A new model CRAC:EPII (Cosmic Ray Atmospheric Cascade: Electron Precipitation Induced Ionization) is presented. The CRAC:EPII is based on Monte Carlo simulation of precipitating electrons propagation and interaction with matter in the Earth atmosphere. It explicitly considers energy deposit: ionization, pair production, Compton scattering, generation of Bremsstrahlung high energy photons, photo-ionization and annihilation of positrons, multiple scattering as physical processes accordingly. The propagation of precipitating electrons and their interactions with atmospheric molecules is carried out with the GEANT4 simulation tool PLANETOCOSMICS code using NRLMSISE 00 atmospheric model. The ionization yields is compared with an analytical parametrization for various energies of incident precipitating electron, using a flux of mono-energetic particles. A good agreement between the two models is achieved. Subsequently, on the basis of balloon-born measured spectra of precipitating electrons at 30.10.2002 and 07.01.2004, the ion production rate in the middle and upper atmosphere is estimated using the CRAC:EPII model.

Keywords: Atmospheric ionization, Stratosphere and Troposphere, Precipitation Electrons, Monte Carlo solution

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1 Introduction

The main source of ionization in the troposphere and stratosphere is due to cosmic rays (CRs), which induce a complicated nuclear-electromagnetic-muon cascade resulting in an ionization of the ambient air (O’Brien, 1970; Usoskin and Kovaltsov, 2006; Bazilevskaya et al., 2008; Stozhkov et al., 2009; Velinov et al., 2013; Mironova et al., 2015). Most of CR are protons and α – particles originating from outer space (Gaisser and Stanev, 2010). Small amounts of heavier nuclei are also
present. Their intensity is modulated by the solar wind and heliomagnetic field, and follows the
11-year solar cycle. In addition, their flux responds to transient phenomena such as Forbush
decreases (Forbush, 1937, 1958).

In addition to energetic CR particles, a softer electron component of corpuscular radiation
is present in the near-Earth space, which also ionizes the atmosphere, and specifically its upper
part (see Li and Temerin (2001); Millan and Thorne (2007); Mironova et al. (2015) and refer-
ces therein). Precipitation of electrons into the atmosphere occurs from various regions of the
magnetosphere resulting from different mechanisms, some of them still poorly understood (e.g.
Dorman, 2004; Mironova et al., 2015, and references therein). Precipitating electrons play an
important role in ion production in the Earth’s atmosphere, specifically in the upper atmosphere
over polar regions (Makhmutov et al., 2003a; Daae et al., 2012; Clilverd et al., 2013). The pre-
cipitating electrons affect the atmospheric chemistry (e.g. Rozanov et al., 2005; Verronen et al.,
2011; Daae et al., 2012; Mironova et al., 2015) as well as several physical properties of the atmo-
sphere and magnetosphere (e.g. Makhmutov et al., 2003a; Clilverd et al., 2008; Malinie.mi et al.
2013). The intensity of the electron precipitation depends on solar activity (Neal et al., 2015;
Makhmutov et al., 2001), season (Makhmutov et al., 2003b), geomagnetic activity (Park et al.,
2013; Rodger et al., 2007; Horne et al., 2009) and other factors (Makhmutov et al., 2006). There-
fore, convenient model for assessment of atmospheric ionization due to precipitating electrons
as well as observations of energetic particles will stimulate better understanding of the impact of
energetic particle to atmospheric processes (e.g. Mironova et al., 2015, and references therein).

Interactions between precipitating electrons and the atmosphere can be either parametrized
using an analytical solution (e.g. Fang et al., 2008, 2010; McGranaghan et al., 2015) or can be
modelled by a Monte Carlo method similarly to Solomon (1993); Wissing and Kallenrode (2009);
Wissing et al. (2011). The parametrization models do not consider Bremsstrahlung, which con-
tribute to ionization of air specifically at lower and middle altitudes, and consider direct ionization
neglecting secondary process (e.g. Fang et al., 2008). On the other hand, Monte Carlo transport
codes consider realistically all the physics processes involved. In addition, models based on
response (yield) function formalism, using precomputed ionization yields are more flexible com-
pared to direct simulation, since not weighting of high energy particles simulation is necessary
(e.g. Usoskin and Kovaltsov, 2006; Velinov et al., 2013; Mishev and Velinov, 2014).

