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Global radiation changes in the lower atmosphere related to solar activity phenomena

S. V. Veretenenko and M. I. Pudovkin

Physics Research Institute, St. Petersburg State University, St. Petersburg, Russia

Abstract. Variations of solar energy input in the lower atmosphere associated with different cosmophysical phenomena in the 11-year solar cycle were analyzed at the network of actinometric stations of Russia for the period 1961–1986. It is shown that the solar radiation fluxes at different latitudes may be strongly affected by galactic cosmic ray (GCR) variations, solar flare activity, and auroral phenomena, their influences revealing both the latitudinal and the seasonal dependencies. The found effects of solar activity on the radiation fluxes seem to provide evidences of cloud cover variations associated with the phenomena under study. The changes in the solar radiation input in the 11-year cycle amount to $\pm(4-6)\%$ and may be of significant importance for the radiation budget of the lower atmosphere.

1. Introduction

The Earth's climate is known to depend strongly on the solar radiation input in the lower atmosphere, being an important energy source of atmospheric circulation. Although the solar irradiance changes at the Earth's orbit turned out to be too small (∼0.1% in the 11-year cycle) to produce appreciable effects on the atmosphere processes [*Lee et al.*, 1995; *Willson and Hudson*, 1988], the solar radiation input in the lower atmosphere varies significantly depending on the cloudiness state, and these variations in turn influence to a large extent dynamic processes in the troposphere. Thus the study of solar radiation flux variability in the lower atmosphere is of particular importance to understand the physical mechanism of solar activity effects on the atmospheric circulation, weather, and climate.

According to contemporary ideas, the variations of solar protons and galactic cosmic ray (GCR) fluxes, the energy of particles being enough to penetrate the stratosphere/upper troposphere heights, seem to be one of the most plausible carriers of solar variability to the lower atmosphere [*Dickinson*, 1975; *Markson*, 1978; *Ney*, 1959; *Tinsley et al.*, 1989; *Vitinsky et al.*, 1976]. The intensity of these particles (∼(0.1–1) GeV) is strongly modulated by physical processes at the Sun and in the solar wind. The low-energy component of GCR flux at the Earth's orbit decreases by a factor of 2 due to the scattering by inhomogeneous magnetic fields of solar wind, with the solar activity increasing to the maximum. There are also short-term variations of cosmic particles associated with solar activity, such as bursts of solar cosmic rays generated during solar flares and Forbush decreases of galactic cosmic rays related to the passage of high-speed plasma streams. In turn, the variations of cosmic ray flux resulting in the ionization changes in the lower atmosphere are suggested to influence high-level cloud formation with the consequent release of latent heat and the radiation budget changes causing the troposphere circulation disturbances [*Dickinson*, 1975; *Tinsley and Deen*, 1991].

Indeed, there are many studies showing the effects of solar protons and GCR on the lower atmosphere dynamics and temperature, precipitation intensity, and ozone contents [*Pudovkin et al.*, 1996, 1997; *Shumilov et al.*, 1995; *Stozhkov et al.*, 1996; *Tinsley and Deen*, 1991; *Tinsley et al.* 1989; *Veretenenko and Pudovkin*, 1993]. The correlation of cloud amount with GCR intensity was reported by *Pudovkin and Veretenenko* [1995] and *Svensmark and Friis-Christensen* [1997]. However, the changes of solar radiation fluxes in the lower atmosphere which are closely connected with the cloud amount and therefore have to be influenced by

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Table 1. List of Actinometric Stations

