SOLAR ACTIVITY OVER THE LAST 1150 YEARS: DOES IT CORRELATE WITH CLIMATE?

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ABSTRACT

Previous studies of solar influence on climate variations have suffered from the relatively short length of continuous solar observations of less than 400 years. Here we present a reconstructed series of sunspot numbers to study this question over a considerably longer time interval of 1150 years. Comparison of these solar data sets with the Earth's hemispheric and global mean surface temperature series reveals very similar trends. In particular, the solar series also show a 'hockey-stick' shape. The long-term trends in solar data and in northern hemisphere temperatures have a correlation coefficient of about 0.7 – 0.8 at a 94% – 98% confidence level. The full data series correlate at a similar significance level, with the bulk of the correlation being due to the similarity in trends. The last 30 years are not considered, however. In this time the climate and solar data diverge strongly from each other.

Key words: Sunspots, cosmogenic isotopes, long-term climate variability

1. INTRODUCTION

The question of how strongly the varying solar magnetic activity affects the global temperature on Earth, is an intensely debated topic in climate research, particularly in view of the discussion 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 radiation (Rottman 1999), and the cosmic ray flux (Bazilevskaya 2000).

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, and one has to resort to proxies like the sunspot number for studies reaching further back in time. 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 non-solar origin of the most recent warming episode since about 1970, a marked (or even dominant) solar effect on climate variability until the middle of the 20th century is suggested when comparing with terrestrial temperature records (Reid 1997; Solanki and Fligge 1998; Krivova and Solanki 2003).

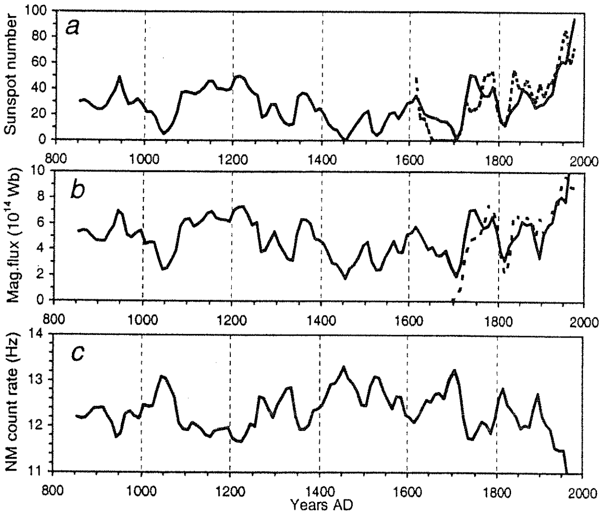

Figure 1. Long-term solar-related indices reconstructed from ^{10}Be data (Usoskin et al. 2003): Sunspot number (panel a*), open solar magnetic flux (panel* b*), and count rate of a standard polar neutron monitor (panel* c*). For comparison, the actual group sunspot numbers (Hoyt and Schatten 1998) and the open flux determined from them using a direct model (Solanki et al. 2000) are shown as dotted lines in panels* a *and* b*, respectively.*

2. DATA

The controversial evidence of such comparisons and the wish 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 ^{10}Be and ^{14}C isotopes can be used as proxies for solar activity: their production in the terrestrial

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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 the sunspot number derived from ^{10}Be data by way of physical models (Solanki et al. 2000; Solanki et al. 2002; Usoskin et al. 2002; Usoskin et al. 2003; Usoskin et al. 2004). The available data allow us to extend the comparison between relevant indices of solar activity, in particular sunspot number, and the heliospheric magnetic field with the terrestrial climate back to AD 850. This nearly triples the time interval for which such a study could be made before.

Since we are interested in time scales exceeding the solar cycle length, we consider decade-averaged data. The sunspot number series used here has been recently reconstructed from the cosmogenic ^{10}Be proxy since 850 AD (Usoskin et al. 2003) (Figure 1a). For the period after 1425, the series represents the average of two reconstructions based on ^{10}Be data from Antarctica (Bard et al. 1997) and Greenland (Beer et al. 1990) respectively. The two reconstructions are quite consistent with each other, except for a few short periods of considerable difference (e.g. 1480–1510 and 1530–1580). Before 1425, only the Antarctica series is available for the sunspot number reconstruction. For comparison, the actually observed group sunspot numbers after 1610 (Hoyt and Schatten 1998) are also shown in Figure 1a. Also plotted in Figure 1 are the Sun's open magnetic flux and cosmic ray flux, although these quantities are not further discussed in this paper.

