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Long-term variations of the solar-geomagnetic correlation, total solar irradiance, and northern hemispheric temperature (1868–1997)

P.V. Kishcha, I.V. Dmitrieva, V.N. Obridko*

Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences, 142092, Troitsk, Moscow Region, Russia

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Abstract

Time series for annual means of sunspot numbers, aa-indices of geomagnetic activity and annual numbers of 3-h time intervals with different values of aa-indices (aa $\leq$ 4 and aa $\geq$ 30) from 1868 to 1997 have been examined by the method of running-window cross-correlation analysis. It has been found that the solar-geomagnetic correlation varies over time. In particular, long-term variations of the 23-year running correlation appear to have a quasi periodicity of about 40–50 years, superposed on a linear trend, where the trend describes a general decrease of the 23-year running-window correlation between 1868 and the present. Long-term variations of the solar-geomagnetic correlation may result from the quasi-periodic fluctuations of the time lag of geomagnetic indices relative to sunspot numbers, superposed on an upward linear trend of time lag. Secular variations of the northern hemisphere land-air surface temperature anomalies and two solar indices that are potential proxy measures for the total solar irradiance (i.e., the length of the sunspot cycle and the Hoyt and Schatten (Hoyt, D.V., Schatten, K.V., 1993. Journal of Physical Research 98, 18,895–18,906.) composite index) have been compared with the long-term variations of the solar-geomagnetic correlation. The extremum points (points where the derivative vanishes to zero) of these variations are found to occur contemporaneously during the periods of low solar-geomagnetic correlation, suggesting, perhaps, that the long-term variations of solar-geomagnetic correlation are due to some long-term processes on the Sun and that they have a measurable effect on the Earth. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

The influence of solar variability on climate remains one of the most important problems of solar-terrestrial physics due to its significance for long-term weather forecasting. A large number of studies have been devoted to this problem (from Wild, 1882; to Bucha and Bucha, 1998) and several mechanisms have been proposed to explain long-term climate changes due to the effects of solar phenomena. For example, long-term changes in the total solar irradiance (Friis-Christensen and Lassen, 1991; Hoyt and Schatten, 1997; Wilson, 1998), modulation of the atmosphere transparency properties induced by galactic cosmic rays and solar ultraviolet variability (Pudovkin and Raspopov, 1992), and modifications of the global electric circuit and cloud microphysics (Tinsley, 1996, 1997) have been suggested as possible mechanisms whereby the Sun (and its solar wind) may influence the Earth's climate.

In particular, Friis-Christensen and Lassen (1991)

* Corresponding author. Fax: +7-95-334-0124.
E-mail address: obridko@lars.izmiran.troitsk.ru (V.N. Obridko)

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obtained a correlation of high statistical significance between the global land-air surface temperature anomalies and the length of the sunspot cycle (Butler, 1994; Butler and Johnston, 1994; Wilson, 1998). However, when the correlation with meteorological parameters is calculated for the sunspot numbers or geomagnetic indices, the results obtained for different epochs are sometimes contradictory (Herman and Goldberg, 1978; Cliver et al., 1998).

We suggest that this contradiction may result from the non-linearity of solar-climate relationships, due to some long-term processes on the Sun. Hence, the same phenomena may be expected to manifest themselves in solar-geomagnetic relations, as well. The aim of this study is to investigate a particular long-term periodicity in the solar-geomagnetic correlation and to compare it with the long-term variations of total solar irradiance and the Earth's temperature, thereby gaining insight on the statistical association between climate on Earth and changes occurring on the Sun.

2. Approach

In this investigation, we use annual indices of sunspot number and geomagnetic data. We do this so that we can neglect the sporadic sunspot related component of geomagnetic activity (see Section 5).

Annual sunspot numbers (R_Z) from 1868 to 1997 are used as the indicator for solar activity, while annual geomagnetic aa-indices for the same period (see http://tango.cept.ipsl.fr/ ~ isgi/) are used as the indicator for geomagnetic activity. We also examined the variations of the annual numbers of 3-h aa-indices between fixed thresholds because this is of interest for comparing with the Earth's temperature. Therefore we used the time series of the T(aa,daa) parameter for the period from 1868 to 1997 as another indicator of geomagnetic activity, where T(aa,daa) is the annual number of 3-h time intervals having a level of geomagnetic activity within the interval of aa−daa to aa + daa.

In the analysis, we apply a 23-year running-window correlation (Kishcha and Dmitrieva, 1997) to the series of R_Z and aa/T(aa,daa). We calculate the correlation coefficient, $r(n)$, referred to the year n, using the following expression:

$$r(n) = \frac{\sum_{i=n-11}^{n+11} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=n-11}^{n+11} (x_i - \bar{x})^2 (y_i - \bar{y})^2}} \quad (1)$$

where x_i refers to a data set of annual sunspot numbers R_Z for the 23-year interval from $n-11$ to $n+11$, $\bar{x}$ refers to the mean value of the x_i data set, y_i refers to a dataset of annual indices aa/T(aa,daa) for the same time interval and $\bar{y}$ refers to the mean value of the y_i data set. The 23-year running-window correlation is obtained for each year between 1879 and 1986. (We use a 23-year running window, instead of a shorter interval, in order to avoid distinctions that may be attributed to even- and odd-numbered cycles, e.g., Cliver and Boriakoff, 1996.).

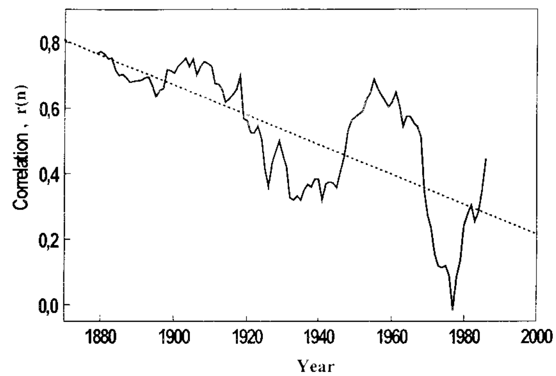

Fig. 1. The 23-year running-window correlation between R_Z and aa-indices. Linear regression fits are shown by dots.

