Dynamics of the ionizing particle fluxes in the Earth's atmosphere

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***Abstract*. A long–term series of balloon-borne measurements of the charged particle flux in the atmosphere is continuously performed by the Lebedev Physical Institute since 1957 at various latitudes and altitudes. This data at the altitude above 15 km forms a good proxy for the primary cosmic rays, but some additional temporal variations occur in the troposphere, that are more pronounced during the last decade and have most probably atmospheric origin. The numerical models GEANT-4 PLANETOCOSMICS and CRAC (developed by the Oulu group) were used to compare the observational data with expectations from the simulations of cosmic ray transport through the atmosphere. It was found that the observed charged particle fluxes and dynamics are consistent with the calculated ones at altitudes above ∼4 km (∼630 g·cm^{-2}). At the lower altitudes the measured particle fluxes and their variability are higher than predicted by the models. The excess in particle fluxes may be due to the natural atmosphere radioactivity but in this case the radioactivity level should be higher than it was accepted till now.**

***Keywords*: charged particles, ionization, atmosphere**

I. INTRODUCTION

Measurements of charged particle fluxes in the atmosphere are continuously performed by the Lebedev Physical Institute (LPI) since 1957 at various latitudes and altitudes. The main goal of this program is investigation of the primary cosmic rays (CR), modulation of galactic CRs, invasion into the atmosphere of solar CRs and accelerated magnetospheric particles [1], [2]. The last decades are remarkable by the growing interest to the geophysical processes including ionization in the atmosphere. Cosmic rays play a major role in the ionization at the altitudes of ∼5–50 km due to charged particles multiplying in the cascade processes of the primary CR interactions with the air nuclei. It would be reasonable to expect that dynamics of the ionizing particles fluxes in the Earth's atmosphere generally reproduced the primary CR modulation. This is really the case for the altitude above 15 km, but some additional temporal variations occur in the troposphere, that were more pronounced during the last decade [3], [4]. While such variations in the northern hemisphere sporadically demonstrate an annual period opposite to the temperature changes, the annual variation is absent in the southern hemisphere. Most probably, the additional variations of particle fluxes in the troposphere are of atmospheric origin but their nature is not clear as yet.

Recently, several models have been developed for simulation of the interaction of primary CRs with the Earth's atmosphere [5]. In particular, the GEANT-4 PLANETOCOSMICS toolkit [6] specially adapted to our experimental data [7] have been applied to the results of solar and magnetospheric particles invasion into the atmosphere [8], [9]. On the other hand, the Cosmic Ray Atmospheric Cascade (CRAC) model developed by the Oulu group gives a possibility to reconstruct the cosmic ray induced ionization ($CRII$) at different atmospheric levels under different conditions of solar modulation [10]. In this paper we compare the data of observation of charged particle fluxes in the atmosphere with the results of the numerical models based on the primary CR input with the aim to distinguish variations of atmospheric origin.

II. OBSERVATIONS AND PARTICLE FLUX MODELING

Charged particle fluxes are detected in the atmosphere by a simple balloon-born device consisting of 2 Geiger counters arranged as a telescope with the 2 g·cm^{-2} Aluminum interlayer. Identity of detectors is carefully maintained during the whole period of observations. Records of both an omnidirectional counter and a telescope along with the air pressure information are transmitted from the atmosphere to the ground-based stations. The balloons are launched several times a week (every day before 1990-s) since 1957 up to now. The main sites of observations are Murmansk region (68°57'N, 33°03'E, from 1957 to 2002, 67°33'N, 33°20'E from 2002 up to now), Moscow region (55°56'N, 37°31'E), and Mirny (66°34'S, 92°55'E, since 1963). Figure 1 presents the averaged charged particles fluxes in 1976 as measured by omnidirectional counters in the Moscow region in the atmosphere versus residual atmospheric depth. The same Fig. 1 gives the results of the GEANT-4 simulation.

