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Influence of solar activity on the lower atmosphere state

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[1] This paper briefly reviews modern ideas about plausible mechanisms of influence of solar activity on the lower atmosphere state and weather. The possible reasons for the disturbances in the lower atmosphere are as follows: (1) variations in solar irradiance, (2) changes in the global electric circuit parameters caused by variations in cosmic ray fluxes, (3) variations in the conditions of propagation and dissipation energy of planetary waves in the atmosphere, and (4) changes in the atmospheric transparency and cloudiness are considered. Specific features of development of individual (with duration of several days) disturbances in the lower atmosphere observed during Forbush decreases of galactic cosmic rays and solar proton events are discussed. It is concluded that at latitudes of 55° – 70° the disturbances considered are mainly due to variations in atmospheric transparency and cloudiness. Data on cyclic variations of the lower atmosphere state and their connection with variations in solar activity, atmospheric transparency, volcano eruptions, and other geophysical phenomena are analyzed. In conclusion, some unresolved problems of morphology of atmospheric disturbances are formulated. *INDEX TERMS:* 7538 Solar Physics, Astrophysics, and Astronomy: Solar irradiance; 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 0365 Atmospheric Composition and Structure: Troposphere – composition and chemistry; *KEYWORDS:* Solar-Terrestrial relations; troposphere; climate and weather.

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1. Introduction

[2] The global climate change and anomalous weather conditions observed during the last decade in different regions of the Earth require a deep understanding of the natural and anthropogenic factors responsible for these phenomena. For this reason, an ever increasing attention of researchers has been devoted to the problem of influence of variations in solar activity on the lower atmosphere state, weather, and climate.

[3] The problem of existence of solar-terrestrial connection and the physical mechanism underlying it has a long history. However, systematic investigations of the link between variations in solar activity and weather phenomena started, in all probability, only from the end of the 19th century. For instance, *Koeppen* [1873] studied the relation between the solar activity level (Wolf numbers) and mean air temperatures in the Northern Hemisphere. He showed that air temperatures exhibit pronounced 11-year variations correlating with similar oscillations in solar activity. However, the sign of the correlation was found to be different: from 1777 to 1790 the correlation was positive, while from 1815 to 1854 it was negative. Further investigations of *Koeppen* [1914] convincingly confirmed the results obtained by him earlier. From that time, hundreds of publications concerned with different manifestations of solar activity in changes of the lower atmosphere parameters, weather, and climate of the Earth have appeared. For instance, *Ohl* [1969], *Shiyatov* [1972], *King* [1975], and *Vitinskiy et al.* [1976] reported the data pointing to the existence of 11-, 22-, 45-, and 95-year cycles in quite different weather conditions, such as, for example, precipitation intensity, variations in surface temperatures and pressures in different regions of the Earth, annual tree ring widths, and drought rhythm in the western United States. There are a number of publications that demonstrate that the solar activity affects circulation of the lower atmosphere. *Wilcox et al.* [1974] have revealed that the area of the low-pressure regions in the troposphere decreases and goes to a minimum in approximately a day after the Earth crosses the sector boundary of the interplanetary magnetic field. *Bucha* [1984, 1988] and *Bucha and Bucha* [1998] have

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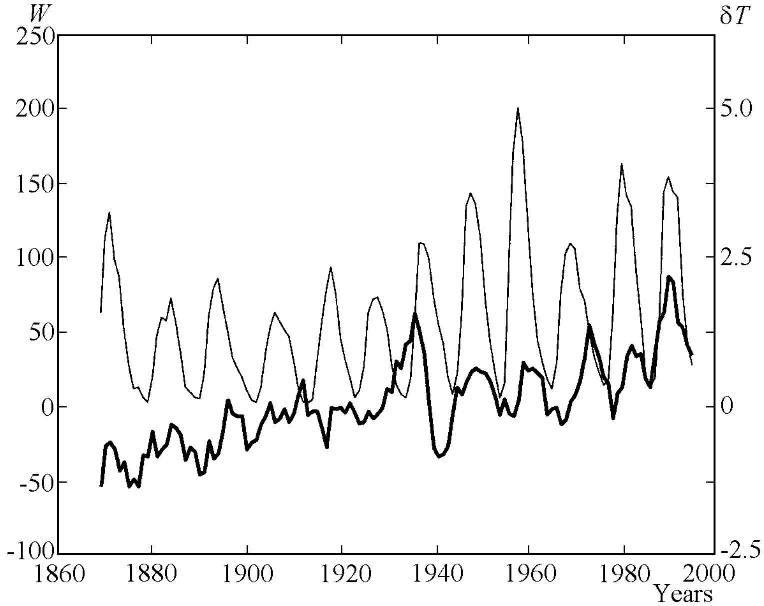

Figure 1. Variations in annual Wolf numbers (thick curve) and 5-year running mean air temperatures (δT_m) in St. Petersburg for 1867–1995 (thin curve).

concluded that an enhanced corpuscular radiation leads to a reduced pressure in the polar regions and hence to enhanced zonal circulation, which results in a considerable rise in air temperatures in Europe. They also point to the existence of a pronounced cyclicity in weather changes.

[4] Thus a vast body of experimental evidence indicating that there are statistically significant relations between different weather phenomena and solar activity has been accumulated. Nevertheless, many specialists, and especially meteorologists, show a good deal of skepticism about the idea that solar activity exerts influence on the lower atmosphere state [*Burroughs*, 1992; *Monin*, 1969; *Pittock*, 1978; *Salby and Shea*, 1991; *Siscoe*, 1978] (see also reviews of *Avdyushin and Danilov* [2000], *Pudovkin and Raspopov* [1992], *Hoyt and Schatten* [1997], and *Carslaw et al.* [2002]).

[5] The reasons for the doubts are rather strong. The main arguments are [*Bucha and Bucha*, 1998] as follows: (1) the absence of steady correlation relations between the solar activity level and different weather conditions, (2) an appreciable unbalance (of several orders of magnitude) between the power of atmospheric processes and intensity of variations in the fluxes of solar wave and corpuscular radiation (a possible solution of the problem will be discussed in sections 2.2–2.4), and (3) the absence of probable physical mechanisms responsible for the possible solar-terrestrial connection.

[6] The assertions given above are illustrated in Figure 1 which shows variations in annual mean Wolf numbers (W) and air temperatures in St. Petersburg (δT) (the 5-year running mean) for the last more than 100 years [*Zaitseva et al.,* 2003]. As can be seen from Figure 1, variations in surface temperatures exhibit pronounced quasi-11-year cycles, which is in full agreement with the results obtained by *Koeppen* [1873, 1914]. However, the relation between these variations and the relevant oscillations in solar activity is rather complicated. For instance, in the periods from 1870 to 1910 and from 1945 to 1995, variations in temperature and solar activity are in phase, while from 1910 to 1930 they are in opposite phase. From 1930 to 1945, there is no relation between variations in temperature and solar activity at all. On the whole, the correlation coefficient during the period considered here is low, and the relation between W and δT is statistically insignificant. Therefore Figure 1 can be interpreted as a visual demonstration of the occasional nature of the connection between solar activity and the lower atmosphere state observed during some periods [*Burroughs*, 1992; *Carslaw et al.*, 2002; *Pittock*, 1978]. This connection can be explained by the fact that some intra-atmospheric processes have periodicities similar to those of the sunspot activity of the Sun [*Donarummo et al.*, 2002; *Hurrel,* 1995; *James and James*, 1989; *Ram and Stolz*, 1999]. The reversal of the sign of correlation between variations in solar activity and air temperature is attributable to gradual accumulation of the phase shift between them.

[7] Note, however, that the data shown in Figure 1 can be interpreted in an entirely different way. If we take into account the fact that variations in the surface air temperatures are brought about by a set of different factors (wind system, cloudiness, atmospheric transparency) rather than one factor, it can be supposed that the observed reversal of the sign of correlation between δT and W variations can be explained by a fairly complicated dependence of these factors on the solar activity level, the connection between temperature and each of these factors being stable. The task of a researcher is to identify these factors and to find their relation with variations in solar activity.

[8] To illustrate this idea, let us consider the following example. Figure 2a shows variations in winter air temper-

atures t° in the polar stratosphere at the 30-mbar height and solar activity level (intensity F of radio emission with a wavelength of 10.7 cm) from 1956 to 1988. As can be seen from Figure 2a, the relation between variations in t° and F during the entire period is rather weak ($r = 0.14$). However, if we separate the analyzed data in accordance with the quasi-biennial oscillation (QBO) phase, the picture becomes appreciably different. Namely, for the years with QBO in the westward phase, there is a distinct positive correlation ($r = 0.76$) between t° and F (Figure 2b), while the years with QBO in the eastward phase are characterized by a negative correlation between t° and F, though it is less pronounced (Figure 2c). Thus the impression that there is no relation between variations in the polar stratosphere temperature and solar activity is gained because the different states of the atmosphere have different responses to variations in solar activity, but the relation does exist. This example shows how careful one should be when discussing whether the solar-terrestrial connection exists or not.

[9] As far as the physical mechanisms underlying the observed Sun-weather relation are concerned, it should be noted that the abundance of the hypotheses rather than the lack of them seems rather suspicious. However, in our opinion, this is the consequence of the diversity of the solar-terrestrial connections and of a wide spectrum of atmospheric processes and their relations with variations in different cosmophysical factors rather than the fact that the subject has been poorly studied.

[10] The basic mechanisms responsible for the specific features of solar-terrestrial connection are as follows: (1) changes in the solar irradiance associated with short- and long-term variations in solar activity, (2) changes in cosmic ray fluxes and the resulting variations in the parameters of the global electric circuit and variations in the cloud formation rate caused by these changes, (3) changes in the lower atmosphere dynamics and variations in the propagation of planetary waves and the energy carried by them, and (4) changes in atmospheric transparency and cloudiness (also under the action of varying cosmic ray fluxes). Let us consider in more detail some of the hypotheses listed above and their experimental and theoretical bases.

