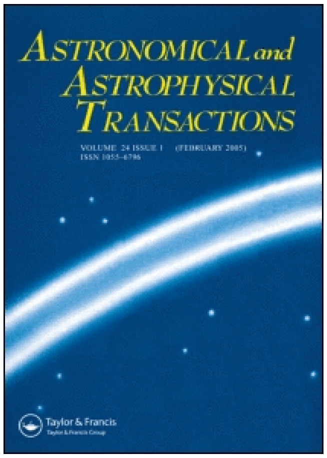

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THE INTERANNUAL MODULATION OF THE SOLAR AND GEOMAGNETIC ACTIVITY RELATIONSHIPS

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The interannual modulation of the geomagnetic activity caused by solar activity is investigated by means of the mutual spectral analysis. The frequency characteristics of connection between the Wolf numbers W_0 and the *aa* index of geomagnetic activity for the time interval 1890–1990 are analysed. Interannual and seasonal variations in the corresponding coherence spectra $CH(T)$ for the quasi-decennial, quasi-pentennial, quasi-triennial and quasi-biennial cycles are revealed. The particular properties of the mean parameters for individual months are outlined.

Keywords: Solar activity; Geomagnetic Activity; Solar terrestrial relationship

1 INTRODUCTION

The Sun ensures that there is a terrestrial biosphere and life on the planet. The very existence of mankind is possible because of the strong stability of the solar emissivity, especially that of the solar electromagnetic luminosity characterized by the so-called solar constant S_0. Its change does not exceed 0.2% (Eddy *et al.*, 1982). Ultraviolet and especially X-ray short-wavelength emission is widely changeable. However, extreme ultraviolet (XUV) emission occupies only a relatively small part of the solar spectrum which in total is of the order of 10^{-6} of the solar constant. Nevertheless it plays significant role in influencing different layers of the Earth's middle and upper atmospheres because of the corresponding parts of the XUV emission. Besides this, cosmic-ray emission (in a somewhat different way from galactic and solar emission) may also regulate the energy balance of the middle and lower atmospheres (Kononovich and Shefov, 2001).

The major factors of the geophysical and technological influences of the Sun are the solar wind disturbances connected with the geomagnetic storms. A classical example is the magnetic disturbance that occurred on 13–14 March 1989 and caused a large blackout of the energy system in Canada and the northern USA. At the same time the four navigation Transit satellites were switched off.

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Solar activity research has allowed us to find new cases of the formation of high-speed streams which are not connected with coronal holes and are observed above the closed magnetic structures (Gibson *et al.*, 1999). The role of a polar solar wind as the energy source forming the non-uniform equatorial belt of the Sun has been found (Pisanko, 1997). Because of the significant successes of solar–terrestrial physics, many multiple-factor mechanisms of solar impact on the geophysical processes have been proposed.

However, elaboration of the prognosis of the solar and geomagnetic disturbances still remains one of the most important theoretical and practical problems.

On the other hand, there is progress in the specification of the mechanisms of the interaction between the solar wind and the Earth's magnetosphere. These mechanisms mostly use the reconnection models applied to the interplanetary magnetic field lines and that of the external areas of the Earth's magnetosphere (Kropotkin and Domrin, 2002).

Because of long solar observations (a row of relative Wolf number values W_0 covers more than 250 years), the opportunity to study the fine structure of the solar activity cycle has appeared (Vitinskij, 1973). At the same time the Wolf numbers W_0 have no precise physical meaning. They do not take into account, for example, the presence of the coronal holes, helmet streamers and other displays of solar activity. Nevertheless, the Wolf numbers have a high level of connection with the variation in the solar constant S_0, and also with the radio emission flux $F_{10,7}$ at 2800 MHz, the total area of calcium flocculae and other indices of solar activity (Vitinskij, 1973; Vitinskij *et al.*, 1986). Such connections made it possible to extrapolate, for example, values of the S_0 index, up to 1874 (Eddy *et al.*, 1982).

There are about ten various indices of geomagnetic activity, for example the (planetary indices A_p, ΣK_p, aa and A_m (Akasofu and Chapman, 1972), which are correlate rather well with each other. However, the structure of the connection between the solar and geomagnetic activity indices appears to be complex and possesses prominent features depending on the chosen indices, and also on the length and step-type behaviour of the rows of data. So, according to Vitinskij (1998), the factors of linear correlation between the indices W_0 and aa depend upon the phase of the 11 year cycles and their parity and, probably, they are different for the growth and recession branches of the corresponding century cycle.