The terrestrial climate data we use are the reconstruction of the northern hemisphere temperature between AD 1000 and AD 1980 by Mann et al. (1999) (MBH99) and the reconstructions of northern hemisphere, southern hemisphere, and global temperatures for the period between AD 200 and AD 1980 by Mann and Jones (2003) (MJ03).

3. CORRELATION ANALYSIS

A comparison between the two data sets for the northern hemisphere temperature and the reconstructed sunspot number is shown in Figure 2. It reveals similar long-term trends: a general decrease well into the 19th century and a steep rise in the 20th century (the 'hockey-stick curve'). It is clear that this trend is likely to dominate the direct correlations, so that we have considered separately the correlations coefficients for the full original data, for the detrended data, and for the trends.

Table 1 shows the results of our correlation analysis. In all cases we have correlated the sunspot number with the four temperature series (MBH99, MJ03 north, MJ03 south, and MJ03 global). Very similar results are obtained if the reconstructed sunspot numbers are replaced by the actual group sunspot numbers after 1610 (dotted lines in Figure 1a,b.) The first block of the table gives the correlation coefficients for the original data. There are positive correlations of the northern hemisphere and global (average of northern and southern) temperatures with the sunspot number and open magnetic flux. These correlations are significant, with confidence levels between 96% and 99% . There is no significant correlation with the southern hemisphere temperatures of MJ03, which is not surprising in view of the fact that the northern and southern temperatures of MJ03 are not correlated either. This may be due to the fact that the southern hemisphere temperature reconstruction is based on rather sparse data sets.

The long-term trends and the effectively decreased number of degrees of freedom (because of serial correlation) means that standard tests overestimate the significance levels, since these tests assume that all data points are independent. To determine the significance of our correlations, we have therefore used the non-parametric 'random-phase' Monte-Carlo method (Ebisuzaki 1997), which does not suffer from this problem.

In order to evaluate the relative importance of the long-term trend and the shorter-term variablity for the correlations, we have fitted sixth-order polynomials to all data sets and determined correlation coefficients after subtraction of the polynomial fits (detrended data) as well the correlations between the fit polynomials alone (trends). All detrended data show a consistent positive correlation between sunspot number and the temperatures. However, the significance of these correlations is marginal. The correlations of the trends are significant at the 94% (MBH99) and 98% (MJ03) significance levels for the two northern hemisphere temperatures.

It is conceivable that the correlation of the used solar indices with the terrestrial temperatures is due to the effect of climate on the ^{10}Be concentrations from which the sunspot numbers were reconstructed. However, we consider this possibility to be rather unlikely for the following two reasons. Firstly, the ^{10}Be data are consistent with the ^{14}C data, which are known to be little (or, at least, very differently) affected by climate variations (Bard et al. 1997; Beer 2000). This is apparent from the similarity of sunspot numbers reconstructed from the two isotopes (Solanki et al., in preparation). Secondly, the best correlations between sunspot number and the temperature data are consistently obtained for a time lag of 10 years in the sense that solar data lead temperature data. This is illustrated in Figure 3, which shows the variation of the correlation coefficient between the northern hemisphere temperatures (MJ03) and the reconstructed sunspot number as a function of time lag, positive lags corresponding to sunspot numbers leading the temperature. This relationship does not support an important climatic effect on the ^{10}Be record.

