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Ionization effect of nuclei with solar and galactic origin in the Earth atmosphere during GLE 69 on 20 January 2005

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ABSTRACT

The ground level enhancement 69 on January 20, 2005 is the second largest event in the history of cosmic ray measurements. Solar protons cause an excess of ionization in the atmosphere, specifically over polar caps following major solar disturbances. At present the contribution of proton nuclei is highlighted. In this study is estimated the ion rate production in the atmosphere due to a major solar energetic particle (SEP) event on 20 January 2005 produced by various solar nuclei, namely proton, Helium, Oxygen and Iron. The contribution of light, middle and heavy nuclei of solar and galactic origin is explicitly obtained. The spectra of the nuclei are considered on the basis of GOES 11 satellite measurements. The Forbush decrease during the event is also explicitly considered. The ionization effect in the Earth atmosphere is obtained for various latitudes on the basis of a full Monte Carlo simulation of induced atmospheric cascade by solar and galactic cosmic ray particles. The evolution of atmospheric cascade is performed with the CORSIKA 6.52 code using FLUKA 2006b and QGSJET II hadron interaction models. The atmospheric ion rate is obtained for 40°N, 60°N and 80°N latitudes. The time evolution of obtained ion rates is presented. It is demonstrated that the ionization effect is significant in sub-polar and polar atmosphere and moderate at middle latitudes.

1. Introduction

Cosmic rays (CRs) constantly impinge the Earth's atmosphere. They are an important source of ionization in the Earth atmosphere (Bazilevskaya et al., 2008). The ionization in the stratosphere and troposphere is governed by galactic cosmic rays (Usoskin et al., 2009). They initiate a complicated nuclear–electromagnetic–muon cascade resulting in an ionization of the ambient air. In such a cascade a small fraction of the initial primary particle energy reaches the ground as high energy secondary particles. Most of the primary energy is released in the atmosphere by ionization and excitation of the air molecules, resulting in an ionization of the ambient air.

The galactic cosmic ray (GCR) flux is affected by solar activity. It follows the 11-year solar cycle and responds to long and short time scale solar-wind variations. The Solar CRs are accelerated during explosive energy release on the Sun and by acceleration processes in the interplanetary space. They enter the atmosphere sporadically, with a greater probability during periods of high solar activity. The heliosphere transient phenomena lead to a strong, relatively short suppression of GCR intensity in the vicinity of Earth, followed by a slower recovery on the time scale of several days known as Forbush decrease (Forbush, 1958). These events are generally interpreted as a result of the influence of coronal mass ejections (CMEs) and/or high-speed streams of the solar wind from the coronal holes on the background CRs.

The abundances of CR are approximately independent of the energy. For lower energies below 1 GeV/nucleon, the relative abundance of heavier nuclei increases, particularly around solar maximum, because they are less modulated than protons. In addition for a given energy, protons produce an atmospheric cascade that develops, deeper in the atmosphere than showers from heavier nuclei.

Previous works have identified that solar particles cause an excess of ionization over the polar caps following some major solar disturbances (Bailey, 1959). The detailed study of ion production during such events is important, because it is related to the atmospheric chemistry processes (Krivolutsky et al., 2002; Bazilevskaya, 2005; Ondraskova and Krivolutsky, 2005; Semeniuk et al., 2011). The cosmic ray induced ion rate could be estimated from the particle flux using the basic physics of ionization in air, an appropriate atmospheric model and realistic description of cascade process in the atmosphere (Usoskin et al., 2004).

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On 20 January 2005 all energy channels of GOES satellite simultaneously register enhancement of proton flux. The solar energetic particle (SEP) onset was registered at 6:50 UT, 3 min before maximum of X-ray flare. During the first hour the proton spectrum parameters change dramatically (Butikofer et al., 2008; Perez-Peraza et al., 2008). The changes of the spectra could be connected with particle acceleration mechanism preceding the CME launch. The next 10 h of acceleration produce spectra with very stable parameters (Bostanjyan et al., 2007), most likely formed at CME driven shock site. It is possible to fit the solar proton spectra with a double power-law function (Mewaldt et al., 2005). Of primary importance is that this event was accompanied by an unusually hard-spectrum of solar energetic particle (SEP) flux near Earth including the second most important major ground-level enhancement (GLE) of the observational history.

At present the contribution of proton nuclei in recent studies of this event is highlighted (Mishev et al., 2010, 2011a; Usoskin et al., 2011) as well as in other similar studies (Ondraskova et al., 2008). In the work presented here we estimate the ionization rate in the atmosphere due to a major solar energetic particle event on 20 January 2005 produced by various solar nuclei, namely proton, Helium, Oxygen and Iron.

