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Long-Term Modulation of Solar Radiation Observed on the Ground of the Earth, and Its Correlation with the Solar Activity Variations

I. Ya. Libin*, R. T. Gushchina*, J. Peres-Peraza, A. Leyva**, A. Yaani***, and Yu. Mikalaiuniene******

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

*** Instituto de Geofisica, National Autonomous University of Mexico, Coyoacan, 04150, Mexico D.F., Mexico*

**** Estonian Meteorological and Hydrological Institute, Ravala pst., 8, Tallinn, EE001, Estonia*

***** Hydrometservice of the Lithuanian Republic, Vilnius, Lithuania*

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Abstract—The solar radiation, observed on the ground of the Earth, and its correlation with the solar activity variations are studied. It is shown that the data on cosmic-ray intensity should be used for developing prognostic models. It is also shown that a choice of the index for a description the solar activity (SA) variations is very important.

INTRODUCTION

A long-term experiment for the solar radiation measurements was carried out in the framework of ecological programs related to the atmosphere pollution in different regions on the Earth, which are causing serious concern, namely, Mexico, Moscow, and Vilnius. In our case parallel with estimates of human industrial activity impact (injections of dust, combustion products, and exhaust gases into the atmosphere, aerosols, etc.), the analysis of a possible modulation of the solar radiation, recorded on the ground, by solar activity was carried out.

A frequency-dependent correlation between the solar activity and variations of temperature, water content (levels of isolated lakes), and atmospheric precipitation levels in different regions of the Earth were revealed by the authors of [1–6]. In this connection, it is necessary to make the right choice for the solar-activity index (or combination of indices) to provide an effective registration control of variations of electromagnetic conditions in the interplanetary space. The Wolf numbers used earlier in some cases did not enable one to obtain good correlations, and for this reason, the total sunspot area is used in the recent studies as the index for correlation [5, 6]. This index was found to be quite efficient for the case of meteorological parameters. However, the analysis of variations of the solar radiation on the ground showed that the total sunspot area appeared to be a rather crude index.

1. The analysis of the correlation between the 11-year cycle of cosmic ray intensity and different solar activity indices (the Wolf numbers, intensity of the coronal green line 5303 Å, solar radioemission, sunspot areas) showed that variations of the considered solar activity characteristics correlate with the cosmic-ray variations [7, 8] in similar ways. The existence of a pronounced correlation between the long-period changes of the cosmic ray intensity and the above indices is not a random event, since each of the indices represents the general characteristics of the solar activity cycles.

As was shown in [6], the direct use of the solar activity indices is possible only when the atmospheric processes are analyzed (but even here, these indices are not always applicable). The use of these indices is not quite correct for the cosmic rays, as the solar-wind plasma streams originating at different heliolatitudes are of a different modulating efficiency [7]. A similar conclusion may be drawn for the solar radiation recorded near the ground, as indicated, due to [8–10], a modulation of the galactic cosmic rays by the solar wind is a plausible mechanism for the solar activity effects on the solar radiation.

This is especial, important for observations on the Earth where the modulating properties of an active region on the Sun is determined not only by its proper activity and helio-coordinates, but also by an angular width of the solar wind stream. The index, based on taking into account the Earth's heliolatitude for a time instant of recording the cosmic ray intensity, a difference in activities of the Northern and Southern Solar Hemispheres, and a change in the heliolatitude of spots during a solar activity cycle, was proposed in [10]:

$$HL(\theta_{\odot}^{+}, \theta, t) = a\int_{-\pi/2}^{\pi/2} K_i(\theta, t)\exp\left(-\left|\frac{\theta - \theta_{\odot}^{+}}{\theta_0}\right|\right)d\theta,$$

Table 1. Normalized values of the *HL*-index (θ = 30)

