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On possible drivers of Sun-induced climate changes

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Abstract

We tested the validity of two current hypotheses on the dependence of climate change on solar activity. One of them states that variations in the tropospheric temperature are caused directly by changes of the solar radiance (total or spectral). The other suggests that cosmic ray (CR) fluctuations, caused by the solar/heliospheric modulation, affect the climate via cloud formation. Confronting these hypotheses with seven different sets of the global/hemispheric temperature reconstructions for the last 400 years, we found that the former mechanism is in general more prominent than the latter. Therefore, we can conclude that in so far as the Sun–climate connection is concerned tropospheric temperatures are more likely affected by variations in the UV radiation flux rather than by those in the CR flux.

Keywords: Climate variability; Coronal mass ejections; Interplanetary magnetic clouds; Solar activity; Sun–climate interaction; Sunspot number

1. Introduction

There is general agreement that variations in the global (or hemispheric) tropospheric temperature are, at least partly, related to those in solar activity (e.g., Bond et al., 2001; Solanki and Krivova, 2003; Usoskin et al., 2005; Kilcik, 2005). A widely cited, though not clearly defined (Jones and Mann, 2004) example of this link is provided by the presumptive cold spell, known as the Little Ice Age, during the period of greatly reduced solar activity, viz. the Spörer and Maunder minima in the 16th–17th centuries (Eddy et al., 1982).

However, the question of how exactly the solar variability can influence the climate is still open. Direct satellite measurements of the total solar irradiance (TSI), i.e. the wavelength-integrated solar radiation flux (also known as the bolometric radiation flux, or the solar constant) performed since 1979 (Fröhlich, 2003, 2004; Fröhlich and Lean, 2004) show clear cyclic variations in phase with the sunspot cycle and with amplitude of about 0.1%. Such a small variation of the TSI would not produce any significant temperature variation (Stott et al., 2003). On the other hand, cyclic variations of the spectral irradiance are different in different wavelength diapasons: while the variations in the visible part of the solar spectrum are small during the solar cycle (discussed in review by De Jager, 2005), the amplitude of the variation is larger by factors up to and above 100 (wavelength dependent) in the UV part of the spectrum (Unruh et al., 1999; Lean, 2000; Woodard and Libbrecht, 2003).

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This part of the solar irradiance spectrum is mostly absorbed in the Earth's stratosphere, resulting in stratospheric heating. Hence, variations of the mean tropospheric temperature must include stratosphere–troposphere interaction. Although a detailed mechanism effectively transferring stratospheric heating into the troposphere is yet not clear, there are several scenarios for that (cf. e.g. Haigh, 1996; Hood, 2004; Matthes et al., 2004; Ruzmaikin et al., 2004; Kodera and Kuroda, 2004; Langematz et al., 2005; Baldwin and Dunkerton, 2005).

Different solutions to the problem have been suggested (see, e.g., a review by Haigh et al., 2005) such as an unknown long-term trend in the irradiance (Fröhlich and Lean, 2004; Solanki and Krivova, 2004; Wang et al., 2005), a terrestrial amplifier of the irradiance variations (e.g., Haigh, 1996; Shindell et al., 1999), or a concurrent mechanism which is also driven by the solar activity. A good candidate for the latter is the variable cosmic ray (CR) flux.

Galactic CRs are always bombarding the Earth's atmosphere. The flux of CRs varies during the solar cycle in an opposite phase to that of sunspots. Modulation of CRs is ultimately driven by the solar chromospheric and coronal activity, viz. by the solar wind with frozen-in magnetic field, eruptive transient phenomena (CMEs, interplanetary shocks), etc. A more active Sun means stronger deflection and thus a weaker flux of CRs impinging on Earth. Nucleonic–electromagnetic cascades initiated by CRs in the atmosphere are the main source of ionization in the troposphere, which alters its physical properties and can affect cloud formation. Two possible mechanisms have been suggested to explain how CRs can control cloud formation: growth of cloud condensation nuclei facilitated by the induced ionisation (e.g., Marsh and Svensmark, 2003; Yu, 2002) and electro-freezing by vertical current system induced by the solar wind interacting with the magnetosphere (Tinsley, 1996). Although details of these mechanisms are still missing, many evidences have been presented of the correlation between the CR flux and the low cloud cover (Pudovkin and Veretenenko, 1995; Svensmark and Friis-Christensen 1997; Svensmark, 1998; Usoskin et al., 2004; Palle et al., 2004). Even a small change in the cloud cover shifts the balance between albedo and transmission of the atmosphere in different wavelengths thus influencing the amount of absorbed radiation, and therefore the climate without invoking notable changes in the solar irradiance. This gives a physically motivated scenario where a small amount of energy can have a dramatic impact via an enhancing trigger effect.

