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ESTIMATED EQUIVALENT RADIATION DOSE AT DIFFERENT ALTITUDES IN EARTH'S ATMOSPHERE

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Abstract. The paper reports the results of simulation of cosmic ray proton transport through Earth's atmosphere. The main objective of this work is to obtain characteristics of secondary particle fluxes at different altitudes and to convert them to equivalent dose values. The technique for the conversion is based on numerical simulation of interaction between the particles and an anthropomorphic phantom. The paper examines two cases, using a model source of primary proton spectra as input parameters, which correspond to both purely galactic cosmic rays and solar cosmic rays. The computational results are tabulated for the altitude range from 0 km to 11 km above sea level; the upper range value corresponds to the flight altitude of civilian airliners. These results are shown to agree well with the results obtained by other research teams.

Keywords: cosmic rays, astrophysics, Monte Carlo method, GEANT4, particle physics, numerical simulation.

INTRODUCTION

In earlier works, we have described a model of cosmic ray (CR) propagation through Earth's atmosphere [Maurchev et al., 2019; Maurchev et al., 2021]. Secondary cosmic ray fluxes were calculated, as well as the ionization rate in accordance with specified characteristics of the source of primary particles (protons), which correspond to galactic CRs (GCRs) or solar CRs (SCRs). We present the output data in our calculations both in the form of energy spectra of secondary particles and in the form of vertical profiles (or depth dependences) of flux or ionization rate, which are measured either in $\text{cm}^{-2}\text{s}^{-1}$ or in $\text{cm}^{-3}\text{s}^{-1}$ respectively. When assessing the radiation safety, such units of measurement are inconvenient and require reduction to a standard value, namely, to an equivalent dose expressed in sieverts. The urgency of the problem is due to the fact that during Ground Level Enhancement (GLE) of solar cosmic rays the absolute primary proton flux can increase by several orders of magnitude [Firoz et al., 2019]. During GLE events, radiation flows increase at aircraft altitudes, and people on board an aircraft can therefore receive a significant equivalent radiation dose. The objective of this work is to quantitatively estimate this commonly used value in practice. Note that the equivalent dose has already been calculated when solving such problems (e.g., in [Menzel, 2010; Mishev et al., 2015]) experimentally and using PLANETOCOSMICS. However, one of the main goals of our work is to develop, on the basis of our existing models, a tool necessary to create a radiation safety assessment system at altitudes from 0 to 11 km.

METHOD

To calculate propagation of cosmic ray protons through Earth's atmosphere, we adopt a model developed at the Polar Geophysical Institute. The model is based on the GEANT4 software development package [Allison et al., 2016; Maurchev, Balabin, 2016]. The model of Earth's atmosphere is parameterized in such a way that the distribution of density, temperature, and composition is as close to reality as possible and optimized for calculations. For this purpose, the air column is divided into the required number of layers, each containing a fraction of the total mass. In this work, for instance, we divide the column into 50 layers, each with the substance content of 2 % of the total mass of the column. Parameters are set using the NRLMSISE-00 model [Picone et al., 2002]. To specify the necessary input data (date, time, height, etc.) before each actuation of the model, the authors converted the NRLMSISE-00 model code into the C++ class. To account for the interaction physics, a ready-made set is used which is called QGSP_BERT_HP in GEANT4 [Amelin et al., 2001; Heikkinen et al., 2003; Garny et al., 2009].

The primary particle generator is defined as a point generator with isotropic distribution (uniform in azimuth and zenith angles). The probability density for choosing the primary particle energy corresponds to the shape of the required spectrum of primary particles, i.e. the primary energy spectrum is converted to a probability density function and then a random number generator with this function is used. The energy spectrum of primary protons for GCRs is set in accordance with GOST [GOST 25645.104-84, 1985]; and for SCRs, in accordance with the method described in [Vashenyuk et al., 2011]. According to this method, the SCR spectrum consists of prompt (PC) and decay (DC) components. The primary proton spectra used in the simulation are shown in Figure 1. The geometry of the model atmosphere and paths of 10 GeV protons in the Z–Y projection are illustrated in Figure 2.

We describe a method for determining the equivalent dose (ED). ED is an indicator of how radiation of different types affect an irradiated object at the same radiation dose $H=\sum_r w_r D_r$. To estimated values in the absence of data on secondary radiation spectra, we apply the absorbed dose D_r equal to the ratio of the mean energy dE, transported by radiation to the volume of substance dm, as well as the efficiency coefficients w_r listed in Table 1 for radiation r of different types [http://nuclphys.sinp.msu.ru/radiation/rad_5.htm; Loshchakov, 2008].