Year	1	2	3	4	5	6	7	8	9	10	11	12
1952	174.7	113.7	77.5	156.0	143.2	165.6	294.9	370.4	162.3	175.8	186.4	233.4
1953	147.7	4.4	27.1	174.4	77.0	79.6	35.4	137.7	71.8	15.0	5.0	1.5
1954	0	0.2	89.1	0.8	0.4	0	4.1	18.3	0	3.3	14.9	25.1
1955	124.1	67.3	13.4	15.9	68.9	112.6	40.6	147.2	123.0	263.7	416.8	282.2
1956	296.1	695.3	487.9	338.4	635.6	444.1	523.9	836.6	633.6	655.3	1050.5	1034.9
1957	714.9	301.2	582.1	680.7	886.3	1207.1	908.5	712.3	1552.7	1290.0	944.9	1224.0
1958	992.0	827.2	1261.9	1075.1	929.0	725.9	1068.8	997.2	1007.5	872.9	533.7	1146.2
1959	1337.7	550.5	947.2	681.8	854.6	1057.4	966.7	1331.4	909.6	713.1	772.0	850.5
1960	935.8	546.5	444.2	675.6	775.3	540.7	817.9	832.0	493.6	406.1	476.4	334.9
1961	222.3	134.4	237.5	269.9	225.0	474.0	584.1	229.0	434.7	126.1	133.7	180.7
1962	216.6	278.2	242.6	192.2	272.4	147.6	136.4	65.2	286.7	162.4	119.9	76.5
1963	64.5	59.9	44.8	114.0	113.9	137.1	71.6	148.8	254.3	187.2	99.1	25.9
1964	30.5	29.0	11.1	8.4	51.0	28.2	23.6	4.2	40.7	45.6	28.6	45.2
1965	30.5	29.1	11.1	8.4	50.8	28.2	23.7	4.2	40.8	45.7	28.7	45.3
1966	65.4	31.9	108.4	133.2	119.1	77.3	183.5	179.9	333.2	239.5	236.5	168.0
1967	479.0	234.7	466.9	152.3	364.3	235.6	307.7	589.1	242.2	327.7	370.6	504.4
1968	596.1	439.4	282.0	208.2	438.8	507.3	487.9	430.9	387.4	323.7	325.5	444.3
1969	458.0	317.2	626.4	476.1	440.7	400.1	342.0	392.9	247.3	600.7	474.6	371.5
1970	515.7	627.4	461.2	696.5	739.5	492.8	626.6	522.4	443.4	482.6	582.6	449.2
1971	755.7	525.4	278.7	391.7	237.1	156.4	443.7	347.9	227.7	437.1	329.6	418.4
1972	210.9	432.0	494.1	144.2	529.9	584.1	362.2	416.4	284.7	343.3	213.7	184.5
1973	164.5	171.1	348.9	302.2	201.4	199.7	239.9	100.4	379.8	151.2	122.3	114.7
1974	110.3	92.9	68.5	211.9	190.3	120.5	267.8	155.7	273.1	312.3	152.5	89.3
1975	57.7	33.1	29.4	6.9	31.8	51.6	36.0	50.7	30.5	43.5	111.4	14.2
1976	48.3	6.2	124.3	160.8	42.4	35.9	3.0	111.4	57.8	56.1	37.0	71.0
1977	21.9	53.8	14.3	33.6	25.4	157.0	68.7	72.8	275.0	138.6	75.5	158.7
1978	166.3	398.4	323.4	307.5	363.1	313.9	261.9	122.8	514.0	397.0	401.1	656.4
1979	793.2	563.8	458.2	485.1	422.7	777.9	452.8	632.6	648.4	912.2	703.0	575.3
1980	707.4	942.3	457.1	688.4	975.4	714.2	618.7	531.7	746.6	640.1	981.3	909.4
1981	460.6	754.7	714.6	693.5	619.9	361.8	1015.1	804.1	811.3	924.0	582.0	766.0
1982	502.7	1163.1	1168.0	496.4	449.6	919.7	599.7	753.9	507.7	462.2	559.4	1039.5
1983	411.1	292.2	314.8	350.1	600.0	511.0	399.5	305.6	242.6	365.5	133.5	167.8
1984	474.8	658.1	432.0	653.7	666.6	269.7	194.3	140.4	120.9	114.3	159.1	137.4

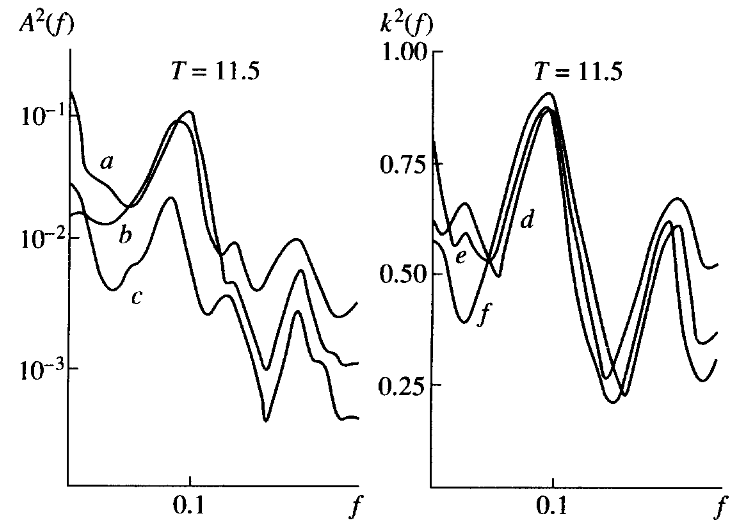
where K_i is the parameter characteristic for the solar activity at a moment t at the heliolatitude θ, θ_0 is the parameter of the angular half-width of the solar wind streams, $\theta_\oplus$ is the Earth's heliolatitude included to eliminate the effects, due to an inclination of the Earth's orbit to the equator plane, and a is a normalized factor derived from the condition:

$$a\int_{-\pi/2}^{\pi/2}\exp\left(-\left|\frac{\theta-\theta_\oplus}{\theta_0}\right|\right)d\theta = 1,$$

which results in

$$a = \left\{2\theta_0\left[1-\cosh(\theta_\oplus/\theta_0)\exp\left(-\frac{\pi}{2\theta_0}\right)\right]\right\}^{-1}.$$

