JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 110, A10102, doi:10.1029/2004JA010946, 2005

Solar activity, cosmic rays, and Earth's temperature: A millennium-scale comparison

I. G. Usoskin
Sodankylä Geophysical Observatory, University of Oulu, Oulu, Finland

M. Schüssler and S. K. Solanki
Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany

K. Mursula
Department of Physical Sciences, University of Oulu, Oulu, Finland

Received 2 December 2004; revised 20 April 2005; accepted 28 June 2005; published 1 October 2005.

[1] Previous studies of a solar influence on climate variations have often suffered from the relatively short length of continuous direct solar observations of less than 400 years. We use two recently reconstructed series of the sunspot number and the cosmic ray flux to study this question over time intervals of up to nearly 1800 years. Comparison of the Sun-related data sets with various reconstructions of terrestrial Northern Hemisphere mean surface temperatures reveals consistently positive correlation coefficients for the sunspot numbers and consistently negative correlation coefficients for the cosmic rays. The significance levels reach up to 99% but vary strongly for the different data sets. The major part of the correlation is due to the similarity of the long-term trends in the data sets. The trend of the cosmic ray flux correlates somewhat better with the terrestrial temperature than the sunspot numbers derived from the same cosmogenic isotope data.

Citation: Usoskin, I. G., M. Schuessler, S. K. Solanki, and K. Mursula (2005), Solar activity, cosmic rays, and Earth's temperature: A millennium-scale comparison, *J. Geophys. Res.*, *110*, A10102, doi:10.1029/2004JA010946.

1. Introduction

[2] The question of how strongly the varying solar magnetic activity affects the global temperature on Earth is intensely debated in climate research, particularly concerning the causes of the global warming starting around the beginning of the 20th century. Several physical quantities that vary with the magnetic activity of the Sun and may affect the global climate have been identified, among them the total solar irradiance [*Fröhlich*, 2000], the UV irrradiance [*Woods*, 2001], and the cosmic ray flux [*Bazilevskaya*, 2000]. However, reliable quantitative estimates concerning their effects on climate have been difficult to obtain [e.g., *Cubasch and Voss*, 2000; *Larkin et al.*, 2000; *van Loon and Labitzke*, 2000; *Marsh and Svensmark*, 2000].

[3] The empirical estimation of the long-term climatic relevance of these quantities is complicated by the fact that they have been directly measured only since a few decades so that one has to resort to proxies like the sunspot number for studies reaching further back in time. Proxies are either used in simple correlation studies or in reconstructing other quantities on the basis of their known relationship during the period of simultaneous measurements. Using the sunspot number proxy, it is possible to reconstruct the total and spectral irradiance and to extend the Sun-climate correlation studies until the beginning of the systematic (telescopic) sunspot observations around the beginning of the 17th century [*Hoyt and Schatten*, 1993; *Lean et al.*, 1995; *Fligge and Solanki*, 2000]. While such studies and climate simulations [*Bertrand et al.*, 2002; *Stott et al.*, 2003] indicate a nonsolar origin of the most recent warming episode since about 1970 [see also *Solanki and Krivova*, 2003], a marked solar effect on climate variability until the middle of the 20th century is suggested when comparing with terrestrial temperature records [*Reid*, 2003; *Solanki and Fligge*, 1998; *Krivova and Solanki*, 2003].

[4] The controversial evidence of such comparisons and the desire to cover a wider range of temporal scales calls for an extension of the time period for which solar activity and climate data can be compared. For this purpose, the cosmogenic isotopes ^{10}Be and ^{14}C can be used as proxies for solar activity: their production in the terrestrial atmosphere varies owing to the modulation of the flux of galactic cosmic rays by the heliospheric magnetic field which, in turn, varies with solar activity. In most previous studies, simple linear models have been used to estimate potentially climate-relevant quantities like total irradiance from the cosmogenic isotope records [e.g., *Bard et al.*, 2000]. Here we compare terrestrial temperature data with two quantities derived from ^{10}Be data [*Usoskin et al.*, 2003, 2004a] and ^{14}C data [*Solanki et al.*, 2004] by way of physical models

0148-0227/05/2004JA010946$09.00

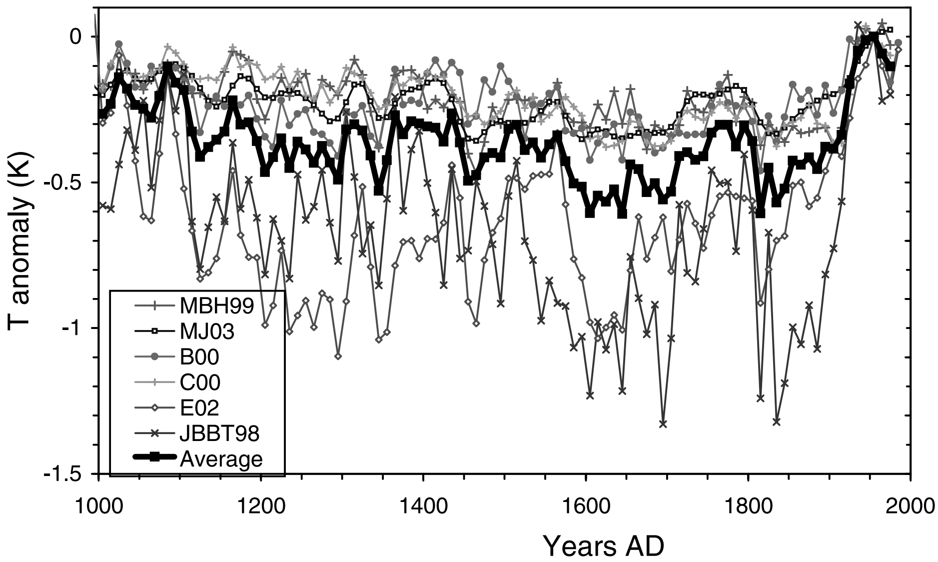

Figure 1. Data sets of Northern Hemisphere temperature reconstructions (temperature anomalies with respect to the recent instrumental record) used in this study. The labels in the legend correspond to *Mann et al.* [1999, MBH99], *Mann and Jones* [2003, MJ03], *Briffa* [2000, B00], *Crowley* [2000, C00], *Esper et al.* [2002, E02], *Jones et al.* [1998, JBBT98], and the average of these temperature series. See color version of this figure at back of this issue.

[*Solanki et al.*, 2000, 2002; *Usoskin et al.*, 2002a, 2002b]: (1) the sunspot number, which is related to the total solar irradiance and the UV flux, and (2) the flux of galactic cosmic rays impinging on the Earth's atmosphere.

[5] Over a solar activity cycle, the darkening due to sunspots is more than compensated by the brightening caused by facular regions, whose area coverage varies roughly (but not exactly) in phase with the sunspot cycle. On longer timescales, a secular trend of the total irradiance since the end of the Maunder minimum was inferred on the basis of stellar observations [*White et al.*, 1992]. However, these results have recently been called into question [*Wright*, 2004] so that the magnitude of the secular trend currently is uncertain. Under the assumption that the irradiance changes are due to the magnetic field at the solar surface, the long-term variations of the total and UV irradiances are roughly proportional to the cycle-averaged sunspot numbers, in agreement with the model of *Solanki et al.* [2002]. The actual amplitude of the trend does not enter into our correlation analysis so that its uncertainty does not affect the results.

