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Is the 20th century warming unprecedented in the Siberian north?

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A B S T R A C T

To answer the question "Has the recent warming no analogues in the Siberian north?" we analyzed larch tree samples (*Larix gmelinii* Rupr.) from permafrost zone in the eastern Taimyr (TAY) (72°N, 102°E) using tree-ring and stable isotope analyses for the Climatic Optimum Period (COP) 4111–3806 BC and Medieval Warm Period (MWP) 917–1150 AD, in comparison to the recent period (RP) 1791–2008 AD.

We developed a description of the climatic and environmental changes in the eastern Taimyr using tree-ring width and stable isotope ($\delta^{13}C$, $\delta^{18}O$) data based on statistical verification of the relationships to climatic parameters (temperature and precipitation).

Additionally, we compared our new tree-ring and stable isotope data sets with earlier published July temperature and precipitation reconstructions inferred from pollen data of the Lama Lake, Taimyr Peninsula, $\delta^{18}O$ ice core data from Akademii Nauk ice cap on Severnaya Zemlya (SZ) and $\delta^{18}O$ ice core data from Greenland (GISP2), as well as tree-ring width and stable carbon and oxygen isotope data from northeastern Yakutia (YAK).

We found that the COP in TAY was warmer and drier compared to the MWP but rather similar to the RP. Our results indicate that the MWP in TAY started earlier and was wetter than in YAK. July precipitation reconstructions obtained from pollen data of the Lama Lake, oxygen isotope data from SZ and our carbon isotopes in tree cellulose agree well and indicate wetter climate conditions during the MWP.

Consistent large-scale patterns were reflected in significant links between oxygen isotope data in tree cellulose from TAY and YAK, and oxygen isotope data from SZ and GISP2 during the MWP and the RP.

Finally, we showed that the recent warming is not unprecedented in the Siberian north. Similar climate conditions were recorded by tree-rings, stable isotopes, pollen, and ice core data 6000 years ago.
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1. Introduction

According to the report of the Intergovernmental Panel on Climate Change (IPCC, 2007) some aspects of the current climate change are not unusual, but others are. Therefore we need to look into the past for revealing "unusual" – for instance extremely warm – climatic periods.

The application of natural archives such as long tree-ring and ice-core chronologies, as well as lake sediment and pollen data for paleoclimate reconstructions can help us to evaluate climatic and environmental changes in the past and facilitate a comparison to the magnitude of the recent warming. All these archives have advantages and disadvantages. Tree rings are precise climate archives, which record summer climate information in annual resolution through millennia. However, trees are limited by duration of life time on the Earth compared to ice core or pollen data and sometimes are subject to non-climatic, biological trends (Bradley, 1999). Combination of different archives could help to reduce uncertainties, reveal similarities between proxies and obtain new information, which could not be recorded by a single proxy.

Most paleoclimate temperature reconstructions based on multi-proxy archives were obtained for the last two millennia (Jones et al., 1998; Mann et al., 1998, 2008; Kaufman et al., 2009). These global temperature reconstructions, based mainly on multi-proxy chronologies from the Northern Hemisphere indicate that the 1990s were the warmest decade during the last two millennia. There are few temperature reconstructions based on tree-ring width longer

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than the last millennium for the subarctic regions (Hughes et al., 1999; Briffa, 2000; Esper et al., 2002; Grudd et al., 2002; Hantemirov and Shiyatov, 2002; Naurzbaev et al., 2002; Sidorova and Naurzbaev, 2002), which also confirm that the 1990s were unusually warm but not the warmest for the last 2000 years. Recent studies by Esper et al. (2012) in northern Scandinavia show warming peaks derived from latewood density chronologies during Roman and Medieval times, while recent warming is rather small compared to previously published reconstructions (IPCC, 2007). The temperature signal is very well captured by trees growing under temperature-limited conditions, whereas rather little is known about precipitation changes. Extracting information about hydrological changes and revealing the impact of drought on tree ring formation is possible using stable carbon and oxygen isotope analyses (McCarroll and Loader, 2004; Sidorova et al., 2009; Knorre et al., 2010).

Numerous isotope studies have been carried out for the subarctic forests (Arneth et al., 2002; Saurer et al., 2002; Kagawa et al., 2003; Barber et al., 2004; McCarroll and Loader, 2004; Gagen et al., 2007; Sidorova et al., 2008, 2009, 2011; Young et al., 2012). In these studies the climatic changes are derived from stable carbon (δ^{13}C) and rarely oxygen (δ^{18}O) isotopes (Saurer et al., 2002; Hilasvuori et al., 2009; Sidorova et al., 2011).

In this paper we analyze a unique archive of long-living (up to 840 years) trees and samples of subfossil wood from the permafrost zone in Siberia and use this archive in a sub-arctic transect for climate studies. Based on one absolutely dated 2431 year old and three floating tree-ring width chronologies of 1442, 950 and 474 years constructed for the eastern Taimyr Peninsula (Naurzbaev et al., 2002; Sidorova et al., 2011) we selected periods, which exhibit strong increasing tree growth during so called by Lamb (1977) the Climatic Optimum Period (COP) 4111–3806 BC, the Medieval Warm Period (MWP) 917–1150 AD, and the Recent period (RP) 1791–2008 AD. We chose four samples from living trees, dead trees, as well as from subfossil wood for each selected period for the stable isotope analyses.

