INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **29** (2003) 913–923 PII: S0954-3899(03)54503-0

The role of cosmic rays in the atmospheric processes

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Received 8 October 2002
Published 9 April 2003
Online at stacks.iop.org/JPhysG/29/913

Abstract

The energy flux of galactic cosmic rays falling on the earth's atmosphere is small in comparison with solar electromagnetic irradiation (by 10^8 times). But at altitudes of $h \sim 3$ to 35 km in the atmosphere, cosmic rays are the only ionization source (from the ground level up to $h \sim 3$ km, natural radioactivity is an additional source of ionization). Solar activity modulates cosmic ray flux. The cosmic rays produce atmospheric ions that define the electrical properties of the atmosphere. The electric charges play a very important role in the processes of cloud and thundercloud formation in the operation of the global electric circuit. The changes in electric properties of the atmosphere influence weather and climate. Thus, we have the following chain of the solar terrestrial relationship: solar activity—cosmic ray modulation—changes in the global electric properties of the atmosphere—changes in weather and climate. The following questions are discussed in this paper: light ion production in the atmosphere, role of electric charges in the formation of clouds and thunderclouds, experimental evidences of the relationships between cosmic ray flux and atmospheric current and lightning.

1. Introduction

In recent years, the global warming problem has been actively discussed. During the last century, the temperature on the earth's surface increased by $\sim$0.6 °C (Hansen *et al* 1999). The causes which could explain this phenomenon have not been found until now. Two mechanisms are mainly discussed here: solar influence on the weather and climate, and the influence of human activities on atmospheric processes (greenhouse effect). If the physical mechanism of the greenhouse gases has been understood, the mechanism of solar influence on weather and climate requires further investigations.

The long-term total solar irradiance observations show that its changes do not exceed $\sim$0.7% in the 11-year solar cycle and it cannot be responsible for the positive trend of the earth's surface temperature (Frölich and Lean 1997). It is possible that cosmic ray fluxes

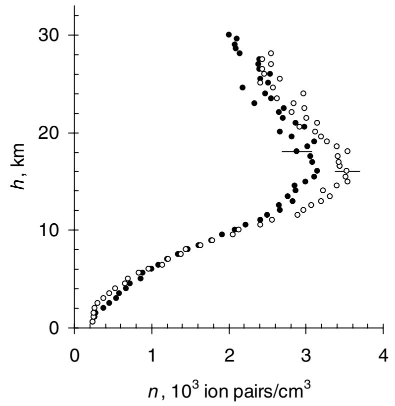

Figure 1. Light ion concentration n versus altitude h measured in the Antarctic winter period during the day (open circles) and night (black points) time. The measurements were taken at the Molodeznaya station in 1989–1990. The horizontal bars give the values of standard deviations.

invading the earth's atmosphere play an important role in atmospheric processes and in the global warming process (CERN 2001).

In the earth's orbit, the solar energy flux is $F_S = 1.36 \times 10^3$ W m^{-2} whereas the cosmic ray flux energy (particles with $\varepsilon \geqslant 0.1$ GeV) is $F_{CR} \approx 10^{-5}$ W m^{-2} (Frölich and Lean 1997, Stozhkov *et al* 2001). Comparing these values, one can believe that it is unlikely that cosmic rays can essentially influence the earth's atmosphere. However, cosmic rays are the only source of atmospheric ionization and they define its electrical conductivity at altitudes from $h \approx 3$ to 35 km. In the surface (boundary) air layer, natural radioactivity can contribute to the ionization of air (PosterdÖrfer 1994). As many atmospheric processes (e.g., atmospheric electric current, cloud and thundercloud formation, lightning production and others) are defined by their electrical properties, the conclusion that cosmic rays have to play important role in the atmospheric processes can be arrived at (Chalmers 1967, Reiter 1992).

The daily changes of galactic cosmic ray flux in the atmosphere are small (Asatryan and Stozhkov 1983). Because of this, during quiet conditions in the atmosphere, ion concentration n does not depend on the local time. In figure 1, the altitude dependence of n measured in the day and night time during the Antarctic winter period are shown (Ermakov and Komozkov 1992, Ermakov *et al* 1992).

The coincidence of altitude profiles shows that solar irradiation do not produce ions in the atmosphere at altitudes below 30–35 km and cosmic ray flux is a main source of ion production.