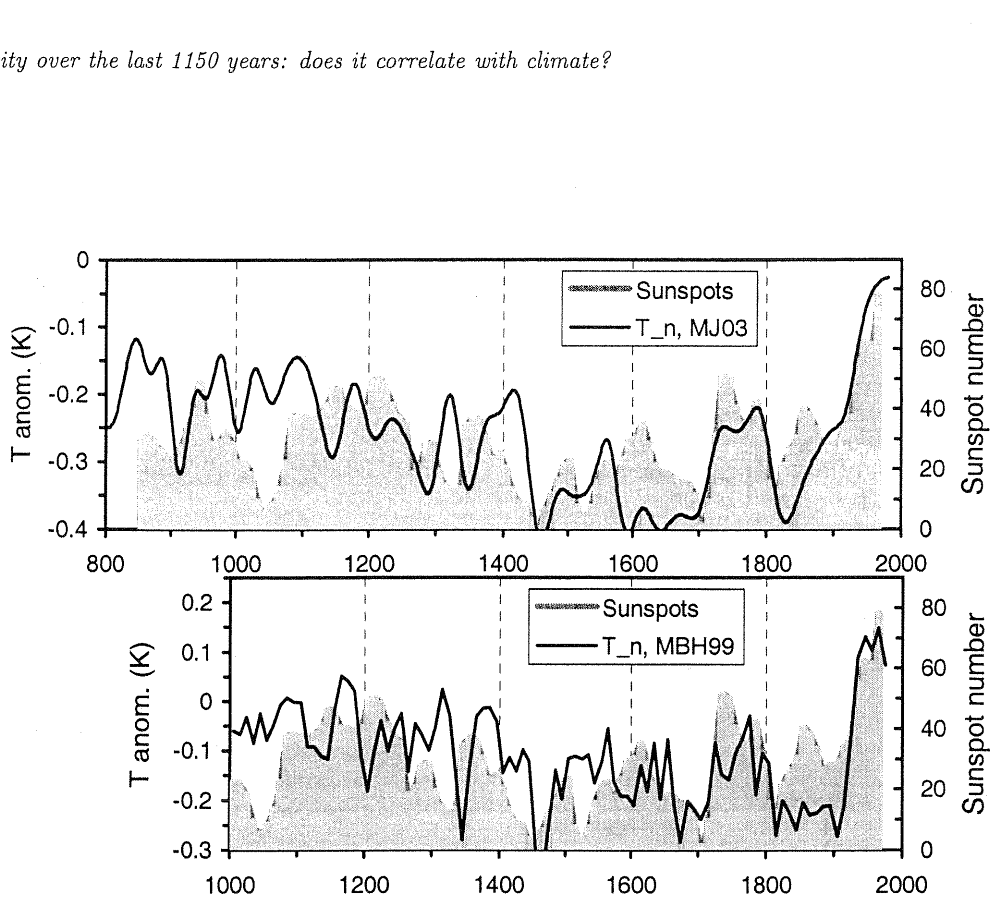

Figure 2. Long-term climate data (black lines) and sunspot numbers (grey-shading, see Figure 1a). The sunspot numbers derived from the ^{10}Be records since AD 850 by Usoskin et al. (2003) are compared with the reconstructions of the northern hemisphere ground temperature by Mann and Jones (2003) (MJ03, upper panel) and by Mann et al. (1999) (MBH99, lower panel).

Table 1. Cross-correlation coefficients between Sunspot number (second column) and, 10-year delayed, Earth's temperature reconstructions (rows). The significance level and the 1σ confidence intervals are given in the last two columns.

a) Original data

T series	Sunspots	Significance	Conf. interval
MBH99	0.51	0.98	+0.16/-0.20
MJ03 N	0.54	0.99	+0.15/-0.19
MJ03 S	-0.1	0.50	+0.20/-0.20
MJ03 G	0.33	0.96	+0.16/-0.19

b) Detrended data

T series	Sunspots	Significance	Conf. interval
MBH99	0.31	0.95	±0.16
MJ03 N	0.22	0.85	±0.17
MJ03 S	0.23	0.88	±0.16
MJ03 G	0.22	0.85	±0.17

c) Trends

T series	Sunspots	Significance	Conf. interval
MBH99	0.71	0.94	+0.17/-0.33
MJ03 N	0.83	0.98	+0.10/-0.22
MJ03 S	-0.74	0.88	+0.18/-0.48
MJ03 G	0.49	0.7	+0.28/-0.44

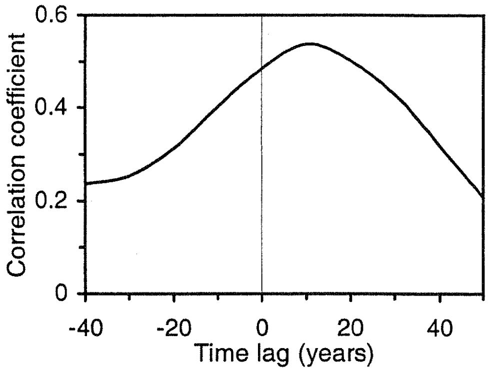

Figure 3. Correlation coefficient between northern hemisphere temperatures (MJ03) and the reconstructed sunspot number as a function of time lag between the two data series. Positive lags correspond to sunspot numbers leading the temperature.