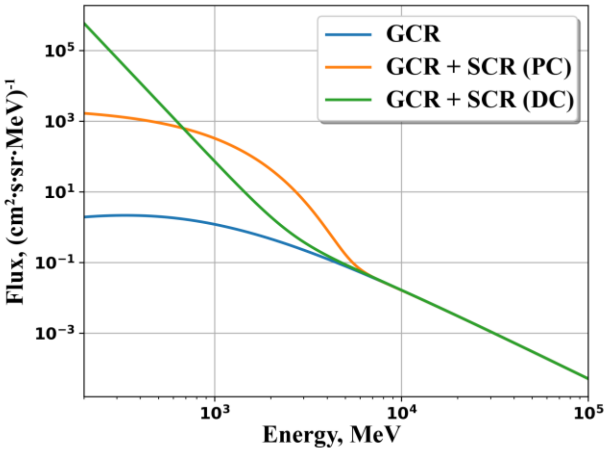

Figure 1. Differential energy spectra of SCRs, obtained from data from a network of neutron monitor stations during GLE69 (January 20, 2005), versus a GCR spectrum

Table 1

Weight coefficient for the equivalent dose

Radiation type and energy range	Coefficient
Gamma quanta and photons of all energies	1
Electrons and positrons	1
Muons+–	1
Protons	5
Neutrons (<0.01 MeV)	5
Neutrons (0.01–0.1 MeV)	10
Neutrons (0.1–2 MeV)	20
Neutrons (2–20 MeV)	10
Neutrons (>20 MeV)	5

In this paper, we directly calculate the absorbed energy in a volume of substance, using the Monte Carlo method. We utilize particle interactions of all known types and thus recieve the most accurate result. Note that modern computing power allows us to carry out simulations in near real time.

Thus, the algorithm for calculating the equivalent dose is as follows:

1. At given heights, the energy spectra of secondary particles are calculated using the model of CR propagation through Earth's atmosphere (the results are presented in Figures 3–5).
2. For each particle type we find the total flux, i.e. the number of particles passing through a unit area per unit time. The total fluxes as a function of height are shown in Figure 6.

Then, GEANT4 is used to develop a calorimeter model (water volume 0.065 m^3) in the form of a cylinder weighing 64.8 kg with a primary source to which the spectral characteristic of the particles of the type considered is assigned. The required number of events is triggered, the amount of energy left in the volume unit is determined, and the conversion to mass is carried out.

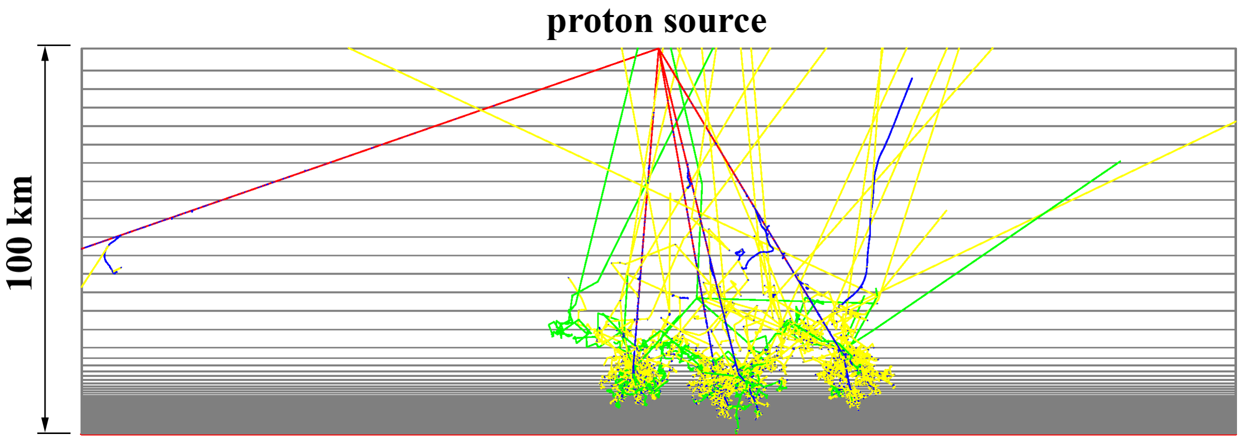

Figure 2. Paths of propagation of five protons with an initial kinetic energy of 10 GeV through Earth's atmosphere. The gray color represents the model atmosphere divided into layers; at the upper boundary, there is a source of primary particles with isotropic angular distribution. The direction of propagation of primary protons from the upper boundary to the lower one. Red color indicates positively charged particles; blue, negatively charged particles; purple, muons; yellow, photons of all energies; green, neutrons