Modeling of the LPI omnidirectional counter response has already been made with GEANT-4 PLANETOCOSMICS in [7], but here we perform a simulation with

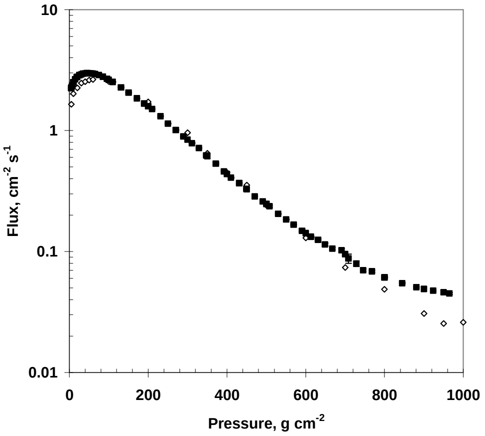

Fig. 1: Charged particle flux as measured by an omnidirectonal Geiger counter in Moscow region averaged over 1976 (black symbols with errors almost within the symbols) and calculated with GEANT-4 (white rhombs) versus residual atmospheric pressure.

special attention to the charged particle flux behavior in the lower atmosphere. The code takes into account the following processes: bremsstrahlung, ionization, multiple scattering, pair production, Compton scattering, photoelectric effect, elastic and inelastic nuclear interaction, and the decay of particles. The energy spectrum of galactic protons in the minimum of solar activity [11] was used as an input. A good agreement is seen between the observations and results of computation with exception for the atmospheric depths less than ~60 g·cm^{-2} and more than ~600 g·cm^{-2}. We believe that the former is due to neglecting the nuclei contribution into the primary CR spectrum during the simulation. In the lower atmosphere the calculated particle flux is systematically lower than the observed one. The same is true for the polar latitudes.

The CRAC model [10] is used in this paper for study of temporal behavior of charged particle fluxes. It is based on the CORSIKA Monte-Carlo package extended by FLUKA package to simulate the low-energy nuclear interactions, and explicitly accounting for direct ionization by primary CR particles. The model provides the ionization rate at any site of the atmosphere and any level of solar modulation.

The charged particle fluxes are closely connected to ionization rate production as is shown in Fig. 2 where ratio of the $CRII$ (cm^{-3}s^{-1}) to the particle fluxes J (cm^{-2}s^{-1}) is given at different atmospheric levels (see also [3]). The ratio between the results of the $CRII$ direct measurements by H. Neher [12] at the middle latitude (geomagnetic cutoff R_c =2.51 GV) for the minimum of solar activity and the LPI particle fluxes over Moscow (R_c =2.35 GV) in 1976 shows the almost linear dependence of $CRII/J$ on atmospheric pressure in the P =5–500 g·cm^{-2} range. The relation between CRAC modeling for Moscow region in 1976 and the LPI observations confirms this result. A certain difference

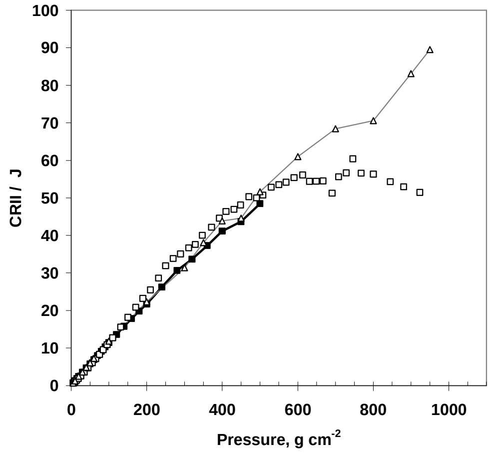

Fig. 2: Ratio of the ionization rate ($CRII$, cm^{-3}s^{-1} to the charged particle flux (J, cm^{-2}s^{-1}) versus atmospheric depth. Black squares and line denote ratio of observed $CRII$ [12] to the LPI observed fluxes, white squares — ratio of the CRAC calculated $CRII$ to the LPI observed fluxes, white triangles — ratio of the CRAC calculated $CRII$ to the GEANT-4 calculated fluxes.