4. CONCLUSIONS

The sunspot number index related to solar activity that has been reconstructed from the cosmogenic ^{10}Be isotope data since AD 850 shows correlation with terrestrial northern hemisphere and global temperature reconstructions at a significance level above 95%. The major part of this correlation is due to similar long-term trends ('hockey-stick curve') in the data, but there is also a consistent (although only marginally significant) correlation in the detrended data, i.e., on centennial and intracentennial time scales. This suggests that long-term climate variations are affected by solar magnetic activity.

Note that the most recent warming, since around 1975, has not been considered in the above correlations. During these last 30 years the solar total irradiance, solar UV irradiance and cosmic ray flux has not shown any significant secular trend, so that at least this most recent warming episode must have another source.

REFERENCES

Bard, E., G.M. Raisbeck, F. Yiou, and J. Jouzel, 1997, Earth Planet. Sci. Lett., 150, 453

Bard, E., G. M. Raisbeck, F. Yiou, and J. Jouzel, 2000, Tellus B, 52, 985

Bazilevskaya, G.A., 2000, Space Sci. Rev., 94, 25

Beer, J., 2000, Space Sci. Rev., 94, 53

Beer, J., A. Blinov, G. Bonani, H. J. Hofmann, and R. C. Finkel, 1990, Nature, 347, 164

Bertrand, C., M.-F. Loutre, M. Crucifix, and A. Berger, Tellus A, 2002, 54, 221

Cubasch, U., and R. Voss, 2000, Space Sci. Rev., 94, 185

Ebisuzaki, W., J. 1997, Clim., 10, 2147

Hoyt, D.V., and K.H. Schatten, 1993, J. Geoph. Res., 98, 18895

Hoyt, D.V., and K.H. Schatten, 1998 Solar Phys., 179, 189

Fligge, M., and S.K. Solanki, 2000, Geoph. Res. Let., 27, 2157

Fröhlich, C., 2000, Space Sci. Rev., 94, 15

Krivova, N. A., and S. K. Solanki, in A. Wilson (ed.): 2003, *Solar Variability as an Input to the Earth's Environment*, ESA SP-535, European Space Agency, 275

Larkin, A., J. D. Haigh, and S. Djavidnia, 2000, Space Sci. Rev., 94, 199

Lean, J., J. Beer, and R. Bradley, 1995, Geoph. Res. Let., 22, 3195

Mann, M.E., R.S. Bradley, and M.K. Hughes, 1999, Northern hemisphere temperatures during the past millenium: inferences, uncertainties, and limitations, Geophys. Res. Let., 26, 759

Mann, M.E., and P.D. Jones, 2003 Geophys. Res. Let., 30, DOI 10.1029/2003GL017814

Marsh, N., and H. Svensmark, 2000, Space Sci. Rev., 94, 215

Reid, G.C., 2003, Clim. Change, 37, 391

Rottman, G., 1999, J. Atm. Terr. Phys., 61, 37

Solanki, S.K., and M. Fligge, 1998, Geoph. Res. Let., 25, 341

Solanki, S. K., M. Schüssler, and M. Fligge, 2000, Nature, 408, 445

Solanki, S. K., M. Schüssler, and M. Fligge, 2002, Astron. Astrophys., 383, 706

Stott, P.A., G.S. Jones, and J.F.B. Mitchell, 2003, J. of Climate, 16, 4079

Usoskin, I.G., K. Mursula, S.K. Solanki, M. Schüssler, and G.A. Kovaltsov, 2002, J. Geophys. Res., 107(A11), SSH 13-1–6, doi: 10.1029/2002JA009343

Usoskin, I.G., S. Solanki, M. Schüssler, K. Mursula, and K. Alanko, 2003, Phys. Rev. Lett., 91(21), 211101, doi:10.1103/PhysRevLett.91.211101

Usoskin, I.G., S. Solanki, M. Schüssler, K. Mursula, and K. Alanko, 2004, Astron. Astrophys., 413, 745

van Loon, H. and Labitzke, K., 2000, Space Sci. Rev., 94, 259