[6] The reconstructions of sunspot number and galactic cosmic rays allow us to extend the comparison between relevant Sun-related indices with the terrestrial climate back to AD 200. This more than quadruples the interval of time for which such a study can be made based on direct solar observations. Moreover, the extended time span provides the opportunity to use the slow variation of the geomagnetic dipole moment as an independent test for the possible existence of a link between cosmic rays and climate. While the sunspot numbers are independent of the geomagnetic field, the variation of the cosmic ray flux entering Earth's atmosphere is due to a combination of solar modulation and geomagnetic shielding, the latter adding a long-term trend to the varying solar signal. Accordingly, the existence of a geomagnetic signal in the climate data would support a direct effect of cosmic rays on climate.

2. Data

[7] We use here recent reconstructions of two solar-heliospheric indices, the sunspot number and the cosmic ray flux, and six different series of terrestrial surface temperatures. Since we are interested in time scales exceeding the solar cycle length, we consider 10-year averaged data.

[8] A number of reconstructions for the terrestrial global or hemispheric temperatures for the last 1000–2000 years have been published during the last decade. The accuracy and validity of such reconstructions have recently been the topic of some debate [see, e.g., *Briffa and Osborn*, 2002; *Soon et al.*, 2003; *Mann et al.*, 2003; *Cook et al.*, 2004; *von Storch et al.*, 2004]. While the reconstructions are based (particularly in the earlier part) on similar proxy data sets (e.g., tree rings), their difference is related to different reconstruction methods. A detailed discussion of the methodological issues and potential errors connected with these reconstructions is beyond the scope of this paper. We have therefore decided to use a variety of temperature reconstructions, most of which are publicly available from the World Data Center of Paleoclimatology (IGBP PAGES/World Data Center-A for Paleoclimatology NOAA/NGDC Paleoclimatology Program, Boulder CO, USA (www.ncdc.noaa.gov/paleo/recons.html)). The sparseness of available proxy data limits the reliability of temperature reconstructions for the Southern Hemisphere, so we restrict ourselves to data for the Northern Hemisphere (NH). We use the following data sets relative to 1950s (see Figure 1): (1) NH temperatures from multiproxy data for AD 1000 to AD 1980 [*Mann et al.* 1999, MBH99], (2) NH temperatures

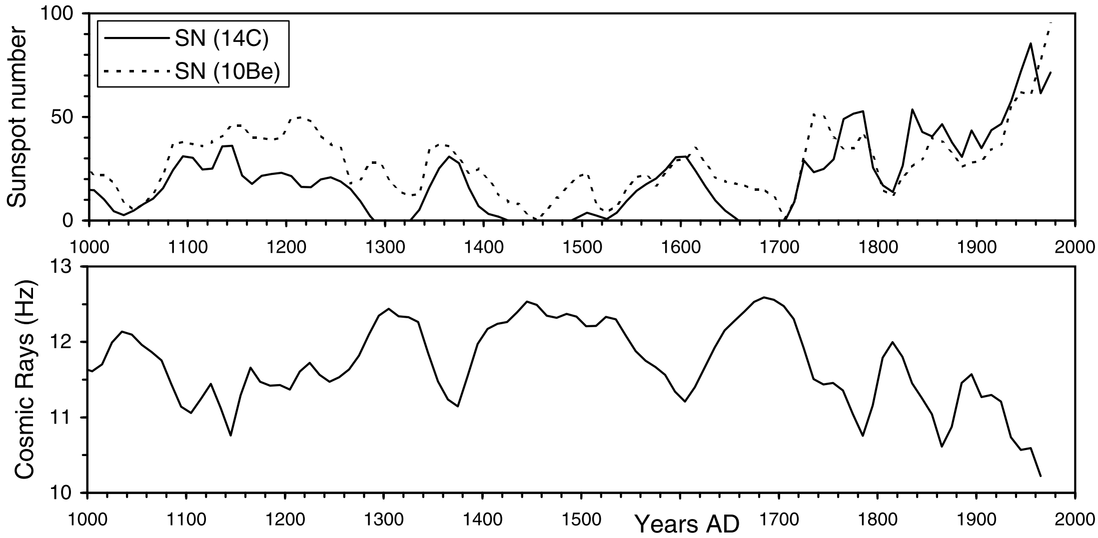

Figure 2. Solar-heliospheric indices reconstructed from cosmogenic isotope data [*Usoskin et al.*, 2003; *Solanki et al.*, 2004]. (top) Sunspot number from ^{14}C (full) and ^{10}Be (dashed); (bottom) cosmic ray flux from ^{14}C, given in count rates of a standard neutron monitor[2]. Owing to possible deviations from the assumption of purely local deposition of ^{10}Be in polar ice, the corresponding sunspot number reconstruction has to be considered as an upper limit [*Usoskin et al.*, 2004a].

from multiproxy data for AD 200 to AD 1980 [*Mann and Jones*, 2003, MJ03], (3) NH temperatures from multiproxy data for AD 1000 to AD 1991 [*Jones et al.*, 1998, JBBT98], (4) NH temperatures from tree-ring chronologies for AD 1000 to AD 1993 [*Briffa*, 2000, B00], (5) NH temperatures from multiproxy data for AD 1000 to AD 1987 [*Crowley and Lowery*, 2000], modified as published in the work of *Crowley* [2000, C00], (6) NH temperatures from tree-ring chronologies for AD 831 to AD 1992 [*Esper et al.*, 2002, E02], in the form given by *Cook et al.* [2004].

[9] As indices for solar activity we use two series of reconstructed 10-year averaged sunspot numbers:

[10] 1. A reconstruction from the cosmogenic ^{10}Be proxy since 850 AD which assumes a local deposition of the isotope in polar ice [*Usoskin et al.*, 2003]. For the period between 1425 and 1900, this series is the average of two reconstructions based on ^{10}Be data from Antarctica [*Bard et al.*, 1997] and Greenland [*Beer et al.*, 1990], respectively. After 1900 the series represents the reconstruction from the Greenland data which, contrary to the Antarctic series (see discussion in the work of *Raisbeck and Yiou* [2004] and *Usoskin et al.* [2004b]), agrees with direct solar activity observations during the 20th century.

[11] 2. A recent reconstruction from the cosmogenic ^{14}C proxy since 11400 BP [*Solanki et al.*, 2004].

[12] These two series of sunspot numbers are shown in the top panel of Figure 2 for the time interval AD 1000–1975. The reconstruction from ^{14}C extends until the year 1900; for the time after that, we use the Group Sunspot Numbers [*Hoyt and Schatten*, 1998] from direct observations. Figure 2 also shows the cosmic ray flux entering the Earth's atmosphere given here in count rates of a standard neutron monitor. (As the standard neutron monitor, we consider here a 1-NM64 type sea-level neutron monitor located at a geomagnetic latitude of 45°.) Since this cosmic ray flux is also derived from ^{14}C, we use values determined on the basis of the actual Group Sunspot Numbers for the time after 1900 [*Usoskin et al.*, 2002a]. The uncertainties of these reconstructions are discussed in detail in the supplementary online material to *Solanki et al.* [2004].