It is well known that low-energy cosmic ray particles (particles with energy $\varepsilon \leqslant$ 15 GeV) undergo solar modulation. During the 11-year solar activity cycle from its minimum to maximum, the flux of cosmic ray particles with $\varepsilon = 0.1$–15 GeV changes more than twofold. This energy interval contains more than 95% of all cosmic ray particles and more than 60% of all cosmic ray particle energy. This energy is spent to excite and ionize air atoms. Thus, one can expect that cosmic ray flux variations will cause the essential changes of electrical properties of the atmosphere.

The data on time changes of charged cosmic ray fluxes versus altitude from the ground level up to $h \approx 30$–35 km at the polar, middle and low latitudes have been obtained in Lebedev Physical Institute, Russian Academy of Sciences. These data representing the homogeneous rows embrace the period from 1957 till the present time (Stozhkov *et al* 2001). As an example,

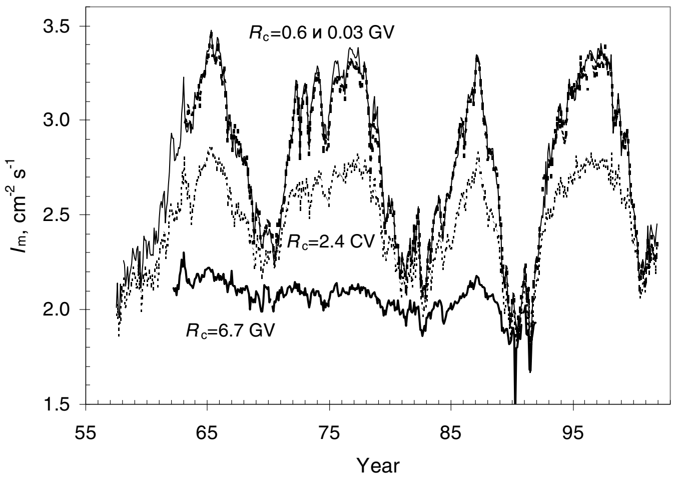

Figure 2. Monthly values of cosmic ray fluxes in the atmosphere at Pfotzer's maximum, I_m. The measurements were made at the northern polar latitude with the geomagnetic cut-off rigidity $R_c =$ 0.6 GV and the I_m position is at $h \approx$ (18–22) km (upper black curve), at the southern polar latitude in Antarctic with $R_c = 0.03$ GV and the I_m position is at $h \approx$ (18–22) km (upper black dotted curve), at the northern middle latitude with $R_c = 2.4$ GV and I_m position is at $h \approx$ (18–20) km (middle dotted curve), and at the northern low latitude with $R_c = 6.7$ GV and I_m position is at $h \approx$ (15–7) km (bottom curve).

the time dependence of cosmic ray fluxes I_m measured in the atmosphere at Pfotzer's maximum at the polar, middle and low latitudes are depicted in figure 2 (Stozhkov *et al* 2001).

One can see significant changes of cosmic ray fluxes in the atmosphere in solar activity cycles. The amplitudes A of these changes go down with the growth of geomagnetic cut-off rigidity R_c and with the increase in atmospheric pressure level (or with the decrease in altitude h in the atmosphere). In the stratosphere of polar and middle latitudes the values of A are approximately tens of per cents and in the troposphere the values of A are about 5–10% (Stozhkov *et al* 2001).

Experimental data on other sources of air ionization are scarce. In the atmosphere at altitudes $h > 35$ km, solar UV and x-ray radiation ionize air atoms. In contrast with cosmic ray fluxes, these kinds of radiation are in the phase of the solar activity cycle and there is a high correlation between the solar soft x-ray flux F_x (corona radiation with temperature $T \approx 2$ MK) and solar activity level (sunspot number R_z). For the period from 1992 to 2000, when there are experimental data on F_x (Pevtsov and Action 2001) the correlation coefficient between F_x and R_z is rather high, $r(F_x, R_z) = +0.97 \pm 0.02$. The flux of UV-solar radiation influences on the ionosphere and ionospheric index F_{ION} gives information about solar UV-radiation. There are experimental data on F_{ION} index from 1956 to 1992 (Antonova *et al* 1996). For this period the correlation coefficient between F_{ION} and R_z equals $r(F_{ION}, R_z) = +0.92 \pm 0.03$.