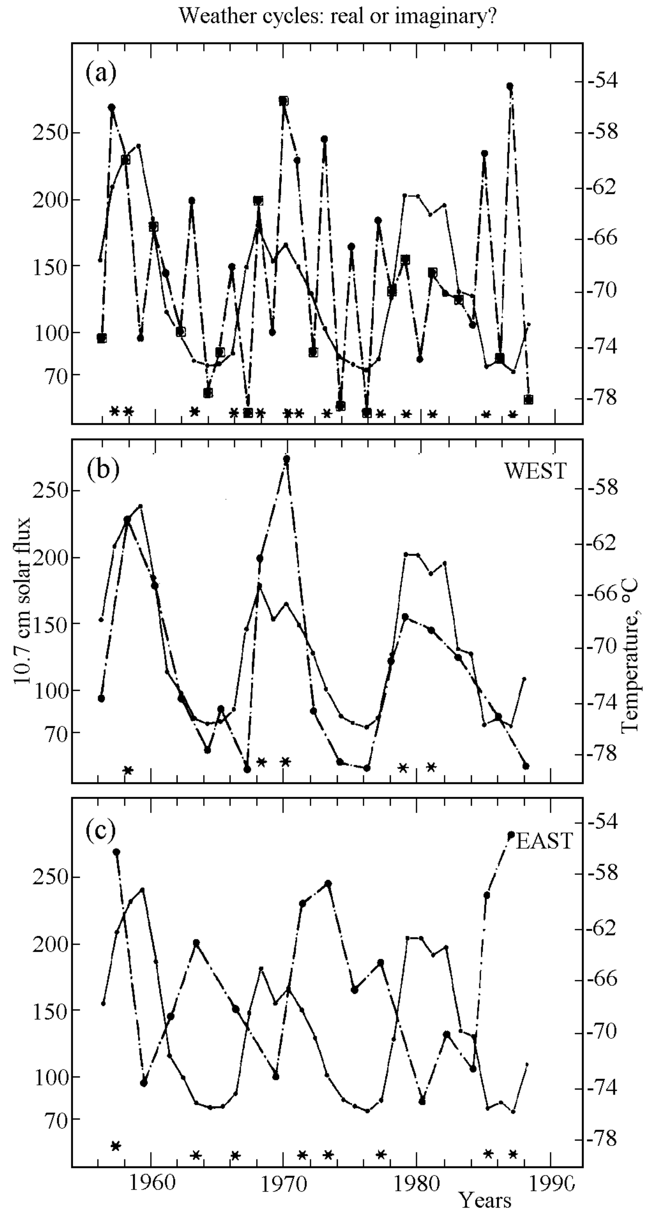

Figure 2. Variations in the solar activity ($F_{10.7}$) and in the temperature of the stratosphere at the 30-mbar pressure level (a) for the entire period under consideration and for the years corresponding (b) to the western phase of QBO and (c) to the eastern phase (from *Labitzke and van Loon* [1988]). Asterisks mark the periods of stratospheric warmings.

2. Mechanisms of the Influence of Solar Activity on the Lower Atmosphere State

2.1. Variations in Solar Irradiance

[11] As it is known, the radiation spectrum of the Sun is similar to that of the absolutely blackbody heated to 5770 K, though with a substantial energy deficit in the near ultraviolet region. At the same time, the intensity of solar radiation in the far ultraviolet and X-ray regions is several orders of magnitude higher than the relevant radiation of the absolutely blackbody. Such a difference in the spectra of the Sun and the absolutely blackbody is explained by the fact that the short-wave radiation in different wavelength ranges is generated in different regions of the Sun's atmosphere. In particular, the radiation with the wavelength $\lambda < 1500$ Å is generated in the chromosphere and corona of the Sun, i.e., in the regions whose temperatures are much higher that the temperature of the photosphere. It is also known that parameters of the chromosphere and corona are rather changeable and profoundly depend on the solar activity level. So, it is not surprising that the intensity of the short-wave solar radiation considerably varies from day to day and with the

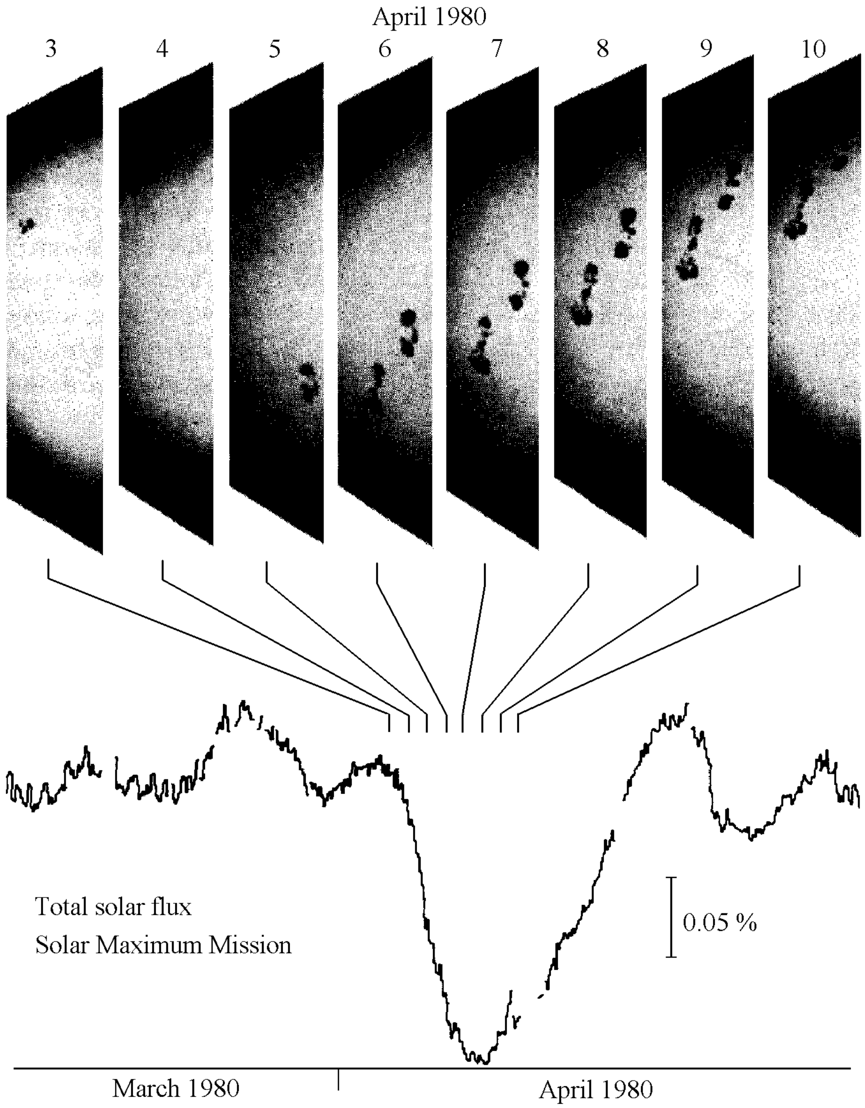

Figure 3. An example of the effects of sunspot blocking on the solar irradiance. (top) A large sunspot group crossing the solar disk in April 1980. Each image represents 1 day. The lines connect the solar image to (bottom) the irradiance variations (reprinted from *Wilson et al.* [1981] with kind permission of Springer Science and Business Media).

level of solar activity. A relative value of cyclic variations in solar irradiance reaches a factor of 10 at $\lambda = 300 - 500$ Å and sharply decreases at $\lambda > 2000$ Å. As a result, the integral intensity of solar radiation (the so-called solar constant equal to $K = 1.37 \times 10^6$ erg cm^{-2} s^{-1} at the Earth's orbit) experiences variations of not more than 0.1%.

[12] It has recently been demonstrated in many publications that the solar irradiance in the white light can also depend on the solar activity level or, to be more exact, on the number and distribution of active formations, such as sunspots, faculae, and flocculi on the surface of the Sun.

[13] For instance, *Hudson et al.* [1982] showed that the appearance of relatively dark sunspots at the solar disk can lead to weakening of the solar irradiance by several tenths of a percent, while relatively bright faculae result in increasing solar radiation. Though an increase in the brightness of the photosphere in the regions of faculae is only several percent, the area occupied by them is typically larger by an order of magnitude than the total area occupied by the sunspots, and so variations in the solar irradiance due to these formations are of the same order of magnitude. Nevertheless, on the whole, the effect of facular emission dominates over the blocking effect of the sunspots in the cyclic variations of the Sun's brightness.

[14] The role of the effects discussed above can be illustrated by Figure 3, which is after *Wilson et al.* [1981]. Figure 3 (top) presents images of the Sun with a large sunspot group crossing the central meridian in April 1980; Figure 3 (bottom) shows variations in solar irradiance S. Thin lines indicate to which point on the $S(t)$ curve the solar image cor-

