Updated model CRAC:HEPII of atmospheric ionization due to high energy protons

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An extension of the CRAC model - CRAC:HEPII (Cosmic Ray Atmospheric Cascade: High Energy Proton Induced Ionization) is presented. The model allows one to compute the ion production by high energy protons entering the Earth's atmosphere. The model is an extension of the CRAC:CRII model and it is focused on the upper part of the stratosphere and mesosphere. The model is also applicable in the low termosphere. The model is based on pre-computed with high statistics ionization yield functions. Therefore, the CRAC:HEPII model is based on a full Monte Carlo simulation of primary proton propagation and interaction with the atmosphere and explicitly considers various physical processes involved in ion production. All simulations were performed using the GEANT 4 simulation tool PLANETOCOSMICS with NRLMSISE 00 atmospheric model. The ionization yield function allows one to compute ion production due to various populations of primary protons in a wide energy range 100 keV – 20 GeV/nucleon for a given altitude, from about 6.5×10^{-9} g/cm^2 (about 200 km a.s.l.) to the sea level considering a given primary proton spectrum. The spacial and height resolution of the model is improved compared to CRAC model. An application of the model for computation of ion production during ground level enhancement events is demonstrated. A quasi-analytical approach, which allows one to compute the ionization yields for events with arbitrary incidence is also presented.

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1. Introduction

The primary source of ionization in the low and middle atmosphere are energetic particles (EPs) of galactic and/or solar origin entering the Earth's atmosphere. The impact ionization is an important topic nowadays [1, 2]. There are several atmospheric processes affected by the impact ionization as well as processes related to global electric circuit and minor constituents in the Earth's atmosphere [3, 4]. While EPs are the main source of ionization below 100 km, the solar UV and X-rays dominate at higher altitudes, but are absorbed below [2]. EPs, which contribute to the atmospheric ionization, are from various populations, including galactic cosmic rays (GCRs), solar energetic particles (SEPs), precipitating protons, relativistic electrons from radiation belts, precipitating electrons, auroral electrons. In this work we focus on a moderate and high energy protons mainly of solar and galactic origin, while other sources are considered elsewhere.

The most important source inducing the tropospheric and stratospheric ionization are cosmic rays, which penetrate deep into the atmosphere. They are interacting with the air molecules inducing a complicated nuclear-electromagnetic-muon cascade leading to an ionization of the ambient air [1, 5]. The maximum of ion production in the atmosphere, observed at the altitude of about 12–15 km above the sea level (a.s.l.) is known as Pfotzer maximum [6]. Following strong eruptive solar processes as solar flares and coronal mass ejections (CMEs) are produced solar energetic particles (SEPs) [7, 8]. In some cases SEPs are accelerated to energies enough high to initiate an atmospheric cascade similarly to GCRs. Strong SEP events can significantly increase the ion production in the atmosphere, specifically over the polar regions [9, 10, 11, 12]. While the ion production in the atmosphere induced by EPs can be assessed by analytical models [13, 14], which are usually constrained to a given atmospheric region and/or cascade component or primary particle, thus are with limited range of validity, the new recently developed models based on a full Monte Carlo simulation of CR particle propagation and interaction in the atmosphere are in expansion and demonstrated an essential progress [15, 16, 17, 18, 19]. In this paper we update and extend the recent model CRAC:CRII [17, 20], validated for the upper troposphere and stratosphere, toward the upper atmosphere. We provide an updated ionization yield function extending the altitude and the energy range and improving largely the resolution in altitude a.s.l.

2. CRAC model for computation of ion production rate in the atmosphere

In this study, the propagation and interaction of high energy protons with the atmosphere are simulated using the PLANETOCOSMICS code [16]. We employ the NRLMSISE 00 atmospheric model [21]. Here, we use a previously developed formalism of a yield function [17]. The ion production rate in the atmosphere is obtained as an integral of the product of the primary particle spectrum and the pre-computed yield function defined as:

