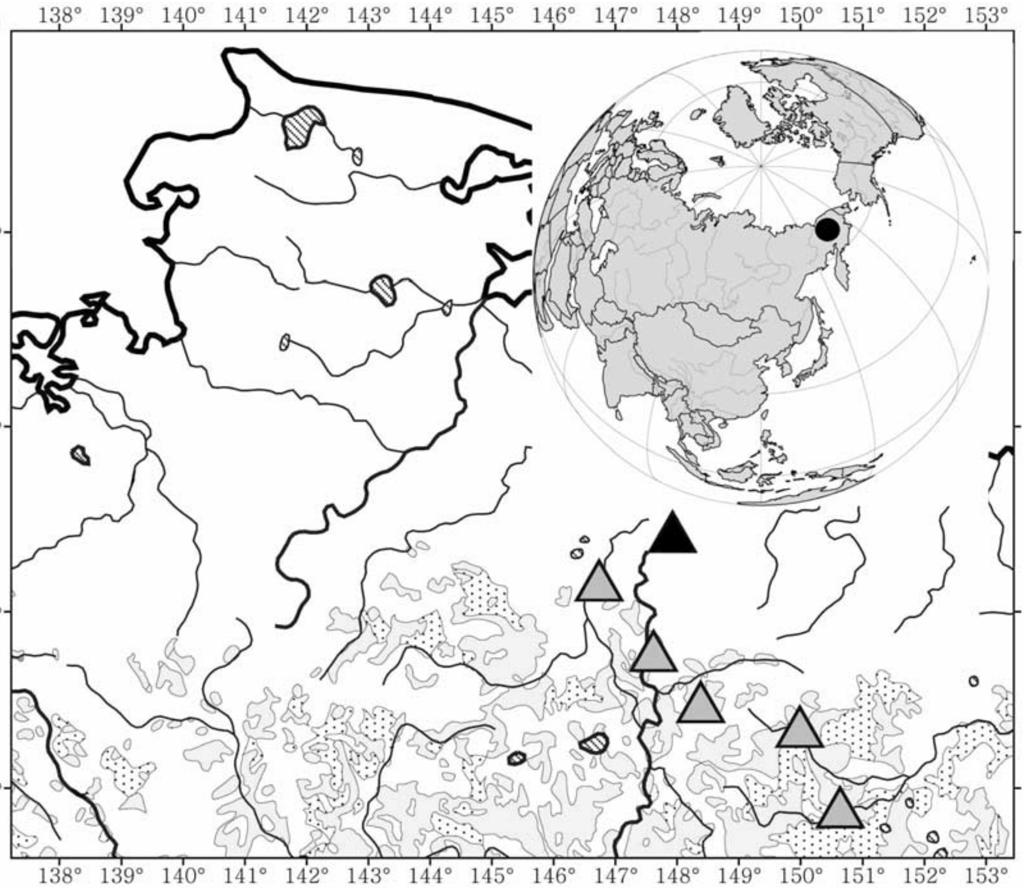

Figure 1. (a) Map with locations of living and dead wood samples from Northeastern Yakutia. Triangles indicate locations of wood samples for the dendrochronological (grey triangle) and isotope (black triangle) studies. The black circle is the location of Northeastern Yakutia on the scheme map. (b) The oldest living and (c) dead larch (*Larix cajanderi* Mayr.) trees from Northeastern Yakutia. Photo A. A. Nikolaev (b) and M. M. Naurzbaev (c).

2003; *Saurer et al.*, 2004; *Schulze et al.*, 2004; *Nikolaev et al.*, 2006]. Studies in subarctic regions have primarily been conducted for carbon ($\delta^{13}C$) [*Kagawa et al.*, 2003; *Nikolaev et al.*, 2006] and rarely for oxygen $\delta^{18}O$ [*Saurer et al.*, 2004]. The $\delta^{13}C$ and $\delta^{18}O$ parameters are sensitive "long-term monitors" of physiological changes, and may preserve information on past temperature and precipitation variations [*McCarroll and Loader*, 2004; *Leng*, 2006]. Plants respond to limited water resources by reducing stomatal conductance (under low precipitation and relatively warm and dry conditions), resulting in a diminished intercellular CO_2 concentration. This leads to reduced ^{13}C discrimination, resulting in less negative $\delta^{13}C$ [*Farquhar et al.*, 1989] and increased $\delta^{18}O$ values [*Farquhar and Lloyd*, 1993]. Often this goes along with improved water use efficiency [*Saurer et al.*, 2004; *Saurer and Siegwolf*, 2007]. Oxygen isotopes in tree rings are mainly influenced by the isotope signal in precipitation (which is also influenced by temperature) [*Craig*, 1961], which represents the source water for trees. Enrichment in $\delta^{18}O$ occurs in the leaf during transpiration, which may be enhanced under drought conditions [*Yakir and Sternberg*, 2000]. A mixed signal of source and leaf water enrichment is finally stored in the wood and cellulose of the tree rings [*Saurer et al.*, 1997; *Roden and Ehleringer*, 2000].

[6] In most dendrochronological isotope studies cellulose extracted from wood samples is used to determine the C and O isotope ratios in tree rings. Wood is a composite of various constituents with different isotopic ratios. The relative amounts of these constituents can vary and thus add to the isotopic variability, yielding a signal, that is not necessarily directly related to climatic parameters [*Wilson and Grinsted*, 1977]. Cellulose is the most abundant compound in wood and easiest to extract. Therefore most studies have concentrated on the analysis of cellulose, assuming that the isotopic signal will contain the most representative climate information. Here, however, we analyze cellulose and whole-wood, since important climatic information may be contained in both.

[7] In this paper we focused our attention on two periods (AD 1880–2004 and AD 900–1000), analyzing tree ring width and isotopic composition ($\delta^{13}C$, $\delta^{18}O$) for larch trees from close to the northern tree-line in Eastern Siberia.

[8] These periods are of particular interest because the current period from AD 1880–2004 is strongly characterized by increasing anthropogenic influences (changes in the atmospheric composition, an increased intensity of land use, changing climate, and seasonality), while during the early Medieval period, human impact was negligible. Our aim in this paper is to explore the value of using isotopic ratios

b)

c)

Figure 1. (continued)

from tree rings to compare environmental conditions during the two periods, one since the industrial revolution, and the other well before it.

2. Material and Methods

[9] Research was conducted in Northeastern Yakutia, near At-Khaya Mountain [70°N–148°E] (Figure 1a). Disc and core samples from larch (*Larix cajanderi* Mayr.) were collected at the upper timber line in the forest tundra of the central Indigirka Lowlands at 200–350 m a.s.l. The oldest living and dead trees growing at this site reach record ages for the boreal zone of 945 (Figure 1b) and 1216 years (Figure 1c), respectively [*Vaganov et al.*, 2000; *Sidorova et al.*, 2005a].

[10] Northeastern Yakutia is a unique region, characterized by low annual precipitation (170 mm/year) compared with central Yakutia (236 mm/year) [*Pozdnyakov*, 1983; *Kagawa et al.*, 2003]. Tree ring growth in Northeastern Yakutia is strongly limited by the temperature regime [*Hughes et al.*, 1999; *Sidorova and Naurzbaev*, 2002, *Sidorova*, 2003]. It is reasonable to assume that tree ring characteristics and their isotope (δ^{13}C, δ^{18}O) composition might reflect indicators for changes in both temperature and the moisture regime in this region [*Dansgaard*, 1964; *Saurer et al.*, 2002].