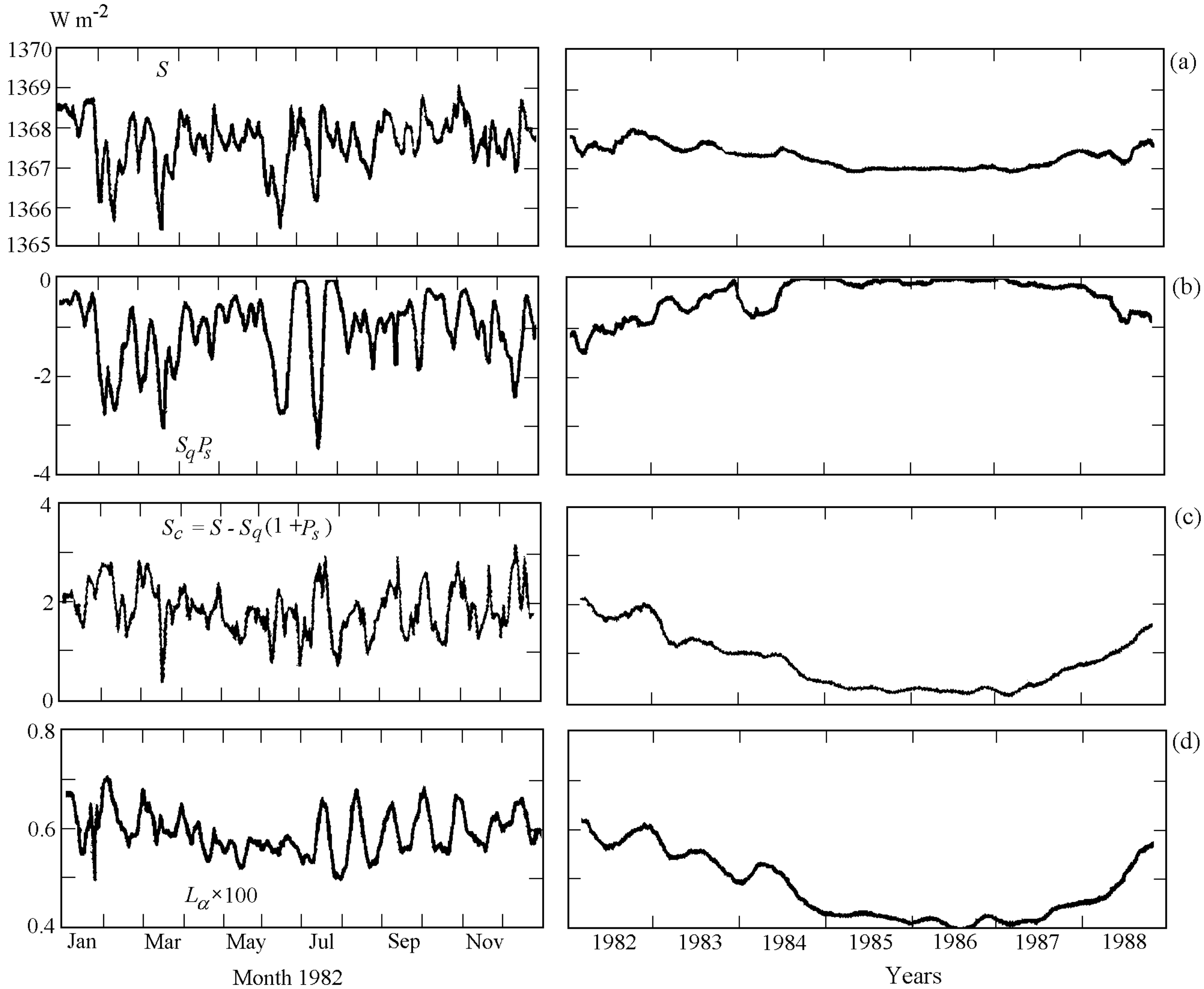

Figure 4. Variations in (left) daily means and (right) 81-day means of (a) the total solar irradiance S, (b) blocking of solar irradiance by sunspots S_qP_s, (c) residual solar irradiance $S_c = S - S_q(1 + P_s)$, and (d) solar irradiance in the L_α light (from *Lean* [1991]).

responds. It is evident from Figure 3 that when the sunspots approach the central meridian of the solar disk, their visible size is at a maximum and the solar irradiance reaches a minimum. The faculae surrounding the spots have a minimum brightness when near the center of the disk, while near the limb their brightness is maximum. After the sunspots pass off the solar disk, some faculae still remain at the disk, and the solar irradiance reaches a maximum. This explains the local maxima observed on the $S(t)$ curve.

[15] In a somewhat different form, this result is shown in Figure 4 (left) [after *Lean*, 1991]. Figure 4 presents variations in the total solar irradiance (S) during 1982 (Figure 4a); weakening of the irradiance due to crossing of the solar disk by sunspots: $\delta S = S_qP_s$, where S_q is the irradiance of the "undisturbed" Sun and P_s is the "blocking function" of this irradiance by the sunspots (Figure 4b); the "residual" solar irradiance $S_c = S - S_q(1+P_s)$ characterizing the surplus irradiance (Figure 4c); and the intensity of the L_α emission generated in the regions of bright formations outside the active region (Figure 4d). It can be seen that some irradiance minima (for instance, those that occurred in February, March, June, and July) are indeed due to the effect of sunspots, while the residual solar irradiance S_c shows a pronounced relation with the L_α emission intensity. Thus crossing of the solar disk by active structures indeed distinctly modulates the solar total irradiance. Along with this, the amplitude of these variations, as seen from Figure 4a, is not higher than 0.25%.

[16] The smoothed curves in Figure 4 (right) present 81-day running means of S, S_qP_s, S_c, and L_α in the course of the 11-year solar cycle. It is apparent from Figure 4 that the solar irradiance experiences a pronounced cyclic variation as well: S is maximum in 1981–1982 and 1989, i.e., in the period of solar activity maximum, and S is minimum in 1985–1987, i.e., in the period of minimum solar activity. This can be explained by the fact that during the solar cy-

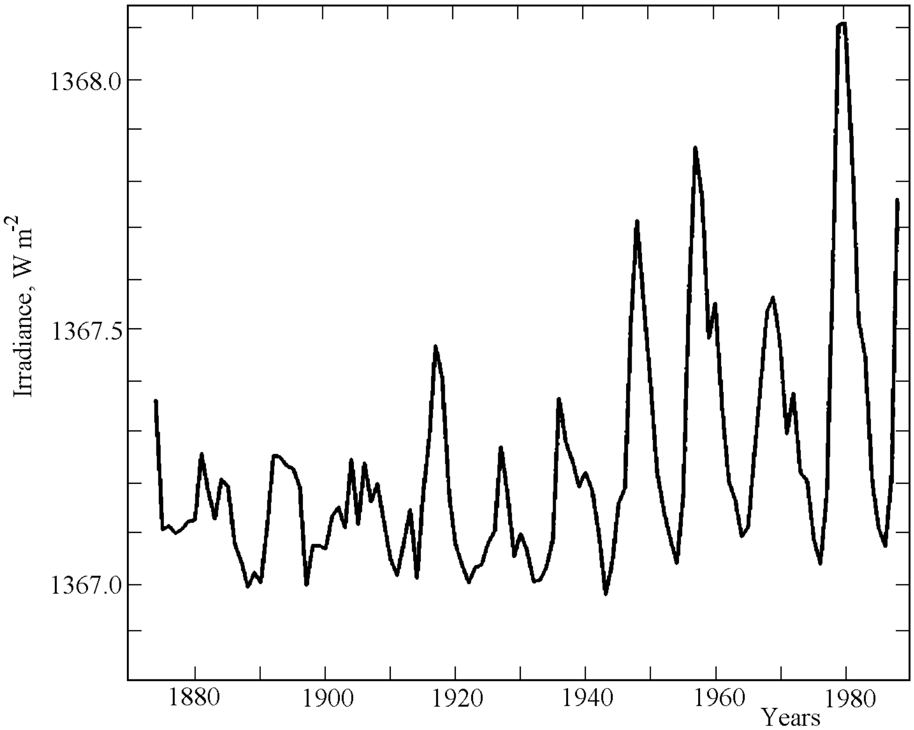

Figure 5. Reconstructed solar irradiance (W m^{-2}) from 1874 to 1988 (reprinted with permission from [*Foukal and Lean*, 1990] American Association for the Advancement of Sciences, http://sciencemag.org).

cle an increase in the brightness of the Sun associated with relatively bright and extended facular fields dominates over the blocking effect of sunspots. The relation between the annual values of the solar constant and Wolf numbers can be written as [*Hoyt and Schatten*, 1997]

$$S = 1371.32 + (0.00734 \pm 0.00069)W \text{ W m}^{-2} \quad (1)$$

where W is the sunspot number.

[17] Along with this, it can be seen that the amplitude of the cyclic variation in the solar irradiance is larger than the amplitude of short-term variation and amounts to about 0.1% of its average value. The obtained empirical relation between solar activity and irradiance allows one to calculate the latter for preceding epochs.

[18] More accurately, S was calculated for the past, to 1874, by *Foukal and Lean* [1990]. They used the data on the area of sunspots obtained at the Greenwich Observatory; the area of flocculi was assumed to be proportional to the Wolf numbers. The results of calculations are shown in Figure 5 taken from *Foukal and Lean* [1990]. It demonstrates that the amplitude δS of cyclic variations in S has been monotonically growing from the middle of the 19th century to the present. However, even maximum δS does not exceed 0.1% of the average S, which is likely to be an order of magnitude lower than the δS value that can explain the variations in the lower atmosphere temperature observed during the 11-year solar cycle [*Burroughs*, 1992]. Indeed, if we assume, as always, that a 1% increase in the solar constant leads to a temperature rise of 1.7° [*Hoyt and Schatten*, 1997], then it follows that the observed cyclic variations in S can lead to changes in air temperature of not more than 0.16% [see also *Wigley and Raper,* 1990]. Moreover, the phase of the observed cyclic temperature variations does not coincide in many cases with the solar cycle phase (see Figure 1). These facts indicate that the solar irradiance variability is not the only cause of cyclic variations in the atmospheric temperature and, apparently, not the main one.

2.2. Changes in Parameters of the Global Electric Circuit

[19] A fundamentally different mechanism of connection between solar activity and weather pattern was suggested by *Markson* [1978]. The advantage of this model is, in the opinion of the author, that it does not require significant changes in solar irradiance. Instead, the mechanism of the efficient use of the energy accumulated in the atmosphere is involved. In addition, the model explains the unexpectedly small lag of variations in the lower atmosphere parameters behind variations in relevant cosmophysical factors (solar flares, cosmic ray fluxes, passage of the sector boundaries of the interplanetary magnetic field past the Earth).

[20] Let us consider this mechanism in more detail. Figure 6 [after *Markson*, 1978] schematically shows basic elements of the global electric circuit. According to the model under consideration, the global thunderstorm activity can be regarded as a powerful generator of electric current maintaining the electric field in the Earth's atmosphere. If

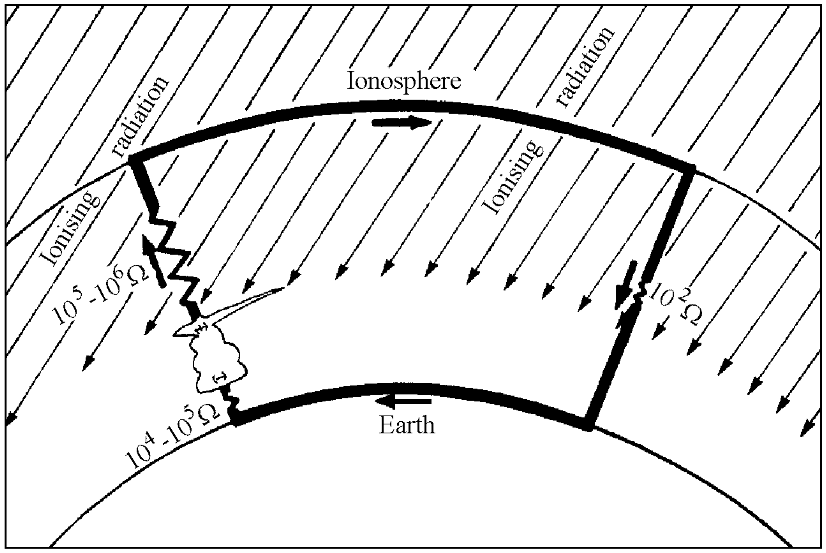

Figure 6. Scheme of the global electric circuit. Wide arrows indicate the flux of positive ions (from *Markson* [1978], used with permission from Nature, http://www.nature.com).

the generator were switched off, the atmospheric electricity would decay with a characteristic decay time $\tau = 15$ min [*Israel*, 1971].