Station	Geographic Coordinates		Geomagnetic Latitude
	φ, deg N	λ, deg E	Φ, deg N
Olenek	68.50	112.40	62.78
Verkhoyansk	67.55	133.38	61.33
Turukhansk	65.78	87.95	60.63
Arkhangelsk	64.58	40.50	60.22
Oymyakon	63.27	143.15	56.73
Yakutsk	62.08	129.75	55.86
Aleksandrovskoe	60.43	77.86	55.59
Vanavara	60.33	102.27	55.08
Voeykovo	59.97	30.30	55.98
Okhotsk	59.37	143.20	52.63
Irkutsk	52.27	104.35	46.97
Chita	52.02	113.33	46.41
Semipalatinsk	50.35	80.25	45.43
Khabarovsk	48.52	135.17	41.73

cosmic ray variations have not been studied enough. Some attempts to find relationships between long-term variations of solar radiation input and solar/geomagnetic activity, with sunspot numbers, faculae area, and $\sum Kp$ indices being used, did not reveal any distinct effect [*Loginov and Kravchuk*, 1982; *Loginov and Pivovarova*, 1975]. Statistically significant results were obtained only when correlating radiation characteristics with GCR intensity [*Kondratyev and Nikolsky*, 1983; *Veretenenko and Pudovkin*, 1997]. In this work we continue to study changes of solar radiation input in the lower atmosphere associated with galactic cosmic ray variations as well as with other cosmophysical phenomena caused by solar activity in the 11-year cycle.

2. Experimental Data and Their Analysis

2.1. Global Radiation Changes Associated With GCR Variations in the 11-Year Cycle

The global (or total) radiation monthly sums registered at the actinometric stations of Russia were taken as an experimental basis of our study [*USSR State Committee for Hydrometeorology and Control of Natural Environment,* 1961–1986] (hereinafter referred to as HCNE). Global radiation fluxes in the lower atmosphere Q are defined as the total of both direct (I) and scattered (D) radiation fluxes on the horizontal plane: $Q = I \sin h + D$, where h is the height of the Sun. A global radiation monthly sum represents the entire amount of solar energy coming to the Earth's surface during a month, decreasing with the cloud amount increase.

The global radiation changes associated with the solar activity phenomena were considered at the stations in three latitudinal belts: $\varphi \approx 65^\circ - 68^\circ$ (Olenek, Verkhoyansk, Turukhansk, Arkhangelsk); $\varphi \approx 60^\circ - 64^\circ$ (Oymyakon, Yakutsk, Aleksandrovskoye, Vanavara, Voyeykovo, Okhotsk), and $\varphi \approx 50^\circ$ (Irkutsk, Chita, Semipalatinsk, Khabarovsk), the exact coordinates of these stations being given in Table 1. It is seen that the observation data spread over sufficiently broad longitude intervals from $\sim 100^\circ$ at higher latitudes to $\sim 60^\circ$ at lower latitudes, so we can say that our study deals with rather large-scale effects of solar activity on the radiation input. The monthly sums of global radiation registered at each station were added up to obtain the half-year sums $\sum Q$ for cold (October–March) and warm (April–September) periods. If registered monthly sums were absent for some months, we used the sums estimated on the basis of mean monthly intensities of global radiation at the fixed times of observation and given by HCNE (1961–1986). In these cases we corrected the estimated sums by 3% and 15% for warm and cold months, respectively, since they are usually less than those obtained by registration by 2–4% in the warm period and by 10–20% in the cold period. The half-year sums of global radiation $\sum Q$ were averaged over the stations of the latitudinal belts under study. Thus the values $\sum Q_\varphi$, calculated in this way for our analysis, represent the average solar energy input at different latitudes during warm and cold half years.