In this work, we present a new model for assessment of atmospheric ionization due to precip-
itating electrons and compare it with a previously proposed parametrization model. The general
aim of this work is a quantitative comparison and demonstration of the ability of the new model to
estimate the electron impact ionization. The new model, whose detailed description is given el-
sewhere, is an extension of the CRAC model for CR induced ionization (Usoskin and Kovaltsov,
2006), based on the ionization yield function formalism. It is a full target model similar to
CRAC model for cosmic ray induced ionization and other similar models based on a Monte
Carlo simulation of the atmospheric cascade (Desorgher et al., 2005; Usoskin and Kovaltsov,
2006; Velinov et al., 2009, e.g.).

2 The model CRAC:EPII

As was stated above, Monte Carlo simulation possess an advantage compared to parametrization
by considering realistically all the physics processes involved. Here we apply Monte Carlo simi-
ulation of electron propagation and interaction with matter in the Earth atmosphere. The main advantage of Monte Carlo transport codes is that they consider, in a realistic manner, the physics processes, namely energy deposit, ionization, pair production, Compton scattering, generation of Bremsstrahlung high energy photons, photo-ionization and annihilation of positrons. Moreover the multiple scattering of electrons is realistically considered. In addition, since electrons produce Bremsstrahlung photons which penetrate deeper in the atmosphere, compared to primary particles (e.g. Schröter et al., 2006), and produce ionization there, it is important to use adequate modelling of their production and propagation.

In this work the propagation of precipitating electrons and their interactions with atmospheric molecules, leading to production of secondary particles, is modelled using the GEANT4 based (Agostinelli et al., 2003) simulation tool PLANETOCOSMICS (Desorgher et al., 2005). Here we use a realistic curved atmospheric model NRLMSISE 00 (Picone et al., 2002). The code represents a Monte Carlo simulation tool for detailed study of cascade evolution in the atmosphere initiated by various primary particles. The code simulates the interactions and, where appropriate, decays of nuclei, hadrons, muons, electrons and photons in the atmosphere up to high and very high energies. It gives detailed information about the secondary particle flux at a selected observation level and the energy deposit, explicitly considering particle attenuation. The PLANETOCOSMICS also allows simulation of a purely electromagnetic cascade in a realistic manner.

We have computed the ionization yields (response function) i.e. the number of ion pairs produced per gram of the ambient air at a given atmospheric depth by a single primary precipitating electron with a given energy. The computations were carried out in the energy range between 50 keV and 500 MeV. An example of ionization yields for several energies of primary electron is given in Fig.1.

The ionization yields $Y$ given as ion pairs $\cdot$ cm$^2$g$^{-1}$, which corresponds to the atmospheric depth $x$, is defined as:

$$Y(x, K) = \frac{\Delta E}{E_i \Delta x}$$

(1)

where $\Delta E$ is the mean energy loss in the atmospheric layer $\Delta x$ centred at the atmospheric depth $x$ per one simulated primary electron with the kinetic energy $K$, and $E_i$=35 eV is the average energy needed to produce one ion pair (Porter et al., 1976).

The ionization yields $Y(x, K)$ is related to the ion production rate $Q(x)$ at a given depth $x$ as:

$$Q(x) = \int_{E_i}^{\infty} \frac{dJ_e}{dK} Y(x, K) \rho(x) dK$$

(2)

where $\frac{dJ_e}{dK}$ is the differential energy spectrum of the primary precipitating electrons with energy $K$, $\rho(x)$ is the atmospheric density at given atmospheric depth $x$. As expected the maximum of ionization yields strongly depends on the energy of the precipitating electron. The maximum is lower for electrons with greater energy (Fig.1). In addition, significant fluctuations, specifically in a low energy range, of ionization yields are observed in the upper atmosphere at altitudes of about 90 km a.s.l. They are most-likely due to cascade to cascade development and/or attenuation fluctuations, rather than insufficient number of test particles in the model run.
3 Comparison with a parametrization model