[21] The electrical conductivity of air in the lower atmosphere results mainly from ionization of air molecules by fluxes of energetic particles of galactic cosmic rays (GCR); at higher altitudes it is caused by fluxes of ultraviolet or X-ray emission of the Sun. As a result, the atmospheric conductivity exponentially grows with increasing altitude (Figure 7, from *Israel* [1973]). Let us now consider Figure 6 from which we see that the resistance of an air column with a cross section of 1 cm^2 is about 10^7 Ω m^2, in which 2×10^{16} Ω m^2 fall at the lower layers of the atmosphere (from the Earth's surface to the lower boundary of the cloud layer), 5×10^{16} Ω m^2 is the internal resistance of the generator (R_0), and about 10^{16} Ω m^2 is the resistance of the air column from the upper boundary of the thunderstorm generator ($\sim$ 13 km) to the ionosphere (h = 60 km). Therefore the total resistance of the atmosphere above the generator (the generator area is taken into account) is 10^6 Ω, while the integral resistance of the atmosphere in the region of closing currents does not exceed 200 Ω. Thus the total resistance of the circuit and hence the current strength in it are mainly determined by the atmospheric resistance in the region of the thunderstorm generator. At the same time, local variations in the electric currents in the circuit can be due to variations in the atmospheric conductivity immediately in the region of closing currents.

[22] The cosmic ray fluxes modulated by variations in solar activity give rise to changes in the atmospheric conductivity in the region of the thunderstorm generator and above it, which, in turn, leads to changes in the electric field intensity and current in the entire circuit.

[23] Increasing electric field intensity leads to increasing growth rate of water droplets in the cloud (see below) and hence higher precipitation intensity [*Mason*, 1971]. The droplets of sufficiently large size reach the Earth's surface before they evaporate and, as a result, a large amount of latent evaporation heat is released.

[24] Further development of an atmospheric disturbance in *Markson*'s [1978] model is presented in Figure 8. The mechanism of influence of solar activity on the lower atmosphere dynamics suggested by the author is as follows. As a result of intense precipitation and release of latent evaporation heat, the temperature of the low-latitude atmosphere increases and causes the ascent of the heated air to the tropopause heights and intensification of the Hadley's convection cell, which has been, on the whole, confirmed experimentally [*van Loon and Labitzke,* 1994]. This, in turn, activates the middle-latitude cell and increases the convergence of airflows in the region of the cell polar front. According to Markson's calculations, the lag of the processes in the region of middle-latitude convergence behind the processes of intensification of the equatorial cell is 2–3 days.

[25] Intensification of the meridional circulation is accompanied by blocking of the zonal streams. Observations show that the meridional circulation indeed becomes stronger during the period of solar activity maximum [*Schuurmans*, 1969], and the height of the equatorial tropopause at this time is maximal [*Rasool*, 1975].

[26] Thus the model suggested by *Markson* [1978] qualitatively explains the mechanism of impact of solar activity on the lower atmosphere state. At the same time, the model does not contain any quantitative estimates of the changes in the atmospheric parameters it involves (temperature, pressure, wind velocity). *Markson*'s [1978] model was significantly developed by B. A. Tinsley and his colleagues [*Tinsley*, 2000; *Tinsley and Deen,* 1991; *Tinsley and Heelis*,

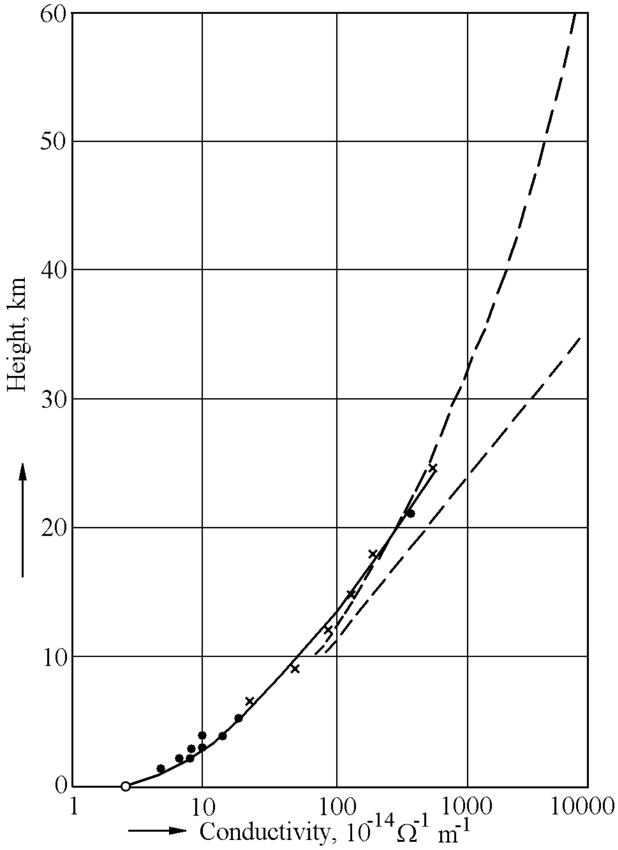

Figure 7. Average vertical profile of atmospheric conductivity from measurements of Sagalyn and Faucher (dots) and Stergis and his coworkers (crosses), and also in accordance with computations by Israel and Kasemir (dashed lines) (from *Israel* [1973]).

1993; *Tinsley et al.*, 1989, 2000].

[27] One of the fundamental parameters characterizing the optical properties of clouds and determining the precipitation intensity is the concentration of raindrops. In turn, the concentration of raindrops is determined by the concentration of nuclei of aerosol particles with a diameter of not more than 0.1 μm.

[28] Another important characteristic of clouds is the rate of formation of ice crystals in them. The presence of ice crystals sharply increases the formation rate of raindrops and hence the precipitation intensity. In addition, formation of ice affects the thermodynamic structure of the clouds, which in turn affects the cloud cover area.

[29] In the cloud, ions are rather efficiently scavenged by raindrops, and as a result, the atmospheric conductivity in the cloud significantly decreases. Since the electric current is continuous, this leads to enhancement of the electric field and accumulation of electric charges at the upper and lower boundaries of the cloud. As a consequence, the aerosol particles in this region acquire rather a large charge (to 1000 e) [*Reiter,* 1992]. Tinsley and his colleagues put forward the hypothesis that charged aerosol particles are fairly effective ice forming nuclei. The experimental proof of this statement is that scavenging of aerosols appreciably increases if the aerosol particles are charged. Theoretical calculations also indicate that the rate of aerosol scavenging rapidly grows as their charge increases [*Tinsley et al.,* 2000].

[30] Thus the model suggested by *Markson* [1978] can be summarized as follows.

[31] Variations in the parameters of the global electric circuit caused by variations in cosmic ray fluxes give rise to changes in the vertical current density and electric field intensity in the lower atmosphere and thus in ion concentration and electric charge of aerosol particles near the cloud boundary. As noted above, this leads to acceleration of the growth of ice crystals and raindrops, to intensification of precipitation, and an increase in the rate of release of latent evaporation heat.

[32] The works of Tinsley and his colleagues give significant insight into the physical processes relating the changes in the parameters of the global electric circuit to the lower atmosphere state and climate. However, even in such a modified form the Markson-Tinsley model does not provide any reliable quantitative estimates of the expected effects.

2.3. Dynamic Mechanism

[33] The dynamic mechanism of the impact of solar activity on the lower atmosphere state suggested by *Avdyushin and Danilov* [2000] is as follows.

[34] It is known that there is a spectrum of internal waves with relatively large amplitudes in the atmosphere. Propagation of these waves into the upper layers of the atmosphere depends on the zonal air circulation in the stratosphere. For instance, the interplanetary waves can propagate into the stratosphere and then to the mesosphere only in the case of the eastward zonal circulation and if the velocity V is less than a critical velocity V_{cr} [*Avdyushin and Danilov*, 2000;

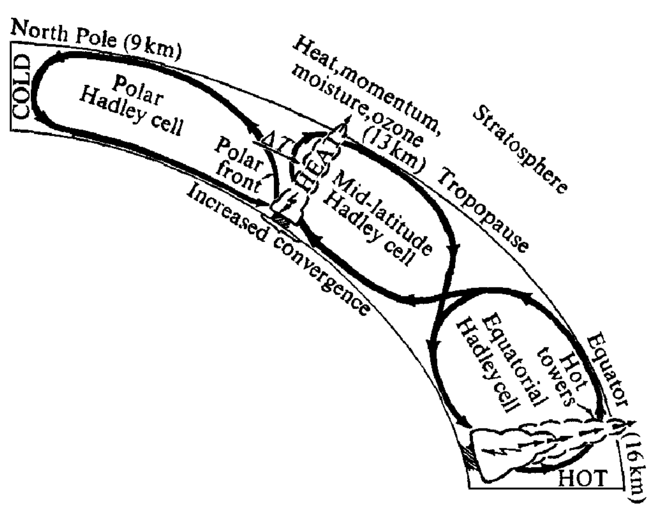

Figure 8. Meridional cross section of the atmosphere illustrating how solar modulation of physical processes in clouds might influence the general circulation.

Geller, 1983]. Changes in solar activity are accompanied by variations in the solar ultraviolet radiation, a part of which is absorbed by the ozone layer, thereby causing changes in the air temperature and circulation in the stratosphere. Thus, if, during some period, the circulation in the stratosphere is formed by westerly winds whose velocity is close to the critical one, even insignificant changes in the circulation rate in the stratosphere induced by solar activity variations can control the exit of the internal atmospheric waves into the stratosphere or their confinement in the troposphere. In the latter case, the energy of these waves dissipates in the lower atmosphere, thereby causing its heating and changes in the topography of isobaric surfaces.

[35] This mechanism seems interesting. However, in its present form, the model does not allow assessment of either the intensity or spatial distribution of the expected disturbances in the lower atmosphere.