[11] The mean air temperature for January ranges from −34°C to −38°C, and for July from +9°C to +15°C. The duration of the winter season is about 8 months (from the end of September / early October to the middle of May), with a very short growing season of between 50 and 70 days [*Abaimov et al.*, 1997]. The land surface is characterized by permafrost. The depth of seasonal thawing is not more than 20 to 30 cm, resulting in low activity of soil forming processes. Soil temperature at the end of June in northeastern Yakutia is still below the freezing point at a depth of 20 cm, but increases in July; whereas the soil temperature in central Yakutia is already positive by the end of May [*Pozdnyakov*, 1983].

[12] Monthly and daily meteorological data (temperature and precipitation) are available for AD 1945–1989 within 200 km of the isotope study site (Chokurdach weather station: 70°62′N, 147°88′, 61 m) and gridded data sets (resolution 5° × 5°) are available at monthly resolution for the extended area (65°N–150°E) from AD 1901–2003 [*New et al.*, 1998] (Climatic Research Unit, UEA, Norwich, UK; CRU 05, http://www.cru.uea.ac.uk). The two data sets are strongly correlated (r = 0.93, p < 0.005) over the common period AD 1945–1989. Five-day averages of air temperature from Chokurdach were used for detailed analysis, and gridded data for monthly comparisons with isotope chronologies.

[13] The vapor pressure deficit (VPD) was calculated, assuming that $T_{dew} = a + bT_{min}$, (where *a* and *b* were calculated using available daily data for relative humidity from the Chokurdach weather station (AD1948–1989). "T_{dew}" is the dew point temperature and "T_{min}" the minimum air temperature) [*Murray*, 1967].

2.1. Dendrochronological Data

[14] A well-replicated chronology based on ring width measurements was used for the period AD 1400–1994 [*Hughes et al.*, 1999; *Sidorova*, 2003]. *Hughes et al.* [1999] reported a strong early summer temperature signal in the ring-width chronology. It accounts for more than 60% of the early summer temperature variance for the period AD 1945–1989, capturing interdecadal as well as interannual variability (Calibration R^2 was 0.62 (F = 71.2, p < 0.0001) and $R^2_{prediction} = 0.60$).

2.2. Isotope Data

[15] For the period AD 1945–2004 the δ^{13}C and δ^{18}O isotope ratios were analyzed for four individual trees. However, small sample size resulted in the need to pool material (milling each annual ring from four trees together) for the periods AD 1880–1944 and AD 900–1000. The trees used for isotopic analysis were between 452–524 years old. The 80 rings closest to pith were not analyzed, thus excluding any juvenile effect for the analyzed periods.

[16] A Soxhlet apparatus was used to extract resin from the wood samples over 36-hour period using ethanol. Samples were then washed in distilled water and air dried [*Lenz et al.*, 1976; *Cook and Kairiukstis*, 1990]. The whole wood samples were milled to a fine powder and weighed into tin capsules for analysis (0.6–0.8 mg for ^{13}C/^{12}C and 1.1–1.3 mg for ^{18}O/^{16}O). For cellulose extraction, another sub-sample of the whole wood was enclosed in filter bags (F57, Ankom Technology, NY, USA) and washed twice for 2 h in 5% NaOH to remove remaining lipids, resins and hemicellulose. A 7% $NaClO_2$ treatment was then performed for 36 hours to remove the lignin, according to the method described in *Loader et al.* [1997]. The packets were dried for 24 h at 50°C. The resulting alpha-cellulose was weighed into tin capsules for measurement in the mass spectrometer.

[17] The isotope ratios (δ^{13}C and δ^{18}O) were determined on cellulose and whole wood using a delta-S mass spectrometer (Finnigan MAT, Bremen, Germany) linked with an elemental analyzer (EA-1108, and EA-1110 Carlo Erba, Italy) at the Paul Scherer Institute, Villigen, Switzerland. The δ^{13}C was determined by combustion under excess oxygen at 1020°C, whilst samples for δ^{18}O measurement were pyrolysed to CO at 1080°C [*Saurer et al.*, 1998] in the continuous flow mode. This guarantees a high sample throughput rate with good precision for δ^{13}C (σ ± 0.1‰) and δ^{18}O (σ ± 0.2‰). The isotopic values were expressed in the delta notation relative to the international standards:

$$\delta_{sample} = \left(R_{sample}/R_{standard} - 1\right) \times 1000,$$

where R_{sample} is the molar fraction of ^{13}C/^{12}C, or ^{18}O/^{16}O ratio of the sample and $R_{standard}$, of the standards VPDB for carbon and VSMOW for oxygen.

[18] The δ^{13}C data of wood and cellulose were corrected for the Suess effect (decline of the ^{13}C/^{12}C ratio of atmospheric CO_2) using δ^{13}C values of atmospheric CO_2 obtained from South Pole ice core and the Mauna Loa Observatory, Hawaii [*Francey et al.*, 1999] (http://www.cmdl.noaa.gov./info/ftpdata.html). This correction is necessary because the emission from fossil fuel combustion and biomass burning have both resulted in decreasing δ^{13}C of atmospheric CO_2. Data from records before AD 1800 (in this case, the Medieval period) were not corrected.

[19] The δ^{18}O ice core data (GISP2 – Greenland Ice Sheet Project 2) were obtained from the web site ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/greenland/summit/gisp2/isotopes/d18o1yr.

3. Results

3.1. Isotopic Values of Individual Trees and Recent Period

[20] Figures 2a–2d show the δ^{13}C and δ^{18}O isotope ratios of wood and cellulose. For the period AD 1945–2004 four trees were analyzed separately. We found stronger relationships between the four trees for δ^{13}C than for δ^{18}O. The range of the correlation coefficients between the four series of δ^{13}C in whole wood is r = 0.56 − 0.83 (p < 0.05) and only slightly lower for cellulose r = 0.51 − 0.79 (p < 0.05) (Figures 2a and 2b). δ^{18}O correlation coefficients between