3. Results

[13] A comparison between the full MJ03 data set (AD 200–1980) for the Northern Hemisphere temperature and the two solar-heliospheric parameters reconstructed from ^{14}C for the same period is shown in the top and middle panels of Figure 3. It reveals similar long-term trends, most pronounced for the time after AD 800. In particular, during the last millennium we have a cooling trend until 300–400 years ago and a rather steep temperature rise thereafter. Similar results hold for the other, shorter series of temperature reconstructions. It is clear that the similarity of trends dominates the direct correlations; accordingly, we have considered the correlation coefficients for the original data, for the detrended data, and for the trends separately. All correlations are calculated for the period 1000–1980, except for the complete MJ03 data, which begin in the year 200.

3.1. Correlation Coefficients

[14] We first consider the correlations among the various temperature reconstructions themselves and also among the three indices related to solar activity in 1000–1980. The pairwise correlation coefficients are given in Table 1 for the temperature series and in Table 2 for solar indices. The significance levels have been carefully considered (see section 3.2); they exceed 98% for all correlations between the solar indices and for all but two correlations between the temperature series.

[15] Table 3 and Figure 4 show the results for the correlations between the solar indices and the terrestrial

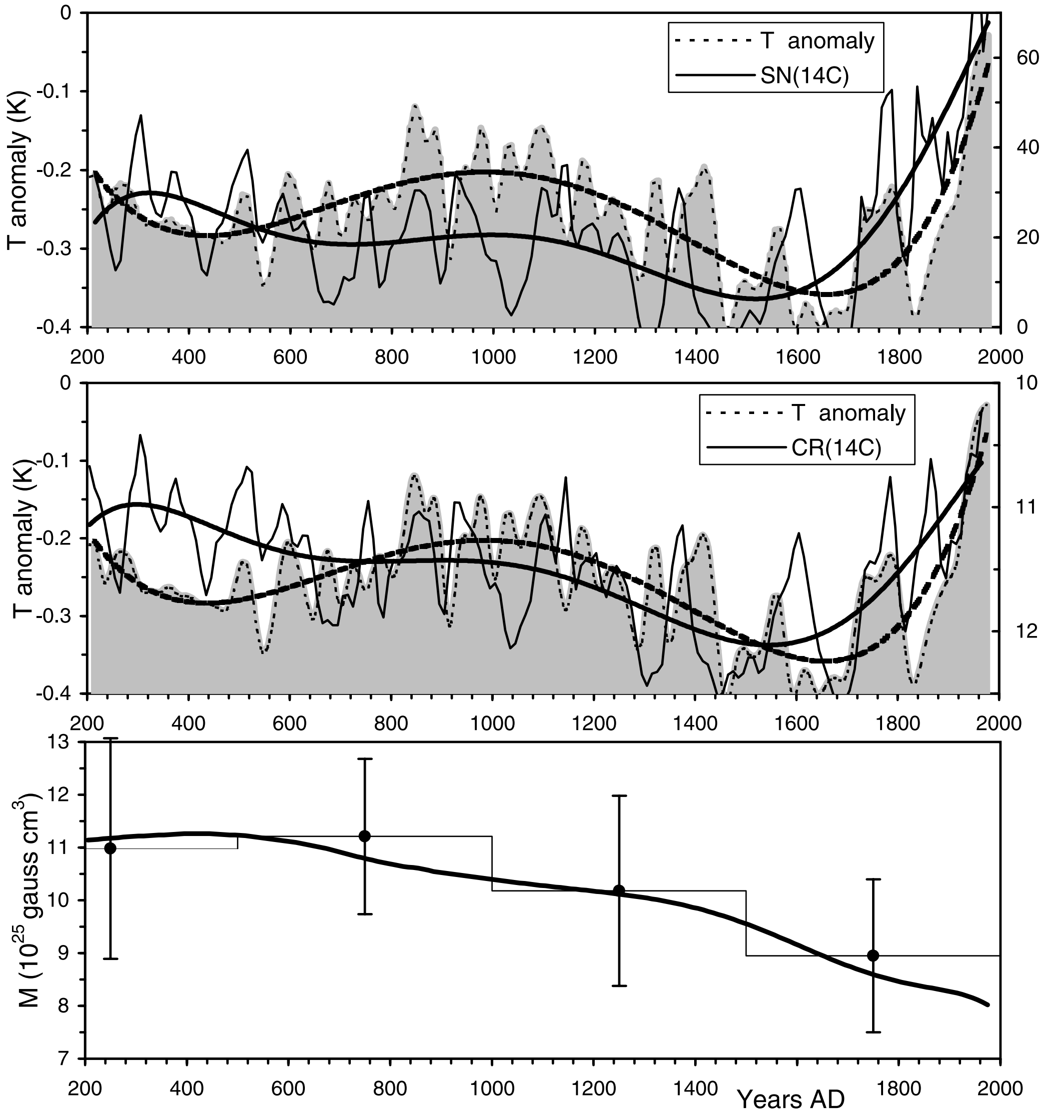

Figure 3. Temperature anomaly [*Mann and Jones* 2003, MJ03] and reconstructed solar indices for the period of time between AD 200 and AD 1975. (top) Temperature data (grey-shaded) and their long-term trend (dashed curve, sixth-order polynomial fit) in comparison with the reconstructed sunspot number from ^{14}C (thin curve) and its long-term trend (thick solid curve). (middle) Same for the reconstructed cosmic-ray flux (note the inverted scale). (bottom) Virtual geomagnetic dipole moment derived from the reconstructions of *Hongre et al.* [1998] and *Yang et al.* [2000]. The points with error bars connected by the thin curve represent the values given by *Yang et al.* [2000].

temperature series in 1000–1980, including the average of the latter. In addition, we give the correlations of the ^{14}C-based sunspot numbers and cosmic ray fluxes with the long MJ03 series for time interval 200–1980. Very similar results are obtained if the reconstructed sunspot numbers are replaced by the actual Group Sunspot Numbers for the time after 1610.

[16] The first block of Table 3 gives the correlation coefficients for the original (10-year averaged) data. All values are consistently negative for the correlations with the cosmic ray flux and consistently positive for the sunspot reconstructions. These correlations indicate higher temperatures during times of more intense solar activity (higher sunspot number, lower cosmic ray flux). However, the significance levels in many cases do not exceed 90%.

Table 1. Cross-Correlations Between the Various Temperature Series[a]

Temperature	MJ03	B00	C00	E02	JBBT98	Average
MBH99	0.76	0.51	0.81	0.47	0.76	0.80
MJ03	–	0.64	0.79	0.64	0.72	0.87
B00	–	–	0.81	0.73	0.66	0.83
C00	–	–	–	0.43 (87%)	0.79	0.82
E02	–	–	–	–	0.47 (95%)	0.78
JBBT98	–	–	–	–	–	0.89

[a]The significance levels (see section 3.2) exceed 98% in all cases except two, for which the levels are given in parentheses. "Average" refers to the arithmetic average of the six temperature series.

Table 2. Cross-Correlations Between the Solar-Activity Related Indices (Original Data Series, Sixth-Order Polynomial Trends, and Detrended Series Considered Separately)[a]

Series	SN(^{10}Be)/SN(^{14}C)	SN(^{10}Be)/CR(^{14}C)	SN(^{14}C)/CR(^{14}C)
Original	0.78	−0.83	−0.90
Trends	0.86	−0.90	−0.92
Detrended	0.67	−0.76	−0.88

[a]The significance levels (see section 3.2) exceed 98% in all cases.

Values above 95% are only found for the MBH99 and MJ03 data sets. The determination of the significance levels is described in section 3.2.