In Figure 1, one can see the variations of global radiation half-year totals $\delta(\sum Q_\varphi)$, obtained by subtracting the linear trends, for all the latitudinal belts and seasons under study. The variations of solar radiation input are compared with those of GCR fluxes δN, the mean yearly values of Climax neutron monitor counting rate characterizing the GCR intensity [*U.S. Department of Commerce*, 1993], and the linear trend is also removed. All the data presented in Figure 1 are normalized to the corresponding trend values and expressed in percent. The thick solid line displays the 2-year running average of $\delta(\sum Q_\varphi)$ used to remove the apparent quasi-biennial oscillation and to show the 11-year variation more clearly. The correlation coefficients R between $\delta(\sum Q_\varphi)$ and dN as well as R_{sm} between 2-year smoothed values $\delta(\sum Q_\varphi)_{sm}$ and dN are presented in Table 2, with the confidence level given in parentheses. When evaluating

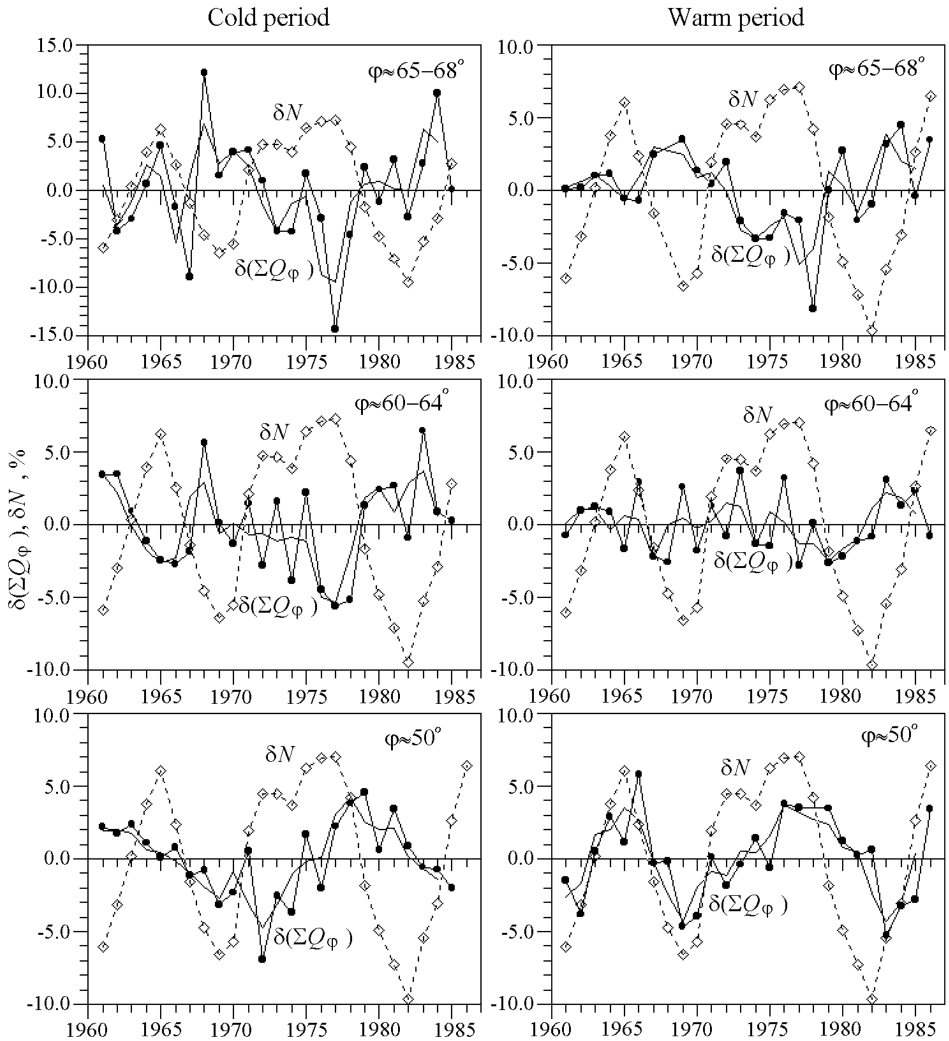

Figure 1. Variations of the global radiation half-year totals $\delta(\sum Q_\varphi)$ (thin line) and of GCR intensity δN (dashed line) in the different latitudinal belts. Thick line shows the 2-year running averages of $\delta(\sum Q_\varphi)$.

the statistical significance of the correlation coefficients for 2-year smoothed data, their persistence was taken into account, the number of independent points being reduced by a factor of 2.