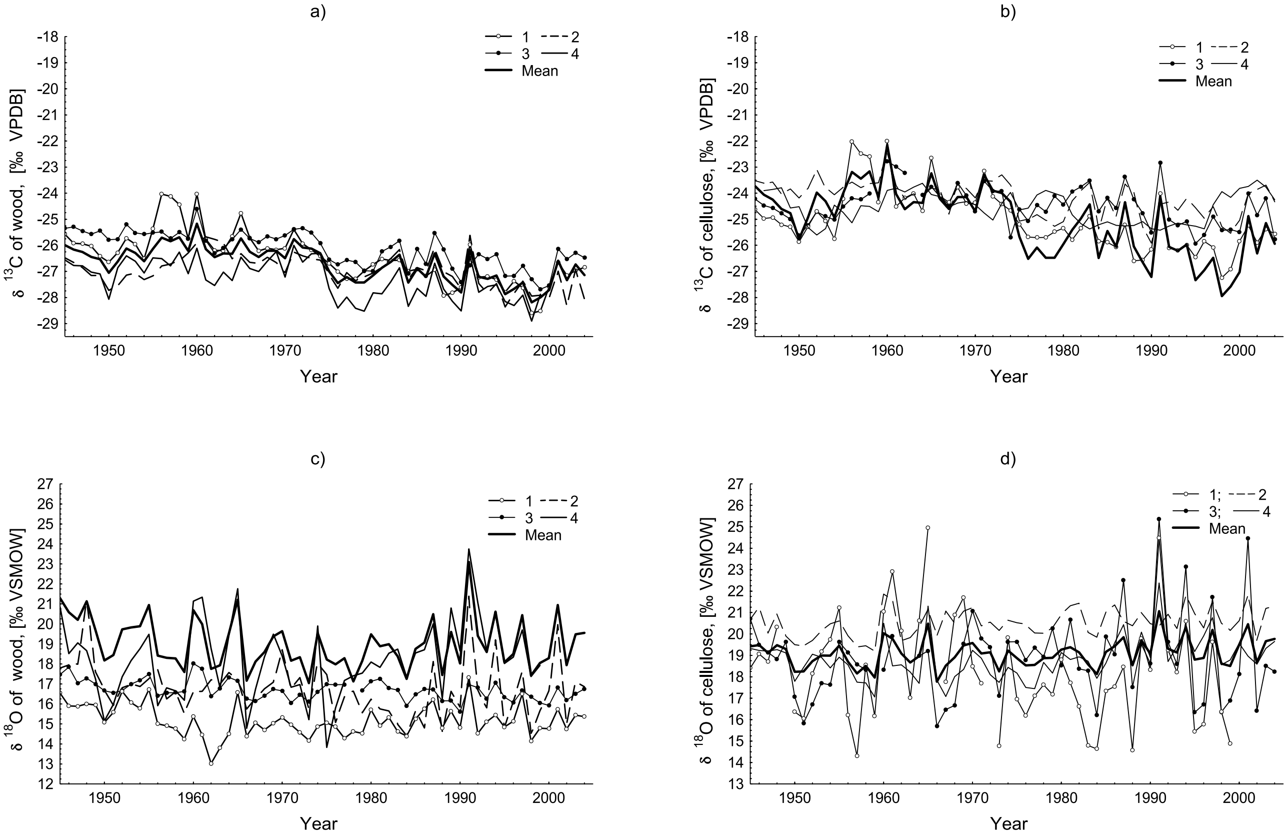

Figure 2. The δ^{13}C of wood (a) and cellulose (b), and the δ^{18}O of wood (c) and cellulose (d) series for four individual trees, as well as their mean series are presented for the period AD 1945–2004.

the four individual trees are lower than for δ^{13}C, yielding $r = 0.40 - 0.56$ ($p < 0.05$) for cellulose and $r = 0.30 - 0.65$ ($p < 0.05$) for wood (Figures 2c and 2d). Especially good statistical correlations between the four trees were observed for the period AD 1990–2004. Results for both whole wood and cellulose show that δ^{13}C values exhibit lower inter-annual variability than those of δ^{18}O. After combining the periods AD 1945–2004 (single tree analysis) and 1880–1944 (pooled analysis), the average δ^{13}C of wood and cellulose was corrected for the Suess effect (declining δ^{13}C

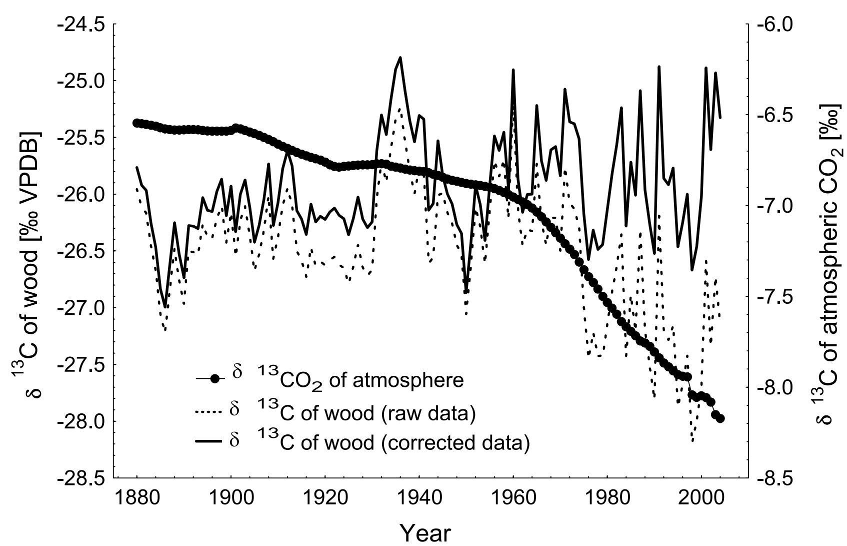

Figure 3. The raw and corrected δ^{13}C series for wood. The series was corrected using δ^{13}C of atmospheric CO_2 obtained from the South Pole ice core, and from the Mauna Loa Observatory data, Hawaii [*Francey et al.*, 1999] (http://www.cmdl.noaa.gov./info/ftpdata.html).

Table 1. Mean Values of $\delta^{13}C$ and $\delta^{18}O$ of Wood and Cellulose

Periods	$\delta^{13}C$ of Wood	$\delta^{13}C$ of Cellulose	$\delta^{18}O$ of Wood	$\delta^{18}O$ of Cellulose
1904–1954	−25.95	−24.30	15.95	18.98
1954–2004	−25.82	−23.82	15.15	19.14
1904–2004	**−25.88**	**−24.05**	**15.55**	**19.06**
900–950	−25.72	−24.31	15.57	18.55
950–1000	−25.86	−24.36	15.64	19.07
900–1000	**−25.79**	**−24.34**	**15.61**	**18.82**

of atmospheric CO_2 over the last 200 years) [*Francey et al.*, 1999]. Figure 3 presents the corrected and uncorrected (raw) data. The decrease of $\delta^{13}C$ in organic matter can be explained by the decrease in $\delta^{13}C$ of atmospheric CO_2, a result of fossil-fuel combustion, large scale biomass burning (in the tropical forests), and land-use changes. The data show a slightly positive trend after the correction.

3.2. Isotope Values in the Medieval and Recent Periods

[21] We calculated the mean values of the carbon and oxygen isotope chronologies for both whole wood and cellulose chronologies for the periods AD 1904–2004 and AD 900–1000. These periods were divided into 50 year sub-periods (Table 1). Comparative analyses between mean isotope values during the Medieval period for AD 900–950 and AD 950–1000 show small differences between the $\delta^{13}C$ of wood and cellulose (0.14‰ and 0.05‰ respectively), and larger differences for $\delta^{18}O$ of cellulose (0.52‰). Comparison of the mean isotope values for the periods AD 1904–1954 and AD 1954–2004 revealed a difference of 0.13‰ for the $\delta^{13}C$ of whole wood and 0.48‰ for the $\delta^{13}C$ of cellulose. Differences in $\delta^{18}O$ values between the same periods were 0.80‰ for whole wood and 0.16‰ for cellulose. The comparative analyses of the mean isotope values ($\delta^{13}C$, $\delta^{18}O$ of whole wood and cellulose) between recent (AD 1904–2004) and Medieval (AD 900–1000) periods show substantial overlaps (Table 1).