[17] To evaluate the relative importance of the long-term trend and the shorter-term (decadal to centennial) variability for the correlations, we have fitted sixth-order polynomials to all data sets and determined correlation coefficients between the fit polynomials alone (trends, second block of Table 3). Furthermore, we have considered the correlations between the data series after subtraction of the polynomial fits (detrended data, third block of Table 3). In all cases, both the trends and the detrended data again show consistent signs of the correlation coefficients in agreement with the results for the original data sets. The values of the correlation coefficients for the trends are generally larger than those for the original data. However, because of the small number of degrees of freedom, the formal significance levels in trend correlations do not exceed those for original data.

[18] In order to further disentangle the contribution of long-term trends and shorter-term variations to the correlations, we have carried out the following procedure. After removing the sixth-order polynomial trend from a temperature time series, we randomized the detrended series using the "random-phase" method (see section 3.2) and then added the trend back to the result. The new series, which has the same trend as the original series, but a randomized short-term component, is then correlated with a series of a solar quantity. From a set of 1000 realizations, we thus obtained a distribution of the cross-correlation coefficients. Figure 5 shows the result for the correlation between cosmic ray flux and the MJ03 temperature series for the time period since 200 AD. The distribution of the correlation coefficients has a mean of −0.39 with an asymmetric 68% (1 sigma) confidence interval [−0.44; −0.32]. The correlation coefficient between the original series series is −0.47 (see Table 3) as indicated by the vertical line, exceeding the mean value by 1.6 standard deviations. This indicates that the large part of the correlation between the original series results from their similar long-term trends, but that there is also a considerable contribution from shorter timescales. This conclusion is also valid for the other temperature series.

Table 3a. Cross-Correlation Coefficients Between the Indices Related to Solar Activity (Columns) and Northern Hemisphere Temperature Reconstructions (Rows) for Original Data[a]

Temperature	CR (^{14}C)	SN (^{14}C)	SN (^{10}Be)
MBH99	−0.38 (88%)	0.32 (78%)	0.47 (97%)
MJ03	−0.54 (94%)	0.46 (90%)	0.55 (99%)
B00	−0.29 (88%)	0.27 (89%)	0.18 (71%)
C00	−0.32 (80%)	0.17 (34%)	0.41 (87%)
E02	−0.32 (81%)	0.36 (86%)	0.21 (64%)
JBBT98	−0.28 (73%)	0.31 (86%)	0.31 (84%)
Average	−0.40 (90%)	0.34 (78%)	0.38 (92%)
MJ03(long)	−0.47 (98%)	0.37 (90%)	N/A

[a]"Average" refers of the arithmetic average of the six temperature series. The significance levels of the correlations (see section 3.2) are given in parentheses. All series are considered for the period 1000–1980 expect for the MJ03(long) which starts in the year 200.

Table 3b. Cross-Correlation Coefficients Between the Indices Related to Solar Activity (Columns) and Northern Hemisphere Temperature Reconstructions (Rows) for Trends[a]

Temperature	CR (^{14}C)	SN (^{14}C)	SN (^{10}Be)
MBH99	−0.55 (68%)	0.32 (40%)	0.71 (93%)
MJ03	−0.79 (93%)	0.57 (74%)	0.74 (99%)
B00	−0.41 (77%)	0.32 (68%)	0.17 (42%)
C00	−0.41 (40%)	0.14 (14%)	0.48 (72%)
E02	−0.58 (85%)	0.57 (83%)	0.30 (59%)
JBBT98	−0.54 (68%)	0.29 (38%)	0.54 (82%)
Average	−0.63 (86%)	0.51 (76%)	0.54 (84%)
MJ03(long)	−0.67 (86%)	0.49 (84%)	N/A

[a]"Average" refers of the arithmetic average of the six temperature series. The significance levels of the correlations (see section 3.2) are given in parentheses. All series are considered for the period 1000–1980 expect for the MJ03(long) which starts in the year 200.

3.2. Significance Estimates

[19] The long-term trends and the effectively decreased number of degrees of freedom (because of serial correlation) prevent the application of standard tests for significance. Assuming all data points to be independent would produce unrealistically high significance levels. This is even more relevant in the case of smoothed, filtered, or detrended data. We have therefore used the nonparametric "random-phase" Monte-Carlo method [*Ebisuzaki*, 1997], which we describe briefly as follows. Let X_k and Y_k be two data series with a cross-correlation coefficient r_0, whose significance we wish to evaluate. We randomize the phase of one of the data series, say X_k, by a three-step algorithm: first a discrete Fourier transform of X_k is computed, then the phase of the Fourier series is randomized, and finally the randomized series, X'_k, is calculated by inverse Fourier transform. This procedure guarantees that the series X'_k has the same Fourier power spectrum and autocorrelation function as the original series, X_k. By applying this procedure N times, we obtain a distribution of cross-correlation coefficients, r', between the N realizations of the series X'_k and the series Y_k. The significance of the correlation coefficient r_0 between the original series is then obtained from $s = 1 - n_0/N$, where n_0 is the number of realizations with a correlation coefficient r' exceeding $|r_0|$ (two-sided criterium). The whole procedure is repeated for the other series, Y_k, and the minimum of the two values of s is taken as the final significance estimate. The results shown in Table 3 were obtained with N = 10,000. The number of effective degrees of freedom, N_{DOF}, can be estimated by comparing the significance determined in this way with the value calculated from the standard formula, $s = f(r_0, N_{DOF})$. For the series of 98 points (AD 1000–1980), we would have $N_{DOF} = 96$ under the assumption of independent data points. However, the above estimated values of the significance level correspond to an effective N_{DOF} of about 50, 20, and 4 for the detrended series, original data, and the trends, respectively. Therefore

Table 3c. Cross-Correlation Coefficients Between the Indices Related to Solar Activity (Columns) and Northern Hemisphere Temperature Reconstructions (Rows) for Detrended Data[a]

Temperature	CR (^{14}C)	SN (^{14}C)	SN (^{10}Be)
MBH99	−0.25 (64%)	0.24 (80%)	0.30 (91%)
MJ03	−0.19 (52%)	0.21 (67%)	0.21 (54%)
B00	−0.15 (62%)	0.17 (80%)	0.34 (99%)
C00	−0.21 (62%)	0.20 (65%)	0.33 (94%)
E02	−0.06 (18%)	0.10 (34%)	0.09 (37%)
JBBT98	−0.04 (6%)	0.06 (26%)	0.12 (50%)
Average	−0.09 (53%)	0.15 (76%)	0.24 (78%)
MJ03(long)	−0.21 (84%)	0.22 (88%)	N/A

[a]"Average" refers of the arithmetic average of the six temperature series. The significance levels of the correlations (see section 3.2) are given in parentheses. All series are considered for the period 1000–1980 expect for the MJ03(long) which starts in the year 200.

the serial correlation and preprocessing of the data reduce the effective number of degrees of freedom and thus decrease the significance levels of the correlations.

3.3. Differences Between Correlation Coefficients

[20] From inspection of Table 3 and Figure 4 we find indications for systematic differences between the correlation coefficients for the various Sun-related indices:

[21] 1. There is a tendency for the correlations of temperature with the cosmic ray flux determined from ^{14}C to be stronger than those with the sunspot numbers determined from the same isotope, particularly so for the trends.