$$Y(x,E) = \frac{\partial E(x,E)}{E_{ion}\partial x} \tag{2.1}$$

where ∂E is the energy deposition of all components of the atmospheric cascade in atmospheric layer ∂x at depth x, averaged per primary particle with kinetic energy E, and E_{ion}=35 eV is the average energy necessary for production of an ion pair in air [22].
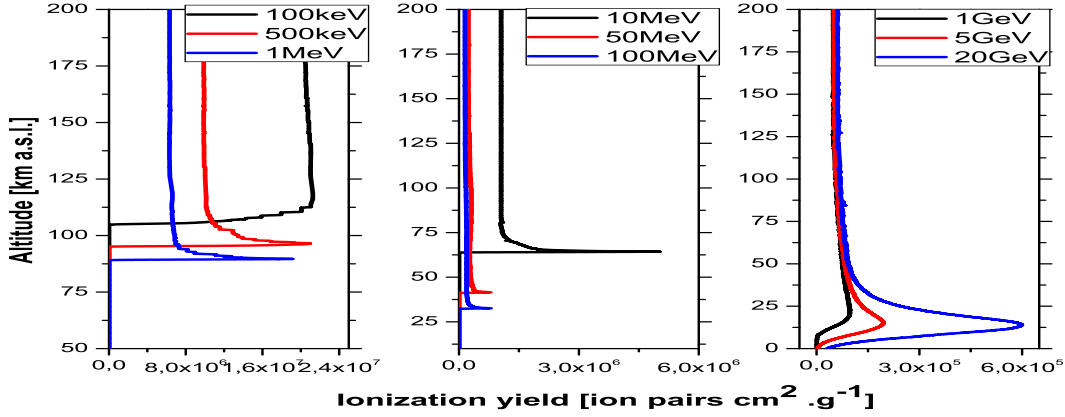
Figure 1: Ionization yields for primary protons with vertical incidence and with different energies as a function of the altitude a.s.l. as denoted in the legend

The computations were carried out in the energy range of primary protons between 100 keV/nucleon and 20 GeV/nucleon and at atmospheric depths from 6.5×10^{-9} g/cm^2 (about 200 km a.s.l.) to the sea level (1033 g/cm^2). This energy range encompasses the majority of SEPs, including the subclass of GLEs.

An example of ionization yields for several energies of the primary proton is given in Fig.1 (vertical incidence) and Fig.2 (isotropic incidence). The ionization yield function $Y(x,E)$ convoluted with a primary particle spectrum gives the ion production rate q(x) at a given depth x as
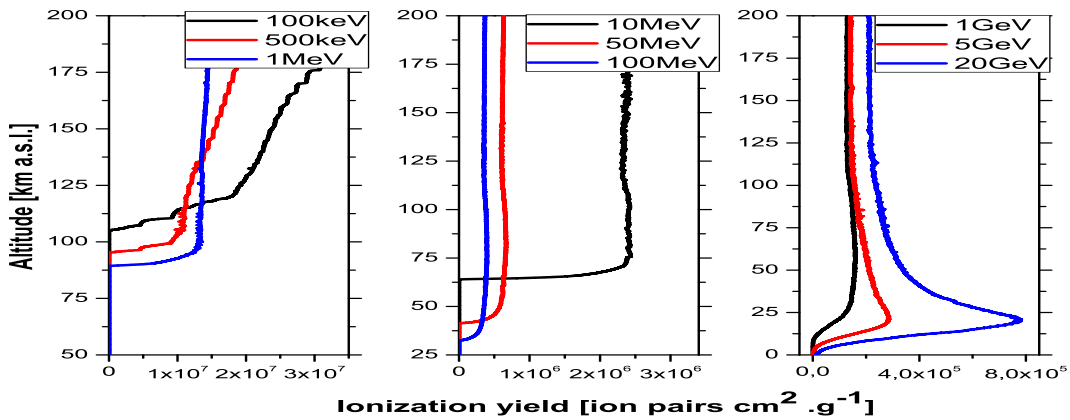

Figure 2: Ionization yields for primary protons with isotropic incidence and with different energies as a function of the altitude a.s.l. as denoted in the legend

$$q(x) = \int_{E_{cut}(R_c)}^{\infty} J(E)Y(x,E)dE \qquad (2.2)$$

where J(E) is the differential energy spectrum of the primary particles with energy E. The integration is over the kinetic energy above $E_{cut}(R_c)$, which is defined by the local rigidity cut-off R_c for

a nuclei of type i at a given geographic location by the expression $E_{cut,i} = \sqrt{\left(\frac{Z_i}{A_i}\right)^2 R_c^2 + E_0^2} - E_0$, where $E_0 = 0.938$ GeV is the proton's rest mass.