3.3. Comparison of Wood and Cellulose

[22] To investigate the similarity of the isotope signals in wood and cellulose, we performed a correlation analysis between whole wood and cellulose values for the current period (AD 1904–2004) and for the beginning of the Medieval Period (AD 900–1000), showing that the wood and cellulose curves have broadly similar trends (Figures 4a–4d and Table 2). However, there are significant differences between wood and cellulose for the two isotope chronologies. These differences are not constant over time. Between AD 1904–2004 $\delta^{13}C$ of wood and cellulose exhibit a relative offset of 2‰ and are highly correlated ($r = 0.92$; $p < 0.05$), demonstrating a common signal response in both materials, which may be explained by increased atmospheric CO_2 concentration (Figure 4a) (Table 2). The $\delta^{13}C$ curves of wood and cellulose obtained for the beginning of the Medieval Period (AD 900–1000) (Figure 4b) have likewise a high correlation ($r = 0.85$; $p < 0.05$) but with smaller differences (1.45 ‰) between the two materials (see Table 2, column 2). For the period from AD 950–1000 there was a higher correlation coefficient between

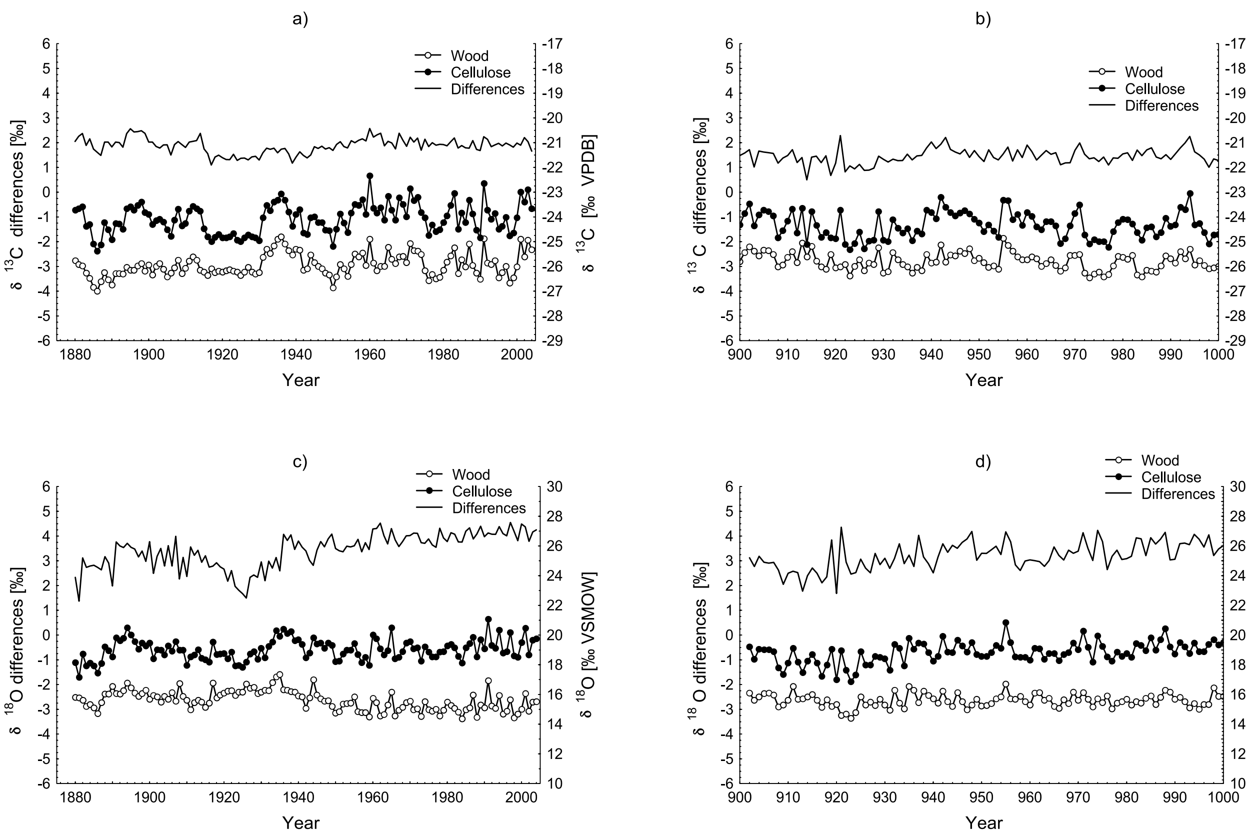

Figure 4. Comparison of wood and cellulose $\delta^{13}C$ and $\delta^{18}O$ chronologies for the period AD 1880–2004, (a, c) and AD 900–1000 (b, d).

Table 2. Correlation Coefficients and Differences Between Wood and Cellulose for the δ^{13}C and δ^{18}O Chronologies[a]

Period	Correlation Coefficient Between δ^{13}C of Wood and Cellulose	Differences Between δ^{13}C of Wood and Cellulose, ‰	Correlation Coefficient Between δ^{18}O of Wood and Cellulose	Differences Between δ^{18}O of Wood and Cellulose, ‰
1904–2004	**0.92**	**1.83**	**0.63**	**3.51**
1954–2004	0.97	1.99	0.92	3.99
1904–1954	0.88	1.83	0.56	3.51
900–1000	**0.85**	**1.45**	**0.72**	**3.21**
950–1000	0.91	1.50	0.78	3.43
900–950	0.80	1.41	0.68	2.97

[a]Level of significance: $p < 0.05$.

δ^{13}C of wood and cellulose ($r = 0.91$; $p < 0.05$) than for AD 900–950 ($r = 0.80$; $p < 0.05$). The largest differences (3.99‰) were observed between δ^{18}O of whole wood and cellulose for the most recent period (AD 1954–2004). The δ^{18}O values for the Medieval period (AD 950–1000) were lower (3.43‰) (Figures 4c and 4d and Table 2).

3.4. Correlation Analysis Between Climatological and Isotope Data

[23] A correlation analysis was carried out between δ^{13}C and δ^{18}O of whole wood and cellulose, and monthly values of climatic parameters (temperature, precipitation) for the period AD 1901–2003 as well as for approximately 50-year sub-periods (Table 3). Positive correlation coefficients were found between July and August air temperature and δ^{13}C of wood ($r = 0.58$; $r = 0.37$; $p < 0.05$) and cellulose ($r = 0.49$; $r = 0.26$; $p < 0.05$), whilst negative relationships occurred between δ^{13}C of both parameters and July precipitation ($r = -0.21$; $p < 0.05$) (Table 3). June temperature shows moderate correlations with δ^{13}C of wood and δ^{18}O of wood and cellulose for AD 1901–1953.

[24] Regarding the oxygen isotopes, we found that July and August air temperature positively correlated with δ^{18}O of cellulose. The relationships between δ^{18}O of wood, cellulose and air temperature were highest in July ($r = 0.45$ and $r = 0.40$; $p < 0.05$, respectively) for the period from AD 1953–2003 (Table 3). Significant negative correlations between δ^{18}O of cellulose and July precipitation (up to $r = -0.36$; $p < 0.05$) were found. However, a significant correlation between precipitation and δ^{18}O of whole wood was only observed for the last 50 years.