[22] 2. There is also a tendency for the correlations of temperature with the sunspot numbers reconstructed from ^{10}Be to be stronger than those with cosmic rays or sunspot numbers from ^{14}C, particularly so for the detrended data.

[23] Although these differences are insignificant for each individual temperature series, the effect is systematic. We can quantify this observation and estimate the significance of the differences between correlation coefficients as follows. Let $r_{a,i}$ and $r_{b,i}$ denote the correlation coefficients between two Sun-related series (a and b) and the various temperature series, indicated by the index i. Let the errors of the correlation coefficients be $\sigma_{a,i}$ and $\sigma_{b,i}$. The difference is $\Delta r_i = r_{a,i} - r_{b,i}$ with error $\sigma_i^2 = \sigma_{a,i}^2 + \sigma_{b,i}^2$. We treat the Δr_i as a series of varying accuracy so that the mean value is $\Delta r = \sum(p_i \Delta r_i)/p$, where $p_i = 1/\sigma_i^2$ is the weight of each point and $p = \sum p_i$. The one-sigma significance interval of Δr is defined as the arithmetic mean $\sigma = (\sigma^* + \sigma')/2$ of the expected $\sigma^* = 1/\sqrt{p}$ and the actual $\sigma' = \sqrt{\sum p_i(\Delta r_i - \Delta r)^2/[(n-1)p]}$ errors. If $\sigma' > \sigma^*$, possible systematic errors have to be considered. In all our cases $\sigma' < \sigma^*$, so additional tests are not required.

[24] Table 4 shows the mutual average differences between the correlation coefficients of the solar activity indices with the temperature reconstructions, together with the corresponding one-sigma confidence intervals as defined above. These results largely confirm the two observations listed above: (1) temperatures correlate better with cosmic rays than with sunspots as far as the long-term trends are concerned (the difference is significant nearly at the three-sigma level for the ^{14}C-based solar indices), (2) in the case of detrended data, the sunspot numbers derived from ^{10}Be correlate better with temperature than both sunspot numbers and cosmic rays from ^{14}C. The first result (if further substantiated, see below) suggests that processes connected to the cosmic ray flux (e.g., cloud formation) may affect the long-term climate changes. The second result could possibly be understood in terms of a direct climate effect on the ^{10}Be deposition in polar ice.

[25] In order to further examine the significance of the difference in the correlations between the trends in temperature and the two solar indices, we have performed two additional tests. Table 3b shows that for all six temperature reconstructions, the absolute values of the correlation coefficients with CR(^{14}C) are larger than those with SN(^{14}C). A simple sign test shows that the chance probability of this result is only about 2%, i.e., the difference is significant at about the 98% level. The second additional test is based upon a Monte-Carlo simulation. We computed a large number of synthetic temperature series defined by $T_S = T_{av} + R\sigma_T$, where T_{av} and σ_T are the average of the six temperature reconstructions and the corresponding standard deviation, respectively, while R are normally distributed (zero mean, unit width) quasi-random numbers. This implicitly takes into account the uncertainties of the temperature reconstructions. We determined the correlation coefficients between the trends of these series and the (similarly randomized) cosmic rays and sunspots series reconstructed from ^{14}C (the errors of the latter are given in the supplementary online material to *Solanki et al.* [2004]). Only in two out of 10,000 realizations, the correlation was better for sunspots than for cosmic rays, with the difference being distributed normally as 0.15 ± 0.05. This implies that the difference is significant at the three-sigma level (99%). Therefore all three tests consistently indicate that the long-term trends in the temperature correlate better with cosmic rays than with with sunspots, all at the significance level above 97%.

[26] This result can either imply that within the statistical uncertainty, modulations of the cosmic ray flux have at least as large an influence on climate as other solar parameters (e.g., irradiance) or that the solar parameters relevant for influencing the Earth's climate do not follow exactly the sunspot number.

3.4. Effect of the Geomagnetic Field

[27] Although we have seen that the long-term correlations of the various temperature series with cosmic rays are systematically stronger than those with the sunspot numbers reconstructed from the same ^{14}C isotope, this by itself does not prove that the cosmic rays have an effect on the long-term terrestrial climate. Since cosmic ray variations are anticorrelated with sunspot numbers, the solar effect on climate could be mainly due to another quantity connected with the sunspot numbers, like the total irradiance or the UV flux. However, we can use the fact that cosmic rays are modulated not only by the variable solar activity but also by the slowly changing geomagnetic field to obtain additional information. Thus if cosmic rays affect the climate, a correlation should exist between the temperature and the variations of the geomagnetic field strength. Any other Sun-related parameters should not show a dependence on the geomagnetic field. In fact, correlations between long-term paleomagnetic and paleoclimatic series have been reported, mostly for the periods of geomagnetic field reversals [*Doake*, 1978; *Courtillot et al.*, 1982; *Christl et al.*, 2004].

