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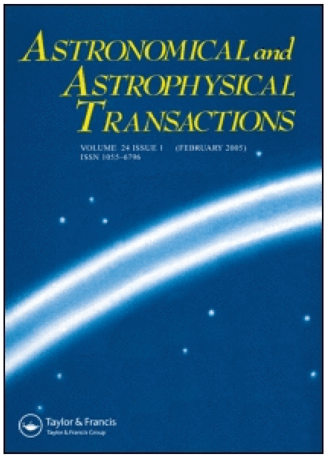

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SOLAR CYCLICITY AS A FACTOR OF CLIMATIC CHANGES

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Frequency characteristics of the connection between the Sun and the terrestrial atmosphere caused by the cyclic changes of the solar activity are considered. Cross-spectral and dispersion analyses are used. Manifestations of the 11 and 80-year solar cycles in the global dynamics of the atmosphere such as recurrence of circulation patterns, meridional and zonal pressure gradients and some oceanic parameters are revealed.

1 INTRODUCTION

The origin of climatic changes sources is a fundamental problem in modern theoretical and applied geophysics. Numerical model calculations have led to a certain progress in understanding heat and momentum exchange in the ocean–atmosphere system. These models, however, refer only to a middle-term weather forecast. As far as physical climate theory is concerned, the main input parameters are: the amount of solar radiative energy, the positions of continents and oceans, the cryosphere state and the atmospheric composition. The difficulty of this problem is that a climatic system with given input parameters might have no unique solution. In other words, there is a possibility that climatic theory equations have several stable solutions. Weather changes are a result of mainly barotropic and baroclinic atmospheric instability. In contrast to this, the climatic system as a whole is very sensitive to the input parameters changes. The appearance of forced of self oscillations in the climatic system might be considered in terms of nonequilibrium phase transitions. In this case the system becomes sensitive to low-energy external influences.

We shall not consider large period such as several million years not covered by accurate observations. Instead we consider those for which there are instrumental observational sets. For the Sun these are well-known Wolf sunspot numbers available from observations over more than 250 years. Geomagnetic indices of activity cover more than a 100-year period. There are similar sets of data representing pressure, temperature and several other meteorological parameters over the whole Northern hemisphere. Using these data one can definitely reveal a statistically significant 11-year cyclicity.

A permanent character of cyclicity in the solar activity (11-year and 22-year) is apparently real. Even Maunder and Sporer minima occur as states with smaller cycle amplitude rather than with no cycles at all. In any cases, Precambrian Australian band clays reveal a periodicity keeping the same cyclicity period as the solar cycle (Williams, 1985). This fact cannot be overestimated provided that the solar activity manifested itself through climatic processes during hundred million years.

The problem of the Sun–Earth atmosphere relationship has developed from the early simple comparison between solar and meteorological parameters of activity to the modern comprehensive appreciation of a complex nature of the relationship. The main difficulty of the problem is the fact that the energetically weak solar influence is revealed against the powerful background of the interlocking processed in the ocean – atmosphere – continent system. It is just this fact that permitted to disentangle gradually the complexity of the space-time structure of the solar-atmospheric relationship after the first successful solar-meteorological data sets comparison were made. It turned out that a relationship found in one certain region (or latitude interval) does not occur in other regions, or it shows much lower intensity or even an opposite sign of the correlation. Initial synoptic conditions, influence of the atmospheric circulation predecessor pattern and the season proved to be of importance. It was discovered that a relationship observed in a given region may lose its stability and even change its sign. The cycle phase and its parity (i.e. odd or even) also have their influence upon the relationship characteristics. All this produced some skepticism among several meteorologists and at the same time added difficulties to the prognostic model calculations based on solar predictors.