2. Cosmic ray induced ionization model and simulation tool

The estimation of cosmic ray induced ionization as was recently demonstrated could be carried out on the basis of a full Monte Carlo simulation of the atmospheric cascade (Usoskin et al., 2004). In this study the cosmic ray induced ionization is estimated using formalism similar to Oulu model (Usoskin and Kovaltsov, 2006). The ionization yield function Y is defined as

$$Y(x,E) = \frac{\Delta E(x,E)\Omega}{\Delta x E_{ion}} \tag{1}$$

where ΔE is the deposited energy in an atmospheric layer Δx, Ω is the geometry factor—a solid angle and $E_{ion}=35$ eV is the ionization potential in air (Porter et al., 1976). We express x, during the simulations in g/cm^2, which is a residual atmospheric depth i.e. the amount of matter (air) overburden above a given altitude in the atmosphere. This is naturally related to the development of the cascade. Subsequently the mass overburden is transformed as altitude above sea level (a.s.l.) in (km).

The atmospheric ionization is given by the integral (2) (Usoskin and Kovaltsov, 2006) following the procedure described in (Mishev and Velinov, 2007; Velinov and Mishev, 2007; Velinov et al., 2009)

$$Q(x,\lambda_m) = \int_E^{\infty} D(E)Y(E,x)\rho(x)\, dE \tag{2}$$

where $D(E)$ is the differential cosmic ray spectrum for a given component of primary cosmic ray, Y is the ionization yield function defined according to (1), ρ is the atmospheric density, λ_m is the geomagnetic latitude, E is the initial energy of the incoming primary nuclei on the top of the atmosphere. The geomagnetic latitude λ_m governs the rigidity, which is related to the integration (integration above E).

The evolution of atmospheric cascade is carried out with the CORSIKA 6.52 code (Heck et al., 1998) with corresponding hadron interaction models FLUKA 2006b (Fasso et al., 2005; Battistoni et al., 2007) and Quark Gluon String with JETs QGSJET II (Ostapchenko, 2006). COsmic Ray SImulations for KASKADE (CORSIKA) code is a widely used atmospheric cascade simulation tool. The code simulates the interactions and decays of various nuclei, hadrons, muons, electrons and photons in the atmosphere. The particles are tracked through the atmosphere until they undergo reactions with an air nucleus or in the case of unstable secondary particles, they decay. The result of the simulations is detailed information about the type, energy, momenta, location and arrival time of the produced secondary particles at given selected altitude a.s.l. The primary particles that can be considered are protons, light, middle and heavy nuclei up to Iron.

3. Ionization effect on 20 January 2005 due to various nuclei

The event on 20 January 2005 is characterized by an anisotropic component with a very hard spectrum at the onset of the event, followed by a long isotropic emission with a softer spectrum (Plainaki et al., 2007; McCracken et al., 2008). In general the differential spectrum of cosmic rays (Nakamura et al., 2010) could be described as

$$D(E) = KE^{-\gamma} \tag{3}$$

The spectral index for SCR during GLE is typically between 4 and 6. The solar proton spectrum is obtained on the basis of GOES 11 satellite measurements (high energy channels) and additional data (Mewaldt et al., 2005; Makhmutov et al., 2009). We express the proton spectrum in two different moments: at 08:00 UT a high energy part with a slope of 2.32 and at 23:00 UT a low energy part with a slope of 3.43 (Mishev et al., 2010).

As was recently demonstrated the described algorithm is applicable for various primary nuclei (Usoskin and Kovaltsov, 2006; Mishev and Velinov, 2011). Therefore the Helium, Oxygen and Iron nuclei are also considered (Mishev and Velinov, 2012). A summary of solar nuclei spectra is presented in Table 1. Since the SEP event on 20 January 2005 occurred during the recovery phase of Forbush decrease the reduced GCR is also considered taking into account a realistic mass composition including various cosmic ray nuclei.

3.1. Ion rates at various latitudes produced by solar and galactic CR nuclei

The ion rates are obtained on the basis of the above described formalism. The ionization rates are estimated for various latitudes, namely 40°N, 60°N and 80°N taking into account the corresponding rigidity cut-off P_c.

We simulate 100 000 events per spectrum per particle per latitude. The ion pairs produced in 1 cm^3 of the ambient air at a given atmospheric depth by one particle of the primary cosmic ray with given kinetic energy are determined according to (1) and to expression (2) taking into account spectra described in Table 1. In this study the winter profile of the atmosphere is assumed divided per 10 g/cm^2, which permits a detailed and realistic description of ionization profiles (Mishev and Velinov, 2008, 2010). The estimated ion pair production rates at various latitudes as a function of atmospheric depth and time are presented in Fig. 1.

In general the ion production rate by a hard proton spectrum at 08:00 UT is greater than at 23:00 UT. The ion rate production by proton nuclei at 23:00 UT for 40°N and 60°N is negligible (Fig. 1B and D). The solar proton nuclei govern the ion rate

Table 1
Solar particle spectra characteristics.

Particle	*Proton*$_{08:00}$	*Proton*$_{23:00}$	*Helium*	*Oxygen*	*Iron*
K	1.55×10^7	10^7	0.519×10^7	9.2696×10^5	7.94×10^4
γ	2.32	3.43	2.18	2.61	2.45