Estimation of Characterized Ionization Rates During Geomagnetic Disturbances with Kp = 4 Based on Balloon Observations

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Abstract Geomagnetic disturbances induce energetic electron precipitation (EEP) that plays an important role in changing the chemical composition of the polar atmosphere. Understanding the atmospheric impacts of energetic electron particle deposition remains challenging, from quantifying the response in ionization rates of the atmosphere, chemical compositions and to the effects on ozone. Both are necessary to understand the relationship between EEP and regional climate variability. In this paper, we retrieve the ionization rate in the atmosphere caused by the precipitation of energetic electrons from balloon observations in the polar atmosphere for four selected events observed with balloons in a high-latitude atmosphere above Apatity (67.57° N, 33.56° E, L = 5.3) during geomagnetic disturbances characterized with Kp = 4.

Keywords Energetic electron precipitation (EEP) · Balloon observations · Electron spectra · Ionization rates induced by EEP · Geomagnetic disturbances

1 Introduction

Energetic electron precipitation (EEP) linked to solar activity and space weather and plays an important role for the Earth's polar atmosphere [1–3]. Energetic electrons, with energies from tens of keV to several MeV, during geomagnetic disturbances precipitate into the atmosphere and induce additional ionization rates of the polar

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middle atmosphere [1, 4–6]. These induced ionization rate of atmosphere leads to the production of radicals in ion-molecular reactions at the heights of the mesosphere and upper stratosphere, forming reactive compounds of nitrogen NOx (N, NO, NO_2, NO_3) and hydrogen HOx (H, OH, HO_2) that are involved in catalytic reactions that destroy ozone [1–3].

With an increase in solar activity, deformations of the geomagnetic field increase sharply and cause magnetic storms. Energetic particles trapped in Earth's magnetic fields slam or precipitate into the atmosphere during geomagnetic disturbances in the Near-Earth space environment. Precipitated particles enter the upper layers of the atmosphere, including its ionized layers, the ionosphere. This process is called energetic particle precipitation. The main manifestations of geomagnetic activity are magnetic disturbances-magnetic substorms and magnetic storms. The strength of geomagnetic disturbances or storms is usually determined using various geomagnetic indices like as AE, Kp and Dst. Kp index is a planetary index characterizing the global disturbance of the Earth's magnetic field in a three-hour time interval. The Kp index is defined as the average value of the disturbance levels of two horizontal components of the geomagnetic field observed at 13 selected magnetic observatories located in the subauroral zone between 48 and 63 degrees north and south geomagnetic latitudes. To determine the Kp index, the standardized values of the local K indices of these 13 observatories are used. Kp index has values ranging from 0 to 9, where Kp index of 9 is an extreme geomagnetic storm. For our study, we chose a moderate geomagnetic environment with a Kp index of 4.

The bremsstrahlung of energetic electrons in the X-ray range can be measured with balloon instruments, which provide information on energy spectra and fluxes. This information about the precipitation of energetic electrons makes it possible to calculate the atmospheric ionization. EEP from the outer radiation belt in the subauroral region causes an increase in the ionization rate up to about 20 km altitude.

The purpose of this research to estimate characterized ionization rates during geomagnetic disturbances based on balloon observations. These are typical cases, since electron precipitation is most often observed in a weakly disturbed state of the geomagnetic field. To achieve this goal, we study the response in the ionization rates to energetic electron precipitation in the high-latitude atmosphere with obtaining information on numerous balloon observations over Apatity (67.57° N, 33.56° E, L = 5.3).

2 Balloon Observation

The Lebedev Physical Institute has carried out balloon measurements of ionizing radiation in the atmosphere regularly since 1957 [7–10]. The balloon equipment measures the fluxes of secondary cosmic rays, solar protons entering the atmosphere during energetic solar particle events, as well as the bremsstrahlung of electrons during their precipitation from the outer radiation belt of the Earth. The energy spectrum of the precipitating electrons is reconstructed from observations of absorption of X-ray bremsstrahlung in the atmosphere. The procedure for the transition from X-ray fluxes in the atmosphere to the energy spectrum of electrons was developed on the basis of Monte Carlo calculations [9].

