Temperature response in the Altai region lags solar forcing

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1. Introduction

[2] There is a general consensus that increasing anthropogenic emissions of greenhouse gases are the main source for recent climate warming, whereas direct solar forcing is of minor importance. The direct radiative forcing due to increases in total solar irradiance since 1750 is estimated to be only +0.12 (−0.06, +0.18) W/m² [Forster et al., 2007]. Nevertheless, a number of climate records show a significant response to variations in solar activity [e.g., Versteegh, 2005; Soon, 2005; Mangini et al., 2005; Scafeeta and West, 2007], providing evidence for a solar forcing effect in spite of the fact that the underlying physical processes are still not yet understood. Amplification of the solar signal via indirect mechanisms may cause potentially lagged climate response. Models predict lags of 0–20 years due to the thermal inertia of the climate system [Rind et al., 1999; Schwartz, 2007]. Indeed, comparisons between Northern Hemisphere (NH) temperature and solar activity reconstructions revealed lags of 10–30 and 6–12 years for the time periods 1650–1850 and 1610–2000, respectively [Waple et al., 2002; Scafeeta and West, 2007]. However, sun-climate relationships become weaker over the last millennium. This is due to the fact that in many proxy records influences of other forcings and internal variability (e.g., North Atlantic Oscillation (NAO), El Niño Southern Oscillation (ENSO), and monsoon) become at least temporarily dominant. In addition, proxy records often have insufficient time resolution and dating accuracy, hampering identification of a direct or lagged correlation. Furthermore, the main effect of solar forcing is presumably on location, routes, and stability of atmospheric pressure systems, which all act on regional scales [Versteegh, 2005]. In large spatial scale hemispheric or global reconstructions the solar signal may therefore even vanish. For these reasons there is obviously a need for complementary investigations at regional scales.

[3] In this study we use an ice core δ18O record retrieved from the Belukha glacier in the Siberian Altai in Central Asia to investigate the solar activity-temperature relationship. Due to its remoteness from the oceans, the climate is extremely continental with cold winters and warm summers. This region of central Asia is characterised by the highest degree of continentality in the world [Lydolph, 1977]. In winter, due to the prevailing stable Siberian High, cold and dry arctic air masses are predominant. In summer, humid air masses from the Atlantic Ocean as well as recycled moisture are the main sources of precipitation [Aizen et al., 2006].

[4] Previous studies revealed a strong δ18O-temperature relationship in this region of Central Asia [see, e.g., Aragüas Aragüas and Fröhlich, 1998] (Figure S1 of the auxiliary materials). Here we present an ice core oxygen isotope record from the Belukha glacier serving as a high-resolution temperature proxy for the last 750 years. Comparison of the established temperature record with solar activity proxy and CO2 concentration allows the attribution of pre-industrial and recent temperature change to different climate forcings. The precisely dated ice core record enables the determination of a response time between solar forcing and regional temperatures.

2. Methods

[5] We obtained the δ18O data from analysis of a 139 m long ice core drilled at the Belukha glacier in 2001 (Figure S1, 4062 m a.s.l., 49°48'26"N, 86°34'43"E) [Olivier et al., 2003]. The upper 138 m of the ice core cover the period 1250–2001, which was established by annual layer counting, 210Pb dating, identification of volcanic horizons, and the use of a kinematic glacier flow model. The ice core was melted into 3615 samples and analyzed for soluble ions (e.g., Na+, NH4+, Ca2+, SO42−), oxygen isotopes δ18O, 210Pb, and 3H.

3. Results and Discussion

[6] The δ18O record together with the record of non-dust sulfate (exSO42−) concentration is shown in Figure 1a. Most

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1 Auxiliary materials are available in the HTML. doi:10.1029/2008GL035930.
of the non-dust sulfate maxima, which can be related to volcanic eruptions, coincide with \( \delta^{18}O \) minima. Explosive volcanic eruptions have been shown to cause Northern Hemisphere summer cooling [Robock and Jianping, 1995]. Two of the three most distinct short-term \( \delta^{18}O \) minima occur in 1453 ± 4 and 1598 ± 3 and are attributed to a strong cooling after the eruptions of the volcanoes Kuwae (1452, southwest Pacific) and Huaynaputina (1600, Peru), respectively. This is in agreement with temperature-sensitive tree-ring-density chronologies showing the strongest Northern Hemisphere cooling during the last 600 years in 1601, 1816, 1641, and 1453 [Briffa et al., 1998]. For large explosive eruptions we assume a lag of around 1 year between the eruption date and the strongest temperature decrease and maximum sulfate deposition due to the long stratospheric residence time (see, e.g., Tambora, Figure S2).