The data presented in Figure 1 and in Table 2 show the clear relationships between the variations of solar energy input and of galactic cosmic ray intensity in the 11-year solar cycle, the found effects revealing both the latitudinal and the seasonal dependencies. It is seen that the increase of GCR fluxes in solar activity minima is accompanied by the decrease of global radiation totals at higher latitudes ($\varphi \geq 60°$), the most significant changes being observed in the belt $\varphi \sim 60° - 64°$ in the cold season. This effect is consistent with the negative correlation between the radiation input in the winter months and GCR fluxes in this belt [*Veretenenko and Pudovkin*, 1997]. At lower latitudes, $\varphi \leq 50°$, the global radiation reveals a positive correlation with GCR intensity in the warm period, while in the cold period, one can see it lagging behind by 1–2 years relative to GCR variations. The changes in the solar radiation input amount to $\pm(4\text{–}6)\%$ which seems to be of importance for the radiation budget of the lower atmosphere.

2.2. Auroral Activity and Solar Flare Effects on the Global Radiation Input

Let us consider the variations of solar radiation input associated with solar variability phenomena in more detail. It is obvious that the solar variability influence on the lower atmosphere state may be ambiguous. On the one hand, the high solar activity results in the decrease of the galactic cosmic particle flux causing the ionization decrease in the stratosphere and upper troposphere. On the other hand, the bursts of solar cosmic rays and of hard X rays generated during solar flares and resulting in the stratosphere ionization

Table 2. Correlation Coefficients Between the Variations of the Global Radiation Half-Year Sums and of GCR Intensity

Period	Latitudinal Belt	$\delta(\sum Q_\varphi)$ Unsmoothed Values	2-year Running Averages
Warm	65°–68°	−0.37(90%)	−0.60(95%)
	60°–64°	0.1(−)	−0.03(−)
	50°	0.50(98%)	0.70(99%)
Cold	65°–68°	−0.38(90%)	−0.57(≤ 95%)
	60°–64°	−0.59(99.8%)	−0.82(99.8%)
	50°	−0.13(−)	−0.04(−)

increase seem to provide the effects opposite to the effects of GCR reduction at solar maximum. Indeed, it was shown [*Veretenenko and Pudovkin*, 1997] that the negative correlation between the solar radiation input and the GCR fluxes is broken when the solar flare activity is very high, and besides, the auroral activity is likely to influence the radiation input at high latitudes too. Thus it seems to be quite necessary to separate the effects of different phenomena caused by solar activity on the lower atmosphere characteristics.

To estimate the independent effects of galactic cosmic ray variations, solar flares, and auroral activity on the radiation input at different latitudes, we used the partial correlation analysis that allows us to reveal a linear dependence between two variables, the effects due to other variables having been removed. According to *Brooks and Carruthers* [1953] the partial correlation coefficient between the variables X_1 and X_2, with the influence of variable X_3 being eliminated, is expressed as

$$r_{12.3} = \frac{r_{12} - r_{13}r_{23}}{[(1 - r_{13}^2)(1 - r_{23}^2)]^{1/2}}$$

where r_{ij} is the total correlation coefficient between X_i and X_j. A similar expression may be written for partial correlation coefficient $r_{12.34}$, when the effects of two variables X_3 and X_4 are to be eliminated; in this case, the total correlation coefficients are replaced with the partial correlation coefficients $r_{ij.k}$.