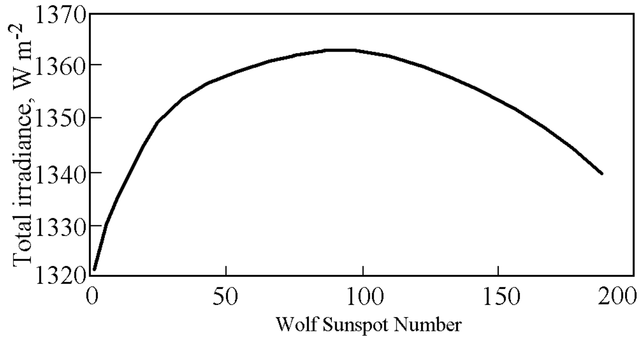

Figure 9. Dependence of solar total irradiance on solar activity (from [*Kondratyev and Nikolsky,* 1970], with permission from Royal Meteorological Society).

2.4. Changes in Atmospheric Transparency and Cloudiness

[36] The mechanisms considered in this section are based on the observations according to which the solar irradiance reaching the Earth's surface exhibits a pronounced dependence on the solar activity level. For instance, Figure 9 [after *Kondratyev and Nikolsky*, 1970] shows solar irradiance as a function of the sunspot number. It can be seen that, as the sunspot number increases from zero to 100, the solar irradiance measured at the Earth's surface grows by ~3%, which can cause a temperature variation in the troposphere of 2°–3°. As the sunspot number further increases, the solar irradiance decreases. The reason for this decrease is not clear. Probably, it can be attributed to the competing effects of variations in the fluxes of galactic and solar cosmic rays [*Pudovkin and Veretenenko*, 1995] and X-ray radiation of the Sun.

[37] As noted above, the solar irradiance at the upper boundary of the atmosphere changes by not more than 0.1% during the solar cycle (see Figure 4). Therefore the variations in solar irradiance shown in Figure 9 can be due to changes in the atmospheric transparency alone (in a more general sense, the transmittance). What processes in the atmosphere can be responsible for the observed changes in atmospheric transparency? *Kondratyev and Nikolsky* [1995] suggest at least two such mechanisms, i.e., formation of cirri and ozone mechanism. Let us consider these models in more detail.

[38] **2.4.1. Condensation mechanism.** The condensation mechanism implies that the presence of ions in the atmosphere increases the rate of formation and initial growth of aerosol particles. An important source of these particles is nucleation of aerosols from water vapors and minor constituents of the atmosphere, such as, for instance, sulfur dioxide. Theoretical estimates of the nucleation rate in the electrically neutral atmosphere give the values much lower that those observed in reality. Therefore, of high importance is the fact that the presence of charged particles reduces the nucleation threshold and stabilizes embryonic particles [*Turco et al.*, 2000]. As a result, nucleation develops at a lower concentration of condensing vapors than in the unionized atmosphere. The ability of embryonic particles of aerosols with a size of 1–2 nm to grow into nuclei with sizes of ~100 nm is determined by the summary effect of the processes of condensation, coagulation, and scavenging of the particles. Calculations have shown that the growth rate of charged particles with sizes from 1 to 5 nm is twice as high as that of uncharged particles [*Yu and Turco*, 2001]. Since the loss rate due to coagulation for the particles with a radius of 5 nm is lower by a factor of 20 than that for the particles 1 nm in radius [*Carslaw et al.*, 2002], the accelerated growth of charged particles results in their higher "survival" at the early stage of formation.

[39] Model calculations show that a 20% change in the ionization rate in the lower atmosphere leads to a 5–10% change in the concentration of the particles with diameters of 3–10 nm [*Turco et al.*, 2000; *Yu*, 2002; *Yu and Turco*, 2001].

[40] In turn, the increase in the number of relatively small water droplets in the cloud must lead to an increase in its reflectivity, decrease in the intensity of precipitation from it and hence to an increase in the cloud lifetime, which is indeed observed [*Brenguier et al.*, 2000].

[41] Laboratory investigations show that ions can, indeed, be the sources of aerosol particles [*Vohra et al.*, 1984]. Of course, many details of this mechanism are still unclear. Nevertheless, the data described above indicate that it has rather a sound experimental and theoretical basis.

[42] **2.4.2. Ozone mechanism.** It is known that atmospheric ozone, which actively absorbs infrared radiation of the Earth, plays a significant role in formation of the global climate via the influence on the radiative, thermal, and circulation regimes in the stratosphere [*Kondratyev,* 1989]. The strongest influence on the ozone layer state is exerted by the solar UV radiation ($\lambda < 242$ nm) and cosmic rays. Since these sources undergo significant changes during both short-term heliospheric disturbances and solar cycle, corresponding variations in the atmospheric ozone content can be expected. Along with this, experimental data show that the link between the solar activity level and ozone content in the

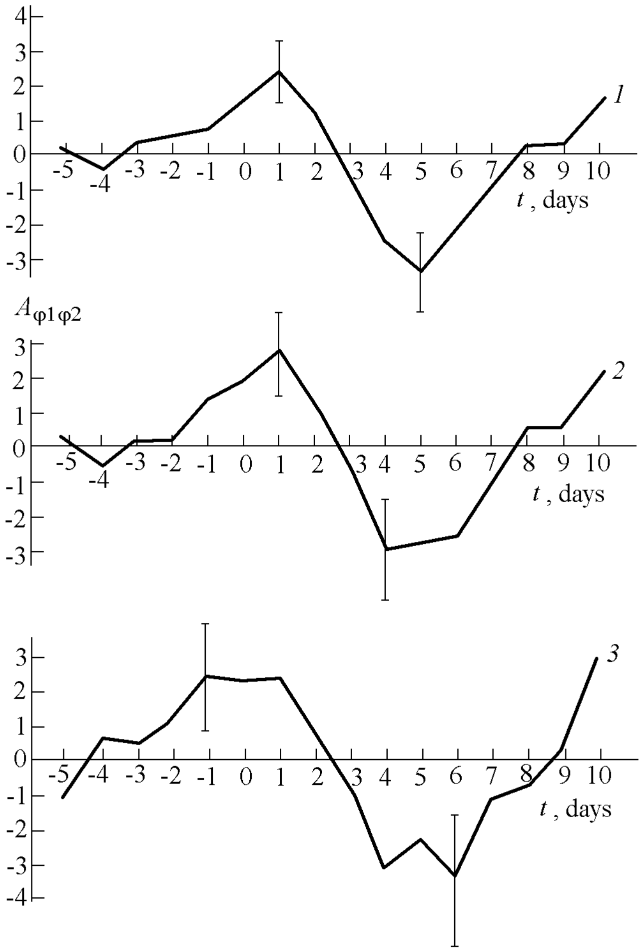

Figure 10. Variations in the Blinova index at different isobaric levels during geomagnetic disturbances. Curves 1, 2, and 3 correspond to 700, 500, and 300 mbar, respectively. Reprinted from Journal of Atmospheric and Terrestrial Physics, Vol. 54, Pudovkin and Babushkina "Influence of solar flares and disturbances of the interplanetary medium on the atmospheric circulation", Page No. 841, Copyright 1992, with permission from Elsevier.

atmosphere is extremely complicated. For instance, *Kondratyev and Nikolsky* [1995] point out that the relation between the sunspot number and ozone content was positive from 1921 to 1928, it was negative from 1933 to 1958, and then this relation again became positive. This complicated and, at first glance, unstable connection between the ozone content and solar activity can be explained, first of all, by the fact that changes in the ionizing radiation intensity give rise to a chain of photochemical processes in the atmosphere that are responsible for both formation and decay of ozone molecules.

[43] Detailed investigations of disturbances in the lower atmosphere caused by penetration of energetic particles of the solar or galactic origin were performed by *Hauglistaine and Gerard* [1990]. According to the model suggested by these authors, penetration of energetic particles into the atmosphere gives rise to ionization and dissociation of N_2 and O_2 molecules. The N_2^+, O_2^+, NO^+, N^+, O^+, and other ions then participate in the reactions of ion-atomic exchange and recombination, one of the products of which is nitric oxide NO. The latter catalytically destroys ozone molecules in the reactions

$$NO + O_3 \rightarrow NO_2 + O_2$$

$$NO_2 + O \rightarrow NO + O_2$$

Thus invasion of energetic particles into the atmosphere causes depletion of ozone and formation of a large amount of nitrogen dioxide. This, in turn, results in significant changes in the radiation budget of the atmosphere. In particular, the flux of solar ultraviolet radiation with a wavelength of $\lambda < 3250$ Å increases in the lower atmosphere and at the Earth's surface due to its weaker absorption by ozone. At the same time, the flux of radiation in the blue-green region decreases due to increasing absorption of the latter by nitrogen dioxide whose absorption cross section has a maximum $\sigma = 6 \times 10^{-19}$ cm^2 at a wavelength of about 4000 Å. The calculations performed by *Hauglistaine and Gerard* [1990] have shown that a sufficiently intense solar proton event (of the type of SPE that occurred on 4 August 1972) causes more than a tenfold decrease in the ozone content and increases the NO_2 concentration by about 2 orders of magnitude at an altitude of 30–35 km. Because of the enhanced absorption of solar radiation by nitrogen dioxide, the air temperature in the stratosphere grows and reaches at an latitude of 30 km a maximum of 300 K, which is 80 K higher than the norm. On the contrary, in the troposphere the deficiency of solar radiation causes a 10° reduction in temperature.

[44] *Haigh* [1996] has shown that the mechanism involving variations in UV radiations may cause significant shift in the stratospheric circulation and climate through the stratospheric ozone production. In this respect, *Hoyt and Shatten* [1997] note that UV variations are an excellent candidate for solar variability influences on climate, not only because solar spectral irradiance fluctuations are proportionally larger at short wavelengths, but also because they carry a significant fraction of the total solar energy variability (about 20% below 300 nm according to *Lean* [1991]). In a climate model experiment, *Haigh* [1996] analyzed the response of the atmosphere to the 11-year solar activity cycle. In this simulation, a small increase in UV radiation caused substantial stratospheric heating, as the excess in ozone absorbed more sunlight in the lower stratosphere. In addition, the stratospheric winds were also strengthened and the tropospheric subtropical jet streams were displaced poleward. The location of these westerly jets determines the latitudinal extent of the Hadley cells, and therefore the poleward shift resulted in similar displacement of the descending limbs of the Hadley cells. This ultimately led to a poleward relocation of the midlatitude storm tracks. The temperature changes in the model result were very similar, although smaller in magnitude, to the observations by *van Loon and Labitzke* [1994]. Moreover, the results of *Haigh* [1996] were supported by an analysis of *Christoforou and Hammed* [1997], showing

a close correlation between solar activity, as expressed by mean annual sunspot numbers, and the intensity and locations of low- and high-pressure centers in the North Pacific area. Similar processes also develop in the stratosphere when the solar X-ray radiation intensity grows.