In [8], the *HL*-indices for 18th and 19th cycles of the solar activity were calculated, and the area and number of sunspots were used as the parameters of the activity. In [9], the *HL*-indices for the 20th cycle were calculated. Continuous series of mean monthly values of the heliolatitude index for a period longer than two cycles of the solar activity (see Table 1) make it possible to carry out the correlation and ARMA analyses between



Intercorrelated spectra of the *HL*-index and solar radiation in Vilnius during 1955–1965 (*a*), 1966–1977 (*b*), 1978–1987 (*c*), and the coherence spectra (*d–f*) for the solar activity cycles analyzed.

the total sunspot area, the solar radiation, the cosmic rays, and the values of the heliolatitude index.

Despite the non-stationarity of all the listed processes it was argued in [11, 12] that a quasi-stationarity does not substantially destroy the spectral estimates obtained by means of ARMA analysis, and does not result in essential changes of the observed delay of the processes under consideration with respect to the solar activity.

2. The authors carried out a combined bivariate auto-regressive spectral analysis of the total sunspot area, *HL*-index, solar radiation, and cosmic rays for the mean monthly data of observations in Mexico, Russia, and Lithuania during 1952–1990. Curves *a–c* in the figure present intercorrelated spectra of the *HL*-index and solar radiation in Vilnius for 1955–1987, and curves *d–f* show the coherence spectra for the analyzed solar activity cycles. (Similar spectra were also calculated for the solar radiation data in Mexico and in Moscow. The coherence coefficient for the identified peaks in the intercorrelated spectra Moscow–Vilnius was equal to 0.81 for variations with a 3-month period, and 0.96 for a period of 11 years.)

As seen in the figure, the variations with periods of 3–4 months and 1.3–2.4 and 11 years are observed within a wide frequency range of the data on the solar radiation on the Earth, and they are closely connected with the solar activity. A comparison of our results with similar studies of the solar activity effects on near-ground air temperature, the level of lake atmospheric precipitation and the storm occurrence demonstrates both a qualitative and quantitative correspondence (an accuracy up to the delay time).

The behavior of the coherence coefficient and residual dispersion of the processes analyzed and the solar activity seems to be the most important in the case when the *HL*-index or the total sunspot areas (see Table 2) are used. As is evident from this table, the use of the *HL*-index results in a higher accuracy than the total sunspot area use as an indicator of the solar activity.

Naturally, the above results should be more refined in the future: data on solar radiation should be more precisely corrected for meteorological conditions and industrial activities (the low-frequency trend, connected with a seasonal dust accumulation in the atmosphere, should be eliminated). Nevertheless, the

Table 2. Behavior of coefficients of coherence and residual dispersion of the processes under consideration for different SA indices

	SA index	Lithuania, Russia			Mexico		
		3 months	5–6 years	11 years	3 months	5–6 years	11 years
Coefficient of coherence between solar activity and solar radiation	Sunspot area *S*	0.41	0.25	0.70	0.42	0.34	0.80
	HL-index	0.62	0.41	0.85	0.62	0.73	0.82
Residual dispersion of the solar radiation in the ARMA-model	Sunspot area *S*	35%	45%	30%	40%	50%	30%
	HL-index	25%	40%	10%	25%	25%	20%

obtained results manifest a good correlation between the solar radiation levels on the Earth (which is dependent on atmosphere pollution) and the solar activity.

A comparison of spectral characteristics of the atmospheric parameters with similar spectra of the galactic and solar cosmic rays [13–17] demonstrates a good agreement both in the frequency and phase domains (in 1952–1992, variations, well-correlated with the solar activity and temperature, were observed in cosmic rays, their periods, of 3–5 months, 1 year, 2–4 years, and 11 years were concordant with the solar activity and temperature variations during the same period).

The most impressive result was obtained for correlating the calculated data on the temperature amplitude and phase spectra in the period of 1937–1979 in Estonia and Sweden, and on cosmic rays for the same period (measured by the ionization chamber during 1937–1953 at station Huancayo and registered by the neutron monitor at Climax in 1953–1979) with the solar activity. The correlating process common for all the database variations with periods of 10.5, 2–3.7, and 1.3–1.7 years were revealed, and a virtually simultaneous phase change of all the observed variations identified near 1958 was discovered.

CONCLUSION

Thus, a probable intercorrelation between the processes on the Sun and in the Earth's atmosphere has been demonstrated, and the studies of a delay between the atmospheric processes and the solar activity events revealed the presence of stable shifts of 12–36 months between the processes; these results agree with the results obtained by other calculation methods.

It is uniquely shown that in a process of study of a correlation between the solar radiation at the Earth and the solar activity, and of a development of prognostic models on the basis of these studies, the right choice for the solar activity index and correctly including of the cosmic ray intensity contribution are very important. This condition agrees with a mechanism for the solar activity effects on meteorological parameters [18, 19].

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