3. Ionization yield function and applications

The yield function $Y(x,E)$ is the response of the atmosphere, the ionization yields, to the mono-energetic unit flux of primary particles entering the Earth's atmosphere.
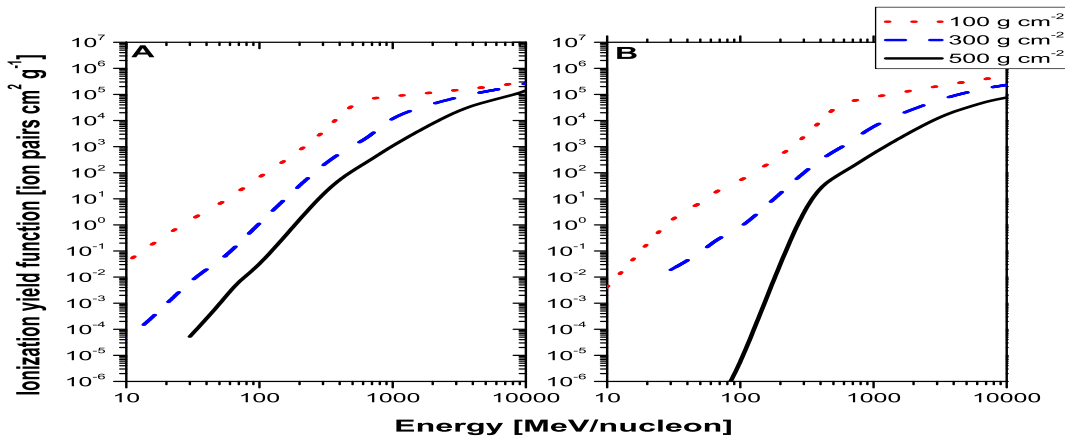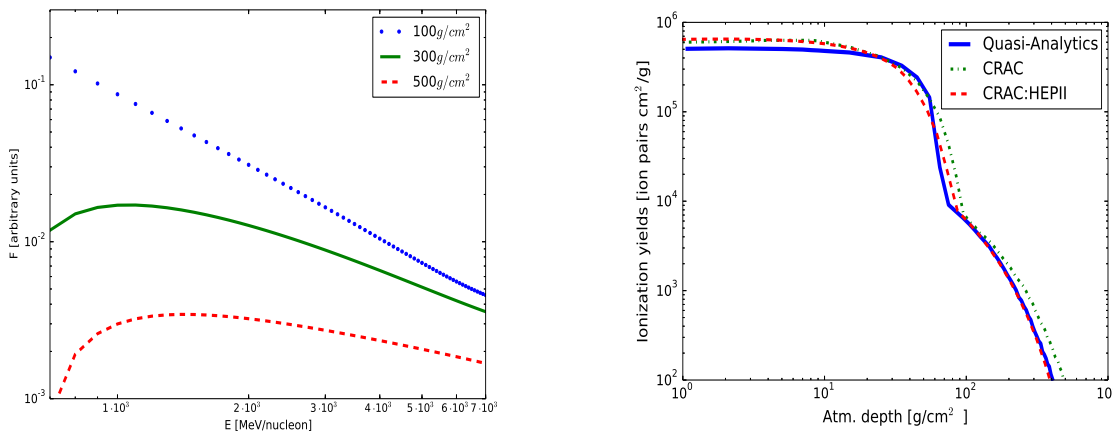

Figure 3: Ionization yield function for primary protons with various incidence at several depths as denoted in the legend. a) Particles with vertical incidence; b) Particles with isotropic incidence. The curves are smoothed over the computed data points.

(a) Differential ionization function F for primary protons with vertical incidence at several depths as denoted in the legend

(b) Comparison of ionization yields for primary protons with energy 1 GeV/n computed with the CRAC:HEPII, CRAC and analytical approach

Figure 4: Differential ionization function F and comparison of ionization yields between CRAC:HEPII, CRAC and quasi-analytical approach.

The shapes of the ionization yield functions as a function of the altitude are similar to each other at depths greater than 50 g/cm^2, but different at smaller depths, specifically at 1 g/cm^2 and less, where spikes and features are observed, most-likely due to large fluctuations of the computed energy deposit and the lack of secondary particles, because the cascade is not fully developed. The differential ionization function F (the integrand of Eq. 2), defined as a product of the ionization yield function (Fig. 3a,b) and a given spectrum of primary protons (hard primary proton spectrum during the GLE 70 event on December 13, 2006), is shown in Figure 4a for several atmospheric depths. Here we assumed a hard spectrum of SEPs (the spectrum at 03:00, December 13, 2006 from Table 2 in [23]), typical for the initial phase of GLEs [24]. The differential ionization function F allows one to estimate the most effective energy of primaries to induce ionization, which strongly depends on the atmospheric depth. The maximum of the differential ionization function shifts to higher energies with decreasing altitude (increasing the depth). At depths of about 500 g/cm^2 the differential ionization function F flattens, because of the diminishing number of high-energy primary EPs, which could produce an atmospheric cascade. The bulk of ion production in the upper atmosphere is due to primary particles of MeV energies, while at depth of about 300 g/cm^2 it is produced by primary particles with energy of about 1 GeV.