We conclude that our \( \delta^{18}O \) record and thus, our study site in Central Asia, is very sensitive to temperature changes. For the temperature calibration of the \( \delta^{18}O \) record\textsuperscript{1} instrumental data from Barnaul, Russia (52°26'N, 83°31'E) were used, which is the closest station providing data spanning more than 100 years. A good correlation between 10-year averaged \( \delta^{18}O \) data and March–November Barnaul temperatures was found (Figure S3, \( r = 0.83 \), \( p < 0.001 \) for the period 1850–1980), suggesting that \( \delta^{18}O \) in precipitation at Belukha glacier is suitable as a proxy of atmospheric temperature, which is in good agreement with previous studies. Using the derived slope of the regression line of (0.88 ± 0.36 \%/°C) (see Figure S3) we reconstructed the temperature record for the last 750 years (Figure 1b), revealing centennial fluctuations and an increasing trend starting from the mid-18th century. The relative temperature variation of 3.2 ± 1.7°C exceeds that of Northern Hemisphere reconstructions with a typical 0.8–1°C difference between the Maunder minimum and the end of the 20th century [e.g., Hegerl et al., 2006]. This is consistent with instrumental data and model simulations [Bradley et al., 2003; Hansen et al., 1998] suggesting that warming is strongest at highly continental sites in North America and North Central Asia. Periods of low temperatures occurred around 1300, 1450–1550, 1700, 1840, and 1930, coinciding at first glance with periods of low solar activity (Wolf, Spörer, Maunder, Dalton, Gleissberg minima).

Direct satellite measurements of total solar irradiance (TSI) are only available since 1979. Thus, solar activity proxies need to be used for a comparison with our temperature record. Direct observations of sunspot numbers using telescopes have been carried out since 1610. Further back in time, cosmogenic radionuclides \(^{10}\)Be and \(^{14}\)C are the most reliable proxies for changes in solar activity. The group sunspot number (SN) together with the solar activity proxy inferred from \(^{10}\)Be and \(^{14}\)C (solar modulation function [Muscheler et al., 2007]) are shown in Figure 2a. Generally, all three proxies agree well. However, there are some differences between the records mainly concerning the amplitudes (e.g., around 1600 and 1750) indicating the uncertainty of the reconstructions. For a comparison with our data we used the solar activity reconstruction inferred from the \(^{10}\)Be record, which shows a higher correlation with the SN (\( r^2 = 0.90 \)) compared to the \(^{14}\)C based reconstruction (\( r^2 = 0.68 \)) in the period 1610–2000. Our temperature record is significantly correlated (\( r^2 = 0.66, p < 0.001 \)) with

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**Figure 1.** Chronology of the volcanic eruptions and the temperature reconstruction for the past 750 years at the Belukha site. (a) Records of exSO\(_4^{2-}\) and \( \delta^{18}O \) (2-year means) show a response to major volcanic eruptions (VEI 4 or greater). Volcanic chronology was established for exSO\(_4^{2-}\) maxima with [exSO\(_4^{2-}\) ] > 4 \( \mu \)eq/l (time period 1940–2000 was not considered due to a maximum of anthropogenic input of exSO\(_4^{2-}\) ): 1-unknown (1259), 2-unknown (1286), 3-Cerro Bravo (1325 ± 75), 4-Oshima (1442), 5-Kuwae (1452 ± 10), 6-Sakura-Jima (1471), 7-unknown (1571), 8- Huaynaputina (1600), 9-Momotombo, Colima (1605/6), 10-Katla (1625), 11-Komaga-Take, Parker (1640/41), 12-Shikotsu (1667), 13-Oraefojokull (1727), 14-Shikotsu (1739), 15-Hekla (1766), 16-Laki (1783), 17-Tambora (1815), 18-Shiveluch (1854), 19-Katmai (1912), 20-Cerro Azul/Kharimkotan (1932/33). Eruptions dates were taken from the Global Volcanism Program (http://www.volcano.si.edu/world/largeeruptions.cfm) and Zielinski [1995]. (b) \( \delta^{18}O \)-derived temperature reconstruction. Temperature data are anomalies based on the 1250–2001 mean. Shown are individual values (grey), 10-year averages smoothed with a 5-point running mean (red) and the ±1σ bands arising from uncertainties in the \( \delta^{18}O \) record and calibration (black, dashed).
the \(^{10}\text{Be}\) based solar reconstruction (Figures 2 and S4a), suggesting that the sun was an important if not the main driving force for the temperature variation during the last 750 years.