Studies based on recent data cannot reliably distinguish between different solar drivers (e.g., CR or UV), which are strongly interrelated and whose effects are concurrent (Usoskin and Kovaltsov, 2006). Moreover, solar–terrestrial links can be masked by the rapidly increasing anthropogenic factor during the last decades. Here we try to disentangle these effects using data of the sunspot activity, the CR flux and the temperature for the last 400 years. To that extend we have to define proxies for the two effects.

The enhanced UV flux is emitted by facular fields in Active Regions in and slightly above the solar photosphere (i.e. regions around sunspot groups), leading to a close relation between the UV spectral irradiance and the sunspot number (e.g., Floyd et al., 2005). Accordingly, we consider the historical record of the Group Sunspot Number R_G (Hoyt and Schatten, 1998) as a proxy for the UV flux (cf. Lean, 2000a). We note that a possible long-term trend in the UV flux might have been overlooked in such an approach, but this cannot be properly accounted for. On the other hand, other spectral ranges of the solar irradiance may equally well correspond to the sunspot number series.

Here we use two different proxies for the CR flux modulated in the heliosphere. One is a theoretical proxy, based on the modulation theory. CR modulation is driven by the solar magnetic field taken away by the solar wind, and can be quantified by the source term S of the open magnetic flux (cf. Solanki et al., 2000, 2002). This quantity has been computed by Usoskin et al. (2002) from the sunspot numbers since 1610. Another empirical proxy, called B henceforth, is related to the deposition rate of the cosmogenic radionuclide ^{10}Be in Greenland ice cores (Beer et al., 1990). Deposition of ^{10}Be is straightforward and quick and is commonly considered to be directly proportional to the ^{10}Be production rate and, thus, to the CR flux (Usoskin et al., 2003). In this paper we will use both proxies.

We want to stress that while R_G and B are anti-correlated, they are defined by different processes. E.g., only a fraction of the CR flux variations can be directly associated with the sunspot numbers. That fraction is mainly due to Coronal Mass Ejections (Harvey, 1993; Lockwood et al., 1999; Shrivastava and Jaiswal, 2003) which occur in a fairly broad band inside and around the Active Regions (cf. review by Zhang and Low, 2005). Their frequency of occurrence is directly related to the variation in the number of strong flares (Lin, 2004) and to R_G. However, another part of interplanetary disturbances modulating CRs is related to coronal holes and polar faculae, solar features that are related to the poloidal magnetic field component (elaborated in review by De Jager, 2005). We note that the sunspots and Active Regions originate from the solar toroidal magnetic field component and that the polar faculae and associate phenomena are related to the poloidal field component (Dikpati and Charbonneau, 1999). Therefore, the R_G and B or S-indices correspond partly to different components of the solar magnetic fields. These two variables are not always closely related. A notorious example is the Maunder Minimum (review by Soon and Yaskel, 2004), when only a few or no sunspots at all were visible, while ejection of coronal plasma did continue to occur at a regular pace (Beer et al., 1998; Usoskin et al., 2001).

The aim of this investigation is to examine whether tropospheric temperature variations are related to R_G or rather to the B- or S-variables. In other words: direct solar radiation effect (presumably UV heating) versus CR-induced cloud formation. We will do this by statistically comparing seven recent data sets of tropospheric temperatures with R_G and B or S-data. We restrict this investigation to the period between 1610 and 1965 for the following reasons: A continuous series of R_G data is only available after 1610, while the cosmogenic ^{10}Be data are not reliable for the last few decades because the top part of an ice core is sometimes omitted for technical reasons (e.g., Usoskin et al., 2004a). Moreover, T-data after ~1965 may become dominated by the anthropogenic influence (Solanki and Krivova, 2003). Since we are interested in the long-term trend, we do this investigation for smoothed data in order to avoid the strong 11-year cyclic variation. We note that, as can be expected, the S and B functions are strongly correlated, as is shown in Fig. 1, where the smoothed data of B are plotted against those of S.