3. Long-term variations of the solar-geomagnetic correlation

Variations of the 23-year running correlation between R_Z and aa from 1868 to 1997 are shown in Fig. 1. In particular, we find the following: a secular decrease seems to exist for the solar-geomagnetic correlation, and the correlation appears to vary quasi periodically relative to the downward linear trend (with years of high correlation alternating with years of low correlation).

We also applied the 23-year running-window correlation to the variations of the annual numbers of the 3-h aa-indices between fixed thresholds T(aa, daa). Here we used daa = 2 and aa changed from 2 to 30. Variations of the 23-year running-window correlation between R_Z and T(aa) over the entire range of the aa-indices are represented in Fig. 2 by the field of isolines of the $r(n)$ values. We see that a value of the aa-index of about 8 or 9 is associated with $r \approx 0$. Therefore, we infer that such a level serves as a boundary separating intervals of disturbed geomagnetic conditions (having $r(n) > 0$) from quiet intervals (having $r(n) < 0$). On either side of this boundary, long-term variations are found to occur, being weaker for moderate geomagnetic activity (aa-values from 12 to 25) and stronger for both low and high geomagnetic activity levels (aa ≤ 4 and aa ≥ 30).

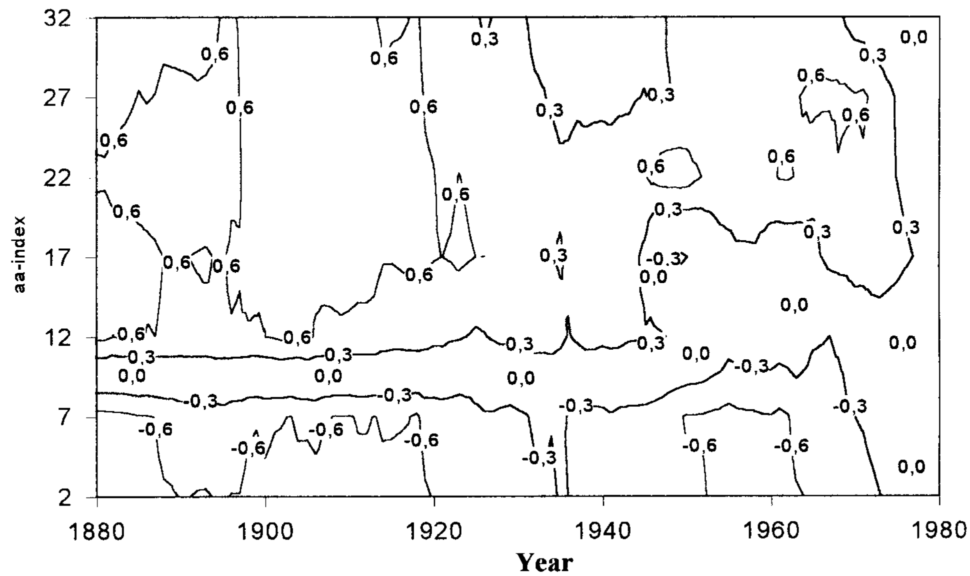

Fig. 2. The field of isolines of the 23-year running-window correlation between R_Z and T(aa,2) over the entire range of aa values.

Variations of the 23-year running correlation between R_Z and $T(\text{aa} \leq 4)/T(\text{aa} \geq 30)$ from 1868 to 1997 are depicted in Fig. 3 (taken from Kishcha and Dmitrieva (1997)). Plainly, linear trends exhibiting decreases of the solar-geomagnetic running-window correlation are again found. The correlation varies quasi periodically relative to the downward linear trends.

To estimate the significance level for the obtained 23-year running-window correlation coefficients r, we used the method Z as proposed by Fisher for small data sets (Panofsky and Brier, 1958; Isaev, 1988). The values of Z are calculated using the expression:

$$Z = \frac{1}{2} \ln \frac{1+r}{1-r}$$

and distributed in accordance with the normal distribution with the mean-square error given as

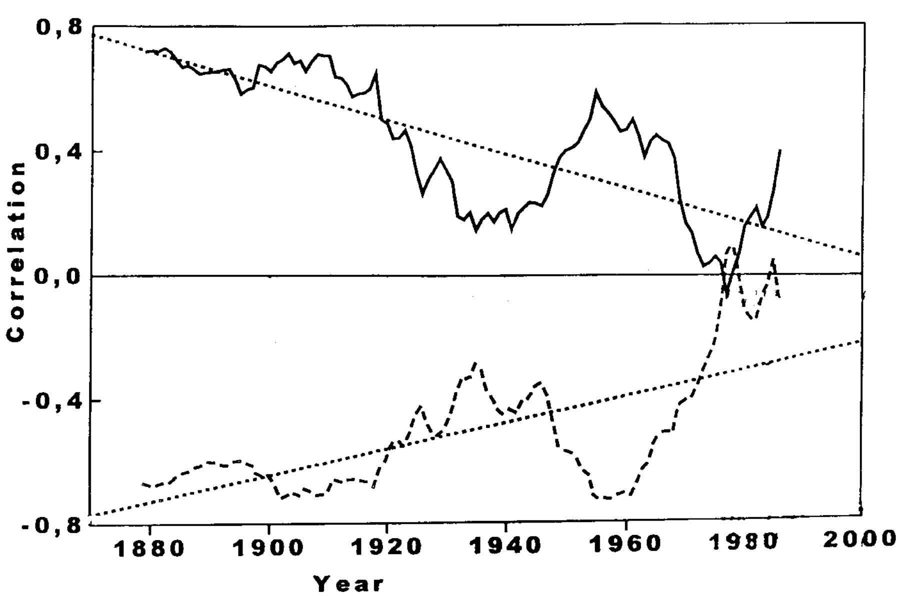

Fig. 3. The 23-year running-window correlation between R_Z and $T(\text{aa} \leq 4)/T(\text{aa} \geq 30)$: R_Z and $T(\text{aa} \leq 4)$ dashed line, and R_Z and $T(\text{aa} \geq 30)$ solid line. Linear regression fits are shown by dots.