[45] Thus these are the most widely discussed physical mechanisms linking variations in solar activity to changes in the lower atmosphere state. In order to understand to what extent these mechanisms explain the phenomena observed in the lower atmosphere, let us consider in more detail the morphology of these phenomena. To exclude from the analysis, to a greatest possible degree, the variations in the atmosphere parameters caused by intra-atmospheric processes, we begin with discussing short-term (with duration of the order of several days) atmospheric disturbances associated with different manifestations of solar activity.

3. Short-Term Disturbances in the Lower Atmosphere

[46] First of all, let us see what kind of disturbance develops in the lower atmosphere under the action of solar flares. For this purpose, Figure 10 [after *Pudovkin and Babushkina*, 1992a] shows variations in the Blinova index [*Blinova*, 1978; *State Committee of USSR on Hydrometeorology and Environmental Control*, 1977–1989] calculated through the superposed epoch method for the latitude range $\varphi = 45^\circ - 65^\circ$ at isobaric levels 700, 500, and 300 mbar for intense geomagnetic storms. The key day is taken to be the day of the geomagnetic disturbance onset. Let us remind that the Blinova index $A_{\varphi1\varphi2}$ characterizes the average angular velocity of zonal atmospheric circulation α in the latitude range $[\varphi1, \varphi2]$; $A_{\varphi1\varphi2} = 10^3\alpha_{\varphi1\varphi2}/\Omega$, where Ω is the angular velocity of the Earth's rotation. At the latitude of St. Petersburg, the linear velocity of the zonal circulation corresponding to $A = 1$ is about 25 cm s^{-1}.

[47] As can be seen from Figure 10, the evolution of the geomagnetic disturbance is accompanied by considerable changes in the zonal atmospheric circulation rate. The changes in the rate occur synchronously at all the levels considered and are characterized by increasing A at the first stage of disturbance and by a significant decrease in A during the subsequent period. According to calculations of *Pudovkin and Babushkina* [1992a] presented in Figure 10, variations in A are due to ± 20 m changes in the heights of isobaric surfaces, which requires an additional energy input (or output) of $\pm(5-8) \times 10^{26}$ erg to (from) the lower atmosphere.

[48] What is the source of this energy? Depending on the suggested mechanism, this may be either the latent evaporation heat or deficit (or surplus) of solar irradiance modulated by variations in the atmospheric transparency or cloudiness. In this connection, Figure 11 from *Pudovkin and Babushkina* [1992b] shows variations in the daily Kp index and intensity of the GCR flux (Figure 11b) obtained by the method of superposed epochs as well. Figure 11a presents variations in the direct solar radiation at the Earth's surface (at the plane perpendicular to the line of sight) in the auroral

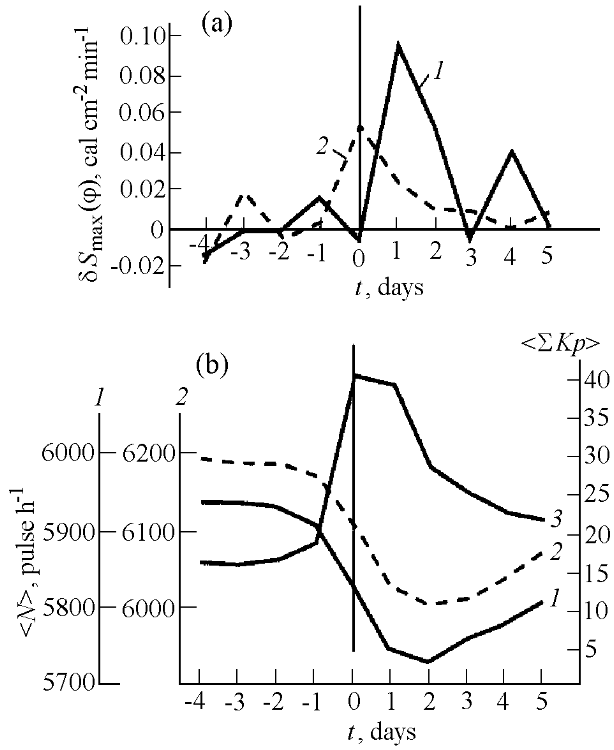

Figure 11. Storm time variations in solar radiation intensity and in some geophysical indices. (a) Storm-time variations in the noon intensity of solar radiation at the Earth's surface: curve 1, auroral zone; curve 2, subauroral zone. (b) Storm-time variations in geophysical indices: curve 1, cosmic ray intensity at Apatity ($\varphi \approx 67^\circ$); curve 2, cosmic ray intensity in Moscow ($\varphi \approx 55^\circ$); curve 3, geomagnetic $\Sigma_8 Kp$ index. Reprinted from Journal of Atmospheric and Terrestrial Physics, Vol. 54, Pudovkin and Babushkina, "Atmospheric transparency variations associated with geomagnetic disturbances", Page No. 135, Copyright 1992, with permission from Elsevier.

($\varphi = 65^\circ - 75^\circ$) and subauroral ($\varphi = 55^\circ - 62^\circ$) zones. It is evident that the development of the Forbush decreases is accompanied by a considerable (5–10%) increase in the solar irradiance and hence atmospheric transparency [*Veretenenko and Pudovkin*, 1997]. The increase in the solar radiation flux given above corresponds to an additional input of energy to the lower atmosphere, depending on the season, of the order of $(0.2 - 2.6) \times 10^{26}$ erg day^{-1}, which is rather close to the energy of the disturbances considered here [*Veretenenko and Pudovkin*, 1999a].

[49] Because of a relatively small amount of data used for plotting Figure 11, it can be supposed that the obtained relation between variations in the cosmic ray flux and atmospheric transparency is occasional. However, if the increase in the atmospheric transparency observed during a Forbush decrease were indeed due to the reduction in the cosmic ray flux, the increase in the flux would be accompanied by a lower atmospheric transparency. It is possible to check this hypothesis by analyzing variations in atmospheric trans-

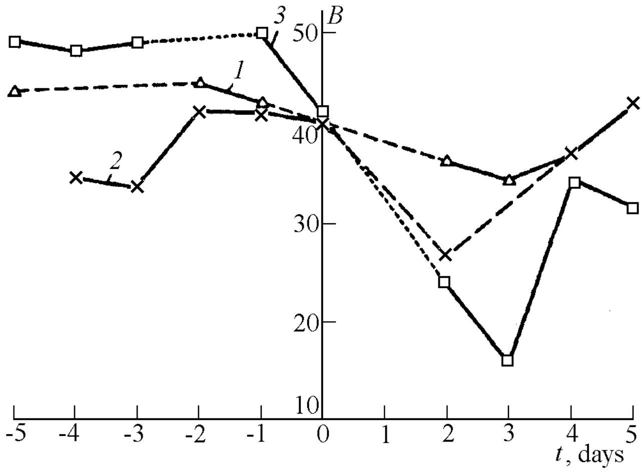

Figure 12. Variations in atmospheric transparency B in relative units at stations: (1) Murmansk on 30 April 1976 and Arkhangelsk on (2) 3 April 1979 and (3) 17 August 1979. The key day is the SCR event onset. The solid lines show the days without missing data, the dashed lines present the days with missing data.

parency in the course of solar proton events (SPE) associated with precipitation to the Earth's atmosphere of energetic (with energies to several hundreds of MeV) solar protons generated on the Sun during intense chromospheric flares. Figure 12 [from *Roldugin and Vashenyuk*, 1994] shows variations in the atmospheric transparency at a wavelength of $\lambda = 3440$ Å at stations Murmansk and Arkhangelsk in the course of several proton events. It is evident from Figure 12 that the SPE development is accompanied by a considerable decrease in the atmospheric transparency, which confirms the hypothesis that it is the intensity of cosmic ray fluxes that determines the optical properties of the atmosphere.

[50] Naturally, then the question arises as to what is the reason for changes in atmospheric transparency: variations in the ozone content in the atmosphere or condensation mechanism? To a certain extent, the question was answered by *Roldugin and Vashenyuk* [1994], who stated that a decrease in the atmospheric transparency is accompanied (or is caused?) by a twofold to fourfold increase in the concentration of aerosol particles with a radius of 0.1–1 μm, which apparently points to a significant role of the condensation mechanism.

[51] Of interest are also the data shown in Figure 13 [after *Veretenenko and Pudovkin*, 1994] that demonstrate variations in the cloud cover (in percent) during Forbush decreases of GCR at different latitudes. As can be seen from Figure 13, at latitudes 60°–64° (most probably, at higher latitudes as well), a pronounced decrease in the total cloud cover of the order of 10% is observed on the 1st and 2nd day after the Forbush decrease onset.

[52] In addition, Figure 13 also indicates that the effect of the Forbush decreases in the cloudiness vanishes at a latitude of the order of 50°. If we assume that such a latitudinal behavior of this effect is explained by the magnetic cutoff of particles, the energy of the particles should be about 1 GeV. Protons with such energies penetrate into the atmosphere to the heights of the order of 10 km, where the phenomena considered here are likely to occur. The latter supposition is confirmed by the fact that the effect of Forbush decreases is observed most distinctly at the stations where the high-level clouds prevail, and the main type of clouds are cirri [*Pudovkin and Veretenenko*, 1996; *Veretenenko and Pudovkin*, 1994].