3.5. Correlation Analysis Using Pentad Temperatures

[25] For a more detailed analysis we have calculated the correlation coefficients between pentad temperatures (5 day average groups) and isotope data (Figures 5a and 5b) for AD 1948–1989 (Chokurdach weather station).

[26] We found the highest significant correlation coefficients between early July (2–6) air temperature and the δ^{13}C of wood and cellulose ($r = 0.54$ and $r = 0.50$; $p < 0.05$, respectively) (Figures 5a and 5b).

[27] The δ^{13}C values of whole wood and cellulose have almost identical patterns of relationships with summer pentad air temperatures, with only a slight influence of temperature in late July and early August. In our previous studies we found that tree ring width showed significant relationships with pentad temperatures from June 6–July 17 [*Hughes et al.*, 1999; *Sidorova and Naurzbaev*, 2002; *Sidorova*, 2003].

3.6. Vapor Pressure Deficit and Isotope Values (Modeled and Measured)

[28] The correlation analysis between vapor pressure deficit (VPD) from May to September and δ^{13}C and δ^{18}O of wood and cellulose showed significant positive correlations for July ($r = 0.69$ and $r = 0.68$; $p < 0.05$) and August ($r = 0.31$ and $r = 0.32$; $p < 0.05$) (Table 3). Correlation coefficients between carbon and oxygen isotopes in wood and cellulose, and August air temperature were not significant for the last 50 years, but a significant relationship with VPD was observed. This suggests that in August the influence of relative humidity was stronger than temperature. For δ^{18}O, a positive correlation coefficient between cellulose and VPD in July ($r = 0.31$; $p <$

Table 3. Statistically Significant Correlation Coefficients Between Isotope and Climatological Data[a]

		Correlation Coefficient						
Isotope Data	Period	Temperature of February	Temperature of June	Temperature of July	Temperature of August	Precipitation of July	VPD of July	VPD of August
δ^{13}C of wood	**1901–2003**		0.22	0.58	0.37	−0.21		
	1901–1953		0.45	0.60	0.60			
	1953–2003			0.58			0.69	0.31
δ^{13}C of cellulose	**1901–2003**			0.49	0.26	−0.21		
	1901–1953			0.46	0.41			
	1953–2003			0.57			0.68	0.32
δ^{18}O of wood	**1901–2003**			0.35	0.33			
	1901–1953		0.42	0.44	0.51			
	1953–2003			0.45		−0.31		
δ^{18}O of cellulose	**1901–2003**	0.21		0.37		−0.32		
	1901–1953	0.30	0.30	0.33	0.34	−0.30		
	1953–2003	0.20		0.40		−0.36	0.31	

[a]Level of significance: $p < 0.05$.

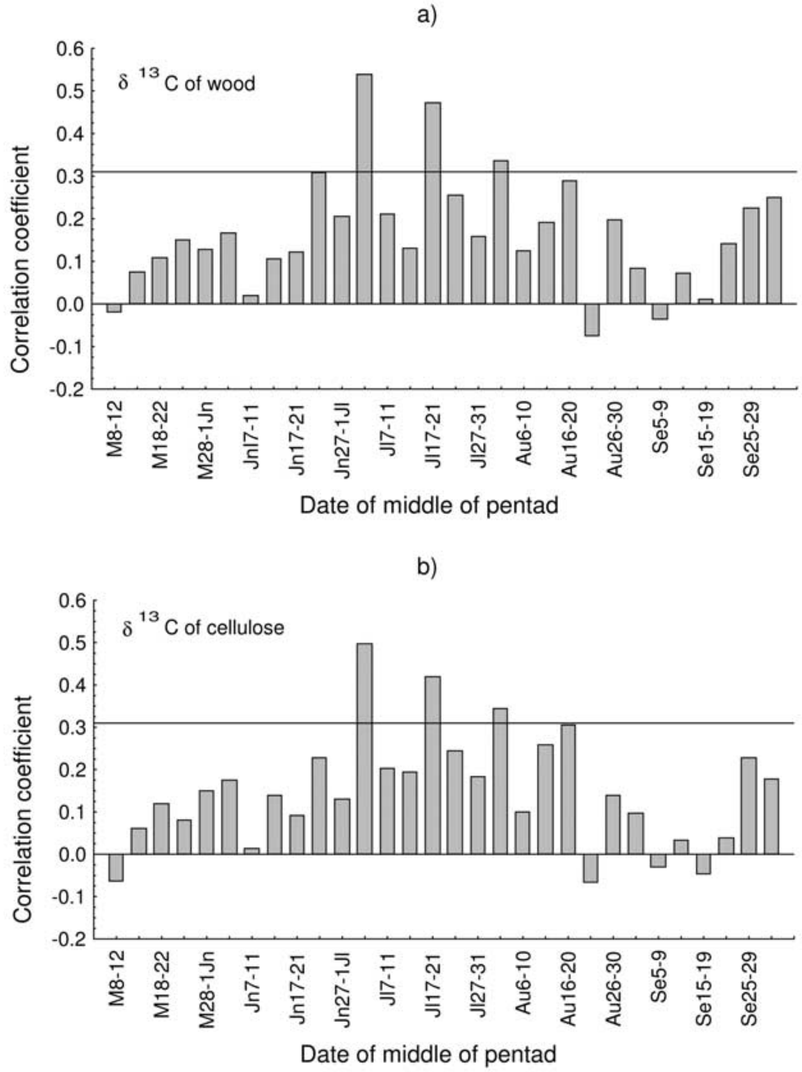

Figure 5. Correlation coefficients of pentad temperatures with isotope data: (a) $\delta^{13}C$ of wood; (b) $\delta^{13}C$ of cellulose. Values above the dotted line are statistically significant ($p < 0.05$).

0.05) was obtained, but no correlation existed with wood. We found a good agreement with $\delta^{13}C$ data calculated according to the "Fritts-Vaganov-Shashkin" model that includes photosynthesis, microclimate and soil water parameters. The model estimates the growth and isotope fractionations in relation to climatic data obtained from the Chokurdach weather station data for the period from AD 1948–1989 [*Hemming et al.*, 2001; *Volodkovich*, 2006; *Vaganov et al.*, 2006]. The correlation coefficient between the $\delta^{13}C$ of whole wood and modeled $\delta^{13}C$ data is r = 0.52 ($p < 0.05$). The modeled $\delta^{13}C$ data show positive relationships with VPD for June r = 0.35, July r = 0.31 and August r = 0.36; ($p < 0.05$), however the $\delta^{13}C$ of whole wood shows higher correlations with July VPD than modeled $\delta^{13}C$ data (Table 3).

3.7. Comparison of Isotope and Ring-Width Based Temperature Reconstruction Data

[29] The $\delta^{13}C$ and $\delta^{18}O$ of wood and cellulose were compared with the June-July air temperature reconstruction derived from tree ring widths [*Hughes et al.*, 1999] for the common period of AD 1880–1990. It was found that $\delta^{13}C$ of whole wood has a better agreement and higher statistical relationship with the reconstructed temperatures (r = 0.54; $p < 0.05$) than cellulose (r = 0.48; $p < 0.05$) for the period AD 1880–1990 (Figures 6a and 6b). The $\delta^{18}O$ of whole wood yields lower correlations with reconstructed temperature (r = 0.31; $p < 0.05$) (Figure 6c) than does cellulose (r = 0.42; $p < 0.05$) (Figure 6d).