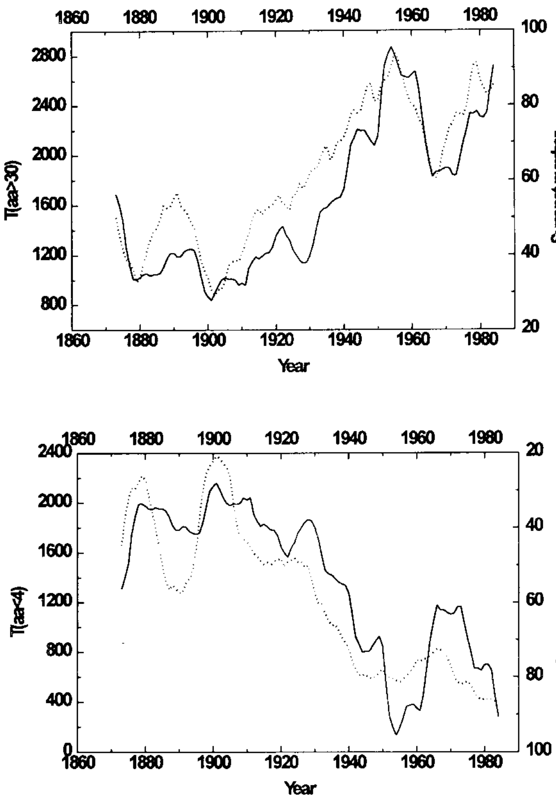

Fig. 4. Top panel — low frequency components of R_Z (solid line) and $T(\mathrm{aa} \geq 30)$ (dots) filtered by the 11-year running mean. Bottom panel — the same components of R_Z (solid line) and $T(\mathrm{aa} \leq 4)$ (dots).

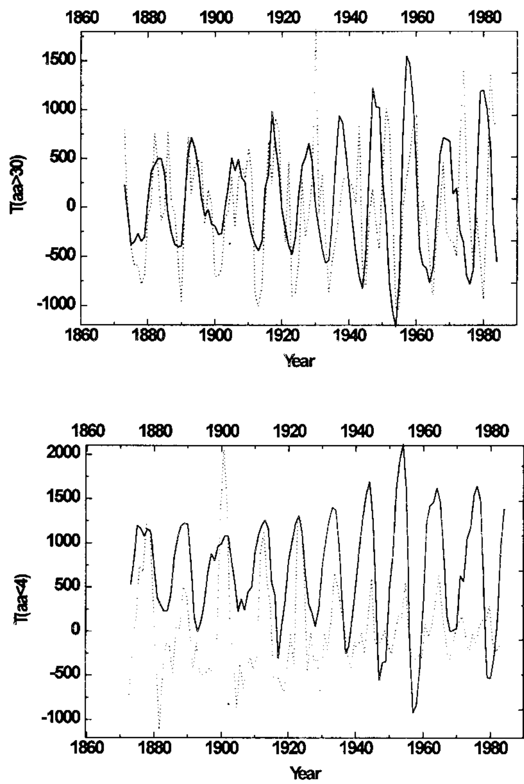

Fig. 5. Top panel — high frequency fluctuations of R_Z (solid line) and $T(\mathrm{aa} \geq 30)$ (dots) with periods no greater than 11 years. Bottom panel — the same fluctuations of R_Z (solid line) and $T(\mathrm{aa} \leq 4)$ (dots).

$$\sigma_z = \frac{1}{\sqrt{N-4}}$$

where N is the number of data points. The statistical significance of the correlation r is estimated by the following condition: $Z/\sigma_z \geq t_\beta$, where t_β is the Student's parameter at the significance level of β. In particular, for the case of $N = 23$, the correlation r is found to be statistically significant at the significance level of 0.05 when $r \geq 0.41$.

When investigating long-term variations of running-window correlation coefficients, we propose that these variations can result from the differences between the trends of R_Z and $\mathrm{aa}/T(\mathrm{aa} \leq 4)/T(\mathrm{aa} \geq 30)$. To test this hypothesis, we must eliminate the trends by subtracting the low frequency components from the initial data sets. First, the low frequency components of the initial data were selected by applying an 11-year running mean to them. As shown in Fig. 4, the filtered low-frequency components of R_Z display a good agreement with that of the $T(\mathrm{aa} \leq 4)$ and $T(\mathrm{aa} \geq 30)$ parameters. The correlation coefficients between R_Z and $T(\mathrm{aa} \leq 4)$ and between R_Z and $T(\mathrm{aa} \geq 30)$ are equal to -0.89 and 0.95, respectively. These correlation coefficients, calculated for the period from 1873 to 1992, are statistically significant at the 1% level of significance.

Next, these filtered low-frequency components of R_Z, $T(\mathrm{aa} \leq 4)$, and $T(\mathrm{aa} \geq 30)$ were subtracted from the original data sets to give the high frequency components of the initial data; these are plotted in Fig. 5. Then, we calculated the 23-year running-window correlation coefficients $r(n)$ between the remaining high-frequency components of the initial data (shown in Fig. 6). We find that the $r(n)$ values for the high frequency components of the initial data sets appear to vary in the same manner as shown in Fig. 1. Therefore, we can reject the hypothesis that the long-term variations of the solar-geomagnetic correlation result from the differences between the trends of sunspot numbers and geomagnetic indices.