A quasi-analytical approach similar to [25], based on re-computation of vertically derived ionization yields allow on to compute the ionization yields for events with arbitrary incidence, the details are given in this volume. The ionization yields $Y_\alpha(x', E)$ for a monoenergetic protons with given kinetic energy E and with angle of incidence α is calculated:

$$Y_\alpha(x', E) = Y(x, E) / \cos \alpha, \tag{3.1}$$

where x' is the rescaled atmospheric depth, calculated as $x' = x / \cos \alpha$ and $Y(x, E)$ is the ionization yields for protons with vertical incidence computed with the CRAC:HEPII model at depth x.

Accordingly, the computation of ion production rate $I_f(x', E)$ as a function of angular distribution $f(\alpha)$ for monoenergetic precipitating particles is:

$$I_f(x', K) = \int_0^1 f(\alpha) I_\alpha(x', E) d\cos \alpha, \tag{3.2}$$

where α is the angle of particle incidence. The ionization $I_f(x', E)$ is given in units of ion pairs cm^{-3}s^{-1}, at the atmospheric depth x' per one simulated primary particle per second with given kinetic energy E. A very good agreement between CRAC:HEPII, CRAC and the quasi-analytic approach as achieved (Fig.4b).

The ion production in the atmosphere due to SEPs could be enhanced compared to the average due to GCRs. A specific interest represent GLE events, when a significant increase of ion production in the atmosphere can be observed [10]. During GLE events the ion production in the atmosphere is a superposition of contributions from particles of both galactic and solar origin. Here, we employ SEP spectra derived on the basis of neutron monitor data and convenient optimization procedure, details are given elsewhere [23]. With the derived SEP spectra we compute the ion production rate during the GLE 70 on 13 December 2006 similarly to [26]. For the GCR spectrum we assume the force field model [27, 28] with the corresponding parametrization of local interstellar spectrum [17] and modulation potential calculated according to [29]. For the ion production rate computations we consider explicitly the dynamical evolution of the SEPs spectral and angular
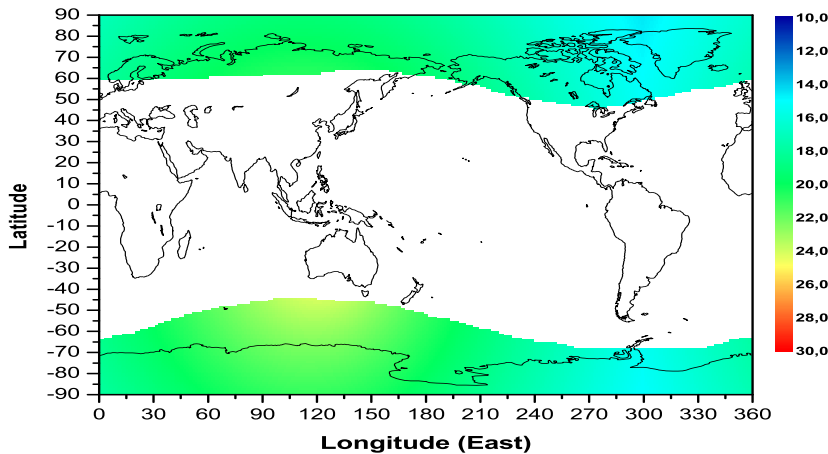
Figure 5: 24^h ionization effect in the region of the Pfotzer maximum of about 15 km a.s.l. in the region with $R_c \leq 1$ GV during the GLE 70 on 13 December 2006.

characteristics throughout the event. Subsequently, the 24^h ionization effect relative to the average due to GCR is computed at altitude of 15 km a.s.l. similarly to [30, 31]. The 24^h ionization effect is about 20 % in the region of the Pfotzer maximum (Fig.5). The ionization effect is maximal in the sub-polar and polar regions of Southern hemisphere, while it is minimal near to the anti-sunward direction of the incoming SEPs, since their anisotropy considerably reflects on the magnitude of ion production in a given geographic region.

4. Conclusion

Here, we have presented an upgraded full numerical model CRAC:HEPII, which allows one to compute the ion production in the Earth's atmosphere due to high energy protons, in particular during GLE events. The model is based on a full Monte Carlo simulations and is applicable in the whole atmosphere, with depth resolution better than 1 g/cm^2 and upgrades the CRAC:CRII. The applicability of a quasi-analytical approach for computation of the ionization yields for particles with arbitrary incidence, based on re-computation of vertically derived ionization yields is demonstrated. The CRAC:HEPII model allows one to compute the ion production rate and accordingly the ionization effect in the atmosphere for any desired location and conditions considering a given primary particle spectrum. An application of the model for ion production and the corresponding ionization effect during GLE 70 on 13 December 2006 is shown. Thus, we demonstrated that the upgraded CRAC:HEPII is a useful tool to address important problems related to the influence of EPs on atmospheric chemistry and physics.

Acknowledgements

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