The modern approach to the solar-tropospheric problem is characterized by new conceptions and search for new casual relationships. For example, solar plasma and interplanetary magnetic field (IMP) parameters made allow to deduce the influence of the sectorial IMP structure upon the relationship pattern (Smirnov, 1967, 1969). As a result, a series of similar papers appeared (Wilcox, 1976; Wilcox, *et al.* 1973; Markson, 1979). The energy approach to the problem has led to numerical results on long–wave kinetic energy changes in the troposphere depending upon geomagnetic disturbances (Smirnov, 1974). A relation between solar activity and the available potential energy in the troposphere was also discovered (Zadvernjuk *et al.*, 1987; Avdjushin *et al.*, 1987). Further, a complex spatial solar activity-terrestrial atmosphere relationship was analyzed. It was shown hat there are zones in the troposphere with the largest intensity of both solar-tropospheric effects and the response rate of the solar disturbances. This implies a conclusion on the predominant role of energy-active regions in the troposphere with high baroclinic instability in solar-atmospheric relations (Smirnov, 1984).

The suggestion of Labitzke (1987) to compare stratospheric data sets separately for eastern and western phases of the quasibiannial cycle turned out to be very stimulating.

2 A METHOD OF DATA ANALYSIS

The solar activity manifestation in the terrestrial atmosphere should be investigated most properly by means of spectral or cross-spectral analysis. The latter allows to reveal not only the main energy supplying components, but also to estimate a degree of connection between different processes for definite frequencies. Moreover, it also gives the relation sign and phase dependence between processes under consideration and accurate estimations of statistical significance. The data sets of the chosen solar and meteorological parameters were primary tested for stationarity by using mean values and standard deviations. Then long-period trends were filtered out. The spectral window was narrowed using Parsen and Tjuky filters.

The results of cross-correlation analysis present a frequency structure of the corresponding processes relationship. The most informative are cross-spectra, quadrature, coherence and phase. Here, we discuss only coherence spectra $CH(T)$. A $CH(T)$ spectrum represents a degree of correlation as a function of frequency or period T, namely

$$CH(T) = \frac{[Co_{\mathrm{xy}}(T)]^2 + [Q_{\mathrm{xy}}(T)]^2}{S_x S_y},$$

where $Co_{\mathrm{xy}}(T)$ and $Q_{\mathrm{xy}}(T)$ are the corresponding cross and quadrature spectra, and S_x and S_y are spectral densities of the processes x and y.

3 ANALYSIS OF THE SOLAR-TERRESTRIAL ATMOSPHERE RELATIONSHIP

Macrosynoptical hemispheric processes are determined by tropospheric long-waves distributions of wind velocity field, cloudiness, temperature and air pressure together with the transformation of the available potential energy into kinetic energy. Long-wave dynamics shows redistribution energy in the form of altitude ridges and depressions. This means a transformation of circulation types. The recurrence of certain circulation forms over a long time period causes the droughts or positive precipitation anomalies and predominance of anomalies in temperature, pressure and cloudiness in certain regions of a hemisphere. Therefore a change of the circulation form recurrence provides the main contribution to climatic variations.

The problem is to recognize manifestations of the solar cyclicity by using long-term data sets of the circulation form recurrence.

There are several circulation form classifications. The one used in this paper was suggested by Girs (1971). His classification uses a spatial tropospheric long-wave structure as an indicative parameter. According to Girs, there are three main types of circulation in the Atlantic European sector. They are: the zonal one W and two meridional ones, eastern E and meridional C. In the Pacific-American sector, there are also the zonal Z and two meridional types of circulation M_1 and M_2. Each of these types of circulation is characterized by a definite position of altitude ridges and depressions. Therefore, they have specific cyclonic and anticyclonic activity