2. Electrical characteristics of the atmosphere and global electric circuit

As was mentioned earlier, the electrical characteristics of the atmosphere are defined by cosmic ray fluxes, radioactivity (at $h < 3$ km), and UV and x-ray solar fluxes (at $h > 35$ km). It is known that the earth has a negative electric charge $Q \approx -600\,000$ C. This charge produces an electric field E with $E \approx -130$ V m^{-1} near the earth's surface. Between the surface and equipotential layer at $h \approx 55$–80 km, electric current flows. Its density is about

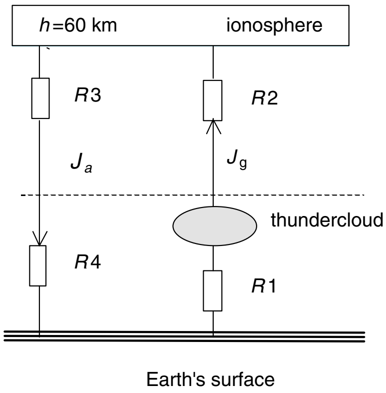

Figure 3. The schematic view of the global electric current: J_a—electric current in the atmosphere at fair weather conditions; R_1, R_2—resistances of the atmosphere below and above thundercloud; R_3, R_4—resistances of the quiet atmosphere; J_g—electric current of thundercloud generator (these generators are mainly in the equatorial regions); the dashed line is a boundary between troposphere and stratosphere.

$J_a \approx 10^{-12}$ A m^{-2} and the total atmospheric current is about 1800 A (Chalmers 1967). In the atmosphere, thunderclouds are formed and lightning discharges occur. In recent years, new phenomena were discovered in the atmosphere: electric discharges between the thundercloud top and ionosphere, the so called sprites and elves (Lyons *et al* 2000, Williams 2001). The elve is the acronym of emission of light and very low frequency perturbations from electromagnetic pulsed sources. The sprites and elves are observed in the large-scale thunderstorm systems after electric discharges of the earth's surface-thundercloud (Lyons *et al* 2000).

To explain the electric properties of the atmosphere and the phenomena observed, Wilson (1922) put forward the idea of the existence of the global electric circuit. Lightning discharges are the generators of electric current in the atmosphere. They bring negative charges to the earth's surface and support discharged current in the atmosphere equal to $J_a \approx 1800$ A. Without lightning, atmospheric current could discharge the earth's surface in several minutes. Figure 3 gives the schematic view of the global electric current.

In the thundercloud maturity stage, cloud-to-ground lightning transfer negative charge to the earth's surface. The powerful precipitations also transfer negative charge to the ground. In the decay stage of thundercloud, ground-to-cloud lightning transfer negative charge from the ground to cloud. As a whole, the thundercloud charges the earth by negative electricity (Krasnogorskaya 1972). Integrated over the globe, charged electric current of thunderclouds equals the discharged electric current of the quiet atmosphere.

Thus, thunderclouds are the generators of the global electric circuit. A total electric current of this circuit is about 1800 A. Calculations show that the voltage difference between the top and bottom of thunderclouds is 10^8–10^9 V. The electric power of thunderclouds in a global scale equals 2×10^{11} to 2×10^{12} W. This value is comparable with the power of all electric stations on earth.

In any place of the globe, thunderstorm activity reaches the maximum at 15–16 hours of local time. During the day the thunderstorm activity is changed. So, changes of the electric field strength E on the earth's surface take place, that is, the so-called 'unitary variation' of E is observed. The maximum value of E is at about 19 hours of the universal time when the maximum thunderstorm activity is observed in Africa and America (Markson 1982, Kasemir 1994).