3.8. Oxygen Isotopes, Tree Ring Width, and Greenland Ice Cores

[30] Ice core data contain information about climatic changes for more than 110,000 years into the past. The Greenland Ice Sheet Project Two (GISP2) successfully completed drilling through the base of the Greenland Ice Sheet and another 1.55 m into bedrock at a site on the Summit region of central Greenland (72°60′N; 38°50′W; 3200 m. a.s.l.) [*Mayewski et al.*, 1994]. GISP2 recovered the deepest ice core in the world (3053.44 meters). Ice originates by evaporation of sea water. As an air mass packet is transported from the site of evaporation towards higher

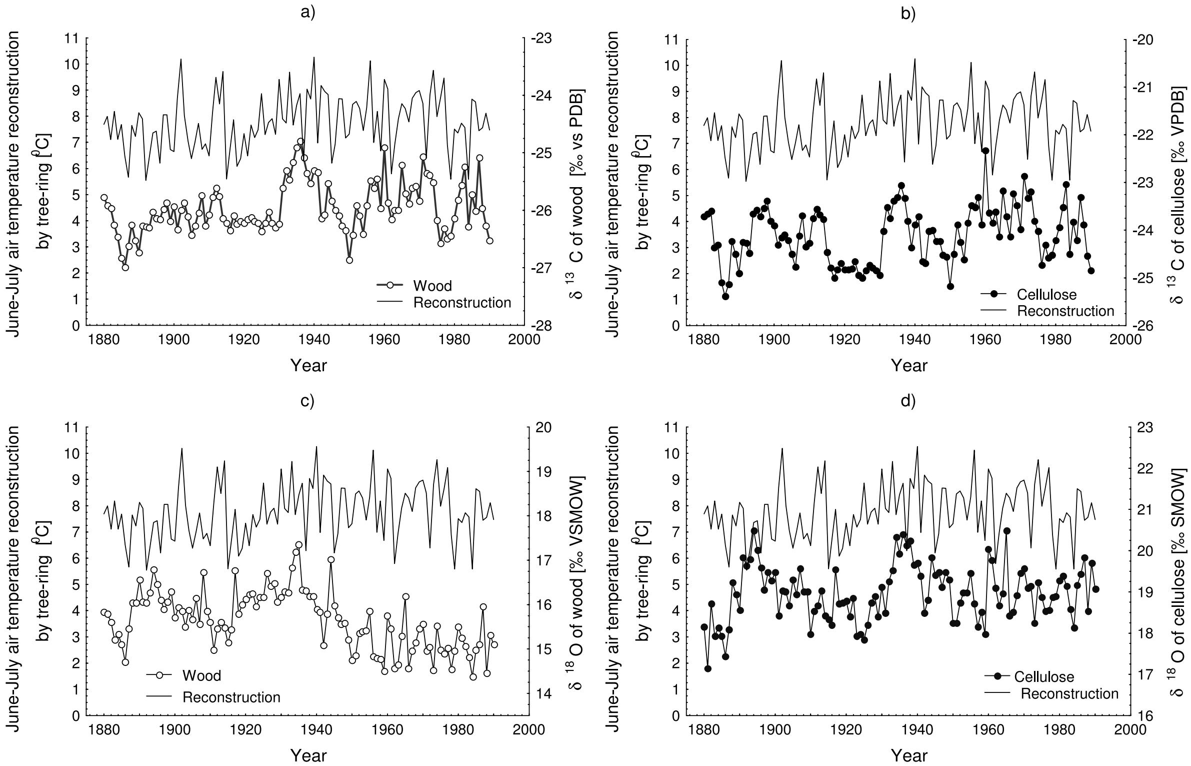

Figure 6. Comparison of the δ^{13}C and δ^{18}O of wood (a, c) and cellulose (b, d) with reconstructed June–July air temperature from tree rings (AD 1880–1990).

latitudes, it cools off and water vapor condenses. Liquid water is lost from the air mass as precipitation (rain or snow). During this condensation process the heavier water condenses more readily than the lighter water molecules, leaving the gaseous phase depleted in $H_2^{18}O$ relative to the condensate. Independent calibrations of the oxygen isotope-temperature relationship have been developed through the analysis of the GISP2 borehole, allowing the conversion of isotope-derived surface-temperature histories to temperature-depth profiles [*Cuffey and Marshall*, 2000]. Thus the variations with depth in the δ^{18}O of the ice core reflect past variations of temperature over a defined timescale at the site.

[31] Correlation coefficients between the ice core (GISP2) and δ^{18}O of wood, cellulose and tree ring width (TRW) chronologies were calculated for different periods (Table 4). All series were smoothed by an 11-year averaging (Figures 7a–7d). We observed significant correlations between δ^{18}O of wood ($r = 0.24$; $p < 0.05$) and cellulose ($r = 0.86$; $p < 0.05$), with δ^{18}O of ice core layers (GISP2) for the early Medieval period AD 900–1000. It is striking that the relationship between δ^{18}O of cellulose and δ^{18}O of ice core layers is higher than for wood for all periods, and shows a very good agreement for the period AD 900–950 when the correlation coefficient is ($r = 0.86$; $p < 0.05$) (Table 4). The correlation coefficients calculated for the beginning of the Medieval period are clearly higher than for the current period. For some periods no significant correlations were found between δ^{18}O in wood and the ice core.

[32] No significant relationship was found between tree ring widths and δ^{18}O in Greenland ice core data in the Medieval period (AD 900–1000). However a significant correlation was observed for the period (AD 1887–1987) (Table 4).

4. Discussion

[33] For the first time, unique carbon and oxygen isotope datasets representing whole wood and cellulose for larch have been obtained from the climatically sensitive region from Northeastern Yakutia. The differences between wood and cellulose ranged from 2‰ (for δ^{13}C) up to 4‰ (for δ^{18}O) throughout both analyzed periods. Provided that these differences do not vary over time, both wood and cellulose could be equally well suited as climate proxies. Our results are in agreement with data published by *Borella et al.* [1999] and *Loader et al.* [2003]. Relatively constant differences between wood and cellulose have been reported for δ^{13}C [*Leavitt and Danzer*, 1993; *Borella et al.*, 1998] and to a lesser degree for δ^{18}O [*Gray and Thompson*, 1977;

Table 4. Statistically Significant Correlation Coefficients Between δ^{18}O of Wood, Cellulose, and Tree Ring Width (TRW) and the δ^{18}O in Greenland Ice Core (GISP2) Chronology[a]

Period	δ^{18}O of Wood	δ^{18}O of Cellulose	TRW
1887–1987		**0.74**	**0.71**
1937–1987	0.52		0.56
1887–1937	0.69	0.72	0.56
900–1000	**0.24**	**0.86**	
950–1000		0.60	
900–950		0.86	

[a]Level of significance: ($p < 0.05$).