There are several parametrization models for assessment of electron induced ion production in the atmosphere (e.g. Lazarev, 1967; Roble and Ridley, 1987; Frahm et al., 1997; Fang et al., 2010). Some of the models were focused on evaluation of auroral electron impact ionization (e.g. Roble and Ridley, 1987). In order to assess production of $NO_x$ in the middle and upper atmosphere, by high energy electron precipitation (e.g. Callis, 1991; Callis et al., 1996; Aikin and Smith, 1999; Turunen et al., 2009; Clilverd et al., 2010; Andersson et al., 2012; Krivolutsky and Repnev, 2012) an extension of parametrization models have been proposed (Millan and Thorne, 2007; Fang et al., 2010). Here we compare a mono-energetic ionization yields with a recent parametrization by (Fang et al., 2008, 2010), recently used for computation of ionization due to particle precipitation (Huang et al., 2014).

We compare the ionization yields due to high energy precipitating electrons (monoenergetic electron fluxes of 1 erg cm$^{-2}$ s$^{-1}$ propagating in the atmosphere according to Fang et al. (2010)), namely 100 keV and 1 MeV (Fig.2). The CRAC:EPII model predicts slightly more ions, specifically at the depth of maximum ion production. The observed difference in the maximum is of the order of 35-40%. The level of maximal ion production by CRAC:EPII is at slightly lower altitudes compared to parametrization model. In addition, the contribution of Bremsstrahlung photons to ionization is clearly seen at altitudes of about 30 km above the sea level. We achieve
a satisfactory agreement with parametrization in the integral energy deposit.

![Comparison of ionization yields for primary electron with various energies as a function of the altitude above the sea level computed with CRAC:EPII model and parametrization model according to (Fang et al., 2010). Blue solid circles denote computations with CRAC:EPII, while red solid triangles the parametrization. a) electron flux of 1 erg cm$^{-2}$ s$^{-1}$ with energy of 100 keV; b) electron flux of 1 erg cm$^{-2}$ s$^{-1}$ with energy of 1 MeV.](image)

The observed difference in the region of maximum ion production is due to a combination of various processes related to the complex high-energy electron propagation confined by the Monte Carlo model as well as the different atmospheric model assumptions. In general a good agreement between the two models is achieved, specifically in the upper atmosphere. Therefore, the CRAC:EPII demonstrate very good ability to assess ion production by high energy electron precipitation. The CRAC:EPII accounts, in contrast to parametrization models, the contribution of Bremsstrahlung in the lower atmosphere, which is a important improvement.

### 4 Spectrum of precipitating electrons and derived ion production rate

At present various methods are proposed to estimate the spectrum of precipitating electrons (e.g. Clilverd et al., 2010; Neal et al., 2015; Whittaker et al., 2013; Wild et al., 2010). In general, it is possible to reconstruct the spectra from satellite-born measurements (e.g. Rodger et al., 2010, 2007; Peck et al., 2015). However, this method requires a correction as was recently shown by
Another possibility is proposed by Wild et al. (2010). The detailed description of the precipitating electron spectra is beyond the topic of this work. Here we use the electron spectra obtained from balloon-born measurements (Bazilevskaya and Makhmutov, 1999), whose details are given in this volume (Makhmutov et al., 2015). In general it is assumed that the flux of precipitating electrons at the top of the atmosphere is exponential:

\[ J_e(K) = A_e \cdot \exp(-K/E_0) \]  