seen in Fig. 2 can be easily explained by the fact that the measurements [12] refer not to 1976 but to 1964. An important point is that the $CRII/J$ has become flatter at P >500 g·cm^{-2} and even decreasing at P >700 g·cm^{-2}. The ratio between $CRII$ from CRAC and particle flux simulated by GEANT-4 is also shown in Fig. 2. In this case the quasi linear growth of the ratio is seen up to the Earth surface. Therefore, the flattening of $CRII/J$ in the lower atmosphere is a consequence of increasing of particle fluxes in the near-ground level not expected from the cascade theory.

The temporal behavior of the LPI particle fluxes and the $CRII$ at selected levels of the atmosphere is shown in Fig. 3. The $CRII$ values at P =150 g·cm^{-2} and 390 g·cm^{-2} (upper and middle panels of Fig. 3) are normalized to the particle flux according to linear dependence in the range of P =5–500 g·cm^{-2} seen in Fig. 2. The particle fluxes and $CRII$ are reasonably consistent with each other but the amplitude of the 11 year cycle is smaller in the data than in the simulation.

The lower panel of Fig. 3 gives the $CRII$ normalized at P =890 g·cm^{-2} according to ratio between the $CRII$ and particle fluxes calculated with GEANT-4. The difference between the observed and expected values is persisting throughout the whole period of observations from 1957 up to now. The observed fluxes of charged particles in the near-ground atmosphere are higher than the expected ones by a factor of 1.6 in average, which is in agreement with Fig. 1.

III. Discussion and conclusion

The charged particle fluxes in the atmosphere at the altitudes below ~600-700 g·cm^{-2} (~4 km) are in excess

