NUMERICAL MODELLING OF COSMIC RAY INDUCED IONIZATION IN THE EARTH’S ATMOSPHERE

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Abstract. Cosmic rays form the main source of the atmospheric ionization in low and middle atmosphere. A major progress has been recently achieved in numerical modelling of this process, basing on a full Monte-Carlo simulation of the complicated cascade initiated by cosmic rays in the atmosphere. Here we present a brief review of the modern state of the art numerical models, based on Monte-Carlo simulation of particles’ transport in the atmosphere, that are capable of computing the cosmic ray induced ionization in the entire atmosphere, from ground up to the mesosphere. We discuss also other existing models and approaches, their inter-comparison, range of validity, advantages and missing points. We also perform a comparison between model simulations and direct measurements and provide practical recommendation for a correct choice of the model parameters.

Introduction

The Earth’s atmosphere has different properties at different altitudes and locations that play a key role in the atmospheric dynamics and climate. While the principal chemical composition of the low and middle atmosphere (homosphere from ground to about 90 km) is constant, physical conditions vary quite a lot: six orders of magnitude in density/pressure and more than a hundred degrees K in temperature. This part of the atmosphere is mostly neutral with some degree of ionization, which also varies in space and time. Ions, produced in the atmosphere by permanently or sporadically acting external factors, are involved in different physical-chemical processes, ranging from micro-physics to the global scale dynamics, affecting in particular dynamical changes in climate (e.g., Gray et al., 2010). Influence of ionization on stratospheric processes is relatively well known (e.g., Jackman et al., 2008; Seppälä et al., 2008), as ionizing factors like solar energetic particles and solar radiation in the UV range can affect minor atmospheric components (e.g., HOx and NOy) and control catalytic cycles with ozone destruction (Hood 1997; Rozanov et al., 2005), which in turn may trigger dynamical vertical coupling (top-down) between stratosphere and troposphere and affecting climate dynamics (Haigh, 1994; Haigh et al., 2010; Kodera, 2006). Tropospheric effects of ionization are more obscure. Some studies suggest suppositional mechanisms relating atmospheric ionization to climate changes; a possible effect of the cosmic ray induced ionisation (CRII) on cloud formation via ion-induced nucleation (Marsh and Svensmark, 2000; Carslaw et al., 2002), on precipitation (Knivet et al., 2004), cyclogenesis in mid- to high-latitude regions (Tinsley et al. 1989; Veretenenko & Thejll 2004), atmospheric transparency (Roldugin & Tinsley 2004), aerosol formation (Kazil et al. 2006; Mironova et al., 2008). However, other rigorous studies did not find any significant effect (Pierce & Adams, 2009; Calagovic et al., 2010; Kulmala et al., 2010). In addition, atmospheric ionization directly controls the global electric circuit (Rycroft et al., 2008) which in turn may further affect the cloud properties (Tinsley, 2008; Harrison, 2004). However since theoretical models remain qualitative and unable to give even a rough estimate of the effect and numerous phenomenological studies are controversial, detailed physical mechanisms connecting ionization in the troposphere with the climate parameters are still far from being understood. Therefore it is important to know the primary atmospheric changes, viz. ionization rate caused by outer space factors on different spatial and temporal scales. Direct in situ measurements of the atmospheric ionization are quite fragmentary spatially and temporally and can hardly provide a consistent picture (e.g., Bazilevskaya et al., 2008). Indirect methods of remote sensing are mostly related to the upper part of the atmosphere and may contain systematic uncertainties. Thus, experimental data on the atmospheric ionization can be used to test and calibrate a model but do not pretend to provide a full picture due to their patchy pattern.

Here we briefly review the modern state of the art in CRII modeling emphasizing uncertainties and validities of the models.
Sources of ionization

Principal sources of the atmospheric ionization in the polar region are shown in Fig. 1. All sources are important but in different altitudinal ranges.

Galactic cosmic rays (GCR) are very energetic charged particles with energies from $10^7$ up to $10^{20}$ eV (Dorman 2004) that generate secondary particles through collisions with atomic nuclei in air, leading to a nuclear-electromagnetic cascade in the atmosphere with the maximum of ionization at the altitude of 12–15 km (Bazilevskaya et al., 2008). GCRs form the main source of ionization in the troposphere and stratosphere. GCRs arrive at Earth constantly but their intensity is modulated by the (inversed) 11-year solar cycle, leading to the ensuing cyclic variations of the atmospheric ionization. In addition to that, substantial suppressions, called Forbush decreases, of GCR intensity may sporadically occur for several days in association with transient interplanetary disturbances, leading to reduced CRII.