(e.g. Millan et al., 2007; Comess et al., 2013). The characteristic energy \( E_0 \) is in the range 10 keV - 1 MeV. The spectrum is reconstructed considering the characteristics of energetic electron precipitation in the polar atmosphere according to (Makhmutov et al., 2003a). Here we give an example of the event spectrum derived on the basis of balloon measurement in Murmansk region \( (67^\circ 33' N, 33^\circ 20' E) \) at 30.10.2002 and 07.01.2004. The characteristics of the spectra in Eq. 3 are \( A_e = 9.37 \cdot 10^1 \text{ cm}^{-2} \text{s}^{-2} \text{keV}^{-1} \), \( E_0 = 3.09 \cdot 10^2 \text{ keV} \) and \( A_e = 4.96 \cdot 10^{-1} \text{ cm}^{-2} \text{s}^{-2} \text{keV}^{-1} \), \( E_0 = 5.45 \cdot 10^3 \text{ keV} \), respectively, as shown in Fig.3. This spectra were used as input in the CRAC:EPII model in order to estimate the ion production rate (Fig.4). The derived ion production rate is in a good agreement with previous studies (Makhmutov et al., 2003a; Sloan et al., 2011, e.g.). It is clearly seen the contribution of Bremsstrahlung at altitudes below about 25 km a.s.l. for spectrum 1 and below 40 km a.s.l. for spectrum 2.

![Figure 3: Example of the differential spectra of precipitating electrons. The spectra are derived on the basis of balloon measurement in Murmansk region \( (67^\circ 33' N, 33^\circ 20' E) \). The spectra characteristics are: \( A_e = 9.37 \cdot 10^1 \text{ cm}^{-2} \text{s}^{-2} \text{keV}^{-1} \), \( E_0 = 3.09 \cdot 10^2 \text{ keV} \) (at 30.10.2002, blue curve) and \( A_e = 4.96 \cdot 10^{-1} \text{ cm}^{-2} \text{s}^{-2} \text{keV}^{-1} \), \( E_0 = 5.45 \cdot 10^3 \text{ keV} \) (07.01.2004, red curve).](image-url)
Figure 4: Ion production rate assuming the example spectra (Fig.3) of precipitating electrons (07.01.2004, red triangles) and (30.10.2002, blue dots) computed with CRAC:EPII model.

5 Conclusion

In this work we present a new model for assessment of atmospheric ionization induced by precipitating electrons and demonstrate a quantitative comparison with a parametrization model. The model is based on response (ionization yield) functions, derived with extensive Monte Carlo simulations. In contrast to parametrization models it accounts explicitly the contribution of Bremsstrahlung, importent in the lower atmosphere. Moreover, it extend the energy range above 1 MeV (up to 500 MeV), which is the maximum energy in parametrization of (Fang et al., 2008, 2010). In addition, compared to direct simulation models, it is more flexible (specifically for operational purposes), because it is based on a widely used, simple for application formalism of precomputed ionization yields.

We note that the present results show good agreement with a Monte Carlo model based on satellite measurements, AIMOS (Wissing and Kallenrode, 2009; Wissing et al., 2011), which is based on GEANT4 (Agostinelli et al., 2003) (private communication with J. Wissing during the ISSI workshop on “Specification of ionization sources affecting atmospheric processes”). The direct comparison of these two models based on the same platform would be in practice a comparison of different atmospheric profiles resulting in particle transportation and/or different code versions, but not comparison of different models. A detailed study of various atmospheric profile parametrizations and/or hadron generators within a same platform (tool) is discussed elsewhere (Mishev and Velinov, 2014) and it is beyond the scope of this work.

The application of CRAC:EPII model for estimation of ionization yields demonstrates good
agreement with a recent analytical parametrization model. In addition, CRAC:EPII was applied
for ion rate production in the upper atmosphere using a balloon-born measured spectrum of pre-
cipitating electrons. A complete description of CRAC:EPII with the corresponding look-up tables
of ionization yields, accordingly ionization yield function at several altitudes is presented else-
where.