The value of such scientific results cannot be overestimated. A good example is the discovery of the increase in the solar magnetic flux by a factor of 2.3 during the last century. It has been revealed by analysis of the connection between the variations in the geomagnetic index aa and interplanetary magnetic field (Lockwood *et al.*, 1999).

Spectral analysis of the solar and geomagnetic indices variations has allowed us to determine the similarities and distinctions in display of a large range of cycles beginning from the quasi-biennial up to the Hale cycle (Rivin, 1989).

2 THE RESEARCH TECHNIQUE AND INITIAL DATA

The purpose of this work is to investigate the frequency structure of the connection between the W_0 and aa indices, and its dependence on months and seasons. The monthly averaged values W_0 and aa for the years 1890–1990 have been used.

The individual monthly mean values W_0 have been averaged over this interval separately for each month of the year. The same procedure was performed for the geomagnetic index aa as well. These two rows of data were tested for stationarity and the operation of window narrowing was performed. Then the method of mutual spectral analysis was applied (Smirnov and Kononovich, 1995). The calculations incorporated all set of statistical functions, the individual spectra, autocorrelation, cross-correlation, coherence and phase spectra including. The most informative is the coherence function

$$CH_{xy}(T) = \{[Co_{xy}(T)]^2 + [Q_{xy}(T)]^2\}\{S_x(T)S_y(T)\}^{-1}.$$

Here $Co_{xy}(T)$ is the cospectrum, $Q_{xy}(T)$ is the quadrature spectrum, and $S_x(T)$ and $S_y(T)$ are the spectral densities of the two processes.

3 RESULTS

In Figures 1(a) and (b), the functions $CH(T)$ for winter–spring and summer–autumn months respectively are presented. The abscissæ are the periods T in years, and the ordinates are the values of the coherence function $CH(T)$.

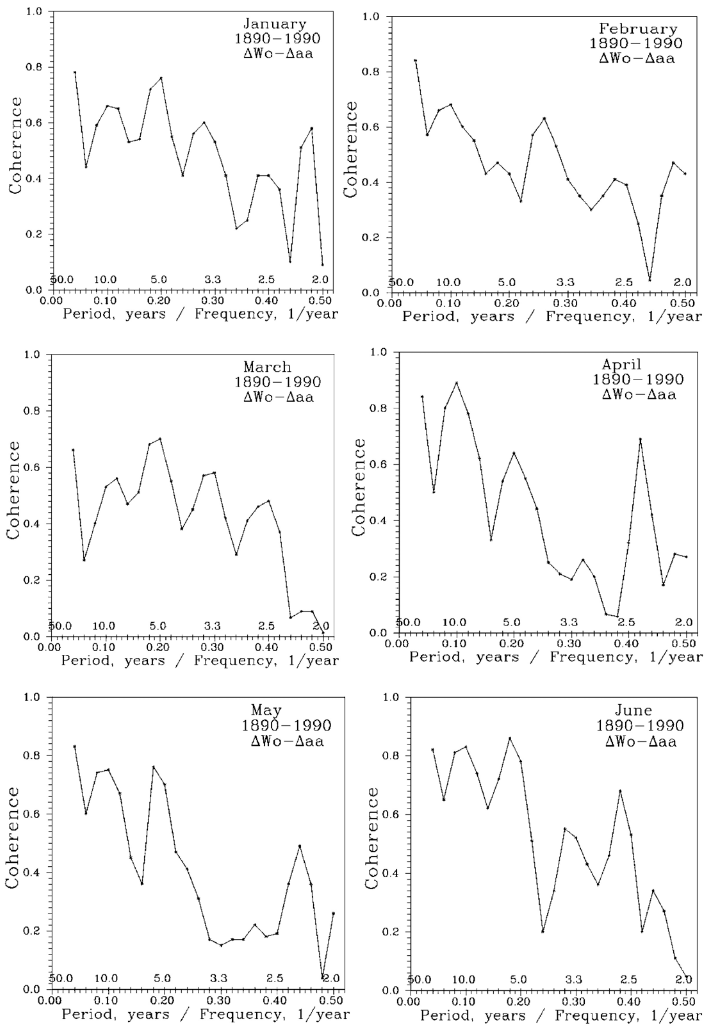

FIGURE 1a The coherence spectra presenting the frequency structure connection between the W_0 and *aa* values for the months January–June.