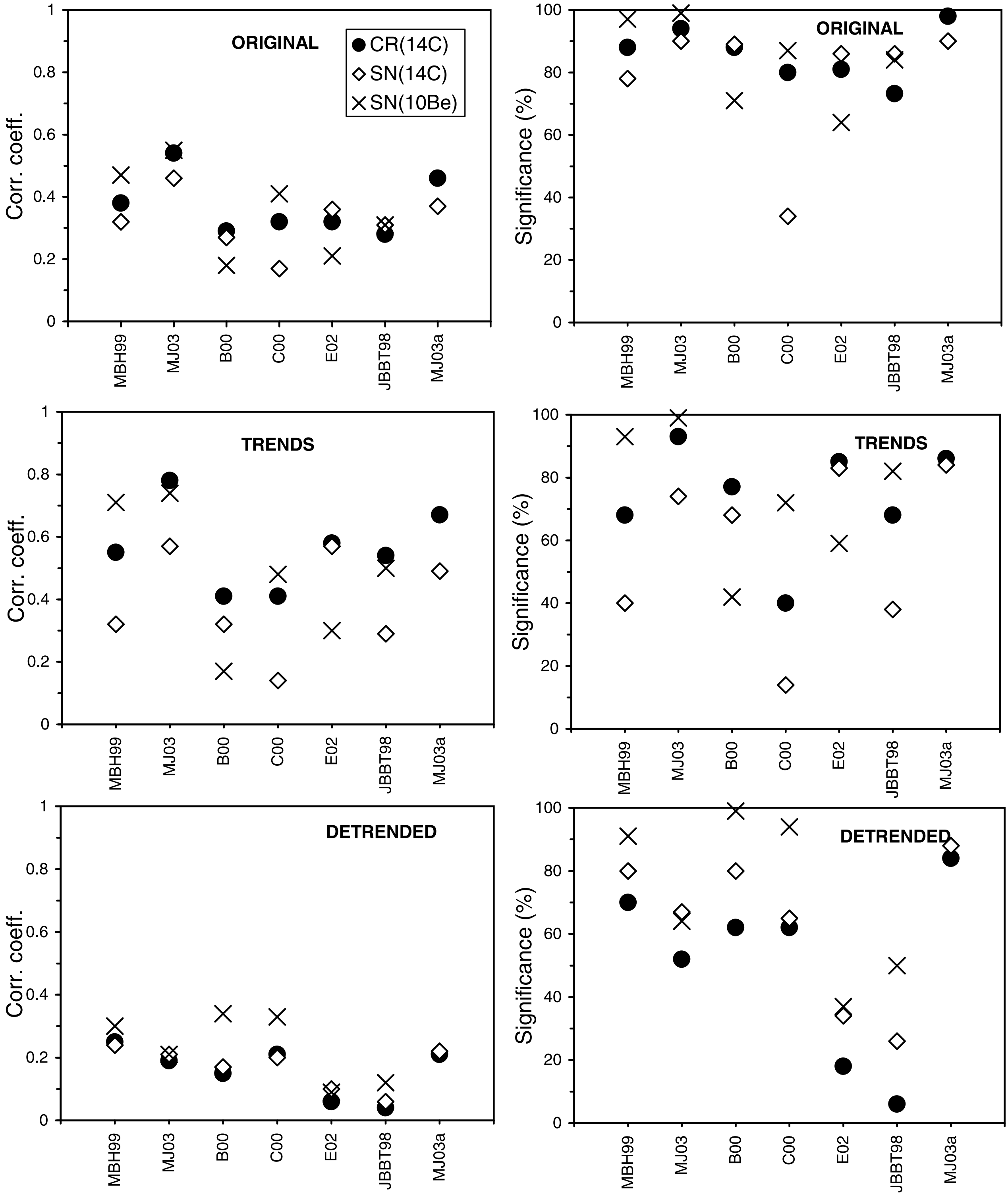

Figure 4. (left) Correlation coefficients and (right) corresponding significance levels of the correlations between the temperature reconstructions (indicated on the horizontal axis) and the three reconstructed indices related to solar activity (dots are the cosmic ray flux from ^{14}C, multiplied by -1; diamonds are the sunspot number from ^{14}C; crosses are the sunspot numbers from ^{10}Be). The numerical values are given in Table 3.

[28] Comparing the time profiles of the cosmic ray flux and the geomagnetic dipole moment (Figure 3), one clearly recognizes the general downward trend of the geomagnetic field connected with a general upward trend of the cosmic ray flux (note the inverted scale of the latter) until the end of the Maunder minimum around AD 1700. There is a similar downward trend also in sunspot numbers (Figure 3) but its slope is much smaller. Thus the larger slope in cosmic rays

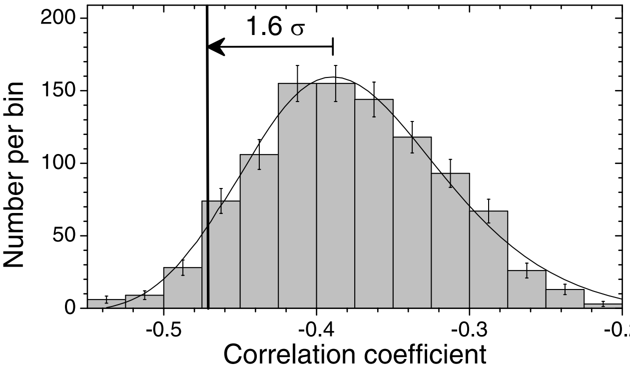

Figure 5. Distribution of correlation coefficients between the sunspot numbers derived from ^{14}C and 1000 synthetic time series determined as the sum of the trend corresponding to the temperature reconstruction MJ03 and phase-randomized shorter-term fluctuations (see text), together with the best-fit curve. The vertical line indicates the correlation coefficient of -0.47 between the original series, which exceeds the mean of the distribution at ($-0.39^{+0.07}_{-0.05}$) by 1.6 standard deviations.

is due to an additional long-term effect on cosmic rays by the decreasing geomagnetic field strength. The temperature data also display a downward trend roughly in the period AD 1000–1700. Figure 3 also shows that the trend in the cosmic ray flux stops following the geomagnetic variation after 1700. Clearly, the strong upward trend of solar activity during that time overcompensates the geomagnetic effect.

[29] Let us now consider direct and partial correlations between the temperature reconstructions and the virtual geomagnetic dipole moment given by *Hongre et al.* [1998] and by *Yang et al.* [2000]. The data by *Hongre et al.* [1998] are used for the time after AD 500 while a smooth interpolation between the two series has been carried out for the time before AD 500. All data have been interpolated on a decadal grid. The resulting series is shown in the bottom panel of Figure 3, together with the four relevant points of the *Yang et al.* [2000] series and the corresponding error bars. For the following correlation study we consider the series up to AD 1900 because of the possible anthropogenic effects unevenly distributed over the globe.

[30] The direct correlations, r_{dir}, between the geomagnetic field strength and the different temperature series are shown in the middle column of Table 5. All correlations are positive, which indicates that higher temperature goes along with a stronger geomagnetic field (via a lower cosmic ray flux). The variation of the cosmic-ray flux is a result of two processes: solar modulation (represented by sunspot numbers) and geomagnetic shielding. Here we assume that these processes are independent and that the two corresponding signals are linearly superposed in the cosmic-ray series. This assumption is justified as long as the variations of the modulation are not too large; in our case, the slow changes in the geomagnetic field and the use of decadal means, which average over the strong heliospheric modulation in the course of the 11-year cycle, support the applicability of the linear approximation. In this case, the correlation between cosmic ray flux and temperature series, r_{CT}, can be split into the partial correlations between sunspot numbers and temperature, r_{ST}, and between geomagnetic dipole moment and temperature, r_{GT}. The correlation between the geomagnetic field and the solar indices shows that while cosmic rays are anticorrelated with the geomagnetic dipole moment ($r_{GC} = -0.48^{+0.35}_{-0.24}$, significance level = 84%), the latter has no significant correlation with either sunspot number series: $r_{GS} = -0.12^{+0.23}_{-0.22}$ and $r_{GBe} = 0.1^{+0.21}_{-0.22}$ for the ^{14}C-based and the ^{10}Be-based reconstructions, respectively. Using standard methods, we can write the expected partial correlation between geomagnetic dipole and temperature as

$$r_{GT} = \frac{r_{CT} - r_{ST} \cdot r_{GC}}{\sqrt{\left(1 - r_{ST}^2\right)\left(1 - r_{GC}^2\right)}}. \qquad (1)$$

Using the values of r_{ST} and r_{CT} calculated before (see Table 3), we can determine the partial correlation coefficients r_{GT}. The results are shown in the last column of Table 5 together with the one-sigma confidence intervals, which were calculated using the standard error propagation formula. One can see that the computed partial correlation coefficients are consistent with the direct correlations (except for the E02 series). Differences between the calculated partial and direct correlations may arise from a nonlinear mixing of solar and geomagnetic effects in the cosmic ray series. Except for the B00 and E02 series, the partial correlation coefficients r_{GT} are all significant at the two-sigma (95%) level, which is consistent with an effect of cosmic rays (subject to both solar and geomagnetic modulation) on climate. We should keep in mind, however, that many of the individual correlations on which this result is based are only of low to moderate significance, so a firm statement concerning the relative importance of irradiance variations and

Table 4. Average Differences Between the Correlation Coefficients of the Solar Activity Indices With the Temperature Reconstructions, Together With One-Sigma Confidence Intervals (See section 3.3)[a]

Δr	Raw	Trends	Detrended
CR(^{14}C)-SN(^{14}C)	0.05 ± 0.05	**0.175 ± 0.06**	−0.03 ± 0.03
CR(^{14}C)-SN(^{10}Be)	0 ± 0.05	0.07 ± 0.06	**−0.10 ± 0.05**
SN(^{10}Be)-SN(^{14}C)	0.05 ± 0.07	0.10 ± 0.11	0.07 ± 0.05

[a]Values which differ from zero by more than two sigma are printed in bold.