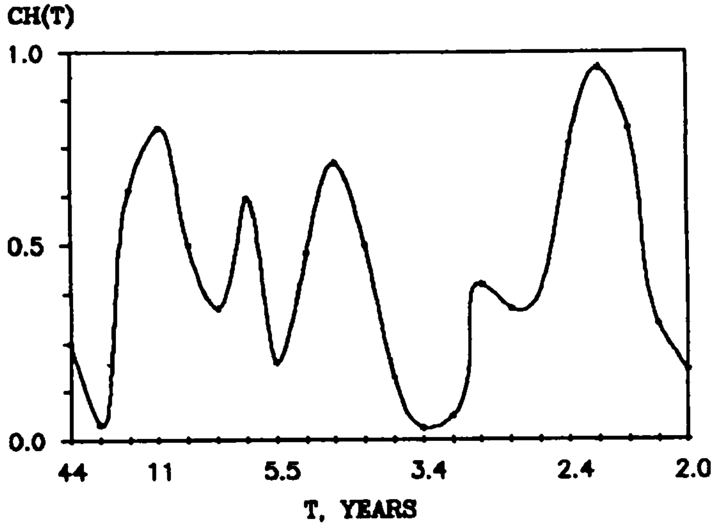

Figure 1 Coherence $CH(T)$ for geomagnetic A_p-index and meridional circulation M_1.

patterns. A macro-synoptic process over the whole hemisphere is characterized by combinations of the circulation types in two sector: W_z, W_{M1}, W_{M2}, C_z, C_{M1}, C_{M2}, E_z, E_{M1}, E_{M2}.

We used coherence spectral analysis to investigate connection between the above circulation forms, their modifications including, and solar-geomagnetic activity indices for the 1900–1968 interval.

The main results is that the imprint of the 11-year solar cycle and its harmonics is most specific for meridional circulation forms. The solar cyclicity for the circulation form combinations W_z, W_{M2}, C_z, E_z is faintly revealed. The closest relation between frequency characteristics is found for the A_p geomagnetic activity index and for the meridional recurrency M_1. Figure 1 represents the absolute values of the coherence $CH(T)$ as a function of periods T in years. It is evident that the degree of correlation increases sharply towards $T_1 = 11$ years. Its maximum value is 0.82. This suggests a close A_p–M_1 relation for the period T_1. The other $CH(T)$ maxima at $T_2 = 6.3$ years, $T_3 = 4.4$ years and the most prominent at $T_4 = 2.2$ years. The T_2 and T_3 periods are also common to meteorological parameter spectra: the T_2 one is probably connected with nutation forces and T_3 with variations of the rotation rate of the Earth. However, the dominant features of $CH(T)$ spectra are the 11-year and quasibiannual cycles. Levels of significance $q[CH(T)]$ for these periods are higher then 1 percent. Cross-spectra and quadrature spectra have positive values for the T_1 period. This suggests an increase of the recurrency of the circulation type M_1 at a maximum epoch of the 11-year cycle.

The circulation type M_1 considered above, its modifications included, is specified by the development of altitude ridges over the North Atlantic or Western Europe and Atlantic. Positive pressure and temperature air anomalies are observed in these