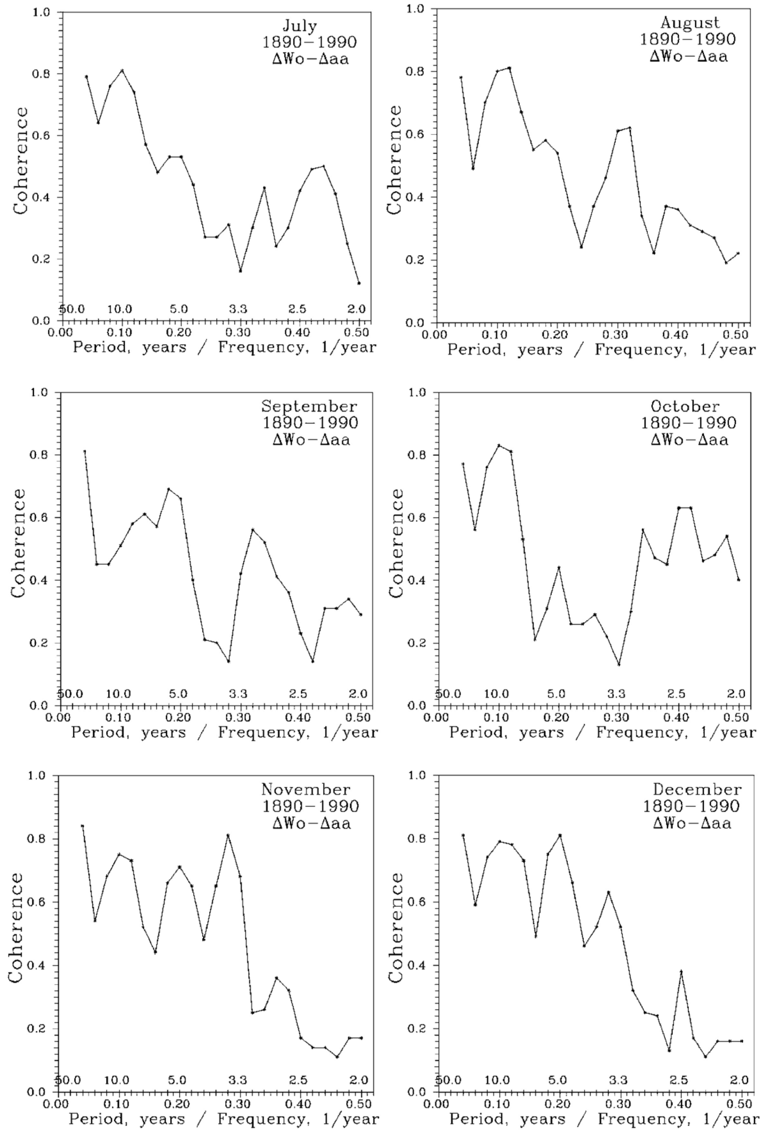

FIGURE 1b July–December.

All the $CH(T)$ functions in Figure 1 reveal a decrease in the amplitude from low frequencies to higher frequencies together with well-defined maxima basically in the quasi-decennial (T_{10}), quasi-pentennial (T_5), quasi-triennial (T_3), and quasi-biennial (T_2) regions. However, the amplitudes and frequency stability of these maxima depends on the given month and season. Thus the quasi-decennial and quasi-pentennial maxima $CH(T_{10})$ and $CH(T_5)$ are steady; the same does not apply to the maxima in the range of periods T from 3.1 up to 3.8 years and from 2.4 up to 2.6 years.

In contrast with the $CH(T_{10})$ and $CH(T_5)$ values, more high-frequency maxima are not characterized by frequency stability. They vary depending on the given month. High $CH(T)$ values suggest a connection between the indices W_0 and aa for the periods T_{10} and T_5 with average amounts $CH(T_{10}) = 0.74$–0.89 and $CH(T_5) = 0.62$–0.81 respectively. Calculation of the significance values give the following parameters. For $CH(T_{10})$ in eight cases the significance value is higher than 0.01%, and in two cases (January and February) it is higher than 0.05%. Significance values for $CH(T_5)$ as a whole are lower, namely in four cases above 0.01% and in four cases higher than 0.05%.

For periods of 3.1–3.8 years the $CH(T)$ maxima rarely attain high values, as in November (0.82). Usually they fluctuate between the limits from 0.51 to 0.67. Quasi-biennial fluctuations are characterized by lower $CH(T)$ values. On the average, they are between 0.37 and 0.58. However in April and October they exceeded the $CH(T_5)$ values.

The spectral differences between the individual months are illustrated by comparison of $CH(T_{10})$ and $CH(T_5)$ during a year. So, the low $CH(T_{10})$ values in winter change in March turn to a small shifted maximum at $T = 8.5$ years; in September this maximum is almost invisible. In the following months, on the contrary, one can see the highest $CH(T_{10})$ values, namely 0.89 in April, and 0.83 in October. On the other hand, another characteristic feature is the steady high $CH(T_{10})$ values in the summer months (0.83, 0.81 and 0.82).