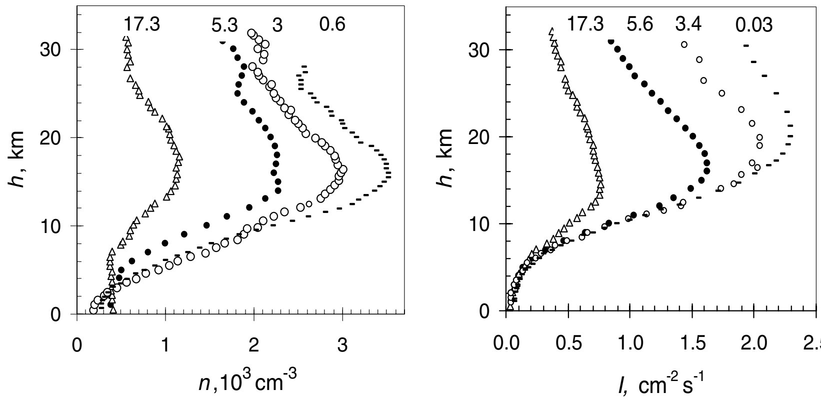

Figure 4. Ion concentration n (left panel) and cosmic ray flux I (right panel) versus altitude h in the atmosphere at the latitudes with the geomagnetic cut-off rigidities $R_c = 17.3$, 5.6, 5.3, 3.4, 3.0, 0.6 and 0.03 GV. The horizontal bars show the standard errors.

3. Ion production in the atmosphere

Light ions provide electric current in the atmosphere and cosmic rays are the only source of these ions at altitudes of $h \approx 3$–35 km (lightning produce ions also). It is generally agreed that in quasi-stationary conditions, ion balance in the atmosphere is described by the quadratic equation

$$q = \alpha n^2, \tag{1}$$

where q is ion production rate, n is light ion concentration and α is the three-dimensional recombination coefficient (Loeb 1960). The ion production rate q is defined by cosmic ray flux and equals

$$q = \frac{I\sigma\rho}{M}, \tag{2}$$

where I is cosmic ray flux depending on the altitude in the atmosphere h (more exactly from the atmospheric pressure X), geomagnetic cut-off rigidity R_c and solar activity level, σ is an effective ionization cross section, ρ is air density at the observation level and M is average mass of air atom. At $h \leqslant 20$ km, the values of σ equal $\sigma \approx 2 \times 10^{-18}$ cm^2 within 10–15% for all latitudes. It is not true for the case of polar latitudes in the periods of low solar activity when σ is increased at $h > 20$ km. From the equations (1) and (2) one can find that

$$n = \left[\frac{I\sigma\rho}{M\alpha}\right]^{0.5}. \tag{3}$$

The experimental data on ion concentrations n and cosmic ray fluxes I obtained at the different altitudes and latitudes in the atmosphere allow checking the validation of the equation (3). Figure 4 show experimental data on n (left panel) and I (right panel) obtained at the latitudes with almost the same values of R_c and during almost the same periods of time. From equation (1) we can construct the following ratio:

$$\left[\frac{q_1(h)}{q_2(h)}\right] = \frac{\left[\alpha(h)n^2(h)\right]_1}{\left[\alpha(h)n^2(h)\right]_2}, \tag{4}$$

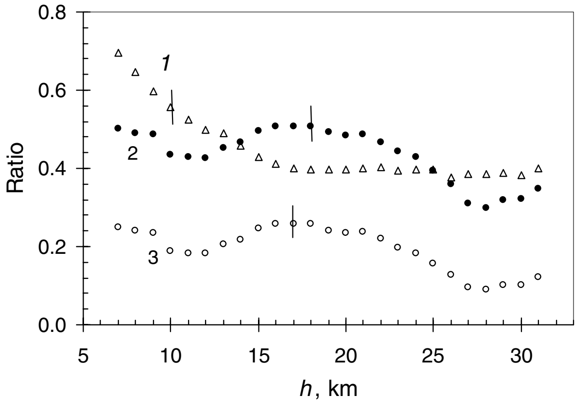

Figure 5. The ratios of cosmic ray fluxes (curve 1), ion concentrations (curve 2) and squared ion concentrations (curve 3) as a functions of altitude. These values were calculated from the experimental data obtained at the equatorial ($R_c = 17.3$ GV) and middle ($R_c = 3.3$ GV) latitudes (see figure 4) without any normalization of the data. The vertical bars give standard deviations.

where the subscripts 1 and 2 correspond to the latitudes with different geomagnetic cut-off rigidities R_{c_1} and R_{c_2}. Taking $(M\sigma)_1 = (M\sigma)_2$ and $\alpha_1 \approx \alpha_2$ (these suggestions are fulfilled in the atmosphere rather well) and using equations (2) and (3) one gets

$$\left[\frac{I_1(h)}{I_2(h)}\right] = \left[\frac{n_1(h)}{n_2(h)}\right]^2. \tag{5}$$

In figure 5, the ratios of charged particle fluxes (curve 1—triangles), ion concentrations (curve 2—dark points) and squared ion concentrations (curve 3—open points) calculated from the experimental data presented in figure 4 are given. The data obtained at the equatorial ($R_c = 17.3$ GV) and middle latitudes ($R_c = 3.3$ GV) were used.