The partial correlation coefficients between the half-year radiation totals and each of the cosmophysical factors under study, the influences of the other two factors being removed, are given in Table 3 for the period 1966–1986. In this table, NM is the mean yearly counting rate of Climax neutron monitor, I_{fl} is the mean yearly values of flare activity index, introduced by *Kleczek* [1952] as $q = i \times t$, where i is the important coefficient of the flare, and t is the flare duration in minutes, the data on flare indices being taken from [*Knoška and Petrášek*, 1984; *Ataç*, 1987]. The intensity of auroral phenomena associated with auroral electrojet development in the high-latitudinal region is characterized by mean values of geomagnetic AE index for the current half year. Note that all the cosmophysical characteristics chosen in this way provided the highest values of correlation coefficients. For the period 1976/1977, when the data on the AE index were missing, the mean AE values necessary for our analysis were calculated basis of on the statistical dependence between AE and $\sum Kp$ indices averaged over the corresponding half-year periods.

The data presented in Table 3 show that all the cosmophysical phenomena under study do really affect the radiation input, their effects strongly depending on the latitude. In the high-latitudinal belt $\varphi \sim 65° - 68°$ the increase of GCR fluxes as well as solar flare activity causes the decrease of global radiation totals. At lower latitudes ∼50°, one can see a positive correlation of the radiation input with GCR intensity and solar flares. Auroral phenomena seem to decrease the global radiation totals only at high latitudes $\varphi \geq 65°$. It should be noted that the elimination of solar flare and auroral activity effects results in the strengthening of GCR influence. Really, the absolute values of partial correlation coefficients of the radiation totals and GCR fluxes

Table 3. Partial and Multiple Correlation Coefficients of the Half-Year Radiation Sums and Different Cosmophysical Factors

Period	Latitudinal Belt	Partial Correlation Coefficients NM	AE	I_{fl}	Multiple Correlation Coefficients
Warm	65°–68°	−0.78(99.9%)	−0.66(99.5%)	−0.63(99.5%)	0.8(99.9%)
	60°–64°	−0.2(−)	−0.13(−)	−0.43(90%)	0.49(−)
	50°	0.7(99.8%)	−0.22(−)	0.65(99.5%)	0.77(99.8%)
Cold	65°–68°	−0.62(99%)	−0.27(−)	−0.5(95%)	0.62(95%)
	60°–64°	−0.57(98%)	−0.05(−)	−0.34(−)	0.6(90%)
	50°	0.37(−)	−0.33(−)	0.62(99%)	0.67(98%)

amount to ∼0.6–0.8 depending on the season and on the latitudinal belt. Similarly, the elimination of GCR intensity influence allows us to reveal rather strong effects of solar flares and auroral activity at high latitudes, as well as of solar flares at lower latitudes. However, we can see that the GCR effects on the radiation input seem to be most pronounced compared with those of other cosmophysical phenomena under study for almost all the seasons and latitudes.

Latitudinal dependence of the partial correlation coefficients between the radiation totals and the GCR fluxes as well as solar flares is presented in Figure 2. It is seen that the changes in the correlation sign take place at latitude $\varphi \sim 57°$. Solar flare effects on the radiation input seem to be independent of the season, while GCR effects are most pronounced in the warm period. It should also be noted that the region of the negative correlation between the radiation totals and the GCR fluxes is displaced southward (lower than 55°) in the cold half year.

The multiple correlation coefficients between the global radiation half-year sums and the cosmophysical indices under study $R(\sum Q_\varphi, NM,\ AE,\ I_{fl})$ are also presented in Table 3. In the warm period these coefficients amount to ∼0.8 for latitudinal region $\varphi \sim 65° - 68°$ and 50°; that is, ∼60–64% of the global radiation variance are due to solar activity and related disturbances of interplanetary medium. The influence of solar activity on the radiation input is likely to decrease in the cold period, the multiple correlation coefficient being equal to ∼0.6–0.7. Nevertheless, one can conclude that GCR variations, solar flares, and auroral phenomena seem to be of significant importance for the radiation budget of the lower atmosphere both in warm and in cold periods.

