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Cosmic rays and atmospheric processes

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Abstract. Cosmic rays play an important role in many atmospheric processes. We consider the following issues: cosmic ray ion production in the atmosphere; the role of cosmic rays in the global electric circuit operation (the relationship of cosmic ray fluxes with air electric current, thundercloud electricity and lightning production); the relationship between cosmic ray fluxes and cloud coverage.

1 Introduction

If one compares the flux of solar electromagnetic radiation falling on the top of the atmosphere ($F_{sun} \approx 10^{10}$ erg m^{-2} s^{-1}) with the flux of cosmic ray energy ($F_{CR} \approx 10^2$ erg m^{-2} s^{-1} for particles with energy $\varepsilon > 0.1$ GeV) the evident conclusion could be made: the influence of charged cosmic ray particles on the processes in the atmosphere is negligible in comparison with influence of the electromagnetic radiation coming from the Sun. However, let us imagine for a moment that cosmic rays stopped to intrude into the Earth's atmosphere. The ion production will be aborted and the global electric circuit will be destroyed. The production of thundercloud electricity and lightning will be over. The cloud area will be decreased and precipitation level will fall down.

The cosmic rays with energy $\varepsilon = (0.1\text{-}15)$ GeV carry about 60 % of all cosmic ray energy and these particles constitute about 95 % of all cosmic ray flux. These particles undergo the influence of the geomagnetic field in such way that the fluxes of primary cosmic rays at polar latitudes is higher than the ones at equatorial regions as much as (30-35) times. In the atmosphere this difference is about 4 times.

Below some aspects of influence of charged particle fluxes on atmospheric processes are considered (see also Stozhkov et al., 2001). In our analysis we use the experimental data of the long-term measurements of cosmic ray fluxes performed at the different atmospheric depths (from the Earth's surface up to 30-35 km) and at the different latitudes.

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2 Global electric current and ion production

It is well known that the Earth has a negative electric charge about 6×10^5 C and the strength of electric field produced by this charge near the Earth's surface measured during fair-well weather equals $E \approx -130$ V/m (directed to the Earth's surface). The value of average current J flowing between equalizing layer to be in the ionosphere at the altitude $h \approx (55\text{-}80)$ km and the Earth's surface is $J \approx 10^{-12}$ A/m^2 (Chalmers, 1967; Reiter, 1992). The sketch of global electric circuit is given in Fig. 1 (see, e.g., Markson, 1978; Tinsley, 1996).

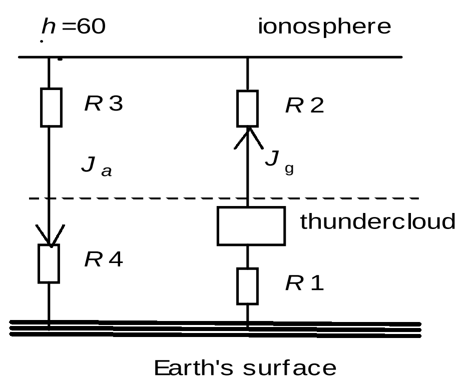

Fig. 1. The sketch of the global electric circuit: $h \approx 60$ km is an equipotential surface in the ionosphere; $R1$-$R4$ are the resistances of air masses; J_a and J_g are the atmospheric and thunderstorm generator currents (positive ion flow) correspondingly; the troposphere boundary at $h \approx 13$ km is shown by dashed line.

The detail description of the global electric circuit was given by Markson (1978). The main characteristics of the circuit are the following: the resistance $R1$ under thunderstorm cloud when lightning are observed is about $R1 \approx 10^4 - 10^5\ \Omega$; $R2$ above thunderstorm cloud is about $R2 \approx 10^5 - 10^6\ \Omega$; the load resistors $R3$ and $R4$ equal to ≈ 15 Ω and ≈ 150 Ω correspondingly. In the atmosphere each moment there are ~ 1500 lightning with total current ~ 1500 A charging the Earth by negative electricity. This current keeps the constant ionospheric potential at ~ +250 kV relative to the Earth's surface. Simultaneously the total discharged current ~ 1500 A flows in the atmosphere (through the load resistors $R1$ and $R2$) over the fair-weather portions of the globe. The tops of the thunderclouds (thunderstorm generator) have a potential of $U \approx 10^8 - 10^9$ V relative to the Earth and equipotential surface in the ionosphere.