2. Dependence of T on R_G and B or S: temperature reconstruction by Moberg et al. (2005)

First, we discuss in great details one recent temperature reconstruction, viz. that by Moberg et al. (2005), which is the most recent publication at the time of preparing this paper. This T-series presents average Northern hemisphere temperatures in relative values, but for simplicity we will call them T (omitting the prefix Δ) in this paper. Before processing, all the R_G, B, S and T datasets were smoothed using a triangular smoothing function $sm(y+t)$ with half width h years, i.e. $sm(y) = 1$ and $sm(y-h) = sm(y+h) = 0$, with linear interpolation in between.

The best value of the smoothing parameter h was found empirically as follows. Changing the h-value, we calculated the correlation coefficient and the r.m.s. scattering for the T and R_G series smoothed using this h value, as shown in Table 1. We see that the 'best' half width values are $h = 8$–9, which correspond to the smallest r.m.s. and which are still close to the maximum correlation value. Throughout this paper we assumed $h = 9$. We checked that

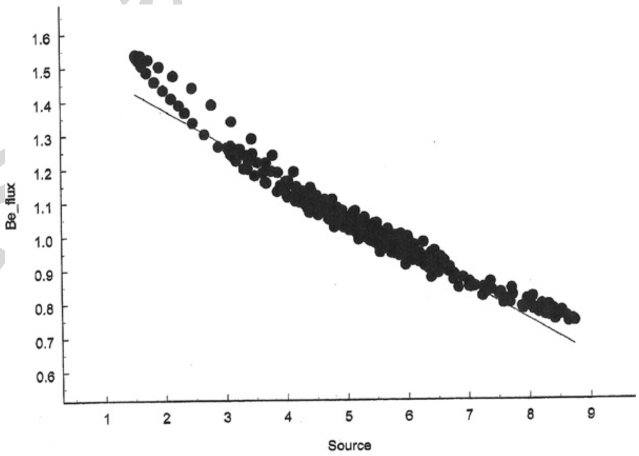

Fig. 1. A plot of the smoothed ^{10}Be data (B) against those of the source function S, for the period under investigation. It shows the strong correlation between these functions.

Table 1
Searching for the 'best' smoothing parameter h

h value (years)	Correlation	r.m.s.
1	0.67	0.21
2	0.70	0.20
3	0.74	0.19
4	0.78	0.17
5	0.811	0.158
6	0.823	0.148
7	0.823	0.141
8	0.814	0.138
9	0.798	0.136
10	0.780	0.136
11	0.76	0.136
12	0.74	0.136

using a slightly different value of h (7–11) does not alter the main result. We used the T–R_G correlation for this exercise because T correlates better with R_G than with S or B, as will be shown below in this section.

Figs. 2–5, respectively show the scatter functions $S(R_G)$, $T(R_G)$, $T(B)$ and $T(S)$. It is clear that there is no random scatter of data but rather a systematic drift of the data in the course of time, with important excursions. Some dates are marked in the Figures for convenience. Note e.g. the Maunder Minimum (1652–1704), the 'loops' of 1726–1749 and 1865–1901, and the years 1921-1923 (cf. Duhau and Chen, 2002), prelude of the exceptional increase of solar activity of the 2nd half of the 20th century.

Figs. 3–5 suggest that T correlates better with the Group Sunspot Number R_G than with the CR flux B (or the source function S). Since the data have been smoothed before the analysis, the significance of the found correlation coefficients cannot be evaluated by the standard formulae. Therefore, we used the non-parametric method (Ebisuzaki, 1997), which includes three steps: First, the time series is decomposed in its Fourier basis, then the phase of the FFT series is randomised while keeping the power spectrum, and finally a new synthetic series is composed by inverse FFT transform. This procedure guarantees that the synthetic series has the same power spectrum and autocorrelation as the original one, but has a totally random phase. Then, for a number N of such synthetic series (we used $N = 10{,}000$) the correlation coefficient is computed and the significance is estimated as $(N–N_0)/N \times 100\%$, where N_0 is the number of simulations

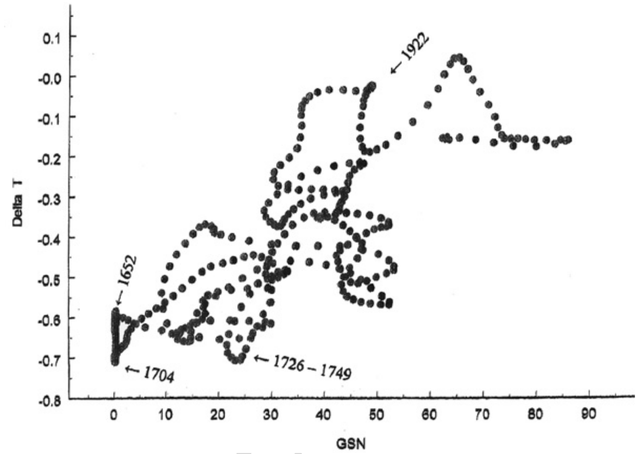

Fig. 3. Dependence of the average Northern Hemisphere temperature T according to Moberg et al. (2005) on the Group Sunspot Number R_G.

