Improved COsmic Ray Ionization Model for Atmosphere and Ionosphere (CORIMIA) with account of Monte Carlo Simulations

P Y I Velinov, S Asenovski, L Mateev and A Mishev
1Space Research and Technology Institute, Bulgarian Academy of Sciences, Acad. G. Bonchev str. Bl.1, 1113 Sofia, Bulgaria
2Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, 72 Tsarigradsko chaussee, 1784 Sofia, Bulgaria
3Sodankyla Geophysical Observatory (Oulu unit), University of Oulu, P.O.Box 3000, FIN-90014, Finland

E-mail: pvelinov@bas.bg

Abstract. The COsmic Ray Ionization Model for Ionosphere and Atmosphere (CORIMIA) is a physical space weather model with fully operational implementations. CORIMIA produces values of electron production for different altitudes (30 - 120 km), solar activities (low, moderate and high), geomagnetic and atmospheric cut-offs. CORIMIA can determine the energy intervals contributions for all groups of CR nuclei. The effects of galactic cosmic rays (GCR), solar cosmic rays (SCR) and anomalous cosmic rays (ACR) in the middle atmosphere are computed. The structure of the proposed model allows its decomposition in several submodels. Each submodel is further decomposed in submodels with account to the different characteristic ionization losses energy intervals. The ionization losses function is calculated taking into account the energetic particles charge decrease interval. The energy intervals investigation takes place according to the goal of the user of the model with respect to accuracy and interval types. CORIMIA program is applicable for the ionosphere and atmosphere above 30 km. Below this altitude numerical model such as CORSIKA are applied. At present the composite CORIMIA - CORSIKA programs are used.

1. Introduction
The investigation of ionization processes in atmosphere is important for better understanding of space weather mechanisms. The galactic cosmic rays (CR) influence on the ionization and therefore into the electrical parameters in the planetary atmospheres. They change also the chemical processes - for example ozone creation and depletion in the Earth’s stratosphere. On this way they transfer the impact of solar activity into the atmosphere.

The lower part (50-80 km) of the ionosphere D-region is formed by the galactic CR, which create there an independent CR layer [1]. However, the cosmic rays ionize the whole atmosphere up to 100 km. Above this altitude the contribution of the electromagnetic X and UV radiations dominate. In such a way cosmic rays influence on the ionization, chemical and electrical state in the region 5-100 km. Three main components are important for CR ionization: (1) high energy galactic CR (GCR) that are always present in the Earth environment and are subject to 11-year solar modulation, (2) anomalous CR (ACR) at high geomagnetic latitudes above 65°-70° and (3) sporadic solar CR (SCR) of lower energy (in comparison with GCR) but high peak flux.

1 Corresponding author Peter Velinov.
2. Cosmic Ray Ionization Model for Ionosphere and Atmosphere (CORIMIA)
The mathematical expression of the fully operational program CORIMIA is the following:

\[ q(h) = \sum_i q_i(h) = \frac{1}{Q} \sum_i \int_{E_i}^{\infty} \int_{\theta=0}^{\pi/2} \int_{\Delta\theta}^{2\pi} D_i(E) \left( \frac{dE}{dh} \right) \sin \theta \, d\theta \, dA \, dE, \]

(1)

where \( \Delta \) is the azimuth angle, \( \theta \) is the angle towards the vertical, \( \Delta\theta \) takes into account that at a given height the particles can penetrate from the space angle (0°, \( \theta_{\text{max}} = 90° + \Delta\theta \)), which is greater than the upper hemisphere angle (0°, 90°) for flat model. \( E_i \) are the energy cut-offs. The summation in the ionization integral (1) is made on the groups of nuclei: protons \( p \), Helium (alpha particles), Light L (3 \( \leq Z \leq 5 \)), Medium M (6 \( \leq Z \leq 9 \)), Heavy H (\( Z \geq 10 \)) and Very Heavy VH (\( Z \geq 20 \)) nuclei in the composition of cosmic rays. \( Z \) is the charge of the nuclei, \( Q = 35 \text{eV} \) is the energy which is necessary for formation of one electron-ion pair. \( D_i(E) \) is corresponding differential spectrum (cm\(^{-2}\).s\(^{-1}\).st\(^{-1}\).MeV\(^{-1}\)) which in the case of GCR is calculated as follows:

\[ D(E) = K(0.939 + E)^{-\gamma} \left( 1 + \frac{\alpha}{E} \right)^{-\beta} \]