The light ions provide the conductivity of the atmosphere. The ions are produced by cosmic particles (radioactivity of soil also gives ions but only in the lower atmosphere at $h <$ 3 km). If cosmic ray flux changes the ion density and the air conductivity changes also, that is, the resistance over the thunderstorm $R2$ is changed.

From the experimental data on ion concentration n and cosmic ray flux N one can get that the ion production rate q is proportional to charged particle flux: $q(h)=m(h)\cdot\sigma(h)\cdot N(h)$, where m and σ are the number of air particles per cm^3 and ionization cross-section. The values of m and σ are the same for different latitudes and depends on the altitude only. It isn't true for the case of polar latitudes at $h >$ (15 - 20) km where σ is increased. At $h <$ 20 km the value of σ is constant and equals $\sigma \approx 2\times10^{18}$ cm^2 within (10-15) %.

In the atmosphere at fair-weather conditions between the processes of ion production rate q and recombination of ions there is a relationship (Ermakov et al., 1997).

$$q = \beta(h)\cdot n(h)\ , \qquad (1)$$

where $n(h)$ is light ion concentration at altitude h and $\beta(h)$ is linear recombination coefficient In turn, the ion production rate q can be written as

$$q(h) = N(h)\cdot\sigma(h)\cdot\rho(h)/M\ , \qquad (2)$$

where $N(h)$ is cosmic ray flux at the altitude h, ρ(h) is air density and M is the average mass of air atom.

2 Cosmic ray fluxes and atmospheric electricity relationship

As cosmic rays are the only source of ionization in the atmosphere at $h >$ 3 km, the changes of these particle fluxes will change atmospheric conductivity. According to Fig. 1 the changes of resistances of $R2$ and $R4$ could mainly influence on global electric circuit operation because $R2 > R1$ and $R4 > R3$ in ~ 10 times. The cosmic ray fluxes in the stratosphere and troposphere define the values of $R2$ and $R4$ correspondingly. In Fig. 2 the time dependences of cosmic ray fluxes in the stratosphere and the troposphere at the middle latitude (geomagnetic cutoff rigidity R_c = 2.4 GV) are shown.

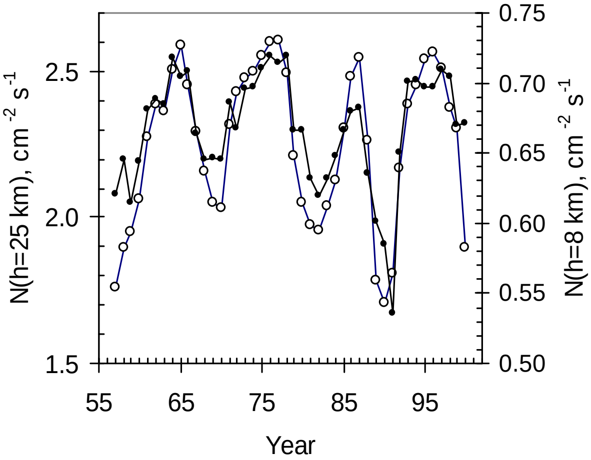

Fig. 2 The yearly averages of cosmic ray fluxes at the middle latitude with R_c = 2.4 GV in the stratosphere at h = 25 km (open points) and in the troposphere at h = 8 km (dark points).

One can see that the cosmic ray modulation is larger in the stratosphere than in the troposphere. The relative changes of cosmic ray fluxes from its minimum values to maximum ones are $A \approx 50$ % in the stratosphere at h=25 km and $A \approx 15$ % in the troposphere at h=8 km.

The comparison cosmic ray fluxes $N(h)$ in the atmosphere and atmospheric current J shows a good correlation between these values (see Fig. 3).