[53] In view of the above said, it can be supposed that, in contrast to Forbush decreases, solar proton events associated with an increase in the flux of energetic particles must give rise to increasing cloudiness. Figure 14 [after *Veretenenko and Pudovkin*, 1996] presents variations in the cloud cover during the SPE at a number of meteorological stations at which the low-level cloudiness is typically weak. It can be seen from Figure 14b that as expected, the SPE is accompanied by a considerable increase in cloudiness. Like in

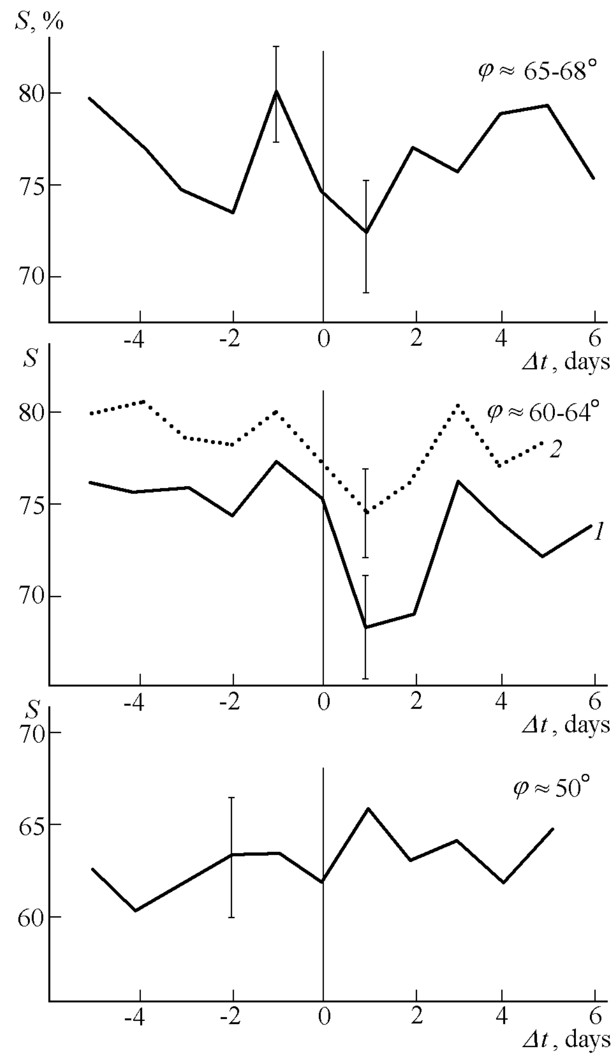

Figure 13. Variations in mean total cloud cover during Forbush decreases of GCR in different latitude ranges. The key day $\Delta t = 0$ corresponds to the Forbush decrease onset: 1, winter period ($N = 42$); 2, summer period ($N = 21$).

the case of the Forbush decreases, the effect of SPE depends on the latitude of the observation point and decreases from 40% at a latitude of 70° to zero at 55°. The decrease in the cloudiness on the minus third day is most likely to be due to the X-ray radiation of solar flares [*Veretenenko and Pudovkin*, 1996].

[54] Taking the estimates of *Schneider* [1972], according to which a 8% change in the cloud cover is equivalent to a 2% change in the "solar constant," we infer that the Forbush decreases cause the effect at the Earth's surface equivalent to the 2.5% change in the "solar constant."

[55] On the other hand, solar proton events lead to an increase in the cloud cover of up to 40%, which is equivalent to the reduction in the "solar constant" by 5%. Such changes in the solar irradiance in the lower atmosphere must cause rather large changes in the vertical temperature profile in the troposphere and lower stratosphere. Variations in the vertical temperature profile Δt° (deviations from the "quiet" level) during the Forbush decrease were obtained (also by the superposed epoch method) from the data of the Sodankyla observatory ($\varphi = 67^\circ$) in Finland by *Pudovkin et al.* [1995, 1999] obtained results are shown in Figure 15. It can be seen that as Forbush decreases of GCR develop, the temperature in the troposphere increases by several degrees and reaches a maximum on the second day after the Forbush decrease onset. At the same time, in the lower stratosphere, the temperature decreases by several degrees.

[56] Figure 16 [after *Pudovkin et al.*, 1995] shows variations (also deviations from the "quiet" level) in the vertical temperature profile at Sodankyla during 19 solar proton events taking place in 1981–1988. As could be expected, the temperature in the troposphere decreases by several degrees on the second day after the disturbance onset. Along with this, attention should be paid to the fact that on the first day of the disturbance the temperature in the troposphere rises by 1°–2° rather than decreases. This is likely to be the evidence of changes in the optical properties of the clouds in the course of disturbance or, more probably, of formation of two different types of clouds, each with its own optical properties and lifetime.

[57] It is obvious from Figures 15 and 16 that in the case of Forbush decreases of GCR and also during solar proton events, Δt° reverses its sign at an altitude of $\sim$ 10 km, which points, evidently, to the fact that the cloud or aerosol layer responsible for the observed changes in temperature is located precisely at this altitude.

[58] Thus the data presented above indicate that variations in cosmic ray fluxes are, indeed, accompanied by significant changes in air temperatures in the lower atmosphere. Therefore it can be anticipated that these changes will lead to variations in the atmospheric circulation as well. Figure 17 [from *Veretenenko and Pudovkin*, 1993] shows variations in the Blinova indices at an isobaric level of 500 mbar during Forbush decreases of GCR (Figure 17a) and solar proton events (Figure 17b). It is obvious from Figure 17 that a decrease in the cosmic ray flux is, indeed, accompanied by decreasing zonal circulation rate, while an increase in the SCR flux leads to increasing circulation rate.

[59] On the basis of the results described above, we can interpret the data on variations in the atmospheric circulation

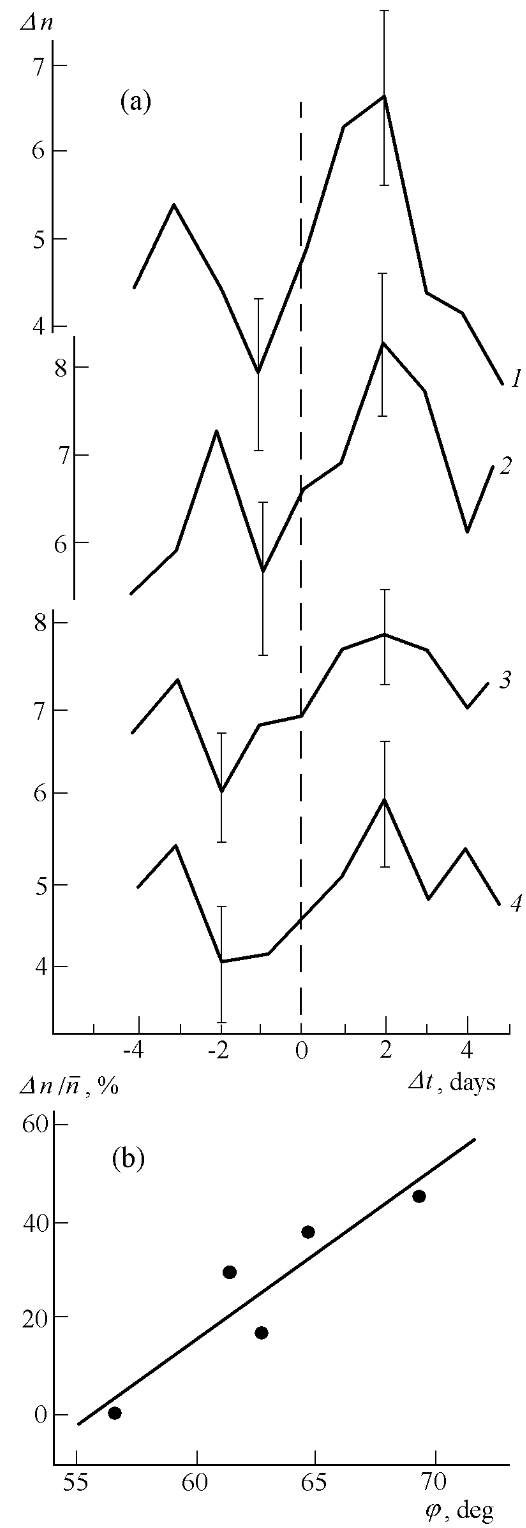

Figure 14. (a) Average changes in the cloud cover at high-latitude stations during SCR bursts with particle energies $E_p > 90$ MeV (1, Kotelnyy island (number of events $N =$ 15); 2, Chetyrekhstolbovyy island ($N = 30$); 3, Olenek ($N =$ 30); 4, Verkhoyansk ($N = 40$)) and (b) dependence of the effect intensity on the geomagnetic latitude of the station.

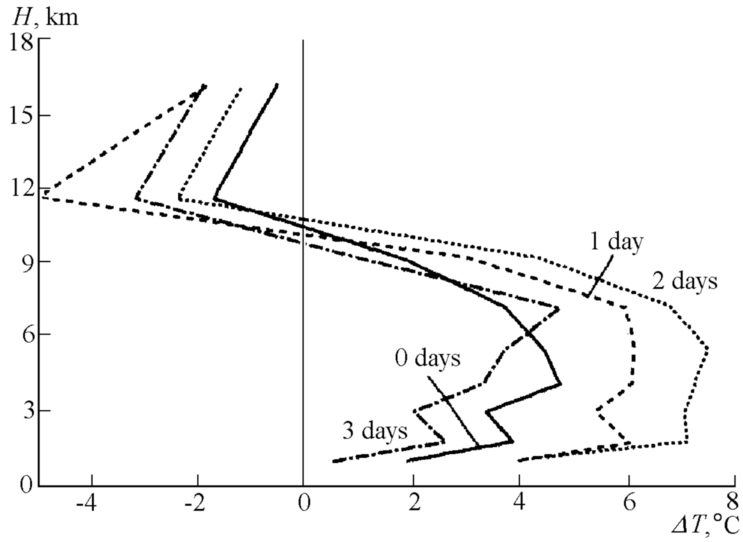

Figure 15. Variations in the $\Delta T(h)$ profile during Forbush decreases derived by the superposed epoch method for windless days ($N = 19$). The key day $t = 0$ corresponds to the day of the Forbush decrease onset.

rates during geomagnetic disturbances shown in Figure 10 as resulting from the superposition of the effects of penetration of solar protons (and solar X-ray radiation) and Forbush decreases of GCR developing with a time shift of 1–2 days.

[60] Analysis of the results obtained in the investigations mentioned above leads to the conclusion that at the 55°–70° latitudes the disturbances in the lower atmosphere associated with different manifestations of solar activity are mainly due to variations in the solar irradiance reaching the lower atmosphere [*Veretenenko and Pudovkin*, 1998]. In turn, these variations are related to changes in atmospheric transparency and cloudiness at the altitudes of the upper troposphere and lower stratosphere that are modulated by variations in cosmic ray fluxes. This suggests that the key role in changes of atmospheric transparency, at least in the latitudinal range considered here, is played by the condensation mechanism. This does not mean, of course, that the ozone mechanism does not provide any contribution into changes of the optical properties of the atmosphere.