It is seen that the ratio of cosmic ray fluxes (curve 1) coincides with the ratio of ion concentration (curve 2) and significantly differs from the squared ion concentration ratio (curve 3). Thus, the important conclusion must be made: the light ion balance in the atmosphere under quiet conditions is described by the linear equation (not quadratic)

$$q(h) = \beta(h)n(h), \tag{6}$$

where $\beta(h)$ is the linear recombination coefficient (Ermakov *et al* 1997). From the available experimental data on cosmic rays in the atmosphere and light ion concentrations, the value of $\beta(h)$ and $q(h)$ can be calculated for any site of the earth and any level of solar activity.

4. Relationship of cosmic ray fluxes with atmospheric current

As cosmic ray fluxes are responsible for light ion production in the atmosphere one can expect the relationships between atmospheric electrical phenomena and cosmic particle fluxes. Below we consider the relationships of cosmic ray fluxes with atmospheric current. The ion production rate q can be written as

$$q(h) = \frac{I(h)\,\sigma(h)\,\rho(h)}{M}, \tag{7}$$

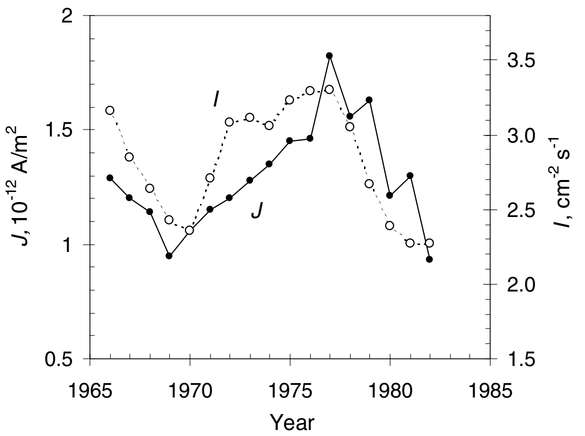

Figure 6. The yearly average values of atmospheric electric current J (Roble, 1985) and cosmic ray flux I at $h \approx 20$ km in the polar region.

where $I(h)$ is cosmic ray flux at altitude h, σ is effective ionization cross section in air, $\rho(h)$ is air density and M is average mass of air atom. The relationship between atmospheric electric current J, electric field strength E and conductivity λ is expressed as

$$J = \lambda(h)\, E(h) = n(h)\, k(h)\, E(h), \tag{8}$$

where $k(h)$ is the mobility of light ions at altitude h. Thus, using the expressions (6)–(8) one can find that

$$J = \frac{I(h)\, \sigma(h)\, \rho(h)\, k(h)\, E(h)}{M\, \beta(h)}. \tag{9}$$

On the right-hand side of this equation all values are constant except cosmic ray flux $I(h)$ and electric field strength $E(h)$. If one supposes that $E(h)$ is constant or weakly changes in the periods of fair-well weather then there is the linear relationship of cosmic ray flux $I(h)$ and atmospheric electric current J. The experimental data shown in figure 6 confirm such a conclusion. The correlation coefficient between electric current values J and cosmic ray flux $I(h)$ is positive and equals $r(J, I) = +0.64 \pm 0.15$. The correlation of J with solar activity level (sunspot number R_z) is low, $r(J, R_z) = -0.32 \pm 0.22$.

5. Thundercloud electricity and lightning production

Wilson's fascinating idea on the existence of the global electric circuit was very fruitful and abundant experimental evidences supporting this hypothesis have been obtained (see references in Reiter (1992)). However, the mechanisms of thunderstorm electricity production (separation of negative and positive charges in thundercloud and lightning production) have been under discussion until now (see, e.g., Baker and Dash (1994), Brooks and Saunders (1994)). Cosmic rays could be responsible for the thundercloud electrification (Ermakov 1992, Ermakov and Stozhkov 1999).