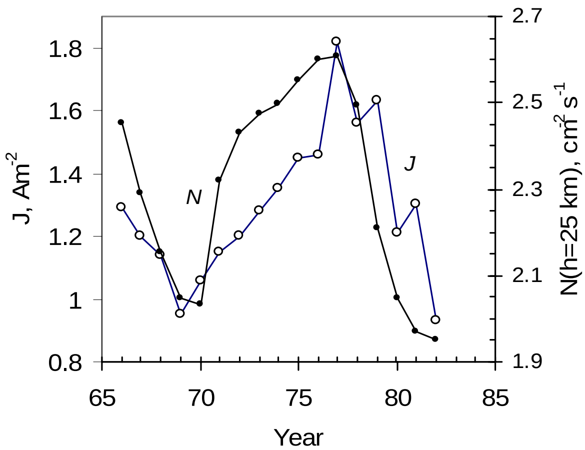

Fig. 3. Time dependence of atmospheric current J and cosmic ray flux $N(h$=25 km). The data on J were taken from Roble (1985).

The correlation coefficient between $J(h)$ and $N(h)$ is positive and equals $r(J, N) = +0.77\pm0.10$. The correlation of J and solar activity level (sunspot number W) is negative and low, $r(J, W) = -0.32\pm0.22$.

Cosmic ray fluxes play a very important role in the electric processes of thunderclouds (Ermakov and Stozhkov, 1999). Figure 4 demonstrates the link between cosmic ray flux and number of lightning. The data on lightning over the United States were obtained by Orville and Huffines (1999).

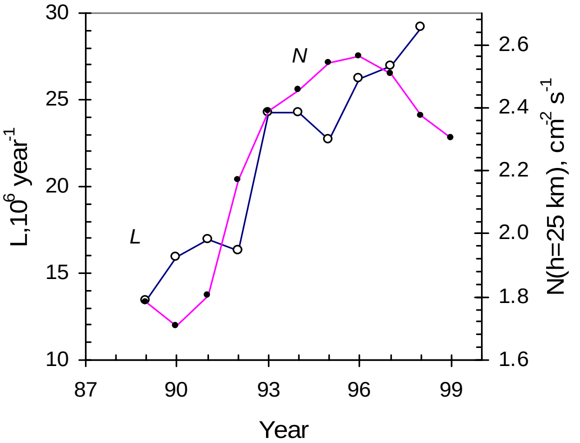

Fig. 4. The cloud to ground lightning number L per year over the United States in 1989-1998 (open points) and cosmic ray flux N at the latitude with R_c = 2.4 GV and at h = 25 km (black points).

It is seen that the number of lightning increases with the cosmic ray flux increase. The correlation coefficient between these values is r(L, N)=+0.86±0.09.

3 Discussion

When cosmic ray flux increases the ion production rate and ion concentration in air grow, cloudiness increases and one can expect that the number of thunderclouds (or thundercloud coverage) will increase also. The electric current in the atmosphere will grow and process of thundercloud formation and thunderstorm activity will be enhanced. The correlations between cosmic ray fluxes and electric phenomena in the atmosphere given above confirm the important role of charged particle fluxes in the atmospheric processes.

Let us consider in detail the relationship between atmospheric electric current J, atmospheric electric field strength E and lightning activity of thundercloud.

The value of electric current J in the atmosphere can be expressed as

$$J = \lambda(h)\cdot E(h) = n(h)\cdot k(h)\cdot E(h)\,, \qquad (3)$$

where $\lambda(h)$ is air conductivity, $k(h)$ is a mobility of light ions at the altitude h. From the expressions (1 - 3) one can find that

$$J = N(h)\cdot\sigma(h)\cdot\rho(h)\cdot k(h)\cdot E\ \ (h)/(\beta(h)\cdot M) \qquad (4)$$

On the right side of this equation all values are constant except cosmic ray flux $N(h)$ and electric field strength $E(h)$. From the expression (4) one can get the relative changes of electric current

$$\frac{\delta J}{J} = \frac{\delta N(h)}{N(h)} + \frac{\delta E(h)}{E(h)}\ . \qquad (5)$$

If one supposes that $E(h)$ is constant or weakly changes in the 11-year solar activity cycle then there is the linear relationship between the relative changes of cosmic ray flux $N(h)$ and atmospheric electric current J. The experimental data shown in Fig. 3 confirm this relationship. The value of J depends mainly on the $R3$ resistance because $R2 > R1$, $R3$, and $R4$. When cosmic ray flux in the stratosphere above the top of thundercloud increases air conductivity increases also ($R2$ decreases) and atmospheric current value is growing. The amplitudes of ($\delta J/J$) and ($\delta N/N$) changes in the 11-year solar activity cycle are compatible: ($\delta J/J$) ≈ 1.8 and at h = 25 km ($\delta N/N$) ≈ 1.5 (see Fig. 3).