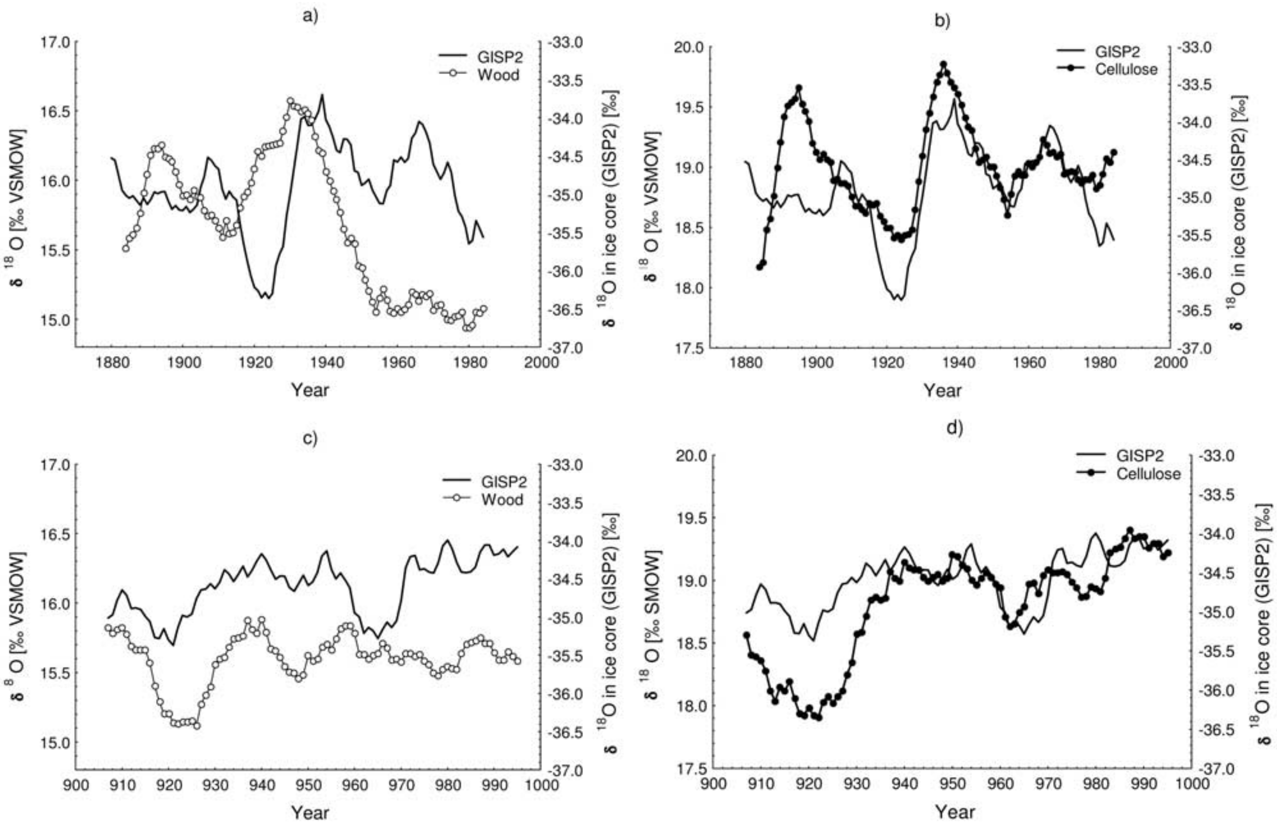

Figure 7. Comparison of oxygen isotope values in wood (a, c), cellulose (b, d), and the Greenland ice core (GISP2) during the current and Medieval periods. Data are shown after smoothed 11-year running averages.

Borella et al., 1999; *Barbour et al.*, 2001], suggesting that similar climatic information is contained in both materials. Data on δ^{18}O from tree rings suggest that the fractions producing the isotope signal for oxygen are more complex than for carbon, involving, for instance, isotopic exchange with hydroxyl groups in metabolic reactions in leaves and in the stem [*Roden and Ehleringer*, 2000]. Cellulose is often assumed to be a more reliable climatic proxy for oxygen than wood. Our results indicate that the oxygen isotope variations in wood and cellulose are different, and that the deviations are not just random, but show trends over time. *Saurer et al.* [1997] showed that in some cases carbon and oxygen isotopes are affected by the same environmental variables, (e.g., soil water availability), because stomatal control and transpiration may affect both isotope ratios, although the isotope fractionation mechanisms involved for carbon and oxygen are entirely different. For the last 50 years of the most recent period we found that isotope values of wood and cellulose show larger differences; yet correlate highly with each other. These changes in the relationship between wood and cellulose over time could be explained by: (1) changes in climatic factors (temperature/precipitation) [*Barber et al.*, 2000], in particular a response of trees to increasing atmospheric CO_2; (2) a change in the ratio of different wood constituents (cellulose/lignin ratio, sucrose, lipids, starch and other substances); and (3) compositional differences in heartwood and sapwood [*D'Alessandro et al.*, 2004].

[34] Statistical analyses between monthly air temperature, precipitation and isotope data show positive correlations between δ^{13}C of wood and cellulose for June, July and August temperatures, and a negative correlation with July precipitation. The positive correlation with one of the warmest months (July) in Northeastern Yakutia could indicate an increase in photosynthetic capacity, because warm and dry conditions cause stomatal closure and lower the isotopic fractionation, leading to less negative δ^{13}C values. Even during the warmest month of July, the soil water is still frozen at a soil depth of 20–30 cm. Thus the water accessibility for trees is limited, which can lead to drought situations. An increase in water availability allows for a higher stomatal conductance, resulting in lower δ^{13}C values, leading to a negative relationship with summer precipitation.

[35] The relatively weak relationship between July air temperature and the δ^{18}O of wood and cellulose is a result of the complex soil hydrology. The soil water body is a mixture of winter precipitation and summer rainfall. As soon as the soil has thawed (middle or end of June) the trees have access to a mixture of water, which is initially dominated by the isotope pattern of winter precipitation. This could explain a rather smooth isotope variation and a lower sensitivity of the δ^{18}O to climate variation.

[36] The highly positive relationships between vapor pressure deficit in July, August and δ^{13}C and δ^{18}O in whole wood and cellulose indicate decreased stomatal conduc-

tance, an expression of moderate drought. This leads to reduced $^{13}CO_2$ discrimination and less negative $\delta^{13}C$ values. The simultaneous increase of $\delta^{18}O$ also indicates a reduction in stomatal conductance under rather dry conditions or drought [*Yakir and Sternberg*, 2000]. The results obtained between isotope data and vapor pressure deficit are in agreement with the carbon and oxygen results of *Ferrio and Voltas* [2005] for the East Iberian Peninsula. The isotopes thus provide complementary information on hydrological changes that have not been detected by tree ring width analysis in this region. Our results are in agreement with carbon isotope data (obtained from cellulose) for the Suntar Khayat region (Eastern Yakutia) [*Nikolaev et al.*, 2006].

[37] The unexpected positive correlation between $\delta^{18}O$ of cellulose and winter (February) air temperature could be a result of the influence of the Trans Polar Index (TPI), El Niño influence [*Briffa*, 2000], or a time lag between snowfall and snowmelt [*Kirdyanov et al.*, 2003]. February is a high precipitation month and therefore contributes much snow that will eventually recharge water in the shallow root zone.

[38] A detailed correlation analysis between air temperature pentads (5-day-groups) and $\delta^{13}C$ of wood and cellulose showed that the temperature regime of the first ten days of July is most important for explaining the carbon isotope composition of whole wood as well as for cellulose. The $\delta^{13}C$ of wood and cellulose shows a significant relationship until the first pentad of August. In contrast, significant correlations between $\delta^{18}O$ of wood or cellulose and temperature pentads were not observed.