The problem consists in the spatial separation of negative and positive ions in the process of thundercloud formation. The thunderclouds are formed from ascending wet air mass when the fronts of cold and warm air meet each other. The air mass contains heavy ions (charged aerosols) because light ions produced by cosmic rays adhere to the neutral heavy particles. The concentration of aerosols has a maximum in the low atmosphere near the earth's surface

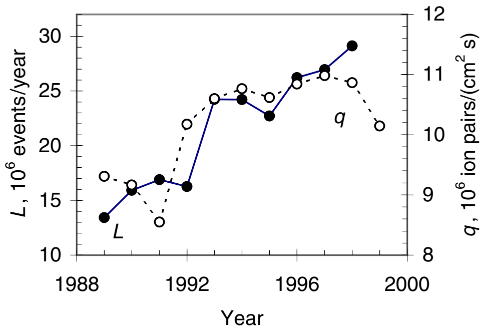

Figure 7. The yearly number of lightning L detected in United States in 1989–1998 (black points) (Orville and Huffines, 1999) and ion production rate q in the air column ($h = 2$–10 km) of the middle latitudes (open points).

and its value is $\sim 2 \times 10^4$ cm^{-3}. Half of these particles carry out positive or negative electric charges (Tverscoy 1962). The ascending air mass picks up the aerosols. During ascending, air mass is cooled and the process of water molecule condensation on neutral and charged aerosols is started. The condensation rate depends essentially on the aerosol electric charge and its sign. Namely, negative charged aerosols grow faster than positive ones, by $\sim 10^4$ times (Rusanov 1978). The rapid growth of aerosols with negative charge makes them heavy and their lift with the ascending air mass is stopped at low altitudes. At the same time the aerosols with positive charge continue to rise and stop their rising at altitudes higher than negative charged aerosols do. In this way the spatial separation of electric charges inside the cloud occurs (Ermakov and Stozhkov 1999, 2002).

Inside the thundercloud the strength of electric field can grow up to $E \approx 3$ kV cm^{-1} and the distance between separated positive and negative charges is roughly estimated as $\Delta h \approx 3$–4 km. The high value of E is observed under thundercloud also. But the observed values of E are much less than the puncture voltage at the altitudes at which thunderclouds exist ($h \approx 2$–7 km). At $h \approx 3$ km, the value of puncture voltage is 15–30 kV cm^{-1}.

In the 1990s, Ermakov (1992) put forward the idea that in thunderclouds the electric discharges (lightning) are produced by extensive air showers arising from high-energy cosmic ray particles with $\varepsilon = 10^{14}$–10^{15} eV. These high-energy cosmic rays interact with the nuclei of ambient air and give rise to many thousands of charged secondaries. Along ionized tracks of these secondary particles in a strong electric field avalanches develop and propagate. The high-energy cosmic ray flux is enough to explain the amount of lightning observed. As cosmic rays hit the earth's atmosphere accidentally in all directions, the lightning arise by chance also (see in details, Ermakov and Stozhkov (2002)). There is another mechanism of lightning production suggested by Gurevich *et al* (1999) and Gurevich and Zybin (2001) in which relativistic electrons are accelerated in the electric field of thundercloud and produces avalanche.

There is a link between the number of lightning and cosmic ray flux in the atmosphere: the number of lightning increases when ionization in the atmosphere increases. Now there are the long-term experimental data on lightning flashes over the United States. In figure 7, the time changes of the number of lightning L and ion production rate q is shown. The correlation coefficient between these values is $r(L, q) = +0.85 \pm 0.09$. The values of q were calculated from the data on cosmic ray flux measured in the atmosphere at the middle latitudes (see figure 2).

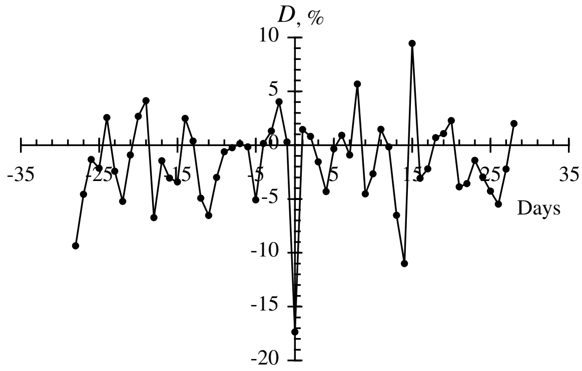

Figure 8. The changes of the daily precipitation level, D,%, relative to mean value evaluated from the precipitation data during one month before (-30 to -1 days) and one month after (1 to 30 days) Forbush-decrease event. The day '0' corresponds to the Forbush-decrease main phase.