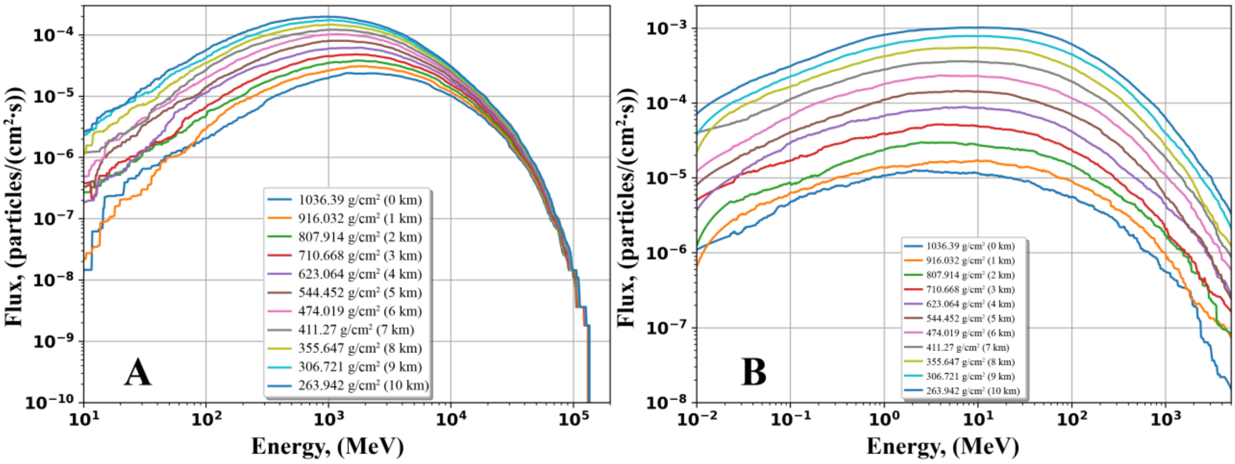

Figure 3. Integral energy spectra of secondary muons (*a*) and electrons (*b*) at different depths (heights) obtained from the simulation of propagation of protons with energy characteristics corresponding to the GCR spectrum through Earth's atmosphere

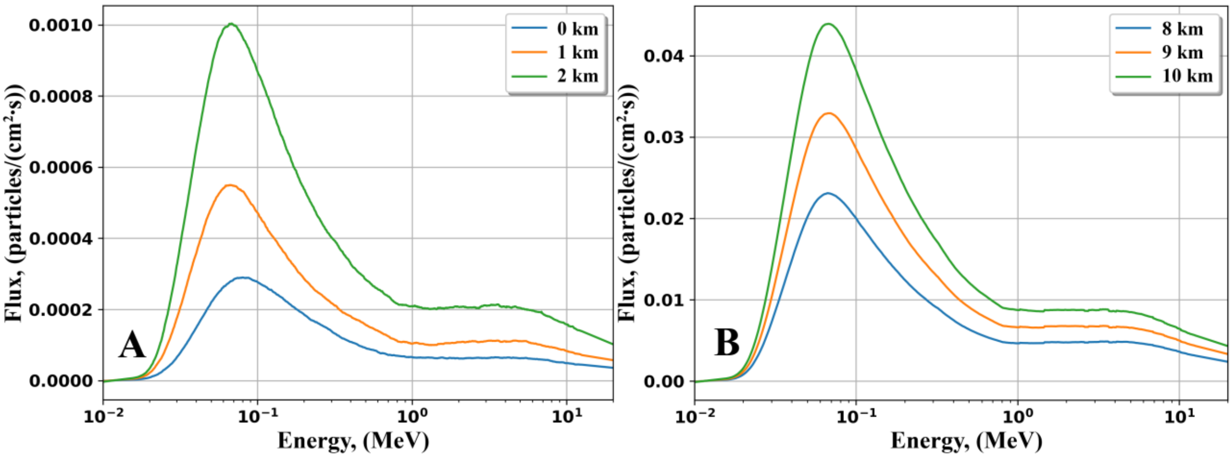

Figure 4. Integral energy spectra of secondary gamma quanta at altitudes 0–2 km (*a*) and 8–10 km (*b*) obtained by simulating propagation of protons with energy characteristics corresponding to the GCR spectrum through Earth's atmosphere