Solar energetic particles (SEP) are produced in explosive energy releases at the Sun or in the interplanetary space (Lario and Simnett 2004). They impinge onto the atmosphere as sporadic events with duration of hours-days, more frequently during periods of high solar activity. SEP are less energetic than GCR particles and their influence is typically limited to the upper polar stratosphere. However, sometimes they are energetic enough to initiate an atmospheric cascade reaching troposphere at high latitudes (see Fig.1). Such strong events occur several times per solar cycle.

Magnetospheric particles (MP) are energetic electrons and protons of magnetospheric origin that can also precipitate into the atmosphere in (sub)polar regions. They are absorbed in the upper atmosphere (mesosphere and above) but X-rays produced as bremsstrahlung radiation by these electrons can penetrate down to the altitude of about 20 km. Energetic particle precipitation (EPP) occurs in association with geomagnetic activity caused by solar wind and interplanetary magnetic field disturbances and is more intensive during the declining phase of the 11-year solar cycle.

In addition to the particles, solar electromagnetic radiation in the UVI and soft X-ray range can affect the upper part of the atmosphere. The effect varies geographically following the insolation pattern, and temporarily as defined by the solar activity (Hargreaves, 1992). Near ground, there is an additional ionization source via natural radioactivity of the soil that may be important in some regions related to radon gas emission.

Modelling of cosmic ray induced ionization in the atmosphere

Since Victor Hess’ discovery of cosmic rays by measuring the level of ionization in the atmosphere, the scientific community is interested in the outer space ionizing radiation and its atmospheric effects. Systematic measurements in the middle of 20-th century (Fobrush, 1954; Neher, 1971) led to first empirical estimates of the effect. The interest grew up during 1960s with atmospheric nuclear tests and measurements.
of their immediate impacts on the atmosphere. Soon after that, first quantitative models aiming to evaluate the atmospheric ionization were developed (e.g., O’Brien, 1970). These models used a simplified approach based on an analytical approximation of the cosmic-ray induced atmospheric cascade empirically normalized to fragmentary experimental data. Although still being used in practical commercial applications (e.g., in evaluating the radiation dose in aviation), this approach is not suited for fine scientific research because of large uncertainties and unclear range of validity.

A breakthrough in the field of modelling CRII in the troposphere was made in 2004 when the full Monte-Carlo approach (CORSIKA+FLUKA simulation tool) was used to model the atmospheric nucleonic-electromagnetic cascade (Usoskin et al., 2004a). This model, called CRAC:CRII (Cosmic Ray Atmospheric Cascade: application for Cosmic Ray Induced Ionization), has been greatly updated (Usoskin & Kovaltsov, 2006; Usoskin et al., 2010) and is presently an international standard to compute CRII caused by GCR in the troposphere and stratosphere. The model is recommended by International programs COST and CAWSES. Several similar models have been developed by other groups during the past few years (Desorgher et al, 2005; Vasiliev et al., 2008; Velinov et al., 2009) based on the same Monte-Carlo approach. The most developed among them is the ATMOCOSMIC model (Desorgher et al., 2005) based on GEANT-4 simulation tool. A detailed comparison of the two independently developed models, CRAC:CRII and ATMOCOSMIC, with each other and with fragmentary experimental data of atmospheric ionization confirmed the validity of the approach and made it possible to evaluate the uncertainty of the model (Usoskin et al., 2009a). The uncertainty appears 10% in the troposphere and up to a factor of 2 in the upper stratosphere (see Fig. 2). The 10% uncertainty in the lower atmosphere is related to nuclear cross-sections used in the nuclear cascade model and is unavoidable. Uncertainties in the mesosphere are difficult to evaluate because of the lack of direct measurements. Larger uncertainties in the stratosphere and above are related to two main factors. One is imperfectness of the model which considers the mean particle’s incident angle on the atmosphere rather than its realistic trajectory. This assumption simplifies computations by reducing 3D (geographical) to a 2D (geomagnetic) pattern of CRII using the concept of the vertical geomagnetic cutoff (Cooke et al., 1991). This is well validated for the troposphere but may lead to large uncertainties in the middle and upper atmosphere. The simplification is particularly crucial for SEP events with highly anisotropic angular distribution of particles (Mewaldt, 2006). Second factor is related to other sources of ionizations compared to cosmic rays - EPP and solar hard electromagnetic radiation. The models are being improved to resolve these problems and decrease the uncertainties in the upper part.