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References

Agostinelli, S., Allison, J., Amako, K., Apostolakis, J., Araujo, H., Arce, P., Asai, M., Axen, D.,
Banerjee, S., Barrand, G., Behner, F., Bellagamba, L., Boudreau, J., Broglia, L., Brunengo,
A., Burkhardt, H., Chauvie, S., Chuma, J., Chytracek, R., Cooperman, G., Cosmo, G., Degt-
yarenko, P., Dell’Acqua, A., Depaola, G., Dietrich, D., Enami, R., Feliciello, A., Ferguson,
C., Fesefeldt, H., Folger, G., Foppiano, F., Forti, A., Garelli, S., Gian, S., Giannitrapani, R.,
Gibin, D., Gomez Cadenas, J., Gonzalez, I., Gracia Abril, G., Greeniaus, G., Greiner, W., Gri-
chne, V., Grossheim, A., Guatelli, S., Gumplinger, P., Hamatsu, R., Hashimoto, K., Hasui, H.,
Heikinen, A., Howard, A., Ivanchenko, V., Johnson, A., Jones, F., Kallenbach, J., Kanaya,
N., Kawabata, M., Kawabata, Y., Kawaguti, M., Kelner, S., Kent, P., Kimura, A., Kodama, T.,
Kokoulin, R., Kossov, M., Kurashige, H., Lamanna, E., Lampen, T., Lara, V., Lefebure, V., Lei,
F., Liendl, M., Lockman, W., Longo, F., Magni, S., Maire, M., Medernach, E., Minamimoto,
K., Mora de Freitas, P., Morita, Y., Murakami, K., Nagamatu, M., Nartallo, R., Nieminen, P.,
Nishimura, T., Ohtsubo, K., Okamura, M., O’Neale, S., Oohata, Y., Paech, K., Perl, J., Pfeiffer,
A., Pia, M., Ranjard, F., Rybin, A., Sadilov, S., di Salvo, E., Santin, G., Sasaki, T., Savvas, N.,
Sawada, Y., Scherer, S., Sei, S., Sirotenko, V., Smith, D., Starkov, N., Stoecker, H., Sulikmo, J.,
Takahata, M., Tanaka, S., Tcherniaev, E., Safai Tehrani, E., Tropeano, M., Truscott, P., Uno, H.,
Urban, L., Urban, P., Verderi, M., Walkden, A., Wader, W., Weber, H., Wielisch, J., Wenaus,
T., Williams, D., Wright, D., Yamada, T., Yoshida, H., Zschiesche, D., 2003. Geant4 - a simu-
lation toolkit. Nuclear Instruments and Methods in Physics Research, Section A: Accelerators,
Spectrometers, Detectors and Associated Equipment 506, 250–303.

Aikin, A., Smith, H., 1999. Mesospheric constituent variations during electron precipitation
events. Journal of Geophysical Research Atmospheres 104, 26457–26471.

Andersson, M., Verronen, P., Wang, S., Rodger, C., Clilverd, M., Carson, B., 2012. Precipitating
radiation belt electrons and enhancements of mesospheric hydroxyl during 2004-2009. Journal
of Geophysical Research Atmospheres 117, D09304.
Asikainen, T., Mursula, K., 2013. Correcting the noaa/meped energetic electron fluxes for detector efficiency and proton contamination. Journal of Geophysical Research: Space Physics 118, 6500–6510.

Bazilevskaya, G., Makhmutov, V., 1999. Precipitations of energetic electrons into atmosphere according to the data using zond particle measurements. Izvestiya Akademii Nauk. Ser. Fizicheskaya 63, 1670–1674.

Bazilevskaya, G., Usoskin, I., Flückiger, E., Harrison, R., Desorgher, L., Bütikofer, R., Krainev, M., Makhmutov, V., Stozhkov, Y., Svirzhevskaya, A., Svirzhevsky, N., Kovaltsov, G., 2008. Cosmic ray induced ion production in the atmosphere. Space Science Reviews 137, 149–173.

Callis, L., 1991. Precipitating relativistic electrons: their long-term effect on stratospheric odd nitrogen levels. Journal of Geophysical Research 96, 2939–2976.

Callis, L., Boughner, R., Baker, D., Mewaldt, R., Bernard Blake, J., Selesnick, R., Cummings, J., Natarajan, M., Mason, G., Mazur, J., 1996. Precipitating electrons: Evidence for effects on mesospheric odd nitrogen. Geophysical Research Letters 23, 1901–1904.

Clilverd, M., Cobbett, N., Rodger, C., Brundell, J., Denton, M., Hartley, D., Rodriguez, J., Danskin, D., Raita, T., Spanswick, E., 2013. Energetic electron precipitation characteristics observed from antarctica during a flux dropout event. Journal of Geophysical Research: Space Physics 118, 6921–6935.