The second harmonic of the quasi-decennial period also reveals significant variations during a year; for example in January, June, and December the $CH(T_5)$ values exceed the $CH(T_{10})$ values. The display of $CH(T)$ spectral components with higher frequencies are specified by enlarged fluctuations both in amplitude and in frequency. So, the greatest $CH(T)$ values for the quasi-triennial period are observed in winter months, and for the quasi-biennial period at the equinoxes.

Let us now consider the displays of connections W_0 and aa for various seasons. The corresponding spectra $CH(T)$ are shown in Figure 2. As in the previous figure, the same set of spectral maxima prevails here. Maxima with high amplitudes $CH(T_{10})$ and $CH(T_5)$ are the

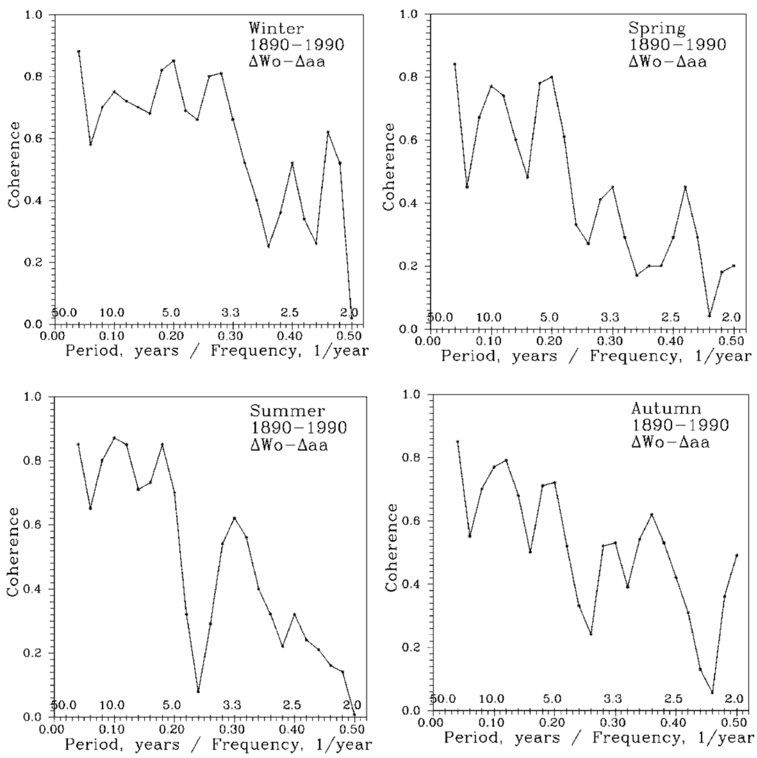

FIGURE 2 The coherence spectra presenting the frequency structure connection between the W_0 and aa values for different seasons.

most stable. Thus, in the winter and spring, $CH(T_5) > CH(T_{10})$. As a whole the seasonal values W_0 and *aa* differ by higher significance values $CH(T_{10})$ and $CH(T_5)$; for all seasons they are higher than 0.01%, with the exception of the $CH(T_5)$ value for autumn.

The quasi-triennial period reveals a rather higher stability of the frequency. Stability of the quasi-biennial period is low both for frequency and for amplitude. As a whole, similarity of the $CH(T)$ spectra is higher for seasons than for months. The lowest $CH(T_{10})$ values are observed in winter and spring, but they have their maxima in summer. This corresponds to the results of the month analysis; occurred in the maximal $CH(T_{10})$ values in June–August, and the minimal values in December–February.

On average the seasonal degree of connection for the second harmonic of the quasi-decennial period was higher than for the monthly values; for winter, $CH(T_5) = 0.85$; for spring, $CH(T_5) = 0.81$; for summer, $CH(T_5) = 0.84$; for autumn, $CH(T_5) = 0.72$. Accordingly the significance levels for the $CH(T_5)$ values for all seasons, except autumn, exceed 0.01%.

The quasi-triennial period (basic period $T = 3.3$ years) reveals changeable $CH(T_3)$ amplitudes for different seasons, reaching a value of 0.81 in winter. The $CH(T)$ values for the quasi-biennial period, in comparison with the periods T_{10}, T_5 and $T_{3.3}$, are less stable as far as frequencies and amplitudes are concerned.

