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Computation of radiation environment during ground level enhancements 65, 69 and 70 at equatorial region and flight altitudes

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Abstract

The radiation environment in the troposphere of the Earth is governed by cosmic rays of galactic and solar origin. During major solar energetic particles events the radiation environment changes dramatically. As a results the risk of biological effects due to exposure to ionizing radiation of aircrew increases. Here we present a numerical model for computation of absorbed dose in air due to cosmic rays of galactic and solar origin. It is applied for computation of radiation environment at flight altitude in the equatorial region during several major ground level enhancements, namely GLE65 on 28 October 2003, GLE69 on 20 January 2005 and GLE70 on 13 December 2006. The model is based on a full Monte Carlo simulation of cosmic ray induced atmospheric cascade. The cascade simulation is carried out with CORSIKA 6.990 code with corresponding hadron generators FLUKA 2011 and QGSJET II. The contribution of different cascade components, namely electromagnetic, hadron and muon is explicitly obtained. The spectra of arriving solar energetic particles are calculated from ground level measurements with neutron monitors and satellite data from GOES. The obtained results are discussed.

Keywords: Radiation environment; Cosmic ray; Ground level enhancement; Monte Carlo; Space weather

1. Introduction

At present it is known that the increased radiation levels in the atmosphere with respect to ground level is due to cosmic rays (CR)s, namely it is result from interactions of primary CR particles with atmospheric nuclei. Cosmic rays constantly impinge the Earth's atmosphere and are the main natural source of ionization in the troposphere (Bazilevskaya et al., 2008; Dorman, 2004; Usoskin et al., 2009) i.e. they typically govern the radiation environment at flight altitudes. Primary CR initiate a complicated nuclear-electromagnetic-muon cascade generating a large variety of secondary particles. 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.

Two different components of primary CRs are responsible for this, galactic cosmic rays (GCR) originating from outside the solar system and solar energetic particles released in eruptions on the Sun. The intensity of galactic cosmic ray is affected by solar activity. It follows the 11-year solar cycle and responds to long and short time scale solar-wind variations. The heliosphere transient phenomena also 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 a Forbush decrease (Forbush, 1958). The GCR are mainly composed of protons and helium nuclei (about 87% protons and 12% alphas) as well as minor quantities of heavy ions

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(up to Iron). The abundances 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.

The solar energetic particles (SEP) are accelerated during explosive energy release on the Sun and by acceleration processes in the interplanetary space (Cliver et al., 2004; Dorman, 2006; Aschwanden, 2012). They enter the atmosphere sporadically, with a greater probability during periods of high solar activity. The majority of SEP events reach energies in the order of a few tens of MeV. Obviously such low-energy particles are absorbed in the upper atmosphere. Therefore they do not contribute to increasing of ion rate, respectively they do not impact the radiation environment in the troposphere at commercial flight altitudes. In some cases SEP are accelerated to high and relativistic energies and can penetrate deep into the atmosphere or even reach the ground, the so called ground level enhancements (GLEs). The average of their occurrence is approximatively of about one per year with higher probabilities during solar maximum and less during quiet solar conditions (Shea and Smart, 1990).

Both GCR and SEP are affected by the magnetic field in the Earth's magnetosphere, which diverts the penetration of charged particles resulting in a shielding effect. The shielding is most effective near the geomagnetic equator. The dipole magnetic field of the Earth provides best protection at low geomagnetic latitudes due to the deviation of the charged particles aligned parallel to the ground. The particle intensity is maximal at high geomagnetic latitudes where the charged particles propagate along the vertical field lines near the poles. In addition the absorption processes in the atmosphere influence significantly the intensity of secondary CR particles i.e. the intensity depends on the altitude above sea level. This results on their contribution to the radiation environment. Therefore the radiation environment due to CR varies with geomagnetic field, respectively geographic position, altitude and solar activity. Although the CR contribution to radiation environment at ground levels is insignificant, they could contribute significantly at flight altitudes, specifically during some major GLEs (O'Brien et al., 1997; Bütikofer et al., 2008; Matthiä et al., 2009a,b).

The space weather refers to the dynamic, variable conditions on the Sun, solar wind and Earth's magnetosphere and ionosphere, that can diminish the performance and reliability of spacecraft and ground-based systems and can endanger human life or health (Baker, 1998). An important feature of space weather effects is the contribution of SEP to the exposure of aircrew (O'Brien et al., 1997; Vainio et al., 2009), specifically during major GLEs. At present there is no evidence for any immediate threat on human health from SEPs, however chromosome aberrations in aircrew members are recently observed (Heimers et al., 1995; Yong et al., 2009). The potential biological risk of radiation doses, specifically of aircrew exposure is still a matter of scientific debate (Sigurdson and Ron, 2004; Ballarini et al., 2007). According publication 60 of International Commission on Radiological Protection (ICRP, 1991) the exposure of flying personnel to cosmic radiation is recommended to be regarded as occupational. In this connection several directives have been released, in particular in the European Union. Several models for estimation of the contribution of CR to dose rate at flight altitudes so far have been proposed (Ferrari et al., 2001; Roesler et al., 2002; Copeland et al., 2008; Sihver et al., 2008) or are operational at present (Schraube et al., 2000; Lewis et al., 2005; Sato et al., 2008; Kataoka et al., 2011). In general, it is possible to estimate the spectra of secondary particles resulting from interactions of primary GCR with atmospheric nuclei and subsequently obtain the dose rate as a function of geomagnetic cut-off and altitude using full Monte Carlo simulation of the atmospheric cascade (Ferrari et al., 2001; Roesler et al., 2002). In the paper presented here, the estimation of radiation environment during several major events, namely GLE65, GLE69 and GLE70 at equatorial latitudes is estimated on the basis of application of a recent numerical model (Mishev and Hristova, 2012).

2. Numerical model for estimation of radiation environment in the Earth atmosphere

For precise estimation of the radiation environment in the Earth atmosphere, a detailed information about spectrum, composition, angular distribution of incoming CR particles is necessary as well as realistic model for atmospheric cascade evolution. In the work presented here, the evolution of atmospheric cascade is carried out with CORSIKA 6.990 (Heck et al., 1998) code using FLUKA 2011 (Fasso et al., 2005; Battistoni et al., 2007) and QGSJET II (Ostapchenko, 2006) hadron generators. COsmic Ray SImulations for KASKADE (CORSIKA) code is one of the most widely used in the last years atmospheric cascade simulation tool. It is a Monte Carlo simulation tool for detailed study of cascade evolution in the atmosphere. The code simulates the interactions and decays of nuclei, hadrons, muons, electrons and photons in the atmosphere up to extreme energies. The result of the simulations is detailed information about the type, energy, direction, location and arrival time of the produced secondary particles at given selected observation level. In addition, it is possible to obtain the energy deposit by different cascade components and particles at given observation levels. By definition the absorbed dose is the energy deposited in a medium by ionizing radiation per unit mass. It is usually measured as joules per kilogram, represented by the equivalent SI unit Gy. The dose rate in Gy, produced in 1 g of the ambient air at a given atmospheric depth by one parti-