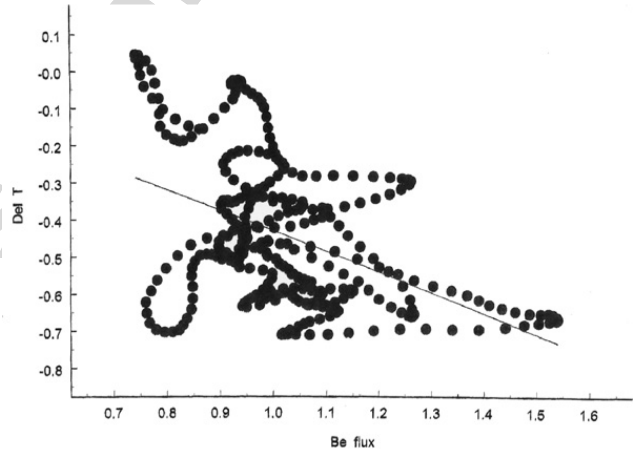

Fig. 4. Dependence of the average Northern Hemisphere temperature T according to Moberg et al. (2005) on the ^{10}Be deposit flux B.

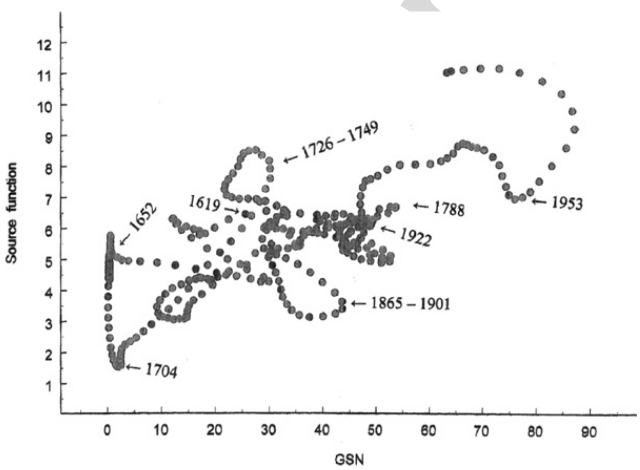

Fig. 2. Relation between the source function S and the Group Sunspot Number R_G. Some important years and episodes are marked.

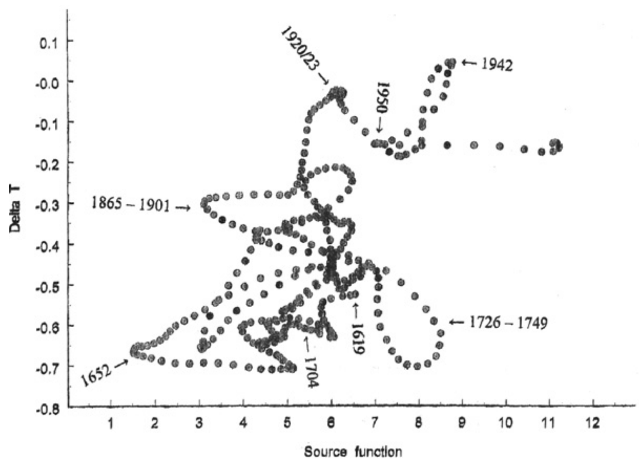

Fig. 5. Dependence of the average Northern Hemisphere temperature T according to Moberg et al. (2005) on the source function S.

where the correlation coefficient exceeds the real one in absolute units. This is repeated for the other series and the worst case is taken as the estimated value.

Thus we find:

Correlation between T and R_G series is 0.77 (+0.10/−0.17), significance level 99.8%.

Correlation between T and S series is −0.53 (+0.21/−0.17), significance level 96%.

The *conclusion* is that the Moberg et al. temperature series is better correlated with the Group Sunspot Number than with the CR flux, indicating that climate is more likely influenced by the variable UV radiation flux rather than by the modulation of CRs.