Table 5. Cross-Correlation Between the Temperature Reconstructions and the Geomagnetic Field for the Period Before 1900: Direct Correlations, r_{dir}, and Partial Correlation, r_{GT} (See Text)[a]

Temperature	r_{dir}	r_{GT}
MNH99	$0.62^{+0.17}_{-0.26}$ (99%)	$0.47^{+0.18}_{-0.24}$ (95%)
MJ03	$0.56^{+0.23}_{-0.36}$ (89%)	$0.70^{+0.15}_{-0.26}$ (98%)
B00	$0.35^{+0.21}_{-0.26}$ (88%)	$0.30^{+0.19}_{-0.23}$ (83%)
C00	$0.53^{+0.26}_{-0.41}$ (81%)	$0.40^{+0.16}_{-0.20}$ (96%)
E02	$0.08^{+0.25}_{-0.26}$ (22%)	$0.41^{+0.20}_{-0.26}$ (90%)
JBBT98	$0.60^{+0.16}_{-0.23}$ (99%)	$0.48^{+0.18}_{-0.23}$ (96%)
Average	$0.58^{+0.19}_{-0.29}$ (96%)	$0.50^{+0.19}_{-0.26}$ (95%)
MJ03(long)	$0.44^{+0.28}_{-0.40}$ (74%)	$0.55^{+0.18}_{-0.26}$ (96%)

[a]Significance level are given in parentheses.

cosmic ray modulation for the terrestrial climate cannot be made.

4. Conclusions

[31] Sunspot numbers and cosmic ray fluxes reconstructed from records of the cosmogenic isotopes ^{10}Be and ^{14}C, respectively, show correlations and anticorrelations with a number of reconstructions of the terrestrial Northern Hemisphere temperature, which cover a time span of up to 1800 years. This indicates that periods of higher solar activity and lower cosmic ray flux tend to be associated with warmer climate, and vice versa. The major part of this correlation is due to similar long-term trends in the data sets. Although the correlations often show only low significance levels, the signs of the correlation coefficients in all cases are systematic.

[32] The long-term trend of the cosmic ray flux determined on the basis of the ^{14}C record seems to correlate better with the terrestrial temperature than the sunspot numbers derived from the same isotope data. This suggests that effects induced by cosmic rays may affect the long-term terrestrial climate. The positive correlation between the geomagnetic dipole moment and the temperature reconstructions provides further evidence favoring the cosmic ray influence on the terrestrial climate. However, the present analysis cannot determine the relative importance of (total and UV) solar irradiance and cosmic ray flux since the irradiance may show a long-term trend that does not exactly follow the averaged sunspot number.

[33] **Acknowledgment.** Arthur Richmond thanks Joanna Haigh and another reviewer for their assistance in evaluating this paper.

References

Bard, E., G. M. Raisbeck, F. Yiou, and J. Jouzel (1997), Solar modulation of cosmogenic nuclide production over the last millennium: Comparison between ^{14}C and ^{10}Be records, *Earth Planet. Sci. Lett.*, *150*, 453–462.

Bard, E., G. M. Raisbeck, F. Yiou, and J. Jouzel (2000), Solar irradiance during the last 1200 years based on cosmogenic nuclides, *Tellus B*, *52*, 985–992.

Bazilevskaya, G. A. (2000), Observations of variability in cosmic rays, *Space Sci. Rev.*, *94*, 25–38.

Beer, J., A. Blinov, G. Bonani, H. J. Hofmann, and R. C. Finkel (1990), Use of Be-10 in polar ice to trace the 11-year cycle of solar activity, *Nature*, *347*, 164–166.

Bertrand, C., M.-F. Loutre, M. Crucifix, and A. Berger (2002), Climate of the last millenium: A sensitivity study, *Tellus A*, *54*, 221.

Briffa, K. R. (2000), Annual climate variability in the Holocene: Interpreting the message of ancient trees, *Quat. Sci. Rev.*, *19*, 87–105.

Briffa, K. R., and T. J. Osborn (2002), Blowing hot and cold, *Science*, *295*, 2227–2228.

Christl, M., A. Mangini, S. Holzkämper, and C. Spötl (2004), Evidence for a link between the flux of galactic cosmic rays and Earth's climate during the past 200,000 years, *J. Atmos. Sol. Terr. Phys.*, *66*(3), 313–322.

Cook, E. R., J. Esper, and R. D. D'Arrigo (2004), Extra-tropical Northern Hemisphere land temperature variability over the past 1000 years, *Quat. Sci. Rev.*, *23*, 2063–2074.

Courtillot, V., J. L. Le Mouel, J. Ducruix, and A. Cazenave (1982), Geomagnetic secular variation as a precursor of climatic change, *Nature*, *297*, 386–387.

Crowley, T. J. (2000), Causes of climate change over the past 1000 years, *Science*, *289*, 270–277.

Crowley, T. J., and T. S. Lowery (2000), How warm was the Medieval Warm Period?, *Ambio*, *29*, 51–54.

Cubasch, U., and R. Voss (2000), The influence of total solar irradiance on climate, *Space Sci. Rev.*, *94*, 185–198.

Doake, C. S. M. (1978), Climatic change and geomagnetic field reversals: A statistical correlation, *Earth Planet. Sci. Lett.*, *38*(2), 313–318.

Ebisuzaki, W. (1997), A method to estimate the statistical significance of a correlation when the data are serially correlated, *J. Clim.*, *10*, 2147–2153.

Esper, J., E. R. Cook, and F. H. Schweingruber (2002), Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability, *Science*, *295*, 2250–2254.

Fligge, M., and S. K. Solanki (2000), The solar spectral irradiance since 1700, *Geophys. Res. Let.*, *27*, 2157–2160.

Fröhlich, C. (2000), Observations of irradiance variations, *Space Sci. Rev.*, *94*, 15–24.

Hongre, L., G. Hulot, and A. Khokhlov (1998), An analysis of the geomagnetic field over the past 2000 years, *Phys. Earth Planet. Int.*, *106*, 311–335.

Hoyt, D. V., and K. H. Schatten (1993), A discussion of plausible solar irradiance variations, 1700–1992, *J. Geophys. Res.*, *98*, 18,895.

Hoyt, D. V., and K. H. Schatten (1998), Group sunspot numbers: A new solar activity reconstruction, *Solar Phys.*, *179*, 189–219.

Jones, P. D., K. R. Briffa, T. P. Barnett, and S. F. B. Tett (1998), High-resolution palaeoclimatic records for the last millennium: Interpretation, integration and comparison with General Circulation Model control-run temperatures, *Holocene*, *8*, 455–471.

Krivova, N. A., and S. K. Solanki (2003), Solar total and spectral irradiance: Modelling and a possible impact on climate, in *Solar Variability as an Input to the Earth's Environment*, *ESA SP-535*, edited by A. Wilson, p. 275, Eur. Space Agency, Paris.

Larkin, A., J. D. Haigh, and S. Djavidnia (2000), The effect of solar UV irradiance variations on the Earth's atmosphere, *Space Sci. Rev.*, *94*, 199–214.

Lean, J., J. Beer, and R. Bradley (1995), Reconstruction of solar irradiance since 1610: Implications for climate change, *Geophys. Res. Lett.*, *22*, 3195.