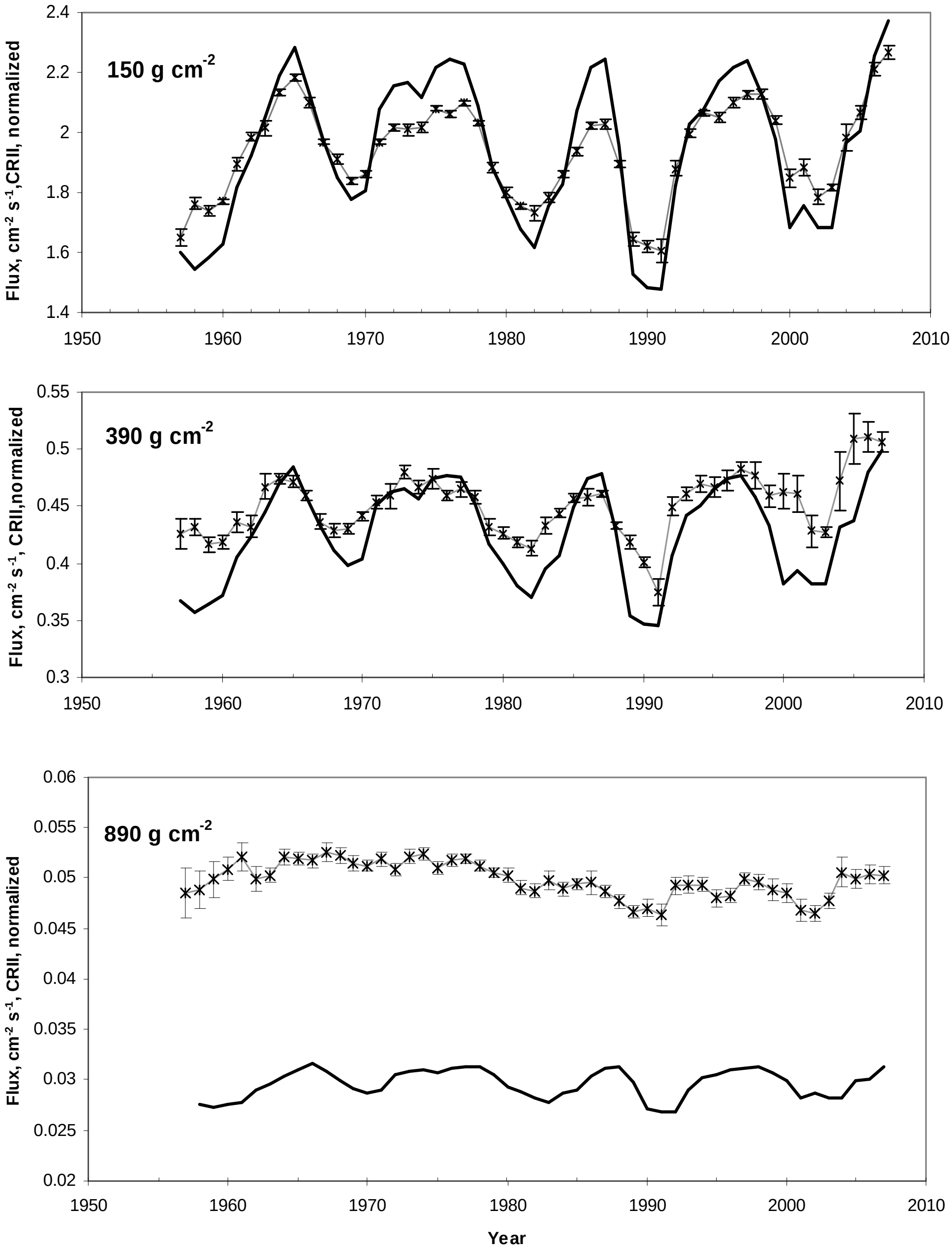

Fig. 3: Temporal variations of charged particle fluxes (crosses with errors) and the CRAC calculated ionization rates ($CRII$, solid curves) in Moscow region at different levels of the atmosphere (indicated on the panels). The $CRII$ values are normalized to the particle fluxes according to quasi linear relation observed at P <500 g·cm^{-2} and expected from calculations.

of values expected from the cosmic ray transport simulation. The fact cannot be consequence of systematic errors in the models because the results obtained by the PLANETOCOSMIC and CRAC model, based on different and independent numerical realizations, agree with each other.

An excess in the charged particle fluxes in the lower atmosphere is most probably of not galactic but of atmospheric origin. In particular, an 11-year solar modulation clearly seen in the calculated $CRII$ in the lower panel of Fig. 3 is not so pronounced in the observed fluxes. It should also be noted that the particle fluxes in the troposphere demonstrate short-term temporal variations with amplitudes more than the 11-year modulation [3], [4], which are not seen in Fig. 3 because of yearly averaging.

In the near-ground layers of the atmosphere the natural radioactivity plays a significant role, e.g., [13]. According to that work, at the level of 900 g·cm^{-2} the total flux of charged particles was 0.045 cm^{-2}s^{-1}, only 0.005 cm^{-2}s^{-1} ($\sim$11%) being estimated as radioactivity contribution. While the total charged particle flux at 890 g·cm^{-2} averaged over 1957-2007 is 0.05 cm^{-2}s^{-1} (consistent with [13], difference between the observed flux and the expected from calculations is 0.02 $cm^{-2}s^{-1}$, i.e. 40%. In addition the radioactivity contribution according to [13] is negligible above 800 g$\cdot$ cm^{-2}). We found discrepancy between the observed and calculated fluxes up to $\sim$630 g$\cdot cm^{-2}$) (see Fig. 1). Thus, at the moment we are not able to explain the excess of charged particle fluxes in the lower atmosphere over the expected from the calculations based on the cosmic ray transport. More work is needed to estimate the natural radioactivity contribution and its variations as well as a possible role of atmospheric processes in the dynamics of charged particle fluxes. In particular, the data of the LPI telescopes will be used for this purpose.

IV. Acknowledgments

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