Moreover, to obtain a comprehensive description of climatic and environmental changes in Northern Eurasia we compared our new data sets with earlier published tree-ring and stable isotope data obtained for Yakutia, which is located at similar latitude as Taimyr, but more to the east (Sidorova et al., 2008), pollen records from the Lama Lake (south of Taimyr Peninsula) (Andreev et al., 2004), δ^{18}O Greenland ice core (GISP2) data (Meese et al., 1994), and δ^{18}O ice-core data from Severnaya Zemlya (SZ) (Opel et al., 2013). The GISP2 ice core data were available for three studied periods, while δ^{18}O data from Akademii Nauk ice cap, Severnaya Zemlya were limited to two periods from 917 to 1150 AD and from 1790 to 1998 AD because the basal age of the Akademii Nauk ice cap is not more than about 3200 years. It has been a growing glacier until the recent times at least. Probably it was almost completely melted in the early and middle Holocene.

With the combined and complementary use of multiple proxies, our main goal was the comparison of the warmest periods during the Late Holocene, with preindustrial and industrial periods for addressing the question: Does the recent warming have past analogues in the Siberian north?

2. Material and methods

2.1. Study site

Our tree-ring investigation is focused on the Eastern part of the Taimyr Peninsula (TAY) (72°N, 102°E) (Fig. 1 A). Trees growing there are very sensitive to temperature changes on both, regional and global scales (Abaimov et al., 1997; Briffa et al., 2002; Naurzbaev et al., 2002; Sidorova et al., 2011). This region is characterized by a pronounced continental climate with short vegetation periods (up to 85 days), determined by varying dates of snow melt and initiation of cambial activity (Abaimov et al., 1997; Vaganov et al., 1999), strongly limiting temperature regimes and low amount of precipitation (up to 280 mm) (Abaimov et al., 1997). Most part of the precipitation falls in July–August. The land surface of the study site is characterized by coarse rocks on continuous permafrost. The maximal depth of permafrost thawing is 40 cm in the middle of August. The soil is covered with a moss layer of 4–5 cm. The mean annual temperature is −12.8 °C. The warmest month in the studied region is July with an average air temperature of 12.6 °C. Tree growth on the studied site is limited by June and July air temperatures (Vaganov et al., 1996; Abaimov et al., 1997; Naurzbaev et al., 2002). Monthly temperature and precipitation data for Taimyr are available for the period 1929–2009 from the “Khatanga” weather station: [71°98′N, 102°47′E, 33 m], http://climexp.knmi.nl.

Larch trees (*Larix gmelinii* Rupr.) growing on eastern Taimyr may reach an age of 840 yr (Fig. 1B) (Sidorova et al., 2005). The distance between the trees is around 5–8 m. 20 increment cores of old living trees, and 138 of preserved dead trees, were taken. 27 subfossil wood samples (Fig. 1C) were collected using a chainsaw to cut radial discs (Naurzbaev et al., 2002; Sidorova et al., 2011). The material was collected from: (a) the present northern larch timberline in the Stow Ary-Mas (72° 28′ N); (b) present upper timberline at 200–300 m a.s.l. in the Kotuy river valley (70° 30′ N – 71° 00′ N) and (c) alluvial deposits in floodplains and terraces of the large tributaries of the Khatanga river (70° 30′ – 73° 00′ N) (Naurzbaev et al., 2002).

2.2. Sites for comparative analysis

For comparison, we used published stable isotope (δ^{13}C, δ^{18}O), tree ring width chronologies obtained for the northeastern Yakutia, Sakha Republic (70°N, 148°E) (Hughes et al., 1999; Sidorova and Naurzbaev, 2002; Sidorova et al., 2008), July temperature and precipitation reconstructions obtained from pollen data of Lama Lake, Taimyr (69°N, 90°E) (Andreev et al., 2004), δ^{18}O chronology from Greenland ice core (GISP2) (Meese et al., 1994) and δ^{18}O chronology from Akademii Nauk ice cap, Severnaya Zemlya (80°N, 94°E, drilling point of AN ice core) (Opel et al., 2013). The δ^{18}O Greenland ice core data (GISP2 – Greenland Ice Sheet Project 2; 72°N, 38°W, 3200 m asl) were obtained from the web site http://www.ncdc.noaa.gov/paleo/icecore/greenland/summit/document/gispisot.htm.

2.3. Stable isotope analysis

We selected four cross-dated tree samples for the stable carbon and oxygen isotope analyses based on similar tree-ring patterns and significant coherence for the periods from 1791 to 2008 AD, from 917 to 1150 AD and from 4111 to 3806 BC.

The mean age of the trees used for the stable isotope analyses was 360 years. The first 50 rings closest to the pith were excluded from the analyses to avoid the juvenile effect (McCarroll and Loader, 2004; Gagen et al., 2008; Sidorova et al., 2008). Each annual ring was separated by a scalpel. The resins from the wood samples were extracted in ethanol using a Soxhlet apparatus and after 36-h treatment the samples were washed and dried. The whole wood samples were milled to a fine powder and after cellulose extraction (Loader et al., 1997) the samples were weighed into tin capsules for the analysis of carbon and in silver capsules for oxygen analysis.

We determined the δ^{13}C and δ^{18}O stable isotope values of cellulose using a delta-S mass spectrometer (Finnigan MAT, Bremen,

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