It is also interesting if there is any time delay between solar variability and tropospheric temperature variations. To study this question we calculated the correlation coefficients in the same way as described above for time shifted series, as shown by Figs. 6 and 7. For the dependence of temperature on R_G we found a small effect: the highest correlation coefficient corresponds to a delay of about 2 years, but the difference from zero-delay is not significant. For the T versus S dependence the delay is remarkably large, about 20 years, but the correlation coefficient is for that time interval still significantly smaller than that for $T(R_G)$. Also for that interval the difference with zero-delay is not significant.

We note that, since the CR flux is related to the sunspot numbers, some residual correlation between T and S is anyway expected even if there is no real physical link between them, simply because they both correlate with R_G. In order to verify this hypothesis we computed the partial correlation

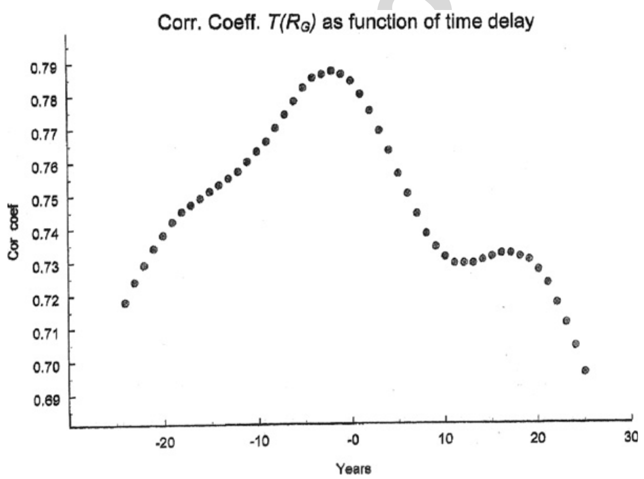

Fig. 6. Searching for a time delay between T and R_G.

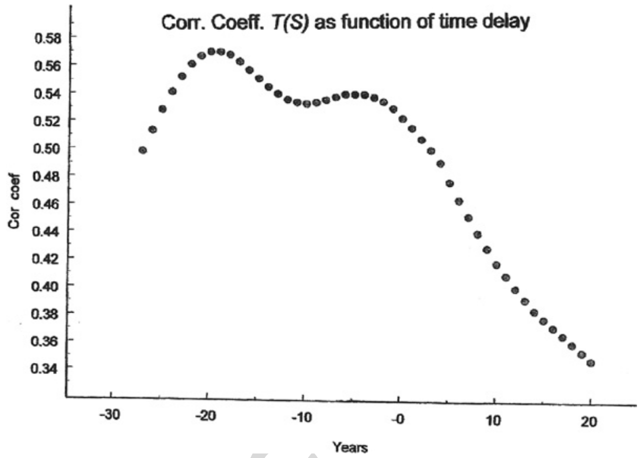

Fig. 7. Searching for a time delay between T and S.

between T and S, while fixing R_G, as

$$P_{T(R)S} = \frac{C_{TS} - C_{TR}C_{RS}}{\sqrt{(1 - C_{TR}^2)(1 - C_{RS}^2)}},$$

where values like C_{AB} denote the coefficient of the bivariate (full) cross-correlation between variables A and B. The value of $P_{T(R)S}$ corresponds to the correlation between T and S assuming the R-variable being fixed constant. In other words, it represents the 'real' $T(S)$ correlation after removing an induced relation due to variations of R which can simultaneously affect the other two variables. For the Moberg et al. time series the values of $P_{T(R)S}$ appears to be 0.07, hence practically zero. This implies that the whole correlation between CRs and climate can be explained by the effect of sunspot numbers on both temperatures and CR flux.

We have also tested an opposite hypothesis, viz. that the CR directly affects T, while the observed $T(R)$ relation is induced by the correlation between R and S. In this case, the partial correlation $P_{T(S)R} = 0.71$, which is very close to the bivariate (full) correlation between T and R. Therefore, there is no need to assume a relation between T and S (or B) in order to explain the observed correlations.

Finally, to graphically illustrate the above conclusions, we take the $T(S)$ dataset and subtract from it the average $T(R_G)$-dependence. That is: subtract from each $T(t)$ value (where t is time) the linear regression relation $\Delta T(t) = x + y \times R_G(t)$. This is done, analogously to what has been done before with the partial correlations, in order to examine what the $T(S)$ relation would look like when the *average* $T(R_G)$ relation is subtracted from it.

Note that this procedure has only approximate significance. It is not perfect because in subtracting the linear average we do not take into account the important excursions in the $T(R_G)$ function as shown in Fig. 3. Anyway, we found $d(T-\Delta T)/dS = -0.0025$, hence about zero (Fig. 8). This again confirms diagrammatically that the partial correlation $P_{T(R)S}$ is practically zero, in other words that tropospheric temperature variations only marginally depend on the source function S or not at all.