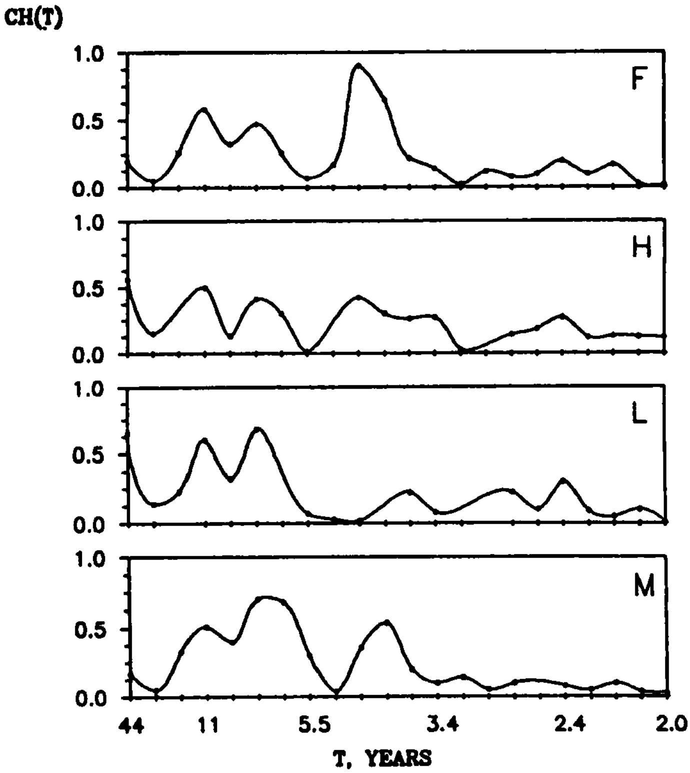

Figure 2 Coherence $CH(T)$ for A_p-index and surface temperature anomalies for the North Atlantic.

regions. There is a feedback in the atmosphere–ocean system. The variability of temperature anomalies over the North Atlantic was investigated to take into account this feedback. The surface temperature data for individual Smed squares and the geomagnetic index A_p were used. The time interval considered covered almost a century. The cross spectral analysis revealed a complicated spatial structure over all the 14 squares (Avdjushin *et al.*, 1982). The 11-year cyclicity is observable over the squares A and B located near the western Greenland coast and for the squares G, K, I, F, H, L and M close to the Iceland. The 11-year cycle is faintly observable over the southern part of the North Atlantic (squares D, E, N). Figure 2 presents the character of the relation change for F and H squares close to Iceland and for the southern L and M squares. Note a significant similarity of the coherence spectra revealed by the presence of the main energetic periods. In our case the most interesting are 11-year periods observed over all the squares. The relationship degree for $T = 11$ years diminishes from F–H to the southern L–M squares.

The second noticeable feature is the $T = 7.3$ year period which is present on all coherence spectra. For the northern squares, this period is a subordinate one.

However, it becomes dominant in the southern direction. It is predominant in the South squares D, E and N. For all the spectra in Figure 2, $q[CH(T)]$ exceeds 0.95 in the $T = 11$ year region. This supports the reality of the connection between the events.

The q values for the south squares for the same T are less than 0.95.

The period $T = 4.4$ year, which was noted in Figure 1, is also present in the Figure 2 spectra.

In principle, the appearance of the $T = 7.3$ year maxima on the $CH(T)$ spectra is the result of existence of the 7–8 year periodicity in the A_p index. This may be produced by a certain structure of the 22-year cyclicity consisting in an alternation of the short (7–8 years) even cycles and longer odd ones. On the other hand, the spatial pattern of this cycle suggests that there is a proper mechanism of the Atlantic water dynamics. Such a mechanism was considered by Shulejkin (1968). It must be connected to the cyclonic overturn of Atlantic waters resulting in the 7 year periodicity of the Gulf Stream – the North Atlantic current.

The cross-spectral and quadrature spectral maxima are positive for the $T = 11$ year period. This suggests formation of positive surface temperature anomalies in the North Atlantic during the 11-year cycle maxima. This important fact is in agreement with results of Smirnov *et al.* (1977), who show that positive temperature anomalies (up to 2.5°C) appeared in the Icelandic region during the time interval under consideration.

The North Atlantic regions and their western part especially belong to energy-active sites with enhanced processes of warmth and momentum exchange. Large amplitude of solar-atmosphere effects are characteristic for such regions.

Therefore, an attempt to reveal solar cyclicity effects in the atmospheric radiation balance R over the North Atlantic has been made. The 1958–1989 meteorologic data on cloudiness, atmospheric and oceanic temperature and humidity fields were used. The accuracy of a single datum does not surpass 10 percent. However, monthly and annual averaging improves the data validity. On the other hand, relative R values should be even more reliable.

Figure 3 presents the coherent function characterizing the frequency structure of the $F_{10.7}$–R relationship, where $F_{10.7}$ is the solar radio flux at the 10.7 cm wavelength. It can be easily seen the main feature of the spectrum is the 11 year maximum of the $CH(T)$ equal to 0.67. The corresponding $q[CH(T)]$ value exceeds by far the 1 percent value. The $CH(T)$ values for $T = 22$ and $T = 7.3$ years are also rather high and q exceeds the 5 percent critical value.