The fluxes of precipitating electrons often fluctuate strongly in time; therefore, for the correct reconstruction of the spectrum, only cases of a monotonic increase in the X-ray fluxes while the balloon is rising are chosen. For this work, four cases of reliable measurements were selected, when precipitation was observed for at least 30 min, see Fig. 1. For example, in the EEP case during September 10, 1998, for deriving the electron spectrum observational data were used only at altitudes of 26–30 km, since X-ray fluxes varied strongly at higher altitudes. We remove the contribution of secondary particles originated from galactic cosmic rays by subtracting the previous flight data without precipitation shown in Fig. 1 by blue symbols. Thus, we obtain data on the absorption of X-ray flux in air and calculate the energy spectrum of electrons using the technique [9]. It should be noted that we record only the fact of precipitation while the balloon is in this place and we have no information about the actual beginning and end of the process.

Table 1 presents 4 selected cases of EEP during geomagnetic disturbances with Kp = 4 [11] based on balloon observation over Apatity (67.57° N, 33.56° E, L = 5.3). The investigation of these EEP events by two versions of the one-dimensional radiative-convective-photochemical model with parameterized and interactive ion chemistry for estimation of ozone and electron density changes during these EEP events was presented in the paper [12].

3 Retrieval Ionization Rate from Balloon Observations

To study the effect of EEP on ionization rates one need to have information on energy spectra (energy of particles and intensity of flux) and parametrization of ion production. The computation of EEP ionization rates (number of ion pairs/gram/second) at a certain height requires knowledge of the parametrization of ion production via ionization yield functions [4]. The ionization yield function at the atmospheric depth is a number of ion pairs created by one precipitating electron with the initial energy at the upper boundary of the atmosphere. In this study, we used modified ionization yield functions for mono-energetic electrons with initial energy from tens of keV to several MeV [4]. Both direct ionization by primary electrons as well as the secondary Bremsstrahlung electromagnetic emissions are considered in this model [4].

The ionization rates for investigated period was calculated taking into account information about EEP obtained by balloon observation presented in Fig. 1 by orange symbols. The description of the response functions and the basis for calculating the ionization rates are presented in [4–6]. Computation of ionization rates requires knowledge of the energy spectra and parameterization of ion production via ionization yield functions. The ionization yield function at atmospheric depth is the number of ion pairs created by one precipitating electron with initial energy at the upper boundary of the atmosphere. It takes into account both direct ionization by primary

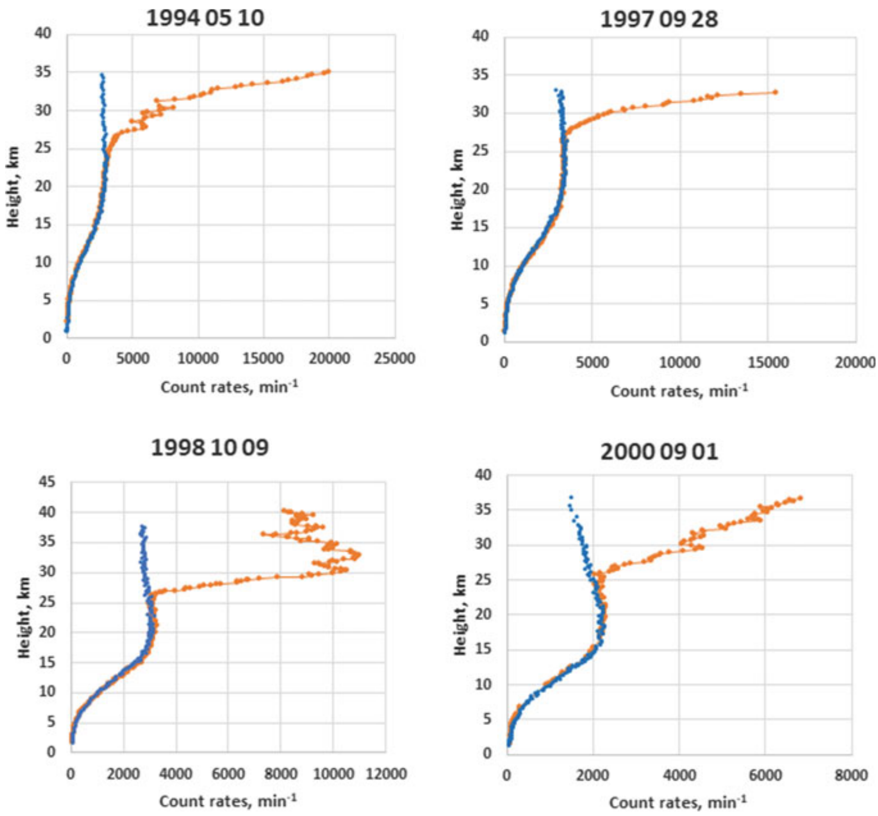

Fig. 1 Count rates of balloon-borne devices at Apatity. Orange symbols present the data obtained during electron precipitation, blue symbols relate to the balloon flights without precipitation and present the background from secondary cosmic rays