3. Checking this result for other temperature sets

Above we considered, as a pilot calculation, only one temperature reconstruction, but many more or less independent reconstructions of global or hemispheric tropospheric temperatures have been published recently. In order to verify our conclusions, we have repeated the analysis for six other datasets,

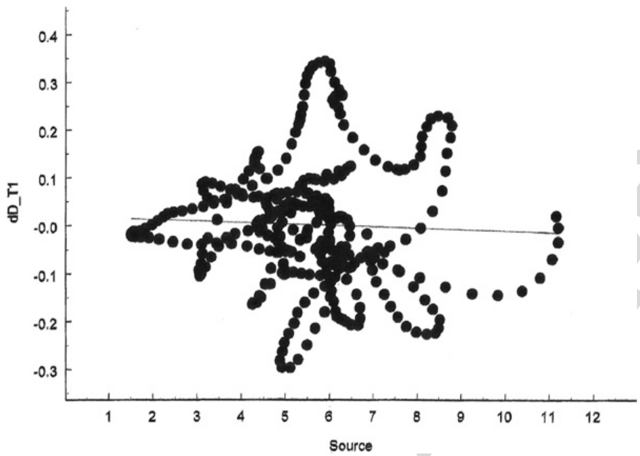

Fig. 8. This plot of T–$\Delta T(R_G)$ against S shows that subtraction of the average dependence of T (for the Moberg et al. dataset) on the Group Sunspot Number R_G from the temperature data leaves virtually no dependence of T on S.

so that the total number of temperature series is seven, viz.:

1. et al. (2005),
2. Jones et al. (1998),
3. Mann et al. (1999),
4. Briffa (2000),
5. Overpeck and Hughen (1997),
6. Crowley and Lowery (2000),
7. Mann and Jones (2003).

The annual temperature data were smoothed as described in Section 1. The results of the statistical analyses are given in Table 2, where we have also included the results for the Moberg et al. dataset that are described in Section 2. The second and third columns contain the full correlation coefficients computed for zero time shifts. Values for non-zero time shifts give essentially the same results, within a bracket of some 5 years (cf. Figs. 6 and 7). The last column gives the partial correlations between T and S-variables with the fixed R_G.

The table shows that correlation coefficients between the T and R_G -series C_{TR} range between 0.58 and 0.77 (significance of all correlations is above 97%). The correlation coefficient C_{TS} for the $T(S)$ dependency is in all cases smaller but also highly significant (above 91%). There are differences, though, from one set to another. For temperature sets #1 and #7 C_{TS} have the highest values, but still just barely above 0.5. For these sets the partial correlations have also the highest values (0.2 and 0.15), but these too remain small and practically insignificant. All results together strengthen the conclusion of Section 2 that the tropospheric temperature variations can be explained by using only variation in the direct solar (UV) radiance.

Table 2
Full and partial correlation coefficients for seven data sets

Temperature dataset	Cor.coeff. C_{TR}	Cor.coeff. C_{TS}	Partial corr. $P_{T(R)S}$
1. Moberg	0.77	0.53	0.07
2. Jones	0.55	0.47	0.15
3. Mann	0.52	0.50	0.20
4. Briffa	0.76	0.48	0.06
5. Overpeck, Hughen	0.60	0.35	0.01
6. Crowley	0.77	0.43	−0.01
7. Mann, Jones	0.72	0.54	0.15

We note that using the *B*-index of the CR variations, instead of the *S*-index, does not alter the results.

4. Conclusion

By means of a statistical analysis we have studied relations between sunspot numbers, the CR flux and seven tropospheric temperature series for the last 350 year, a period for which Group Sunspot Numbers are available. We have shown that the long-term variations of tropospheric temperatures are likely affected by variability in the direct solar radiation, presumably UV flux, rather than by variations in the cosmic radiation flux. This statistical result is indicative and a more detailed study is needed, including longer time scales, where the geomagnetic field changes can be significant to distinguish between the different effects (Usoskin et al., 2005), as well as physical modelling of the relations, in order to make more precise conclusions. CRs may still play a role in cloud formation on different time scales (see e.g. review by Usoskin and Kovaltsov, 2006). Although the sunspot number index is discussed here as a proxy for the UV flux, it may equally well represent other spectral ranges. Accordingly, further studies are needed to refine the exact mechanism of the long-term solar variability affecting the climate.

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