Clilverd, M., Rodger, C., Brundell, J., Bähr, J., Cobbett, N., Moffat-Griffin, T., Kavanagh, A., Sepplä, A., Thomson, N., Friedel, R., Menk, F., 2008. Energetic electron precipitation during substorm injection events: High-latitude fluxes and an unexpected midlatitude signature. Journal of Geophysical Research: Space Physics 113, A10311.

Clilverd, M., Rodger, C., Gamble, R., Ulich, T., Raita, T., Sepplä, A., Green, J., Thomson, N., Sauvaud, J.A., Parrot, M., 2010. Ground-based estimates of outer radiation belt energetic electron precipitation fluxes into the atmosphere. Journal of Geophysical Research: Space Physics 115, A12304.

Comess, M., Smith, D., Selesnick, R., Millan, R., Sample, J., 2013. Duskside relativistic electron precipitation as measured by sampex: A statistical survey. Journal of Geophysical Research: Space Physics 118, 5050–5058.

Daae, M., Espy, P., Nesse Tyssy, H., Newnham, D., Stadsnes, J., Sraas, F., 2012. The effect of energetic electron precipitation on middle mesospheric night-time ozone during and after a moderate geomagnetic storm. Geophysical Research Letters 39, L21811.

Desorgher, L., Flückiger, E., Gurtner, M., Moser, M., Büttikofer, R., 2005. Atmocosmics: A geant 4 code for computing the interaction of cosmic rays with the earth’s atmosphere. International Journal of Modern Physics A 20, 6802–6804.

Dorman, L., 2004. Cosmic Rays in the Earth’s Atmosphere and Underground. Kluwer Academic Publishers, Dordrecht.
Fang, X., Randall, C., Lummerzheim, D., Solomon, S., Mills, M., Marsh, D., Jackman, C., Wang, W., Lu, G., 2008. Electron impact ionization: A new parameterization for 100 ev to 1 mev electrons. Journal of Geophysical Research: Space Physics 113, A09311.

Fang, X., Randall, C., Lummerzheim, D., Wang, W., Lu, G., Solomon, S., Frahm, R., 2010. Parameterization of monoenergetic electron impact ionization. Geophysical Research Letters 37, L22106.

Forbush, S., 1937. On the effects in cosmic-ray intensity observed during the recent magnetic storm. Physical Review 51, 1108.

Forbush, S., 1958. Cosmic-ray intensity variations during two solar cycles. Journal of Geophysical Research 63, 651–669.

Frahm, R., Winningham, J., Sharber, J., Link, R., Crowley, G., Gaines, E., Chenette, D., Anderson, B., Potemra, T., 1997. The diffuse aurora: A significant source of ionization in the middle atmosphere. Journal of Geophysical Research Atmospheres 102, 28203–28214.

Gaisser, T.K., Stanev, T., 2010. Cosmic rays, in: et al., K.N. (Ed.), Review of Particle Physics. Journal of Physics G 37, pp. 269–275.

Horne, R., Lam, M., Green, J., 2009. Energetic electron precipitation from the outer radiation belt during geomagnetic storms. Geophysical Research Letters 36.

Huang, Y., Huang, C., Su, Y.J., Deng, Y., Fang, X., 2014. Ionization due to electron and proton precipitation during the august 2011 storm. Journal of Geophysical Research: Space Physics 119, 3106–3116.

Krivolutsky, A., Repnev, A., 2012. Impact of space energetic particles on the earth’s atmosphere (a review). Geomagnetism and Aeronomy 52, 685–716.

Lazarev, V., 1967. Absorption of the energy of an electron beam in the upper atmosphere. Geomagnetism and aeronomy 7, 219–4949.

Li, X., Temerin, M., 2001. The electron radiation belt. Space Science Reviews 95, 569–580.

Makhmutov, V., Bazilevskaya, G., Desorgher, L., Flückiger, E., 2006. Observation of energetic electron precipitation into atmosphere in october 2003. Bulletin of the Russian Academy of Sciences: Physics 69, 990–993.