To study the quasi-periodic peculiarities of the correlation coefficients (presented in Figs. 1 and 3) we subtracted the linear trends from them. Detrended long-term variations of the 23-year running correlation between R_Z and $T(\mathrm{aa} \leq 4)/T(\mathrm{aa} \geq 30)$ are shown in Fig. 7 (panels 1 and 2). In particular, we find that the

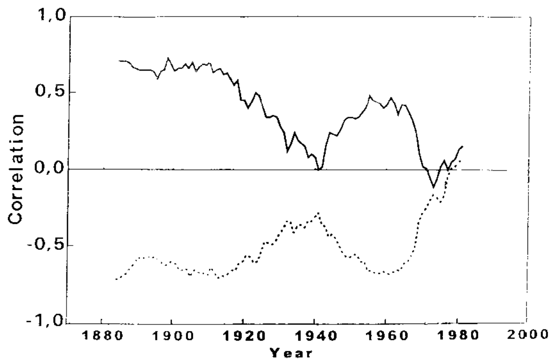

Fig. 6. The 23-year running-window correlation between high frequency fluctuations of R_Z and $T(\mathrm{aa} \leq 4)$ dashed line, and between the same fluctuations of R_Z and $T(\mathrm{aa} \geq 30)$ solid line.

detrended long-term variations of solar-geomagnetic correlation vary quasi periodically, having amplitudes greater in the present century than in the last century and a quasi periodicity of about 40–50 years; these variations of the running-window correlation occur in both analyzed cases (between sunspot numbers and quiet geomagnetic conditions and between sunspot numbers and disturbed geomagnetic conditions).

The correlation between R_Z and $T(\mathrm{aa} \leq 4)$ is found to be in phase and approximately equal in magnitude, but opposite in sign, as compared with the correlation between R_Z and $T(\mathrm{aa} \geq 30)$. Intervals of low solar-geomagnetic correlation correspond to the negative values on panel 1 and positive values on panel 2, and these intervals are approximately 1879–1899, 1921–1947, and 1968–1985. As we shall show in Section 4, these intervals of low solar-geomagnetic correlation seem to be important from the perspective of global climate.

It may be that the selected long-term variations of the solar-geomagnetic correlation arise from the variations of time shift between geomagnetic indices and sunspot number (Kishcha and Dmitrieva, 1998, 1999a, 1999b). The values of time delay can be estimated by

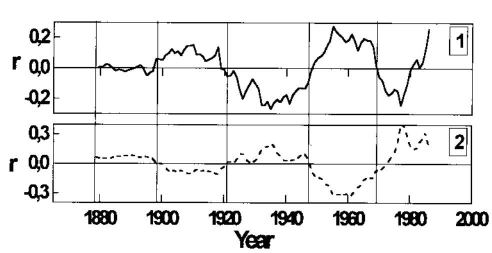

Fig. 7. Detrended long-term variations of the 23-year running-window correlation between R_Z and $T(\mathrm{aa} \geq 30)$ panel 1, and between R_Z and $T(\mathrm{aa} \leq 4)$ panel 2. The times of low solar-geomagnetic correlation are shown by vertical straight lines.

the determination of the time shift of maxima of the crosscorrelation functions in the running 23-year window. Examples of the crosscorrelation functions for two 23-year periods associated with the low and high solar-geomagnetic correlation are presented in Fig. 8. We see that the low correlation corresponds to the bigger time shift of maximum of the crosscorrelation function and, thereby, to the bigger time delay of aa-indices relative to the sunspot number.

Variations of the time delay of the geomagnetic indices aa, $T(\mathrm{aa} \leq 4)$, and $T(\mathrm{aa} \geq 30)$ relative to the sunspot number are shown in Fig. 9. We find that secular linear trends exist in these variations, whereby the values of time delay increase from 0 years at the beginning to about 2 years at the end (1868–1997), and quasi-periodic changes of the time delay (amplitude about 2–4 years) take place on the linearly increasing background during the periods of low solar-geomagnetic correlation.

We suggest that it is the variations of time delay that cause the above mentioned variations of solar-geomagnetic correlation. We base our suggestion on the observed behavior of the long-term variations of maximum solar-geomagnetic correlation derived by using the shifts of maxima of the running crosscorrelation functions (see Fig. 10). We find that they are expressed much more weakly.

4. Long-term variations of the total solar irradiance and northern hemisphere temperature

Two measures of the solar cycle provide indirect evidence that some global long-term processes on the Sun may affect the long-term variations of solar-geomagnetic correlation. These include the length of the sunspot cycle and the Hoyt and Schatten (1993) composite index.

In Fig. 11, we compare the variations of the length of the sunspot cycle (Friis-Christensen and Lassen, 1991) for the period of 1868–1990 (panel 1), the Hoyt and Schatten (1993) composite index (panel 2), the northern hemisphere land–air surface temperature anomalies (Hansen and Lebedeff, 1987) from 1868 to 1990 (panel 3), and R_Z (panel 4). In the Fig. 11 each of these variations has been smoothed using a polynomial (sixth order) fit to obtain the extremum points (points where the derivative vanished). Also plotted in Fig. 11 are the derivatives (panels 5–8). Inspection of the derivatives reveals that for the length of the sunspot cycle, the Hoyt and Schatten (1993) composite index, and the northern hemisphere temperature, vanish at nearly the same time (three instances). The derivative of R_Z behaves differently although, for the last occurring extremum point, all derivatives occur nearly simultaneously. These extremum points are found to