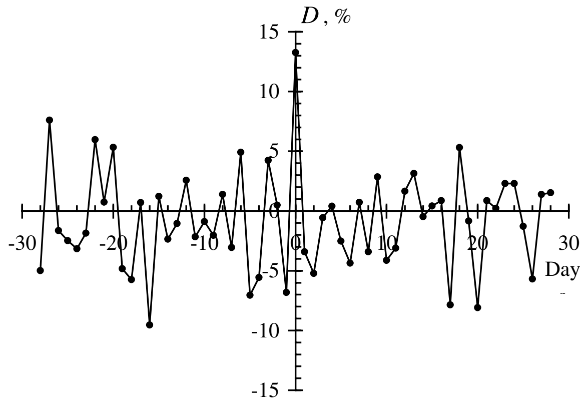

Figure 9. The changes of the daily precipitation level, D,%, relative to mean value evaluated from the precipitation data during one month before and one month after solar proton events recorded by ground-based neutron monitors ('0'-day).

6. The relationships between cosmic ray fluxes and other atmospheric phenomena

There are numerous publications in which the changes of cosmic ray fluxes are considered to be responsible for many atmospheric processes (see, e.g., Veretenenko and Pudovkin 1994, Stozhkov *et al* 1995, 1996, Tinsley and Brain 1996, Svensmark and Friis-Christensen 1997).

The influence of charged particle fluxes on cloudiness was found by Veretenenko and Pudovkin (1994). They found that the value of cloudiness reduced when cosmic ray fluxes in the interplanetary space and the atmosphere decreased (Forbush-effects of cosmic rays). During Forbush-effects, the value of precipitation also decreased. In contrast, when the ionization level is increased due to the invasion of solar flare protons into the atmosphere, the precipitation level increases (Stozhkov *et al* 1995, 1996). Figures 8 and 9 demonstrate the changes of precipitation in the cases of decreases and increases of cosmic ray fluxes in the atmosphere (Stozhkov *et al* 1995, 1996). These results were obtained from the analyses of the precipitation data recorded at the numerous meteorological stations located in Brazil and the former Soviet Union. More than two hundred of Forbush-effects and several tens of solar flare events were analysed. In the analyses the superposed–epoch method was applied. The value of precipitation level decrease obtained by the superposed–epoch method for more than 70 events of Forbush-effects is $D_0 = -(17.4 \pm 2.7)\%$. The probability of the occasional appearance of effect is less than 10^{-4} if the values of D obey a normal distribution. The results on relative increase of rainfall level during solar proton events were obtained by the superposed–epoch method for more than 53 events of solar proton enhancements. The amplitude of positive increase is $D_0 = +(13.3 \pm 5.3)\%$. The probability of effect appearing by chance is less than 10^{-2}.

The very important link of cosmic ray intensity and global cloud coverage was found by Svensmark and Friis-Christensen (1997). Their results demonstrate the high positive correlation of cosmic ray particle fluxes and cloudiness during long-term cosmic ray modulation in the 11-year solar activity cycle.

7. Conclusion

Cosmic ray particle fluxes play an important role in many atmospheric processes and it is only now that this role has begun to be elucidated. The thundercloud electricity and lightning production, cloud formation, influence on the value of global cloudiness and precipitation on the short (days) and long (11-year solar activity cycle) time scales, operation of global electric circuit and large-scale global climate changes depend on the values of cosmic ray flux.

Now the new experiment with the use of particle beam from accelerator to study the influence of electric charge on the water vapour condensation process on microscopic level is under discussion (CERN 2001).

Acknowledgments

The author is very grateful to the colleagues who worked hard to get the experimental data on the long-term cosmic ray variations in the atmosphere.

This work was partly supported by Russian Foundation for Basic Research (grants no 01-02-31005 and 01-02-16131) and Russian Ministry of Industry, Technology and Science (project 'Influence of solar and cosmic radiation on atmospheric processes, No 14').

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