Specific task of ionization by EPP and SEP was successfully addressed in the 1980-1990s by developing 2D and 3D analytical model able to compute ionization of soft (energy < 100 MeV) particles in strato- and mesosphere (e.g., Jackman & McPeters, 1985). Because of the lower energy such particles cannot initiate complicated cascade in the atmosphere and can be adequately treated using an analytical model of direct ionization. There are two approximations – thin target model, where particle’s energy losses are neglected; and thick model, where ionization losses of the particle are explicitly considered. This model was further developed in details (Vitt & Jackman, 1996; Jackman et al., 2008) is still widely used. This (and similar models) is presently a standard tool to model EPP/SEP effect on the middle atmosphere (e.g., Jackman et al.,
but it has several important limitations. First, such models ignore losses of particles due to inelastic 
interactions (nuclear collisions). While reasonable for the first few g/cm$^2$ of the atmospheric depth (about 40 
km altitude) this simplification leads to progressively increasing errors in the lower layers. Another 
limitation is that such models do not consider particles with energy above a few hundred MeV. This is well 
validated for MPs but leads to significant underestimate of the ionization effect for events with hard SEP 
spectrum and for the background ionization due to GCR (Usoskin et al., 2010). The former limitation has 
been recently resolved by the AINOS model (Wissing & Kallenrode, 2010) based on a Monte-Carlo 
approach, but even that model is still limited in the energy range and tends to underestimate the effect, 
especially in the middle atmosphere (see Fig. 3). Moreover, such models are inapplicable outside the polar 
cap region. Input data for EPP ionization models are usually measurements of particle fluxes performed on 
satellites (Fomichev et al. 2002; Wissing & Kallenrode, 2009) or rely upon parameterization based on 
geomagnetic indices (Fang et al., 2008).

CRII models use, as an input parameter, energy spectrum and spatial pattern (usually isotropic) of GCR and 
SEP components, obtained independently. The GCR spectrum is ideally measured in space or reconstructed 
using data from the world-wide neutron monitor network (Usoskin et al., 2005). Spectrum of SEP needs to 
be reconstructed individually for each event by fitting space-borne and ground-based data (e.g., Tylka & Lee, 
2006). As an output, CRII models compute the ionization rate at a given location (geographical and altitude) 
and time. A step from ionization rate to the ion concentration is not straightforward as it includes 
recombination processes, which vary essentially depending on the ambient conditions. This is typically 
considered as a stand-alone problem.

Concluding remarks

Numerical models able to compute realistic cosmic ray induced ionization in the low- and middle 
atmosphere are available, based on the full Monte-Carlo of the cascade induced in the atmosphere by cosmic 
rays. Two independent models, fully developed and thoroughly inter-calibrated, are recommended for 
practical use: CRAC:CRII model (Usoskin and Kovaltsov, 2006; Usoskin et al., 2010) and ATMOCOSMIC 
model (Desorgher et al., 2005). These models provide full consideration of the ionization effects caused by 
energetic particles, viz. galactic cosmic rays and solar energetic particles, in the Earth’s atmosphere. Note 
that the ATMOCOSMIC model, in combination with MAGNETOCOSMIC one, is able to consider 
anisotropic spatial distribution of incoming particles.

Average ionization rate by cosmic rays is modelled with high accuracy in the lower atmosphere (troposphere 
and stratosphere). In higher atmospheric layers, other ionizing factors contribute significantly and need to be 
considered separately.
Truncated models (analytical or with limited energy range) traditionally used to compute the effect of precipitating particles in the middle and upper atmosphere can be used only for the upper polar atmosphere and lower energy particles (soft solar and/or magnetospheric particles). On the other hand, they may underestimate the ionization effect of energetic solar particles and, specifically, the background due to galactic cosmic rays. Thus, a full model is recommended even for stratospheric and mesospheric studies.

Further work on improvements of the existing model approach is in progress and includes considering detailed computations of charged particles’ trajectories in the geomagnetic field rather than an average isotropic or vertical angular distribution of impinging particles, more realistic consideration of precipitating particles, improved modeling of the ion recombination processes.

References

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