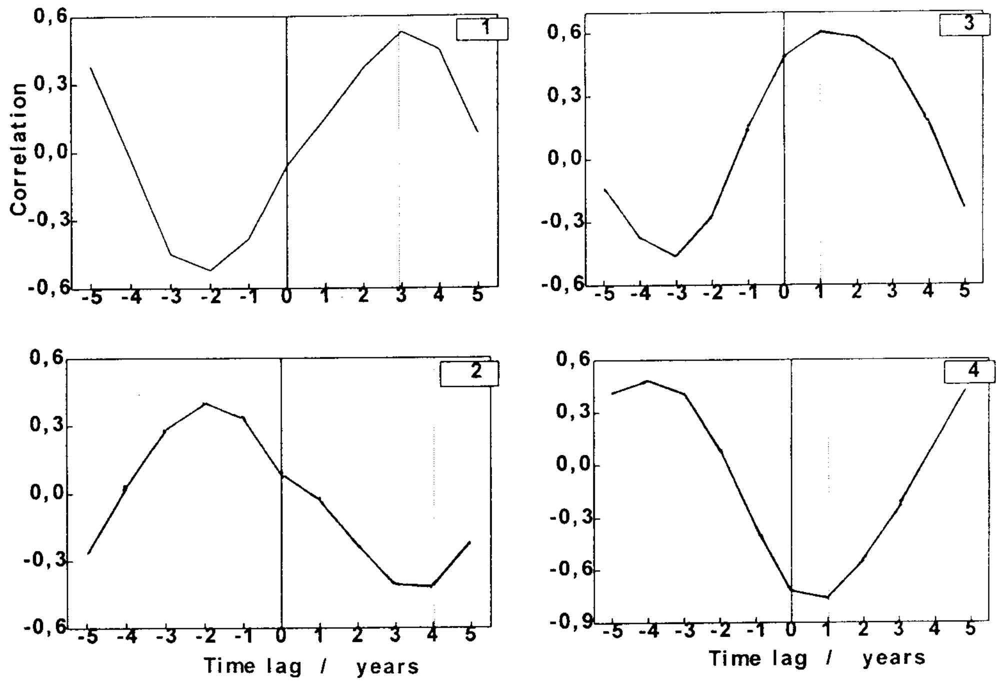

Fig. 8. Examples of the crosscorrelation functions for two 23-year periods with the low (1966–1988) (panels 1 and 2) and high (1947–1969) solar-geomagnetic correlation (panels 3 and 4). Panels 1 and 3 correspond to crosscorrelation between R_Z and $T(\mathrm{aa} \geq 30)$, and panels 2 and 4 between R_Z and $T(\mathrm{aa} \leq 4)$.

occur during periods of low solar-geomagnetic correlation. (The polynomial fit has been employed before by Corbyn (1998) to investigate the correlation between global temperature anomalies and geomagnetic activity indices.)

Presuming that the Sun's total irradiance does vary over time (Foukal and Lean, 1990; Wilson, 1992; Lean et al., 1995; Willson, 1997; Hoyt and Schatten, 1997), in particular, we expect the irradiance to have some effect on the Earth's air temperature. Soon et al. (1996) recently simulated the global climate warming, using the global land-air surface temperature

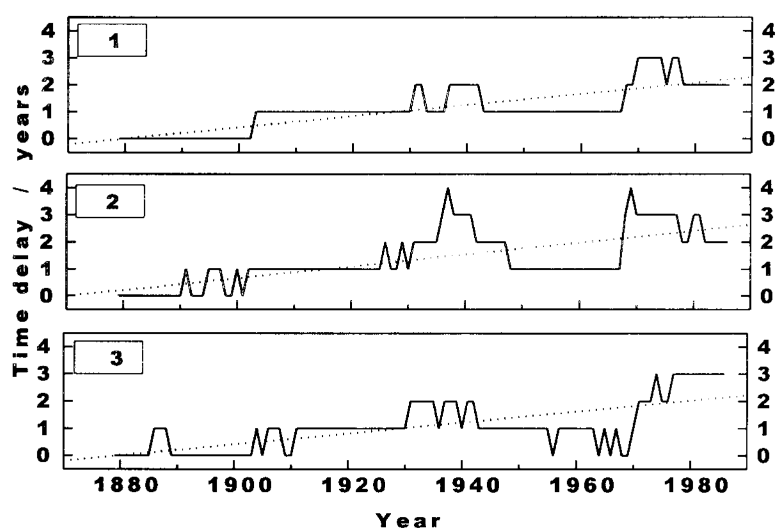

Fig. 9. Long-term variations of time delay of the following geomagnetic indices relative to sunspot numbers: panel 1 — aa, panel 2 — $T(\mathrm{aa} \geq 30)$, panel 3 — $T(\mathrm{aa} \leq 4)$. Linear regression fits are shown by dots.

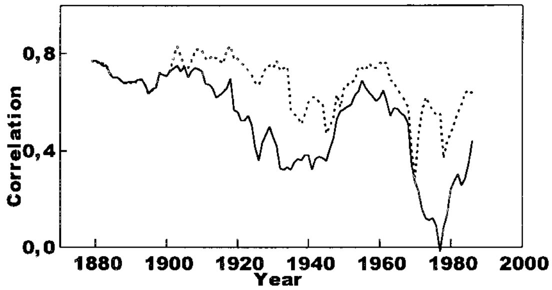

Fig. 10. The 23-year running-window correlation between R_Z and aa corrected for shifts of maxima of the crosscorrelation functions (points) and without correction (solid line).

anomalies derived by Hansen and Lebedeff (1987), and came to the conclusion that a great deal of the global climate phenomena could be explained by the combined greenhouse gas and solar effects. Also, Wilson (1998) has shown that the Armagh observatory temperatures are strongly associated with the length of the sunspot cycle.

Likewise, our analysis supports the notion of a relationship between temperature and the Sun, where extremum points of the global temperature anomalies coincide with occurrences of low solar-geomagnetic correlation.