[61] Unfortunately, there are few papers devoted to specific features of solar weather connection at low latitudes ($<$ 55°). In all probability, the most comprehensive treatment has been given in a series of papers of E. Friis-Christensen, H. Svensmark, and N. Marsh [*Friis-Christensen and Svensmark*, 1997; *Marsh and Svensmark*, 2000; *Svensmark*, 1998; *Svensmark and Friis-Christensen*, 1997]. One of the most important results of their studies is presented in Figure 18, which shows variations in cosmic ray intensity (12-month running mean deviations from the norm), from the data of Climax, and cloudiness (also deviations from the norm, in percent) of, mainly, the low-level cloud cover [*Marsh and Svensmark*, 2000] over oceans derived from the data of a geostationary satellite. It is obvious from Figure 18 that there is a pronounced relation between variations in cloudiness and cosmic ray flux in the region involved. The observed cyclic variations in cloudiness exert a considerable

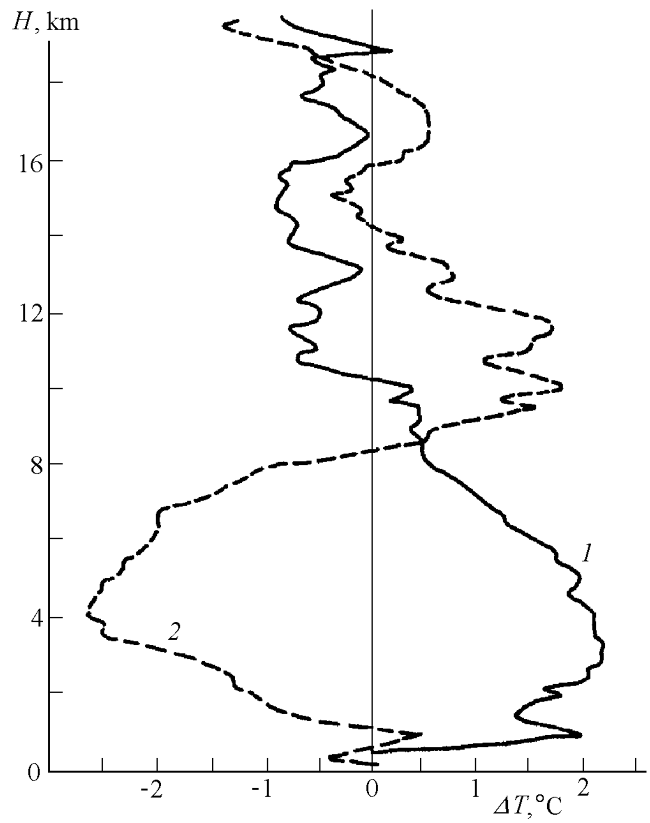

Figure 16. Variations in the mean temperature profiles during SCR bursts ($N = 19$): curve 1, for $t = 0$ (first aerological sounding after the burst onset); curve 2, for $t = +3$ days (from [*Pudovkin et al.*, 1995], reprinted with permission from Journal of Technical Physics).

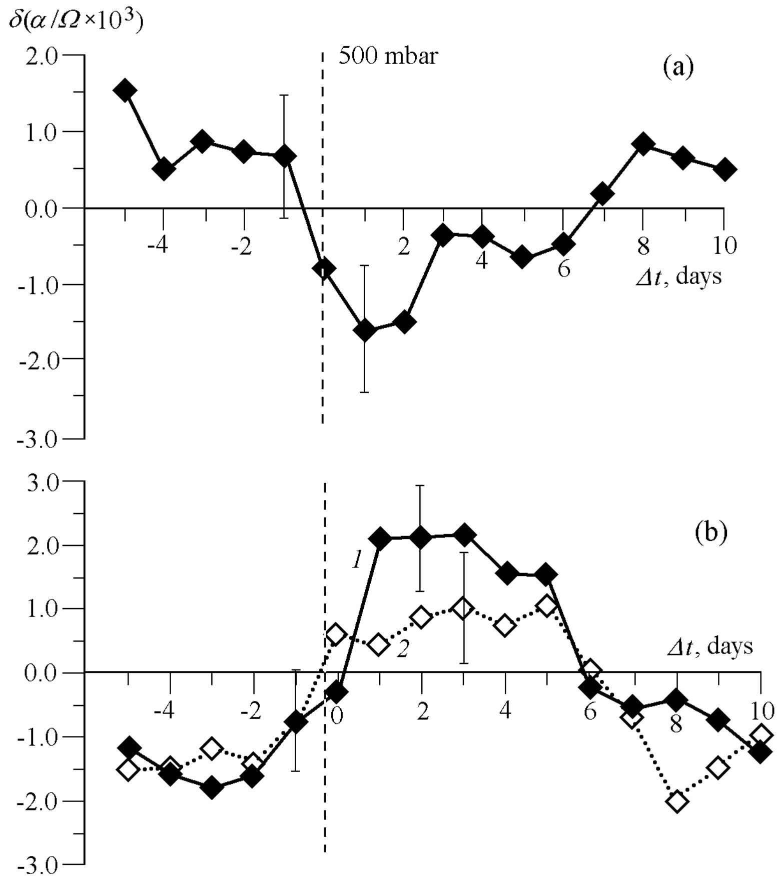

Figure 17. Variations in the zonal circulation rate (Blinova index) during (a) Forbush decreases of GCR and (b) during SCR bursts with the particle energy $E_p > 90$ MeV (curve 1) and $E_p < 90$ MeV (curve 2).

influence on the input of solar energy into the lower atmosphere and, consequently, the air temperatures in it. On the basis of these facts, they concluded that variations in cosmic ray fluxes play a fundamental role in formation of weather and climate at low latitudes. The physical mechanisms that are developed in a cloud under the action of cosmic rays are not discussed in detail in the works mentioned above. According to *Carslaw et al.* [2002] the processes associated with the direct influence of cosmic rays on the atmosphere and also with changes in the parameters of the global electric circuit can develop at low latitudes. However, relative contributions of these processes are not clear.

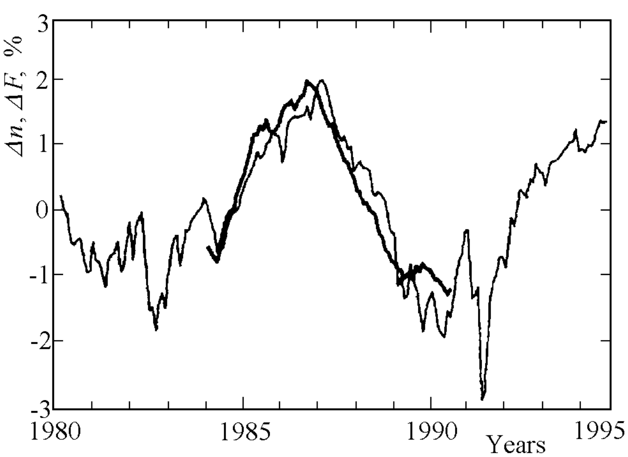

Figure 18. Variations in the total cloud cover n (thin line) and cosmic ray flux F observed at Climax (thick line) [after *Svensmark and Friis-Christensen,* 1997].

[62] So far we have studied morphology of elementary disturbances (i.e., those associated with single isolated heliospheric perturbations) in the lower atmosphere. This allowed us to exclude, to a large extent, many phenomena, secondary in nature though no less important. These were, for instance, changes in air temperature, cloudiness, and atmospheric transparency arising due to transfer of air masses caused by excitation of the additional atmospheric circulation system or variations in the thermal balance of the ocean-atmosphere system. In analysis of long-term variations in the lower atmosphere parameters and their connection with variations in solar activity, the impact of all these phenomena cannot be neglected. Their net effect should be considered, which appreciably complicates the picture [*Veretenenko and Pudovkin*, 1999b].

[63] As an example, let us return to Figure 1. As it has been mentioned above, the data shown in Figure 1 illustrate a rather specific situation. On the one hand, variations in air temperatures in St. Petersburg exhibit the periodicity coinciding in its characteristics with the solar activity periodicity. On the other hand, on the whole, there is no long-term statistical relation between changes in these variables, and *Bucha and Bucha* [1998] point to the fact that this situation is typical. It would be relative to the response of ocean-atmosphere system, which can have regional peculiarities that have own temporal variations.

4. Conclusions

[64] Thus we have considered some experimental data and model approximations of the impact of solar activity on weather and plausible mechanisms involved. As can be inferred from this review, the investigations carried out in recent years have shown that basic objections to the idea of existence of solar weather connection (see section 1 of this review) can be overruled. Indeed, a fairly careful analysis of experimental data reveals, in a number of cases, the reasons for "failures" in the observed links between variations in solar activity and some weather indices. As far as the disbalance between the power of atmospheric processes and the cosmic rays energy is concerned, the works discussed here point out at least two sources of the energy sought. These are the latent heat of vapor and ice formation and solar energy whose input rate into the lower atmosphere is controlled by variations in atmospheric transparency and cloudiness. As to the physical mechanisms, it should be admitted that, in spite of the fact that there are clear ideas about the general character of the processes in the cloud layer caused by invasion of energetic particles, there are still no quantitative characteristics of these processes, which, no doubt, greatly complicates the interpretation of experimental data.

[65] The main results of the works discussed are that the authors have succeeded in outlining the chain of the processes responsible for the development of disturbances in the lower atmosphere caused by variations in solar activity. However, it should be emphasized that the chain itself has been outlined rather schematically. The main reason is that, in spite of numerous research efforts, the morphology of atmospheric disturbances has not been studied thoroughly enough. For instance, it is still unclear how the vertical temperature profile in the lower atmosphere varies with latitude during the disturbance and how this profile changes with volcano eruptions. It is also not clear in what way an increase in the cosmic ray flux causes an increase in the flux of solar energy penetrating into the lower atmosphere at middle latitudes. The relation between development of disturbances at high and tropic latitudes has not been studied. The list of unresolved questions could be continued. However, even this enumeration convincingly demonstrates that combined efforts of scientists all over the world are needed to solve the problem. In all probability, this will be accomplished in future.

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