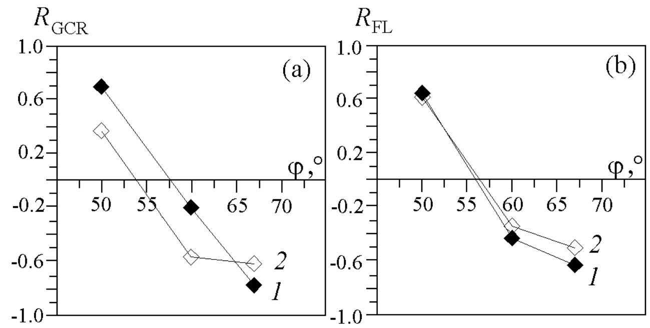

Figure 2. Latitudinal dependence of the partial correlation coefficients of the radiation halfyear totals with (a) GCR intensity and (b) solar flare activity: curve 1, in warm period; curve 2, in cold period.

3. Discussion of the Results

Since the global radiation fluxes in the lower atmosphere strongly depend on the cloudiness state, the found effects of the solar activity on the radiation input provide evidence of cloud cover changes associated with the phenomena under study. First, we should note the decrease of the radiation totals (i.e., the cloud cover increase) in the high-latitudinal belt $\varphi \sim 65° - 68°$ accompanying the galactic cosmic ray increase during the solar minimum. This effect is in agreement with the cloud cover changes correlated with GCR variations more strongly at higher latitudes both over the continental stations [*Pudovkin and Veretenenko*, 1995] and over the oceans [*Svensmark and Friis-Christensen*, 1997]. The increase of solar flare activity as well as auroral phenomena result in the solar radiation decrease in this belt too, partly compensating the effects of GCR flux reduction at solar maximum. Thus cloudiness variations and the corresponding changes of solar energy input at high latitudes seem to be strongly affected by solar activity phenomena, the increase of GCR flux, solar flare, and auroral activity resulting in cloud cover growth. Second, at lower latitudes ∼50° the auroral activity influence is likely to vanish, and the correlation between the radiation totals and GCR/solar flares changes the sign; that is, the cloud cover decreases with GCR growth and solar flare intensification. However, the summary influence of the two last factors on radiation input in this belt remains rather significant, especially in the warm period.

Let us consider the possible reasons of the found correlations. According to the suggested mechanisms of solar activity effects on the troposphere circulation, the increases of ionization produced by cosmic particles penetrating the stratosphere/upper troposphere [*Dickinson*, 1975] as well as of the local ionosphere potential [*Tinsley and Heelis*, 1993] are hypothesized to intensify microphysical processes in high-level clouds by increasing the electrostatic charge on the supercooled water droplets and on aerosols acting as contact ice nuclei and thereby the rate of ice nucleation and cloud particle growth. The consequent disturbances of the troposphere dynamics are suggested to result from the radiation budget changes [*Dickinson*, 1975] and/or from the latent heat release [*Tinsley and Heelis*, 1993] accompanying the cloud formation. Thus the cloud cover growth at high latitudes associated with the increase of GCR and solar flare activity seems to be due to the direct influence of cosmic rays, solar or galactic, on the cloud formation and to the circulation disturbances related to these cosmophysical phenomena. Indeed, the data presented by *Tinsley and Deen* [1991] and *Veretenenko and Pudovkin* [1993] give evidence of the cyclone intensification correlated with the GCR increase in the winter period which have to cause the cloud amount increase at higher latitudes. In the warm period, when the solar activity effects on the troposphere circulation are less pronounced [*Mustel*, 1974], a possibility of the direct influence of cosmic ray variations on the cloud formation may increase, mainly in the region $\Phi \geq 55°$ located higher than the geomagnetic cutoff latitude for the particles with the energy ≤1 GeV which are the most varying cosmic ray components in the 11-year cycle. As to auroral activity effects on the radiation input and cloud cover, they seem to be related to the changes of stratospheric ionization due to bremsstrahlung X ray fluxes generated by electron precipitation and having a sufficient energy (>30 keV) to penetrate the stratosphere heights. The cloud cover increase at middle latitudes associated with solar X ray bursts reported by *Dmitriev and Lomakina* [1977] and *Veretenenko and Pu-*

dovkin [1996] seems to confirm a possibility of similar effects caused by auroral X rays.