Mann, M. E., and P. D. Jones (2003), Global surface temperatures over the past two millennia, *Geophys. Res. Lett.*, *30*(15), 1820, doi:10.1029/2003GL017814.

Mann, M. E., R. S. Bradley, and M. K. Hughes (1999), Northern hemisphere temperatures during the past millenium: Inferences, uncertainties, and limitations, *Geophys. Res. Lett.*, *26*, 759–762.

Mann, M. E., et al. (2003), On past temperatures and anomalous late-20th century warmth, *Eos Trans. AGU*, *84*, 256–257.

Marsh, N., and H. Svensmark (2000), Cosmic rays, clouds, and climate, *Space Sci. Rev.*, *94*, 215–230.

Raisbeck, G. M., and F. Yiou (2004), Comment on "Millenium scale sunspot number reconstruction: Evidence for an unusually active Sun since the 1940s", *Phys. Rev. Lett.*, *92*(19), 199,001.

Reid, G. C. (2003), Solar forcing of global climate change since the mid-17th century, *Clim. Change*, *37*, 391–405.

Solanki, S. K., and M. Fligge (1998), Solar irradiance since 1874 revisited, *Geophys. Res. Lett.*, *25*, 341–344.

Solanki, S. K., and N. A. Krivova (2003), Can solar variability explain global warming since 1970?, *J. Geophys. Res.*, *108*(A5), 1200, doi:10.1029/2002JA009753.

Solanki, S. K., M. Schüssler, and M. Fligge (2000), Evolution of the Sun's large-scale magnetic field since the Maunder minimum, *Nature*, *408*, 445–447.

Solanki, S. K., M. Schüssler, and M. Fligge (2002), Secular variation of the Sun's magnetic flux, *Astron. Astrophys.*, *383*, 706–712.

Solanki, S. K., I. G. Usoskin, B. Kromer, M. Schüssler, and J. Beer (2004), Unusual activity of the Sun during recent decades compared to the previous 11,000 years, *Nature*, *431*, 1084–1087.

Soon, W., S. L. Baliunas, C. Idso, S. Idso, and D. Legates (2003), Reconstructing climatic and environmental changes of the past 1000 years: A reappraisal, *Energy Environ.*, *14*, 233–296.

Stott, P. A., G. S. Jones, and J. F. B. Mitchell (2003), Do models underestimate the solar contribution to recent climate change?, *J. Clim.*, *16*, 4079–4093.

Usoskin, I. G., K. Mursula, S. K. Solanki, M. Schüssler, and G. A. Kovaltsov (2002a), Physical reconstruction of cosmic ray intensity since 1610, *J. Geophys. Res.*, *107*(A11), 1374, doi:10.1029/2002JA009343.

Usoskin, I. G., K. Alanko, K. Mursula, and G. A. Kovaltsov (2002b), Heliospheric modulation strength during the neutron monitor era, *Solar Phys.*, *207*, 389–399.

Usoskin, I. G., S. Solanki, M. Schüssler, K. Mursula, and K. Alanko (2003), A millennium scale sunspot number reconstruction: Evidence for an unusually active sun since the 1940's, *Phys. Rev. Lett.*, *91*(21), 211101, doi:10.1103/PhysRevLett.91.211101.

Usoskin, I. G., S. Solanki, M. Schüssler, K. Mursula, and K. Alanko (2004a), Reconstruction of solar activity for the last millennium using ^{10}Be data, *Astron. Astrophys.*, *413*, 745–751.

Usoskin, I. G., S. K. Solanki, M. Schüssler, and K. Mursula (2004b), Reply, *Phys. Rev. Lett*, *92*(19), 199,002.

van Loon, H., and K. Labitzke (2000), The influence of the 11-year solar cycle on the stratosphere below 30 km: A review, *Space Sci. Rev.*, *94*, 259–278.

von Storch, H., E. Zorita, J. Jones, Y. Dimitriev, F. Gonzalez-Rouco, and S. Tett (2004), Reconstructing past climate from noisy data, *Science*, *306*, 679–682.

White, O. R., A. Skumanich, J. Lean, W. C. Livingston, and S. L. Keil (1992), The sun in a noncycling state, *Publ. Astr. Soc. Pacific*, *104*, 1139–1143.

Woods, T. (2001), Solar vacuum ultraviolet irradiance measurements and models for solar cycle 23, in *SOHO 11 Symposium—From Solar Min to Max: Half a Solar Cycle With SOHO*, *ESA SP-508*, edited by A. Wilson, p. 165, Eur. Space Agency, Paris.

Wright, J. T. (2004), Do we know of any Maunder minimum stars?, *Astron. J.*, *128*, 1273–1278.

Yang, S., H. Odah, and J. Shaw (2000), Variations in the geomagnetic dipole moment over the last 12,000 years, *Geophys. J. Int.*, *140*, 158–162.

K. Mursula, Department of Physical Sciences, University of Oulu, Oulu, FIN-90014, Finland.

M. Schüssler and S. K. Solanki, Max-Planck-Institut für Sonnensystemforschung, D-37191 Katlenburg-Lindau, Germany. (schuessler@linmpi.mpg.de; solanki@linmpi.mpg.de)

I. G. Usoskin, Sodankylä Geophysical Observatory (Oulu unit), University of Oulu, Oulu, FIN-90014, Finland. (ilya.usoskin@oulu.fi)

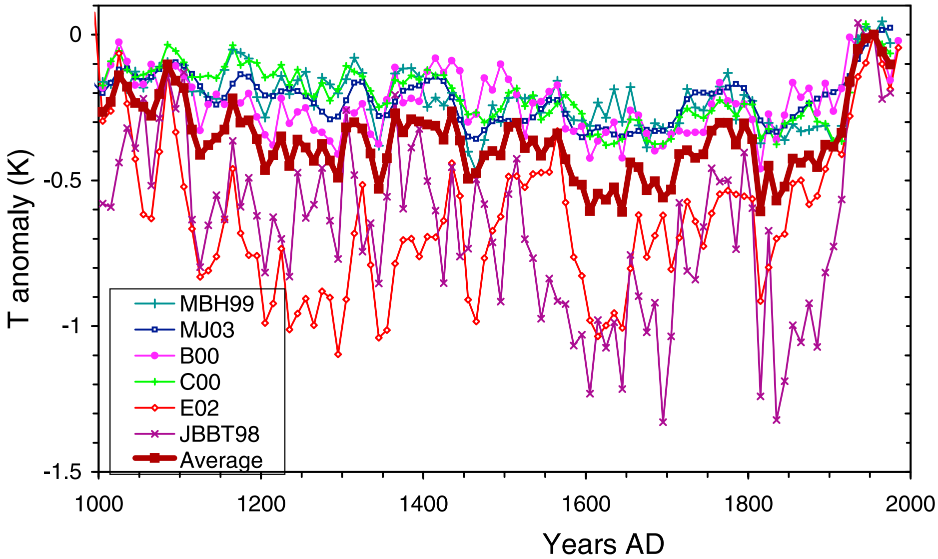

Figure 1. Data sets of Northern Hemisphere temperature reconstructions (temperature anomalies with respect to the recent instrumental record) used in this study. The labels in the legend correspond to *Mann et al.* [1999, MBH99], *Mann and Jones* [2003, MJ03], *Briffa* [2000, B00], *Crowley* [2000, C00], *Esper et al.* [2002, E02], *Jones et al.* [1998, JBBT98], and the average of these temperature series.