Makhmutov, V., Bazilevskaya, G., Krainev, M., 2003a. Characteristics of energetic electron precipitation into the earth’s polar atmosphere and geomagnetic conditions. Advances in Space Research 31, 1087–1092.

Makhmutov, V., Bazilevskaya, G., Krainev, M., Svirzhevskaya, A., Svirzhevsky, N., 2001. Connection of frequency of precipitation of relativistic electrons to atmosphere with the solar activity cycle. Izvestiya Akademii Nauk. Ser. Fizicheskaya 65, 403–405.
Makhmutov, V., Bazilevskaya, G., Stozhkov, Y., 2003b. Seasonal effect in precipitation of energetic electrons into polar atmosphere. Izvestiya Akademii Nauk. Ser. Fizicheskaya 67, 1449–1452.

Makhmutov, V., Bazilevskaya, G., Stozhkov, Y., Svirzhevskaya, A., Svirzhevsky, N., 2015. Catalogue of electron precipitation events as observed in the long-duration cosmic ray balloon experiment. Journal of Atmospheric and Solar-Terrestrial Physics, in press, doi:10.1016/j.jastp.2015.12.006.

Maliniemi, V., Asikainen, T., Mursula, K., Seppälä, A., 2013. Qbo-dependent relation between electron precipitation and wintertime surface temperature. Journal of Geophysical Research: Atmospheres 118, 6302–6310.

McGranaghan, R., Knipp, D., Solomon, S., Fang, X., 2015. A fast, parameterized model of upper atmospheric ionization rates, chemistry, and conductivity. Journal of Geophysical Research A: Space Physics 120, 4936–4949.

Millan, R., Lin, R., Smith, D., McCarthy, M., 2007. Observation of relativistic electron precipitation during a rapid decrease of trapped relativistic electron flux. Geophysical Research Letters 34.

Millan, R., Thorne, R., 2007. Review of radiation belt relativistic electron losses. Journal of Atmospheric and Solar-Terrestrial Physics 69, 362–377.

Mironova, I., Aplin, K., Arnold, F., Bazilevskaya, G., Harrison, R., Krivolutsky, A., Nicoll, K., Rozanov, E., Turunen, E., Usoskin, I., 2015. Energetic particle influence on the earth's atmosphere. Space Science Reviews, 96. Type = Article

Mishev, A., Velinov, P., 2014. Influence of hadron and atmospheric models on computation of cosmic ray ionization in the atmosphere-extension to heavy nuclei. Journal of Atmospheric and Solar-Terrestrial Physics 120, 111–120.

Neal, J., Rodger, C., Clilverd, M., Thomson, N., Raita, T., Ulich, T., 2015. Long-term determination of energetic electron precipitation into the atmosphere from aardvark subionospheric vlf observations. Journal of Geophysical Research A: Space Physics 120, 2194–2211.

O'Brien, K., 1970. Calculated cosmic ray ionization in the lower atmosphere. Journal of Geophysical Research 75, 4357–4359.

Park, M.Y., Lee, D.Y., Shin, D.K., Cho, J.H., Lee, E.H., 2013. Dependence of energetic electron precipitation on the geomagnetic index kp and electron energy. Journal of Astronomy and Space Science 30, 247–253.

Peck, E., Randall, C., Green, J., Rodriguez, J., Rodger, C., 2015. Poes meped differential flux retrievals and electron channel contamination correction. Journal of Geophysical Research A: Space Physics 120, 4596–4612.
Picone, J., Hedin, A., Drob, D., Aikin, A., 2002. Nrlmsise-00 empirical model of the atmosphere: Statistical comparisons and scientific issues. Journal of Geophysical Research: Space Physics 107, 1468.

Porter, H., Jackman, C., Green, A., 1976. Efficiencies for production of atomic nitrogen and oxygen by relativistic proton impact in air. The Journal of Chemical Physics 65, 154–167.

Roble, R., Ridley, E., 1987. An auroral model for the near thermospheric general circulation model (tgcm). Annales Geophysicae Series A-upper Atmosphere and Space Sciences 5, 369–382.