[8] Spectral analysis of the Belukha temperature reconstruction shows significant periods at 205, 86, and 10.8 years, which can be related to the solar Suess, Gleissberg, and Schwabe cycles, respectively (Figure 3a). The 8.3 and 2.3 periodicities are typical of the North Atlantic Oscillation (NAO) index [e.g., Cook et al., 1998; Garcia et al., 2005], whereas the 5.2 year cycle is observed in both, solar and NAO data series. The 3.6 year cycle is found for the Southern Oscillation Index (SOI) [Garcia et al., 2005] and confirms the influence also of El Niño/Southern Oscillation (ENSO) on Central Asian climate [see, e.g., Hara et al., 2006]. The results of wavelet analyses show similar patterns compared to the FFT spectrum (Figure 3b), that are, however, not stable in time. The solar Suess and Gleissberg cycle are present consistently over the last 750 years. The periodicities <10 years are very strong between 1500 and 1800.

[9] The highest correlation between our temperature record and the solar activity inferred from \(^{10}\text{Be}\) was obtained when introducing a lag of 20 years \((r^2 = 0.81, \text{Figure } S4a)\). Cross correlation analysis revealed a consistent lag, varying between 10 and 30 years (Figure 3c). The observed lag cannot be attributed to imprecise dating, since the dating uncertainty of our temperature record does not exceed 5 years for the period 1400–2001 and is still less than 10 years before 1400. Independently dated \(^{10}\text{Be}\) and \(^{14}\text{C}\) records show coinciding minima and maxima (Figure 2a, also with the SN in the period 1610–2000) and yield similar lags (see also Figure S5).

[10] Three other regional temperature proxy records from locations close to the Altai based on tree rings (Mongolia) and ice core data (China: Guliya and Dunde) as well as three NH reconstructions are additionally analyzed (Figures S4b–S4e). From the regional records only the Dunde ice core record shows a significant correlation \((p < 0.05)\) with solar activity. The absence of a significant correlation at the comparable continental sites in Mongolia and China (Guliya) might be due to difficulties with capturing the low frequency signal and the influence of monsoon driven precipitation, respectively. Two of the three NH temperature reconstructions reveal significant correlations \((p < 0.05)\) with solar activity (Figure S4e). However, less than 50% of the data variance is represented. This is probably due to the procedure for obtaining large scale reconstructions, averaging proxy records from sites experiencing different regional climatic patterns. Furthermore, correlations are dominated by the trend during the last 150 years. Thus, all regional and NH temperature records (except the Belukha record) do not show a significant correlation with the \(^{10}\text{Be}\) (and \(^{14}\text{C}\) record) for the preindustrial period 1250–1850 only \((p < 0.05, \text{see Table S1})\). Correlation between the other regional and NH reconstructions with the \(^{10}\text{Be}\) based solar reconstruction could not be significantly improved by introducing a positive lag.

[11] The obtained lag of 10–30 years is also obvious when looking only at the solar frequency bands (see, e.g., Gleissberg cycle, Figure 3d). This is indicative of a variable response time between the initial solar signal and the regional temperature and thus, an indirect effect of solar variability on the temperature evolution at our study site. Possible indirect effects are 1) changes in stratospheric chemistry through variations of solar UV irradiance, and rather speculative: 2) direct influence of the solar wind and 3) changes in cloud cover induced by modulation of the cosmic ray flux [Marsh, 2007]. However, all these mechanisms are supposed to operate on much shorter time-scales and are therefore not sufficient to explain the observed lag. Potential justifications for decadal lags are changes in ocean and atmospheric circulations triggered by variations in TSI. Perry [2007] proposed that increasing solar radiation leads
to a warming of the tropical and subtropical oceans. This temperature anomaly is transported within the ocean conveyor belt to the particular ocean area that affects regional climate with varying lag times due to the heat capacity of the ocean and varying fluctuations in the velocity of the ocean currents. Furthermore, temperature gradients in the ocean influence the atmospheric pressure pattern. Indeed, models calculate that the lower NH temperatures in the period 1650–1850 are due to a decreased solar activity in this time forcing a shift towards a low index state of the NAO/Arctic Oscillation (AO) with a lag of 20 years [Shindell et al., 2001]. Temperatures in Central Siberia are influenced by the NAO [Marshall et al., 2001; Ogi et al., 2003]. This is corroborated by the spectral analysis of the reconstructed temperatures revealing significantly NAO specific periodicities at 8.3 and 2.3 years (Figure 3). Thus, the above mentioned mechanism is one possible solar activity-temperature coupling for this region.

[13] Our reconstructed temperatures are significantly correlated with the 10Be and 14C based solar activity reconstructions in the period 1650–1850, but not with the greenhouse gas CO2 (Figure 2b). This indicates that solar activity changes are a main driver for the temperature variation in the Altai region during the pre-industrial time. However, during the industrial period (1850–2000) solar forcing became less important and only the CO2 concentrations show a significant correlation with the temperature record. Our results are in agreement with studies based on NH temperature reconstructions [Scafetta and West, 2007] revealing that only up to approximately 50% of the observed global warming in the last 100 years can be explained by the Sun.

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