4 DISCUSSION

A complicated structure of the connections between the solar and geomagnetic activity, dependent on cycle duration and phases, is demonstrated when monthly and seasonal average values are analysed. Degrees of connection between the indices W_0 and *aa* for the quasi-decennial and quasi-pentennial periods essentially change both for months and for seasons.

Variations in the $CH(T_{10})$ values are characterized by, firstly, a relative maximum in summers and a minimum in winters, secondly a decrease in the $CH(T_{10})$ values in March and September and, thirdly, a sharp increase in April and October. This increase is connected to the semiannual wave in the A_p index of the geomagnetic activity, with maxima in April and October[†]. At this time the axis of the geomagnetic dipole is perpendicular to the plasma streams of the solar wind, and the Kelvin–Helmholtz instability attains its maximum, modulating geomagnetic activity (Wright *et al.*, 2000).

While the change in the winter solstice $CH(T_{10})$ values correspond to a semiannual wave of geomagnetic activity, the reasons for the $CH(T_{10})$ increase during the summer months is not clear as yet. Probably, the reasons are connected to features of formation of magnetosphere–ionosphere current systems.

Another characteristic of the variations in the monthly averaged values is revealed for the second harmonic of the quasi-decennial period. Maximal $CH(T_5)$ values are marked in December and January and in May and June, near to the solstices. As shown by Rivin (1989), the variation in this harmonic is well correlated to the main cycle; the beginning of the first wave coincides with its ascending branch, while the second wave coincides with its recession branch; the second wave maximum occurs 3–4 years after the main cycle maximum.

While in general the quasi-decennial cycle reveals the frequency of occurrence of the sunspot groups, the indices of solar activity describing the process power have two maxima in a cycle. Such indices include the green coronal line 5303 Å intensity, the number of proton events,

[†] It is necessary to note that the size of the $CH(T)$ values, reflecting the intensity of solar and geophysical processes, characterizes first of all their mutual energy and a correlation at a certain frequency.

the radio emission bursts of the type IV and also the indices describing the average sunspot formation (Vitinskij *et al*., 1986).

The mechanism and location of generation of the second harmonic can differ from those for the main cycle. This is clear from the $CH(T_5)$ variations, which differ from the variations in $CH(T_{10})$ (see above). The other question is why the $CH(T_5)$ values in some cases exceed those for the $CH(T_{10})$. Comparison of the power spectra of indices W_0 and *aa* make it possible to deduce that the relative size of a spectral maximum of the main W_0 cycle is much higher than that of the *aa* index. Together with the weak display of the quasi-decennial cycle in the *aa* index spectrum, the $CH(T_5)$ values are comparable with the $CH(T_{10})$ values, and sometimes on average even exceed them slightly.

This property is more noticeable when one consider the seasonal correlation between the W_0 and *aa* indices for which the $CH(T_5)$ values in the winter and spring are a slightly higher than the $CH(T_{10})$ values. The other particularity of the seasonal connections between the W_0 and *aa* values is the more stable frequency of the quasi-triennial period and comparatively high $CH(T_3)$ values. This means that the increase in the interval of averaging promotes a more noticeable display of interconnection between the W_0 and *aa* indices in the high-frequency part of spectra. The same appliers to the display of the quasi-biennial period as well.

As the phase correspondence between the W_0 and *aa* indices concerns the analysis used, we present them via the phase function $\varphi_{xy}(T) = \arctan[Q_{xy}(T)/Co_{xy}(T)]$. In this work it is not used, but the question has been discussed in a number of papers (Vitinskij, 1973; Vitinskij *et al*., 1986; Rivin, 1989). As a whole the time delay of the phenomena of geomagnetic disturbance relative to the solar activity depends upon a time scale; that is, it reaches values from 2 to 3 days for short-term phenomena up to 1 year for the quasi-decennial cycle.

5 CONCLUSIONS

(i) The complicated character of the connections in the Sun–Earth system depends on the solar acivity cycle, the duration of the cycles and their phase (Vitinskij, 1998). The frequency structure of relationship between the W_0 and *aa* indices has several intraannual and seasonal pecularities.

(ii) As far as the amplitudes and frequencies concern, the most stable are the quasi-decennial and quasi-pentennial components. They have very divese coherence spectra.

(iii) The increase in the $CH(T_5)/CH(T_{10})$ connections during certain months and seasons is probably, due to a weaker display of the main cycle in the events of the geomagnetic activity.

(iv) An increase in the lag of data smoothing allows the short periods, namely the quasi-triennial and to a lesser degree the quasi-biennial components, to he revealed more precisely.

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