5. Discussion and conclusions

Many processes in the Earth's upper and lower atmosphere are defined by the total solar irradiance and depend, in particular, on solar and geomagnetic activities. Our analysis of solar-geomagnetic correlation (using a 23-year running-window cross-correlation analysis) for the time span of 1868–1997 shows that the correlation has varied over time. These variations may be the result of a superposition of a 40–50 year quasi-periodic fluctuation on a linear trend, where this trend describes a general decrease of the 23-year running-window correlation. Furthermore, the long-term variations of the solar-geomagnetic correlation may

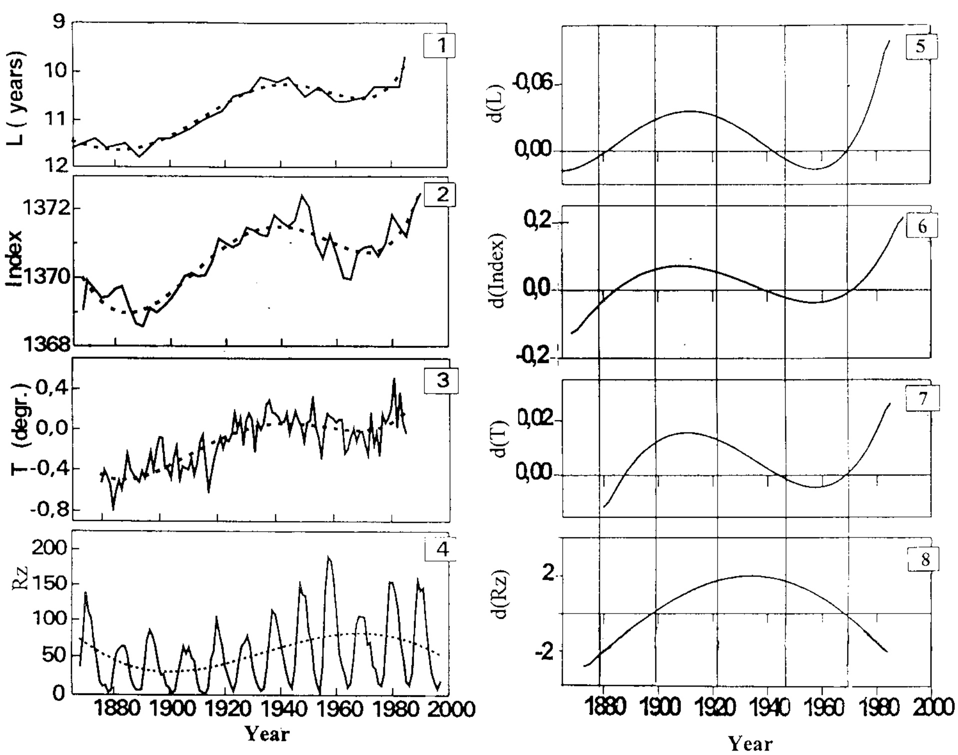

Fig. 11. Left column: variations of the sunspot cycle length — panel 1, the Hoyt and Schatten (1993) composite solar irradiance index (based upon five solar indices, namely cycle length, cycle decay rate, mean level of solar activity, solar rotation and the fraction of penumbral sunspots) — panel 2, northen hemisphere land-air surface temperature anomalies from 1868 to 1990 — panel 3, and the sunspot number — panel 4. Sixth order polynomial fits are shown by dashed lines. Right column: the derivatives of sunspot cycle length — panel 5, of the Hoyt and Schatten (1993) composite index — panel 6, of the northern hemisphere land–air surface temperature anomalies — panel 7, and of the solar sunspot numbers — panel 8. The times of low solar-geomagnetic correlation are shown by vertical straight lines.

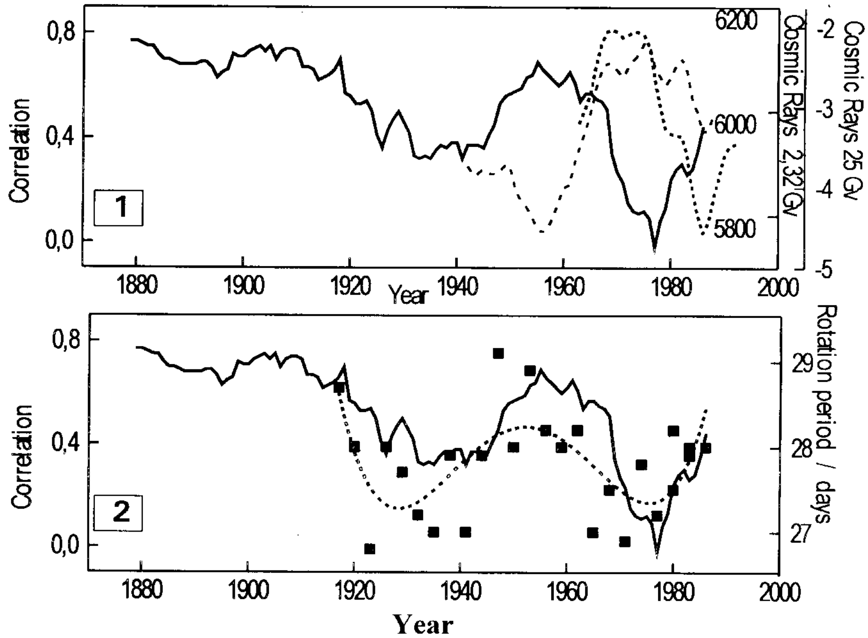

Fig. 12. Panel 1 — the long-term variations of the solar-geomagnetic correlation (solid lines) and parameters of galactic cosmic rays: the variations of Kiel (Germany) neutron monitor pressure-corrected counting rate for 2.32 GV cutoff rigidity (points), and density of galactic cosmic rays for 25 GV rigidity relative to the level in 1965, calculated from the worldwide cosmic ray network stations (dashed line), smoothed by 11-year running mean. Panel 2 — the variations of rotation period of the Sun's large-scale magnetic fields, obtained by Obridko and Shelting (1998) (squares), together with their sixth order polynomial fit (dots) and the long-term variations of solar-geomagnetic correlation (solid line).

result from the quasi-periodic fluctuations of time lag of the geomagnetic indices relative to sunspot numbers (with the same quasi period). We believe that the linear trend of the decreasing solar-geomagnetic correlation may result from the inferred increasing trend of time lag. These trends may reflect the tendency for an interlinking of the solar and geomagnetic activities between 1868 and the present (Kishcha and Dmitrieva, 1999a).