Rodger, C., Clilverd, M., Green, J., Lam, M., 2010. Use of poes sem-2 observations to examine radiation belt dynamics and energetic electron precipitation into the atmosphere. Journal of Geophysical Research: Space Physics 115, A04202.

Rodger, C., Clilverd, M., Thomson, N., Gamble, R., Seppälä, A., Turunen, E., Meredith, N., Parrot, M., Sauvaud, J.A., Berthelier, J.J., 2007. Radiation belt electron precipitation into the atmosphere: Recovery from a geomagnetic storm. Journal of Geophysical Research: Space Physics 112, A11307.

Rozanov, E., Callis, L., Schlesinger, M., Yang, F., Andronova, N., Zubov, V., 2005. Atmospheric response to noy source due to energetic electron precipitation. Geophysical Research Letters 32, 1–4.

Schrøter, J., Heber, B., Steinhilber, F., Kallenrode, M., 2006. Energetic particles in the atmosphere: A monte-carlo simulation. Advances in Space Research 37, 1597–1601.

Sloan, T., Bazilevskaya, G., Makhmutov, V., Stozhkov, Y., Svirzhevskaya, A., Svirzhevsky, N., 2011. Ionization in the atmosphere, comparison between measurements and simulations. Astrophysics and Space Sciences Transactions 7, 29–33.

Solomon, S., 1993. Auroral electron transport using the monte carlo method. Geophysical Research Letters 20, 185–188.

Stozhkov, Y., Svirzhevsky, N., Bazilevskaya, G., Kvaschnin, A., Makhmutov, V., Svirzhevskaya, A., 2009. Long-term (50 years) measurements of cosmic ray fluxes in the atmosphere. Advances in Space Research 44, 1124–1137.

Turunen, E., Verronen, P., Seppälä, A., Rodger, C., Clilverd, M., Tamminen, J., Enell, C.F., Ulich, T., 2009. Impact of different energies of precipitating particles on nox generation in the middle and upper atmosphere during geomagnetic storms. Journal of Atmospheric and Solar-Terrestrial Physics 71, 1176–1189.

Usoskin, I., Kovaltsov, G., 2006. Cosmic ray induced ionization in the atmosphere: Full modeling and practical applications. Journal of Geophysical Research: Atmospheres 111, D21206.

Velinov, P., Asenovski, S., Kudela, K., Lastovička, J., Mateev, L., Mishev, A., Tonev, P., 2013. Impact of cosmic rays and solar energetic particles on the earth’s ionosphere and atmosphere. Journal of Space Weather and Space Climate 3, A14.
Velinov, P., Mishev, A., Mateev, L., 2009. Model for induced ionization by galactic cosmic rays in the earth atmosphere and ionosphere. Advances in Space Research 44, 1002–1007.

Verronen, P., Rodger, C., Clilverd, M., Wang, S., 2011. First evidence of mesospheric hydroxyl response to electron precipitation from the radiation belts. Journal of Geophysical Research: Atmospheres 116, D07307.

Whittaker, I., Gamble, R., Rodger, C., Clilverd, M., Sauvaud, J.A., 2013. Determining the spectra of radiation belt electron losses: Fitting demeter electron flux observations for typical and storm times. Journal of Geophysical Research: Space Physics 118, 7611–7623.

Wild, P., Honary, F., Kavanagh, A., Senior, A., 2010. Triangulating the height of cosmic noise absorption: A method for estimating the characteristic energy of precipitating electrons. Journal of Geophysical Research: Space Physics 115, A12326.

Wissing, J., Kallenrode, M.B., 2009. Atmospheric ionization module osnabrück (aimos): A 3-d model to determine atmospheric ionization by energetic charged particles from different populations. Journal of Geophysical Research: Space Physics 114, A06104.

Wissing, J., Kallenrode, M.B., Kieser, J., Schmidt, H., Rietveld, M., Strømme, A., Erickson, P., 2011. Atmospheric ionization module osnabrück (aimos): 3. comparison of electron density simulations by aimos-hammonia and incoherent scatter radar measurements. Journal of Geophysical Research: Space Physics 116, A08305.