(2)

Here the first multiplier \( K(0.939+E)^{\gamma} \) presents the galactic CR spectrum with kinetic energy \( E \) (GeV/nuclei). The last multiplier describes the CR modulation by the solar wind. The constant 0.939 is the energy of rest of proton. \( K, \gamma, \alpha \) and \( \beta \) are parameters of the spectrum which must be determined.

Five main characteristic energy intervals and one charge decrease interval for electron capturing in the approximation of ionization losses (MeV.g\(^{-1}\).cm\(^{-2}\)) according the Bohr-Bethe-Bloch formula using experimental data are introduced. The approximation for CR nuclei (\( Z > 1 \)) is the following:

\[
\begin{align*}
- \frac{1}{\rho} \frac{dE}{dh} = \begin{cases} 
2.57 \times 10^3 E^{0.5} & \text{if } kT \leq E \leq 0.15 \text{ MeV/n}, \text{ interval 1} \\
1540E^{0.23} & \text{if } 0.15 \leq E \leq E_a = 0.15Z^2 \text{ MeV/n}, \text{ interval 2} \\
231 \times Z^2E^{-0.77} & \text{if } E_a \leq E \leq 200 \text{ MeV/n}, \text{ interval 3} \\
68 \times Z^2E^{-0.53} & \text{if } 200 \leq E \leq 850 \text{ MeV/n}, \text{ interval 4} \\
1.91 \times Z^2 & \text{if } 850 \leq E \leq 5 \times 10^3 \text{ MeV/n}, \text{ interval 5} \\
0.66 \times Z^2E^{0.123} & \text{if } 5 \times 10^3 \leq E \leq 5 \times 10^6 \text{ MeV/n}, \text{ interval 6}
\end{cases}
\]

(3)

Here interval 2 of the expression (3) is the charge decrease interval for CR nuclei (\( Z > 1 \)). For protons (\( Z=1 \)) this interval is not necessary and it falls off.

In this way the accuracy of the obtained results is improved in comparison with fewer characteristic energy intervals approximations. The model can be realized in sub models which evaluate the GCR, SCR and ACR contributions with account to the ionization in the middle atmosphere and lower ionosphere. Other structures in these sub models are the different characteristic energy intervals contributions in the total ionization. This model can investigate the impact of random differential spectrum energy intervals on the ionization in the ionosphere and middle atmosphere. For this purpose satellite measurements of differential spectra are used.

3. Results
The calculations with operational program CORIMIA in this paper concern the cusp region (\( R_c = 0 \) GV) at different altitudes \( h \) (30 – 120 km). The results are presented in Figure 1 (subsection 1&2). The total GCR ionization rate is composed by the ionization rates from main groups of the GCR nuclei. Figures 1A and 1B present the ionization rate for the different groups of GCR. Figure 1C (subsection 3) presents the ionization rate from the ACR main constituents. They are oxygen (O), Helium (He) and protons (p). We take experimental data for the ACR differential spectra [2, 3]. Figure 1D presents the total ionization rate in the cusp region which is composed by GCR and ACR contributions.
The ionization rate by the different constituents is proportional to the magnitude of the corresponding differential spectrum, neutral density and the ionization rate energy interval values. It depends in nonlinear way on the charge $Z$ and the traveling substance path value.

