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Ion production and ionization effect in the atmosphere during the Bastille day GLE 59 due to high energy SEPs

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Abstract

The influence of high energy particles, specifically cosmic rays, on atmospheric physics and chemistry is highly discussed. In most of the proposed models the role of ionization in the atmosphere due to cosmic rays is not negligible. Moreover, effect(s) on minor constituents and aerosols are recently observed, specifically over the polar regions during strong solar particle events. According to the recent findings for such effects it is necessary an essential increase of ion production, specifically during the winter period. The galactic cosmic rays are the main source of ionization in the Earth's stratosphere and troposphere. Occasionally, the atmospheric ionization is significantly enhanced during strong solar energetic particles events, specifically over the polar caps. During the solar cycle 23 several strong ground level enhancements were observed. One of the strongest was the Bastille day event occurred on 14 July 2000. Using a full Monte Carlo 3-D model, we compute the atmospheric ionization, considering explicitly the contribution of cosmic rays with galactic and solar origin, focusing on high energy particles. The model is based on atmospheric cascade simulation with the PLANETOCOSMICS code. The ion production rate is computed as a function of the altitude above the sea level. The ion production rate is computed on a step ranging from 10 to 30 min throughout the event, considering explicitly the spectral and angular characteristics of the high energy part of solar protons as well as their time evolution. The corresponding event averaged ionization effect relative to the average due to galactic cosmic rays is computed in lower stratosphere and upper troposphere at various altitudes, namely 20 km, 15 km, 12 km and 8 km above the sea level in a sub-polar and polar regions. The 24^{h} and the weekly ionization effects are also computed in the troposphere and low stratosphere. Several applications are discussed.

Keywords: Atmospheric ionization; Cosmic rays; Solar energetic particles; Stratosphere and troposphere

1. Introduction

The effect of high energy particles, specifically cosmic rays, on different atmospheric processes related to atmospheric chemistry and physics is extensively discussed (e.g. Bazilevskaya et al., 2008; Mironova et al., 2015, and references therein). In most of the recent models, the induced by energetic particles atmospheric ionization plays an important role. The induced by energetic particles atmospheric ionization affect atmospheric processes, global electric circuit and minor constituents in the Earth's atmosphere (e.g. Krivolutsky et al., 2006; Randall et al., 2007; Jackman et al., 2008; Rozanov et al., 2012; Nicoll and Harrison, 2014; Verronen et al., 2015). The populations of energetic particles inducing atmospheric ionization, include galactic cosmic rays (GCRs), solar energetic

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particles (SEPs), precipitating protons and electrons from radiation belts (e.g. Bazilevskaya et al., 2008; Dorman, 2009; Mironova et al., 2015, and references therein). While the solar UV and X-rays dominate at altitudes above some 100 km above the sea level (a.s.l.), but absorbed below, the most energetic particles are the main source of ionization below 100 km a.s.l. In this work we focus on high and very high energy particles with cosmic origin, namely GCRs and the high energy part of about 300 MeV/nucleon and above SEPs, while the other populations are considered elsewhere (e.g. Mironova et al., 2015, and references therein).

The most important source of high energy particles inducing ionization in the troposphere and stratosphere of the Earth originate from outer space viz. cosmic rays (e.g. O'Brien, 1970; Dorman, 2004; Usoskin et al., 2009; Velinov et al., 2013). The majority of those particles are protons and $\alpha-$ particles, and minor quantities of heavier nuclei are also observed (e.g. Gaisser and Stanev, 2010, and references therein). Most of CR particles originate from the Galaxy, known as GCRs (e.g. Gaisser and Stanev, 2010, and references therein). The cosmic ray particles penetrate deep into the atmosphere, induce a complicated nuclear-electromagnetic-muon cascade, which eventually leads to an ionization of the ambient air (e.g. Dorman, 2004; Usoskin et al., 2009). The maximum of ion production in the atmosphere, observed at the altitude of about 12–15 km a.s.l., is known as Pfotzer-Regener maximum (Regener and Pfotzer, 1935; Pfotzer, 1936). The CR flux is modulated in the Heliosphere, follows the inverse 11-year solar cycle and also responds to transient phenomena e.g. Forbush decreases (Forbush, 1937).