The question arises, however, as to what is the main cause of the fluctuations? We suppose that the answer involves the very nature of geomagnetic activity. In accordance with our present-day understanding of geomagnetic activity, we note that it can be divided into two main components: sporadic sunspot related activity and recurrent geomagnetic activity (Ohl, 1971; Feynman, 1982; Legrand and Simon, 1989; Wilson et al., 1998), where recurrent geomagnetic activity is associated with high speed wind streams from coronal holes that occur during the declining phase of the solar cycle. The maximum of the recurrent component is shifted relative to the sunspot cycle maximum because the open magnetic configurations in the solar corona are more stable during the declining solar cycle. Legrand and Simon (1989) estimated that for about 90% of the time the geomagnetic activity is controlled by the solar wind streams from coronal holes. So it may be that we can neglect the sporadic sunspot related activity when the annual geomagnetic indices are used. Presuming this to be true, we suggest that the variations of the time lag of geomagnetic indices relative to sunspot numbers from cycle to cycle link primarily with the stability of the open field magnetic configurations in the solar corona. Hence, they are associated with long-term variations of the disturbance level of the Sun's large scale magnetic field.

In support of this hypothesis, we can examine some statistical associations between the long-term variations of the solar-geomagnetic correlation and selected parameters relevant to the Sun's large-scale magnetic field (Fig. 12). For example, it has been known (Nagashima et al., 1991) that the intensity of galactic cosmic rays (GCR) is linked with the disturbance level of the Sun's large-scale magnetic field, varying inversely. In Fig. 12 (panel 1) we plot the Kiel (Germany) neutral monitor pressure-corrected counting rates for 2.32 GV cutoff rigidity (taken from Solar-Geophysical Data, No. 645, part 1, 1998) and the GCR density for 25 GV rigidity, calculated from the worldwide cosmic ray network stations relative to the level in 1965 (Belov et al., 1990), smoothed by an 11-year running mean, and the solar-geomagnetic correlation. Clearly, they vary inversely. Thus, the GCR varies in a similar fashion to the Sun's large-scale magnetic field.

Additionally, Obridko and Shelting (1998) reconstructed the structure of the Sun's large-scale magnetic field from 1915 to 1988 using Hα solar observations. They found that the solar rotation period changes systematically from 27 to 29 days during this interval. Because the solar rotation period is also found to vary systematically with depth from helioseismology observations (Kosovichev et al., 1997), it may be that the change in solar rotation period is indicative of time variations in the generation zone of the Sun's global magnetic fields. Such time variations could result in changes in the solar-geomagnetic correlation. In Fig. 12 (panel 2) we display variations of the solar rotation period, originally obtained by Obridko and Shelting (1998), together with their sixth order polynomial fit and the long-term variations of the solar-geomagnetic correlation. There is a hint that there is a statistical association between them.

It is noteworthy that the extremum points of the long-term variations for the total solar irradiance proxies have occurred during the periods of low solar-geomagnetic correlation, while the same distinguishing features have not appeared for sunspot numbers. From this, we infer that sunspot number may not be the best indicator (or proxy) for determining long-term changes in solar irradiance. (Hoyt and Schatten, 1998.)

Taking into account the close association between the length of solar cycle and global land-air surface temperature found by Friis-Christensen and Lassen (1991) and others (Butler, 1994; Wilson, 1998), it is not surprising that the extremum points of the land-air surface temperature anomalies of the northern hemisphere have also occurred during the periods of low solar-geomagnetic correlation. We take this as evidence (albeit a statistical association) that both the long-term variations of solar-geomagnetic interactions and the long-term fluctuations of the temperature anomalies depend on certain long-term processes on/in the Sun.

In conclusion, our 23-year running-window correlation analysis of the solar-geomagnetic correlation has yielded the following results: first, the solar-geomagnetic correlation varies with time. In particular, long-term variations of the 23-year running correlation appear to have a quasi periodicity of about 40–50 years, superposed on a linear trend, where this trend describes a general decrease of the 23-year running-window correlation between 1868 and the present. Second, long-term variations of the solar-geomagnetic correlation result from the quasi periodic fluctuations of the time lag of geomagnetic indices relative to the sunspot number, superposed on an upward linear trend of time lag. Lastly, all extremum points of the time variations for potential proxy measures of total solar irradiance, e.g., the length of the sunspot cycle, the Hoyt and Schatten (1993) composite index, and the northern hemisphere land-air surface temperature, have occurred during periods of low solar-geomagnetic correlation.

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References

Belov, A.B., Gushchina, R.T., Dorman, L.I., Sirotina, I.V., 1990. The rigidity spectra of cosmic rays modulation. Geomagnetism and Aeronomy 30 (4), 558–562.

Bucha, V., Bucha Jr, V., 1998. Geomagnetic forcing of changes in climate and in the atmospheric circulation. Journal of Atmospheric and Solar-Terrestrial Physics 60 (2), 145–169.

Butler, C.J., 1994. Maximum and minimum temperatures at Armagh observatory, 1844–1992, and the length of the sunspot cycle. Solar Physics 152, 35–42.

Butler, C.J., Johnston, D.J., 1994. The link between the solar dynamo and climate — the evidence from a long mean air temperature series from Northern Ireland. The Irish Astronomical Journal 21 (3-4), 251–254.

Cliver, E.W., Boriakoff, V., 1996. The 22-year cycle of geomagnetic and solar vind activity. Journal of Geophysical Research 101, 27,091–27,109.

Cliver, E.W., Boriakoff, V., Feynman, J., 1998. Solar variability and climate change: geomagnetic aa index and global surface temperature. Geophysical Research Letters 25 (7), 1035–1038.

Corbyn, P., 1998. Weather Action, No. 77.