The increase of J above the top of thundercloud enhances thunderstorm activity, in particularly, the frequency of lightning (Ermakov and Stozhkov, 1999). So, we observe the link between lightning number L and cosmic ray flux N in the stratosphere presented in Fig. 4. The amplitudes of relative changes of L and N are compatible also: ($\delta L/L$) ≈ 2.0 and ($\delta N/N$) ≈ 1.5 (see Fig. 4). The small difference of these amplitudes may be due to the growth of ionospheric potential when lightning activity is increased.

The charged particle fluxes in the atmosphere play essential role in cloud and thundercloud formation. Several years ago the link of cosmic ray intensity and global cloud coverage was found by Svensmark and Friis-Christensen (1997). Their results demonstrate the relationship between charged particle fluxes on the Earth's surface and cloudiness during long-term cosmic ray modulation in the 11-year solar activity cycle. Stozhkov et al. (2001) found the link between cloud coverage changes and ion production rate changes in the lower atmosphere in the interval of altitudes h=3-8 km.

When we consider the process of thundercloud formation we need to explain the mechanisms of thunderstorm electricity production (separation of negative and positive charges in thundercloud) and lightning generation. Although there are a number of hypotheses on the thundercloud electricity origin (see, e.g., Williams, 1989; Brooks and Saunders, 1994) these mechanisms are not clear completely till present time. Below we give the phenomenological description of the mechanisms of electric charge separation and lightning production in thunderclouds (Ermakov and Stozhkov, 1999).

The thunderclouds are formed from ascending wet air mass when the fronts of cold and warm air meet each other. The air masses contain heavy ions (charged aerosols) because light ions produced by cosmic rays adhere to neutral heavy particles. As it is known from the observations the concentration of aerosols has a maximum in the low atmosphere near the Earth's surface and its value is $\sim 2\times 10^4$ cm^{-3}. The half of these particles carries out the positive or negative electric charges (Tverscoi, 1962). Ascending air mass picks up the aerosols. During ascending air mass is cooled and processes of condensation of water molecules on neutral and charged aerosols take place. The condensation rate depends essentially on the charge presence and its sign. Namely, negative charged aerosols grow faster than positive ones in $\sim 10^4$ times (Rusanov and Kusmin, 1977; Rusanov, 1978). The rapid growth of aerosols with negative charge makes them heavy and their lift with the rising air mass is stopped at the low altitudes. At the same time aerosols with positive charge continue to rise with ascending wet air mass and stop their rising at higher altitudes than negative charged aerosols. In this way the spatial separation of electric charges inside the cloud occurs (in detail see Ermakov and Stozhkov, 1999).

Inside the thundercloud the strength of electric field can grow up to $E \approx 3$ kV/cm and the distance between separated positive and negative charges is roughly estimated as $\Delta h \approx$ $\approx$ (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 where thunderclouds exist. At $h \approx 3$ km the value of puncture voltage is ~ (15-30) kV/cm (Meek and Craggs, 1953). In 1993 Ermakov put forward the idea that in such electric fields the discharges (lightning) are produced by extensive air showers arising from high energy cosmic ray particles with $\varepsilon \approx 10^{14}$-$10^{15}$ eV. These high-energy cosmic rays interact with 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 the avalanches develop and propagate. The high energy cosmic ray particle flux is enough to explain the number of lightning observed. As cosmic rays hit the Earth's atmosphere accidentally in all directions the lightning arise by chance also. The detection of neutron bursts on the ground in the moment of lightning discharges supports this suggestion (Shyam and Kaushik, 1999).

There is another mechanism of lightning production suggested by Gurevich et al. (1992 and 1999) in which relativistic electron is accelerated in the electric field of thundercloud and produces avalanche.

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