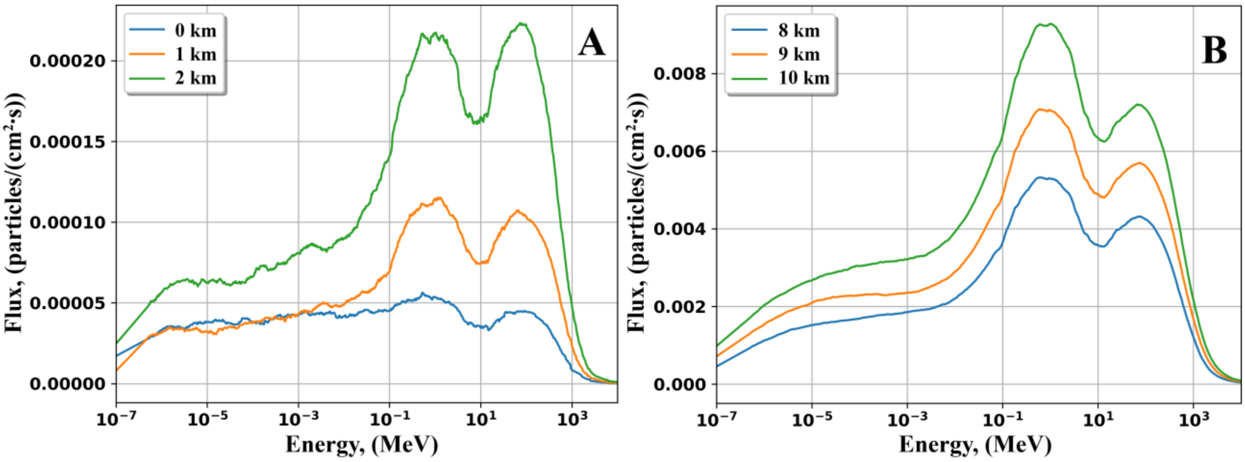

Figure 5. Integral energy spectra of secondary neutrons at altitudes 0–2 km (*a*) and 8–10 km (*b*), obtained by simulating propagation of protons with energy characteristics corresponding to the GCR spectrum through Earth's atmosphere

RESULTS

We have separately simulated propagation of CR protons through Earth's atmosphere and water volume irradiation by particles (a cylinder whose mass, radius, and height are close to human body parameters). At the first stage of calculations, we collected data on energy spectra of secondary particles (protons, neutrons, electrons, positrons, muons, gamma quanta) and their fluxes, which were used as input data for the second stage. When simulating the water volume irradiation, we gathered information about the energy left per unit mass — equivalent dose. Table 2 lists ED values for three cases: GCR, SCR

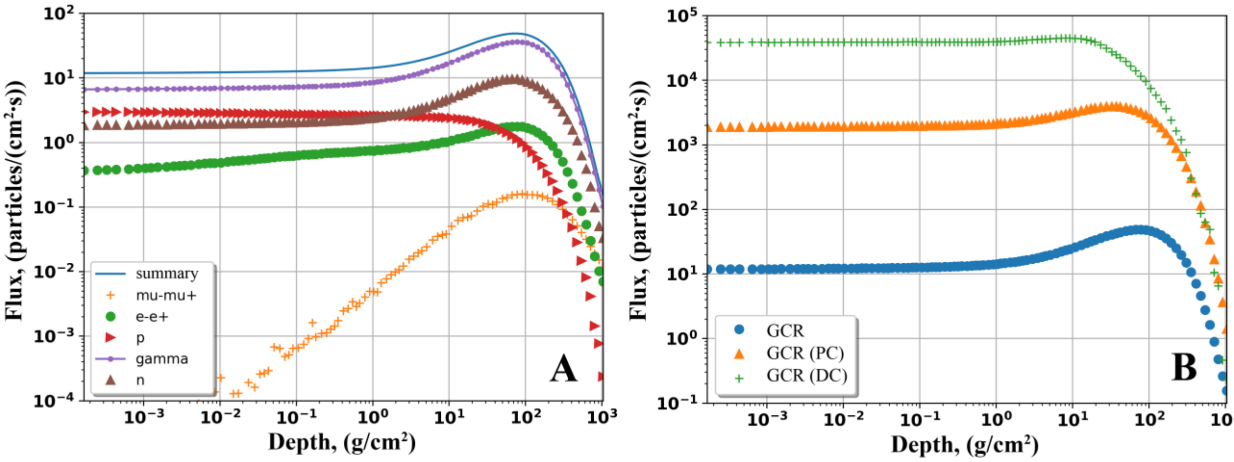

Figure 6. Total fluxes of particles of different types as a function of height of the atmosphere obtained by simulating GCR proton propagation (*a*), and comparison with total fluxes obtained by calculating SCR proton propagation (*b*) during the GLE69 event (January 20, 2005) for a point with geomagnetic cutoff rigidity R=0.65 GW