It can be concluded that positive R anomalies can occur during even maxima of the 11 year cycle. The corresponding mechanism of their origin seems to be intricate and may be connected with the changes in the cloudiness field.

Now we are going to suggest a general conception of the solar influence upon the atmosphere of the Earth. Tentatively the conception may be outlined on the basis of a complex investigation of the cyclicity display in meteorologic, ocean and radiative parameter variations over the North Atlantic. The initial effect reveals itself in energy-active regions of the atmosphere with a high level of geostrophic

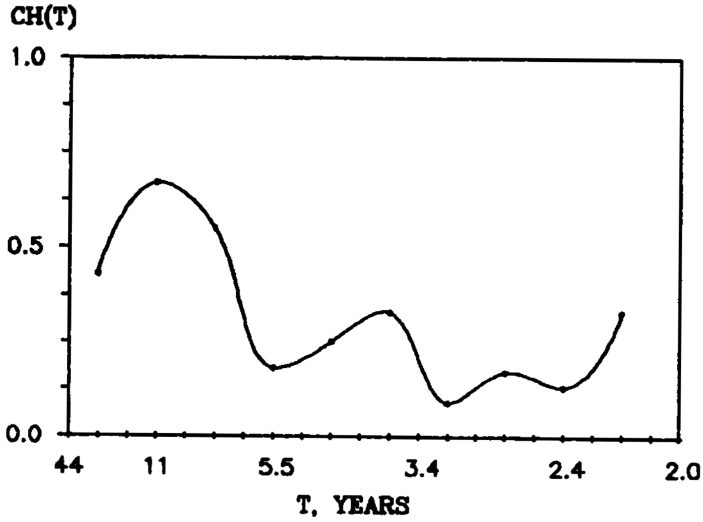

Figure 3 Coherence $CH(T)$ for $F_{10.7}$-index and North Atlantic radiative balance.

advection, horizontal divergency of the wind velocity and baroclinic instability. According to Smirnov (1984) an external disturbance manifestates itself at a certain stage of baroclinic instability. Then it is transported over the main flux due to dispersion properties of the atmosphere. The selective properties of the baroclinic instability produce long waves in the atmosphere with a certain spectrum. The character of the spectrum depends on the minimum values of instability of the vertical wind shifts. The corresponding wave numbers are k = 3–5. These k values are connected with formation of meridional forms C, E, M_1, and M_2. An example of close relationship between A_p and M_1 values was discussed above. A method of dividing the meteorologic disturbances into two parts (the solar-depending one and the pure meteorologic one) was described by Zadvernjuk *et al.* (1987). This conception can be used for a very long term weather and climatic changeforecasting.

We have analyzed solar cyclicity effects in both global atmospheric circulation characteristics (Smirnov, 1972) and middle latitude characteristics (Kononovich *et al.*, 1985; Smirnov *et al.*, 1984, 1987). These papers also covered the effects produced by zonal and meridional temperature and pressure gradients, temperature anomalies, etc. The results have shown that the solar effects strongly depend on season and latitude. The frequency structure of the relationship is rather complicated and has different responses to cycle periods 11, 5.5 and 2 years. As a whole, the relationship closeness drops winter to summer and from 65–70° latitude to lower values. As to the 22 year cycle, its effect is most prominent at higher latitude (Smirnov *et al.*, 1987).