[39] In many tree ring isotope studies early wood is separated from late wood, since late wood often correlates better with the current growing season climate. During the production of early wood at the beginning of the vegetation season, stored carbohydrates from previous years are used. Thus the climate signal from this C-pool is masked by the signals from previous years. In late summer and the beginning of fall when the late wood is formed, freshly assimilated carbon is predominant; thus the isotope ratios of late wood reflect the climate during the current season (July and August). As our samples were very small, we could not separate early wood from late wood. Therefore we had to use the whole tree ring. The results of the correlation analysis are in agreement with the short duration of the growing season in this area. The isotope dataset can be used for verification of the ecophysiological model [*Hemming et al.*, 2001; *Vaganov et al.*, 2006], and may provide the potential for palaeoenvironmental reconstruction and information on ecophysiology (e.g. on water use efficiency) on multi-centennial and possibly millennial timescales.

[40] Comparative analyses of the mean isotope values ($\delta^{13}C$, $\delta^{18}O$ of wood and cellulose) between the current and Medieval period show a considerable overlap.

[41] In a comparison between a ring width based temperature reconstruction and $\delta^{13}C$ and $\delta^{18}O$ of whole wood and cellulose we identified time periods where whole wood yields a higher correlation with temperature than cellulose and vice versa. At this point we cannot clearly determine which of the two substrates yields the better information for a retrospective climate study. One reason for the good correlation with wood could be the more direct link between needle processes and whole wood isotope composition, whereas cellulose is formed in an earlier stage of the season from a mixture of predominantly stored (old) and freshly assimilated carbohydrates [*Loader et al.*, 2003]. Another reason could be that changes of the environmental conditions alter the ratio of the wood constituents, as was found for plants under elevated CO_2 exposure [*Körner*, 2000].

[42] In our previous investigations we found statistical relationships between a long subarctic Eurasian tree ring chronology, which preserved a low-frequency temperature signal, and the $\delta^{18}O$ record from the GISP2 ice core. These proxy records are significantly correlated with each other, both throughout the last two thousands years ($r = 0.34$; $p < 0.05$), and during the shorter and more recent period AD 1880–1986 ($r = 0.65$; $p < 0.05$). However, no significant relationship was found between the tree ring and ice core data for the early Medieval period (AD 900–1000) [*Sidorova et al.*, 2005b, 2007]. For this inconsistency we suggested that either (1) different climatic conditions prevailed during this time in Greenland and northern Eurasia, or (2) possible erroneous dating of the ice core due to ice melting or several years being counted as one year. Unfortunately, it is not possible to apply the cross dating technique for ice cores as in classical dendrochronology, where cross dating provides the required resolution for the construction of a precise chronology [*Sidorova et al.*, 2007]. For the beginning of the Medieval period a good agreement and a similar trend between $\delta^{18}O$ of cellulose and $\delta^{18}O$ of ice cores (GISP2) was found, which indicates a strong link to long-term temperature variations and the influence of atmospheric circulation in the region studied. Climatic connections over such large distances are a result of atmospheric circulation patterns controlling precipitation [*Welker et al.*, 2005]. The resulting temperature changes influence the freezing and thawing processes in the upper soil during several years, which directly influences tree growth (enhanced or reduced photosynthetic activity and growth of the root and shoot system due to water availability, temperature of air and soil). Furthermore, the different accessible sources of water (snow, rain, and melting water) leads to an annual climatic signal similar to that accumulated in $\delta^{18}O$ of ice cores. The positive correlations between oxygen isotope data at our site with Greenland ice cores indicate similarities in the nature of low-frequency temperature variability during the Medieval and recent period in these two regions.

5. Conclusions

[43] We report unique isotope datasets for $\delta^{13}C$ and $\delta^{18}O$ of wood and cellulose from Northeastern Yakutia for the early Medieval (AD 900–1000) and recent (AD 1880–2004) periods. These represent a potentially valuable archive of climatic information, and we base the following conclusions on our analysis of this dataset:

[44] 1. Although there are considerable differences between the absolute delta values of cellulose and whole wood (for $\delta^{13}C$ up to 2‰, and for the $\delta^{18}O$ up to 4‰), they show broadly similar patterns of correlation with monthly and pentad temperatures. Therefore we suggest both cellulose and whole wood should be sampled when sufficient mate-

rial is available, as there is evidence that they both contain information concerning the moisture regime.

[45] 2. Unlike tree ring width and maximum latewood density in this particular region, the isotope records provide information on the moisture regime, specifically July vapor pressure deficit ($\delta^{13}C$). The isotope data reveal summer drought situations in the most recent half-century, even in this cold permafrost region.

[46] 3. The fact that $\delta^{18}O$ of cellulose showed a higher correlation coefficient with $\delta^{18}O$ in Greenland ice core data than $\delta^{18}O$ of wood for all periods indicates that cellulose may well capture the isotope signal of temperature and precipitation, and reflect the large and long-term scale of the atmospheric circulation pattern.

[47] 4. Summer air temperature is well reflected in the $\delta^{13}C$ values in both wood and cellulose. This is an indirect proxy, where the temperature has an effect via increased leaf to air VPD, causing a reduction in stomatal conductance. Contrary to expectations the temperature is not significantly represented by the $\delta^{18}O$ values. We believe this was due to the hydrological complexity caused by the short vegetation periods and the permafrost.

[48] 5. Good agreement between our measured $\delta^{13}C$ of whole wood, cellulose and modeled $\delta^{13}C$ data [*Hemming et al.*, 2001; *Volodkovich*, 2006; *Vaganov et al.*, 2006] provides verification for the ecophysiological model for the current period.

[49] The recovery of multiple climate proxies from one archive, in this case annual tree rings, has the potential to identify more specific mechanistic links between the archive and varying climate. In this case, we enhance the existing quantitative reconstruction of early summer temperature from northeastern Yakutia with isotopic data, and gain a wider insight into the conditions under which the rings were formed. The multiple signals stored in tree rings, in particular isotope data, have the potential to increase our understanding of the influence of permafrost and precipitation on the mechanism of plant growth, and their response to this harsh climate in the vast Boreal zone.

[50] **Acknowledgments.** This work was supported by the European Science Foundation BASIN-SIBAE (596), SCOPES program (IB73A0-111134), KKFN 16G096 and the grant of RFBR 06-05-64095-a, RFBR 07-04-96819_r_Yenisey_a, RFBR 07-04-00293-a. Grants to Malcolm K. Hughes, University of Arizona, from the U.S. National Science Foundation (9413327 and 0308525) supported the collection, dating, and ring-width measurement of material used in this study. This work was conducted in collaboration with the MILLENNIUM project (017008). Special thanks to Malcolm K. Hughes and Aleksander V. Shashkin for help, advice, support and useful discussion. We thank Matthias Mueller and Simon Bohnenblust for laboratory assistance at the Stable Isotope Facility at the Paul Scherrer Institute, Switzerland, and Danny McCarroll and Ewan Woodley from Swansea University, UK, for useful discussion. Thanks to Sergey V. Churakov from Paul Scherrer Institute for help and advice. The authors wish to thank the anonymous reviewers for the useful comments and constructive advice.

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