Feynman, J., 1982. Geomagnetic and solar wind cycles, 1900–1975. Journal of Geophysical Research 87, 6153–6162.

Foukal, P., Lean, J., 1990. An empirical model of total solar irradiance variations between 1874 and 1988. Science 247, 556–558.

Friis-Christensen, E., Lassen, K., 1991. Length of the solar cycle: an indicator of solar activity closely associated with climate. Science 254, 698–700.

Hansen, J., Lebedeff, S., 1987. Global trends of measured surface air temperature. Journal of Geophysical Research 92, 13,345–13,372.

Herman, J.R., Goldberg, R.A., 1978. Sun, weather, and climate. NASA SP-426, Washington.

Hoyt, D.V., Schatten, K.H., 1993. A discussion of plausible solar irradiance variations, 1700–1992. Journal of Geophysical Research 98, 18,895–18,906.

Hoyt, D.V., Schatten, K.H., 1997. The Role of the Sun in Climate Change. Oxford University Press.

Hoyt, D.V., Schatten, K.N., 1998. Group sunspot numbers: a new solar activity reconstruction. Solar Physics 179, 189–219.

Isaev, A.A., 1988. Statistics in Meteorology and Climatology. Moscow State University.

Kishcha, P.V., Dmitrieva, I.V., 1997. Secular variations of solar-geomagnetic links and meteorological parameters. In: Proceedings of the Conference on Modern Problems of Solar Circularity 26–30 May, Saint Petersburg, pp. 116–120 (in Russian).

Kishcha, P.V., Dmitrieva, I.V., 1998. Variations of time shift between indices of solar and geomagnetic activities. In: Proceedings of the VII Symposium on Solar-Terrestrial Physics of Russia and SNG Countries 15–18 December, Moscow, pp. 131–132 (in Russian).

Kishcha, P.V., Dmitrieva, I.V., 1999a. Tendencies of interconnection between solar and geomagnetic activities for XX centure. In: Proceedings of the Second All-Russian Conference on Physical Problems of Ecology 18–21 January, Moscow State University, Moscow, p. 18 (in Russian).

Kishcha, P.V., Dmitrieva, I.V., 1999b. Decadal variations of time shift between indices of solar and geomagnetic activities. Geomagnetism and Aeronomy 39 (2), 19–23.

Kosovichev, A.G., Schou, J., Scherrer, P.H., Bogart, R.S., Bush, R.I., Hoeksema, J.T., Aloise, J., Bacon, L., Burnette, A., De Forest, C., Giles, P.M., Leibrand, K., Nigam, R., Rubin, M., Scott, K., Williams, S.D., Sarbani, B., Christensen-Dalsgaard, J., Dappen, W., Rhodes, E.J., Duval, T.L., Howe, R., Thompson, M.J., Cough, D.O., Sekii, T., Toomre, J., Tarbell, T.D., Title, A.M., Mathur, D., Morrison, M., Saba, J.L.R., Wolfson, C.J., Zayer, I., Milford, P.N., 1997. Structure and rotation of the solar interior: initial results from the MDI MEDIUM-L program. Solar Physics 170, 43–61.

Lean, J., Beer, J., Bradley, R., 1995. Reconstruction of solar irradiance since 1610: implications for climate changes. Geophysical Research Letters 22, 3195–3198.

Legrand, J-P., Simon, P.A., 1989. Solar cycle and geomagnetic activity: a review for geophysicists. Parts I and II. Annales Geophysicae 7, 565–594.

Nagashima, K., Fujimoto, K., Tatsuoka, R., 1991. Nature of solar-cycle and heliomagnetic-polarity dependence of cosmic rays, inferred from their correlation with heliomagnetic spherical surface harmonics in the period 1976–1985. Planetary and Space Sciences 39 (12), 1617–1635.

Obridko, V.N., Shelting, B.D., 1998. Structure and dynamics of the Sun's large-scale magnetic field for long time interval. In: Proceedings of the VII Symposium on Solar-Terrestrial Physics of Russia and SNG Countries 15–18 December, Moscow, p. 38 (in Russian).

Ohl, A.I., 1971. Physics of the 11-year variation of magnetic disturbances. Geomagnetism and Aeronomy 11, 549–551.

Pudovkin, M.I., Raspopov, O.M., 1992. Mechanism of solar activity impact on the lower atmosphere and meteorological parameters (Review). Geomagnetism and Aeronomy 32 (5), 1–22.

Panofsky, H.A., Brier, G.W., 1958. Some Applications of Statistics to Meteorology. University Park, Pennsilvania.

Soon, W.H., Posmentier, E.S., Baliunas, S.L., 1996. Inference of solar irradiance variability from terrestrial temperature changes, 1880–1993: an astrophysical application of the sun-climate connection. Astrophysical Journal 472, 891–902.

Tinsley, B.A., 1996. Correlations of atmospheric dynamics with solar wind-induced changes of air-earth current density into cloud tops. Journal of Geophysical Research 101 (D23), 29,701–29,714.

Tinsley, B.A., 1997. Do effects of global atmospheric electricity on cloud cause climate changes? EOS, Transactions, American Geophysical Union 78, 341–349.

Wild, G., 1882. About the air temperature in Russian Empire. Russian Geophysical Society, Issue 2, St Petersburg.

Willson, R.C., 1997. Total solar irradiance trend during solar cycles 21 and 22. Science 277, 1963–1965.

Wilson, R.M., 1992. On the variation of the Nimbus-7 total solar irradiance. NASA. TR-3316. Marshall Space Flight Center. Alabama.

Wilson, R.M., 1998. Evidence for solar-cycle forcing and secular variation in the Armagh observatory temperature record (1844–1992). Journal of Geophysical Research 103 (D10), 11,159–11,171.

Wilson, R.M., Hathaway, D.H., Reichmann, E.J., 1998. An estimate for the size of cycle 23 based on near minimum conditions. Journal of Geophysical Research 103, 6595–6603.