The 80–100 year cycle is difficult to investigate in the troposphere primarily because rigorous methods of spectral-coherence analysis are invalid. Nevertheless,

Table 1. Comparison of solar and meteorologic activity for two periods: 1900–1930 and 1931–1968

N	*INDEX*	σ_1^2	σ_2^2	F	α	*INDEX*	σ_1^2	σ_2^2	F	α
1	w_0	7.72E+2	2.95E+3	3.82	$\gg .999$	w	835	693	0.83	$<.50$
2	N_0	2.18E+5	9.56E+5	4.38	$\gg .999$	C	722	585	0.81	$<.50$
3	S_0	2.18E+5	8.83E+5	4.05	$\gg .999$	E	626	1792	2.86	$>.99$
4	S_N	6.61E+4	2.59E+5	3.89	$\gg .999$	Z	825	937	1.14	$<.95$
5	S_S	5.17E+4	2.40E+5	4.63	$\gg .999$	M_1	299	1960	6.55	$\gg .999$
6	A_p	5.21	18.63	3.57	$>.999$	M_2	551	701	1.27	$<.90$

Note: 7.72E+5 means 7.72×10^5.

this period is important in view of the formation of circulation epochs and their stages and climate change prognosis as well.

An attempt was made to reveal common and different features of the solar and meteorologic activity for two periods: 1900–1930 and 1931–1968. The annual mean values of the Wolf number W_0, faculae area N_0, the total sums of sunspots S_0, the same sums separately for northern and southern hemispheres S_N and S_S, the geomagnetic activity index A_p, the recurrency of the different forms of atmospheric circulation W, E, C, Z, M_1, M_2 and their modifications were used. The dispersions σ_1^2 and σ_2^2 corresponding to the two time intervals were calculated for the both time intervals. The F-criterion was used to estimate the validity of the dispersions differences. The difference was considered to be significant when $F Z_\alpha$, where Z_α is the level of significancy at α level. The critical α value was accepted to be 0.95. It means that at $\alpha \geq 0.95$ the estimates are significantly different. The results are summarized in Table 1.

The data given in Table 1 show an increase in the solar activity after the 80 year cycle minimum especially in the second time interval. This result is proved by high F and α values especially for the N_0 and S_S indices. The A_p index also show the increase in the second interval but in a somewhat lower degree in comparison to the solar indices. Variability of the circulation form recurrency is also higher as a whole for the second time interval, but not so pronounced as for the solar activity indices, and strongly depends on the circulation form type.

The highest variability in the second time interval is specific to forms E, M_2 and especially M_1. Comparing the corresponding F and α values with those for the solar indices one may come to a conclusion about the relationship between these events in the 80-year cycle. This is also in agreement with the close connection $A_p - M_1$ shown by the Figure 1.

We have not mentioned on purpose the problems of common relation of the solar activity cycles to the Earth atmosphere activity, the cycle fine structure, importance of odd/even cycles and other questions not covered by the purpose of this work. The various mechanisms of the solar activity effects in the Earth atmosphere are also not discussed here because they represent a separate problem.

4 CONCLUSIONS

(1) Solar cyclicity plays a definite role in climate changes together with other internal mechanisms of variability. It causes a rhythmic structure of climate oscillations.

(2) Solar cyclicity effects in the atmosphere are characterized by a complicated spatial-frequency structure. The relationship narrowness depends upon given region, season and circulation pattern. This provides a variability of the relationship narrowness and the alternation of the relationship sign.

(3) There are certain regions of an invariant pattern of the solar-atmosphere relationship. They incorporate energy-active regions of the troposphere, e.g. the North Atlantic regions. This fact is supported by the narrow relationship between $A_p - M_1$, A_p-North Atlantic temperature and $F_{10.7} - R$, which were considered above.

(4) The 11 year period reveals the highest level of significance. This period is reflected by the middle latitude atmospheric characteristics, by the circulation form recurrency and by some ocean parameters.

(5) The 22 year period is better revealed at higher latitudes. The quasibiannual cycle is clearly revealed by several atmospheric characteristics (e.g., M_1 and temperature anomalies).

(6) As a whole, results of this work support the conception suggested by Smirnov (1984) about the importance of the atmospheric energy-active regions in manifestations of solar-atmosphere effects, including solar cyclicity effects in the Earth atmosphere, as it was shown by a complex approach to the North Atlantic case.

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