Another application is related to the modelling of ground level enhancement 69 on 20.01.2005. The corresponding differential spectra (GLE 69) are taken from the available GOES satellite data. We investigate the SCR effects in the polar cap region at geomagnetic latitudes 65° - 80°. For the case of GLE 69 we include two characteristic time points - at 8:00UT and 23:00UT during SCR penetration as was considered in [4]. The results are presented in figure 2 and figure 3. In addition full Monte Carlo simulation of CR induced cascade with CORSIKA [5] is carried out. The ion production rate in the upper atmosphere is obtained on the basis of Oulu model [6] and procedure [7, 8]. A good agreement is observed (Figure 3 and Figure 4 in [4, 9]). However an additional study of both models is necessary.

**Figure 1.** Electron production rate calculated with CORIMIA for GCR and ACR. Figures 1A and 1B present the ionization rate for the different groups of GCR nuclei. Figure 1C presents the ionization rate from the ACR main constituents: oxygen (O), Helium (He) and protons (p). Figure 1D presents the total ionization rate in the cusp region which is composed by GCR and ACR contributions.
4. Summary
The capability of a new analytical model CORIMIA [11, 12] for computation of cosmic ray induced ionization in the atmosphere of the earth is demonstrated. The model is applicable in the upper atmosphere at various latitudes. A comparison with numerical model is carried out. The preliminary results demonstrate a good agreement [1, 11].

CORIMIA program [13-15] is applicable for the ionosphere and atmosphere above 30 km. Below this altitude numerical model such as CORSIKA are applied. At present the composite (combined) CORIMIA - CORSIKA programs are used.

References
[1] Velinov P I Y, Nestorov G and Dorman L 1974 Cosmic Ray Influence on the Ionosphere and on the Radio-Wave Propagation (Bulgarian Academy of Sciences Publ. House, Sofia)
[2] Cummings A C , Stone E C, Webber W R 1984 Astrophysical Journal 287 99
[3] Goddard Space Flight Center, NASA, Anomalous cosmic ray hydrogen, http://imagine.gsfc.nasa.gov/docs/features/bios/christian/anomalous.html
[4] Mishev A, Velinov P I Y and Mateev L. 2010 C. R. Acad. Bulg. Sci. 63 1635
[5] Heck D. Knapp J, Capdevielle J N, Schatz G and Thouw T. 1998 CORSIKA: A Monte Carlo code to simulate extensive air showers Report FZKA 6019, Institut fur Kernphysik Forschungszentrum und Universitat Karlsruhe
[6] Usoskin I and Kovaltsov G 2006 J. Geophys. Res. 111 D21206
[7] Mishev A and Velinov P I Y 2007 C. R. Acad. Bulg. Sci. 60 225
[8] Velinov P I Y, Mishev A and Mateev L 2009 Adv. Space Res. 44 1002
[9] Mishev A, Velinov P I Y, Mateev L and Tassev Y 2011 Adv. Space Res. 48 1232
[10] NOAA/Space Weather Prediction Center, http://www.swpc.noaa.gov/today.html#sateny
[11] Velinov P I Y , Asenovski S, Mateev L 2012 C. R. Acad. Bulg. Sci, 65 in press.
[12] Dorman L 2004 Cosmic rays in the Earth’s atmosphere and underground (Dordrecht, Kluwer Academic Publishers)
[13] Velinov P I Y , Mateev L. 2008 Adv. Space Res. 42 1586.
[14] Velinov P I Y , Mateev L, Ruder H. 2008 C. R. Acad. bulg. Sci. 61 133
[15] Wolfram Research Inc., Mathematica, Version 7.0, Champaign, IL, 2008.

Figure 2. Electron production rate \( q(h) \) (cm\(^{-3}\)s\(^{-1}\)) by solar cosmic ray during GLE 69 [10] with spectrum measured on 20.01.2005 at 08:00UT.

Figure 3. Electron production rate \( q(h) \) (cm\(^{-3}\)s\(^{-1}\)) by solar cosmic ray during GLE 69 [10] with spectrum measured on 20.01.2005 at 23:00UT.