Table 2

Calculated equivalent dose

Altitude, km	Equivalent dose					
	GCR		GLE69 (PC)		GLE69 (DC)	
	mSv/h	mSv/h	mSv/h	mSv/h	mSv/h	mSv/h
0	0.130	1.134	0.413	3.614	0.155	1.358
1	0.192	1.681	1.047	9.171	0.256	2.244
2	0.290	2.543	2.897	25.373	1.457	12.759
3	0.469	4.106	6.210	54.395	2.384	20.880
4	0.764	6.693	11.951	104.693	9.911	86.822
5	1.214	10.637	23.327	204.340	27.267	238.863
6	1.935	16.950	42.444	371.813	35.366	309.804
7	2.940	25.755	70.227	615.191	65.236	571.464
8	4.274	37.437	117.558	1029.809	97.279	852.163
9	6.032	52.837	179.210	1569.880	183.526	1607.688
10	8.166	71.532	277.879	2434.222	298.847	2617.901
11	10.552	92.431	412.100	3609.995	513.438	4497.718

with a spectrum corresponding to PC and DC of GLE69 (January 20, 2005). We present the data for an altitude range 0–11 km above sea level (flight altitudes of most civil airplanes), which allows us to quantify the dose during a flight. Note that the calculations were carried out for the geomagnetic cutoff rigidity R=0.65 GV. Also noteworthy is that annual doses for SCRs are only informative since a GLE event usually lasts several hours (no more than a day), but it is interesting to compare them with the data on GCRs.

We have compared our findings with those received by other researchers. Mishev et al. [2015] present experimental data for 1998 (close to the solar minimum) [Menzel, 2010]. According to these measurements (and hence to the results obtained in [Mishev et al., 2015]), at the altitude of 11 km for R=0.65 GV the dose was 6.5 mSv/h. We have calculated that this value is 10.6 mSv/h, which gives good fit. The discrepancy may be due to many factors: the fact that we use the case with the ideal energy spectrum of GCRs at the solar minimum and an imperfect model of anthropomorphic phantom, as well as the idealization when simulating CR propagation through Earth's atmosphere as a whole. For GLE69 (January 20, 2005) and the 11 km altitude, calculations have also been made by several research teams. In [Matthia et al., 2009], the equivalent dose is 1000 mSv/h for the South Pole and 100 mSv/h for the North Pole; in [Butikofer et al., 2008], these values are 1500 and 100 mSv/h respectively; in [Mishev et al., 2015], 986 and 145 mSv/h. Note that we use a pure SCR spectrum, and the anisotropy axis for the event under study is directed just to the Southern Hemisphere; therefore, for the rigidity considered, the value is 412 mSv/h, which, as expected, is less than that at the pole. Of course, improving the model requires calculations for several values of geomagnetic cutoff rigidities, taking into account the pitch-angular distribution, which is planned to be done in the future. We also intend to develop a full-fledged model of anthropomorphic phantom from GEANT4.

CONCLUSIONS

We have developed a tool for estimating the equivalent radiation dose in Earth's atmosphere, which can be used together with the data on the energy spectrum of primary CRs in order to ensure radiation safety during aircraft flights. As an example, we have calculated GCRs and SCRs during the GLE69 event on January 20, 2005 for one point of geomagnetic cutoff rigidity R=0.65 GV.

In conclusion, let us give some estimates. For people who do not work directly with ionizing radiation sources, but, by place of residence or work, may be exposed to ionizing radiation, the maximum permissible dose is 0.5 rem/year (or 0.005 Sv/year, or 0.571 mSv/h). In the presence of only galactic cosmic rays at the ground level for the geomagnetic cutoff rigidity point R=0.65 GW, the estimated equivalent dose for the entire volume simulating the human body is 0.0011 Sv/year (or 0.11 rem/year, or 0.13 mSv/h). For example, for the January 20, 2005 GLE69 event at an altitude of 5 km, this value is 23.327 and 27.267 mSv/h; and at 10 km, it is already 277.879 and 298.847 mSv/h for prompt and decay components respectively. This is by orders of magnitude higher than the permissible dose per hour. It is noteworthy that at 10 km only for GCRs in the high-latitude region the estimated dose was 8.166 mSv/h, so for one crew member making such flights lasting 4 hours four times a week (for example, Moscow—Murmansk) ED is 0.007 Sv/year or 0.7 rem/year, which already exceeds the permissible dose for the people who do not permanently or temporarily work with ionizing radiation sources (in this case, the maximum permissible dose is 5 rem/year). Therefore, during high solar activity and a long flight in a zone with SCRs with energies in the range from 50 MeV to 1 GeV, ED can exceed the norm several times.

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