The change of the correlation sign between the radiation totals (cloud cover) and GCR/solar flares at lower latitudes requires additional studies to be explained. However, we can suggest that it may be due to the circulation disturbances, i.e., the pressure variations changing sign at some latitude and thus resulting in the opposite variations of cloud cover and radiation input. Indeed, *Schuurmans and Oort* [1969] showed that after strong solar flares the zonal atmospheric pressure decreases in polar and subpolar regions and increases at middle latitudes. A similar change of sign may take place for GCR-associated pressure changes, the increase of the GCR flux being accompanied by zonal pressure decrease (cyclone intensification) at higher latitudes and by its increase at lower latitudes. The latitude where the GCR effects on pressure and, consequently, on cloud cover variations change a sign seems to vary depending on the season, from $\sim 57^\circ$ in the warm half year to $\sim 55^\circ$ in the cold half year.

The found changes of solar radiation input, closely related to the cloud cover state and then to the lower atmosphere circulation, in turn influence significantly the circulation state providing energy for the evolution of long-term atmospheric processes. So, the observed variations in solar energy input amounting to $\pm(4\text{–}6)\%$, i.e., $\pm 110\text{–}170$ MJ m^{-2} in the warm period at high latitudes, may be of particular importance for the radiation budget of the high-latitudinal atmosphere, where the solar activity effects on the circulation state are most pronounced. If even only a 1% change in solar radiation input takes place in the region $\varphi \geq 65^\circ$, the additional energy input in the lower atmosphere of this region in the warm period is equal to $10^{27} - 10^{28}$ ergs for the solar maximum (when the GCR intensity is the lowest), and this value is comparable with the energy of the general atmosphere circulation. In particular, this additional solar energy may affect the heating of the north region of the Atlantic and Pacific Oceans which in turn supplies the energy from the surface to the air in the winter and influences the temperature field at high latitudes causing the circulation disturbances. Thus the changes of solar radiation input in the lower atmosphere may be considered as a possible energy source for the development of dynamic processes related to solar activity phenomena.

4. Conclusions

The data presented here show statistically significant effects of cosmophysical phenomena related to solar activity on the solar radiation input in the 11-year cycle, these effects revealing both the latitudinal and the seasonal dependencies. It was found that the increase of galactic cosmic ray fluxes as well as solar flare activity and auroral phenomena (perhaps, bremsstrahlung X rays generated by electron precipitations during polar substorms) results in the decrease of global radiation half-year sums (i.e., in the increase of cloud cover) in the high-latitudinal region $\varphi \geq 65^\circ$. At lower latitudes ($\varphi \sim 50^\circ$) the input of solar energy correlates with GCR intensity and solar flares which means the cloud cover decreases with GCR/flare activity intensification. The change in correlation sign between global radiation fluxes and these cosmophysical factors is observed at latitude $\sim 57^\circ$. The found solar activity effects on the radiation input seem to provide evidence of cloud cover variations that may be due to the circulation disturbances associated with the phenomena under study as well as to the direct influence of stratospheric ionization changes caused by these phenomena on the cloud formation in the high-latitudinal region. The 11-year variations in the solar energy input amounting to $\pm(4\text{–}6)\%$ seem to be of significant importance for the radiation budget of the lower atmosphere providing energy for the development of long-term dynamic processes caused by solar activity.

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S. V. Veretenenko and M. I. Pudovkin, Physics Research Institute, St. Petersburg State University, St. Petersburg, Russia. (pudovkin@snoopy.phys.spbu.ru; vereten@SV2135.spb.edu)

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