A sporadic source of high energy particles penetrating the atmosphere and eventually inducing ionization follows eruptive solar processes on the Sun as solar flares and coronal mass ejections (CMEs), namely the so-called solar energetic particles (e.g. Reames, 1999; Cliver et al., 2004). The energy of SEPs is usually of the order of tens of MeV/nucleon. However, in some cases it can reach GeV/nucleon, leading to an atmospheric cascade and an enhancement of the count rate of ground based detectors, specifically neutron monitors (NMs). This special class of SEP events is called a ground level enhancement (GLE) (e.g. Shea and Smart, 1982; Dorman, 2004; Aschwanden, 2012). Their occurrence rate is roughly once per year, with increasing probability during maximum and decline phase of the solar cycle (Shea and Smart, 1990; Stoker, 1995; Bazilevskaya, 2005). These events usually lead to a significant increase of ion production in the atmosphere, specifically in polar and sub-polar region in the Earth's upper atmosphere, where the magnetospheric shielding is not as effective as at middle and equatorial latitudes (Jackman et al., 2011; Mishev et al., 2011; Usoskin et al., 2011b; Mironova et al., 2012; Mishev et al., 2013). Detailed study of ion production, accordingly ionization effect, which represents the ion production integrated over the event or a corresponding time interval relative to the ion production due to GCR computed prior to the event is necessary.

The ion production is computed in different parts of the Earth's atmosphere during GLEs. This allows one to estimate the possible effect of CR on atmospheric physics and chemistry in enhanced mode. The ion production rate during GLEs is determined mainly on SEP spectra and anisotropy and depends also on duration and apparent source location. Since, the GLE events differ from each other in spectra, duration, location occurrence, geomagnetic conditions as well as time evolution of the features related to the ion production (Gopalswamy et al., 2012; Moraal and McCracken, 2012), it is necessary to study each strong event separately. In this connection, here we study the ion production and the corresponding ionization effect during one of the strongest GLEs of solar cycle 23, namely the Bastille day GLE 59 on 14 July 2000. In this study we focus on a low stratosphere and upper troposphere, where only the most energetic part of SEPs play an important role, while the low energy part with important contribution at altitudes of 40 km above the level (e.g. Velinov, 1977; Velinov, 1981; Mironova et al., 2015) is not considered.

2. Model for cosmic ray induced ionization

The ion production in the atmosphere induced by high energy particles can be assessed by analytical and/or parametrization models (e.g. O'Brien, 1970; Vitt and Jackman, 1996). However, the parametrization models usually suffer from lack of precision, specifically in the low stratosphere and troposphere and possess constrains to a given atmospheric region and/or cascade component (e.g. Velinov et al., 2013, and references therein). On the other hand full target models based on a full Monte Carlo simulation of the atmospheric cascade allow one to compute the ion production rate, accordingly ionization effect in the atmosphere considering all the physics process involved (Desorgher et al., 2005; Usoskin and Kovaltsov, 2006; Velinov et al., 2009). Therefore, the full target models permit a realistic computation of ion production rate, accordingly ionization effect in the atmosphere during major GLEs, explicitly considering the contribution of cosmic rays with galactic and/or solar origin (Mishev et al., 2011; Usoskin et al., 2011b; Mishev and Velinov, 2015).

In this work we employ a model similar to Usoskin and Kovaltsov (2006). The full description of the model is given elsewhere (Mishev and Velinov, 2007; Velinov et al., 2009). The ion production rate as a function of the altitude a.s.l. is:

$$q(h,E) = \frac{1}{E_{ion}} \sum_i \int_{E_{cut}(R_c)}^{\infty} D_i(E) \frac{\partial E(h,E)}{\partial h} \rho(h) dE \quad (1)$$

where ∂E is the deposited energy in an atmospheric layer ∂h , h is the air overburden (air mass) above a given altitude in the atmosphere expressed in g/cm^2 subsequently converted to altitude a.s.l., $D_i(E)$ is the differential cosmic ray spectrum for a given component i: protons p, Helium (α-particles), the latter also representative for heavier nuclei

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