Table 1 Day of year (DOY) and time of balloon observations and intensity of geomagnetic disturbances during these days

DOY	Time start (UT)–time end (UT)	Kp with time observation (UT)
10/05/1994	7 h 10 m–7 h 58 m	4 (00−21 h)
28/09/1997	7 h 00 m–7 h 32 m	4 (00−06 h)
09/10/1998	7 h 48 m–8 h 16 m	4 (03−09 h)
01/09/2000	7 h 42 m–8 h 37 m	4 (06−09 h)

electrons and secondary electromagnetic radiation of bremsstrahlung. The energy spectra include information about EEP particle energy and flux intensity. In its turn the distribution of the energy spectra requires different fitting functions covering the EEP energy range. In our study, to calculate the EEP ionization rates, we use the parametrization of ion production in terms of the ionization yield functions [4] and

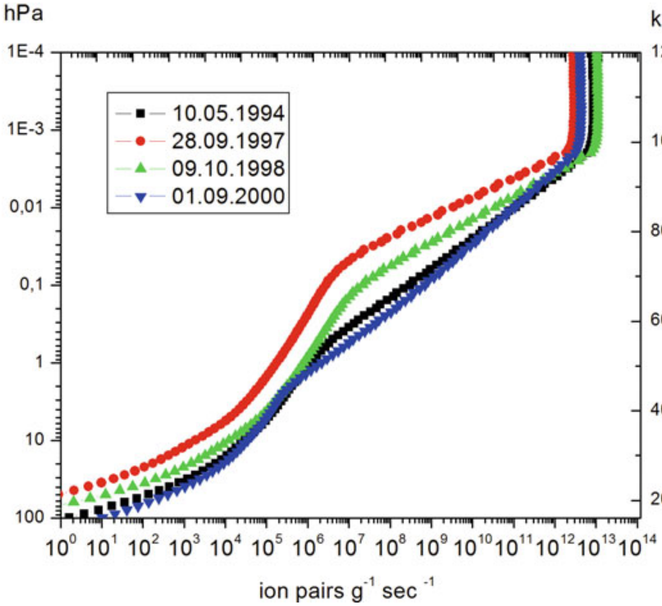

Fig. 2 Altitudinal profile of ionization rate over Apatity (67.57° N, 33.56° E, L = 5.3) during geomagnetic disturbances with Kp = 4

energy spectra obtained during balloon observation over Apatity. EEP spectra have been fitted with a power low energy distribution.

The ionization rate altitude profile during geomagnetic disturbances is shown in Fig. 2. Here once can see that characterized ion production in the altitudes about 120 km not exceed 10^{13} ion pairs per gram per second, in the mesosphere ion production during strong geomagnetic storms can various from 10^6 to 10^{12} ion pairs per gram per second.

4 Discussion and Conclusion

Geomagnetic disturbances, leading to an increase in the precipitation of energetic particles into the atmosphere, cause an increase in the ionization rates of the atmosphere/ionosphere. In turn, one of the important natural factors that destroy the ozone layer and increase the content of electrons are the processes associated with the precipitation of energetic particles into the atmosphere. However, the role of energetic electrons precipitating from the radiation belts under various geomagnetic conditions is not fully understood and is important for studying the behavior of the D-region of the high-latitude ionosphere and ozone fluctuations.

In this work, we reconstructed the atmospheric ionization rate caused by precipitation of energetic electrons from balloon observations in the polar atmosphere for four selected events observed with balloons in the high-latitude atmosphere over Apatity (67.57° N, 33.56° E, L = 5,3) during moderate geomagnetic disturbances characterized by Кp = 4. For obtaining electron spectra, from balloon observations, we removed the contribution of secondary particles originated from galactic cosmic rays and the data are obtained on the absorption of X-ray flux in air.

After this investigation we can conclude that during geomagnetic disturbances the characterized ion production in the altitudes about 120 km not exceed 10^{13} ion pairs per gram per second, in the mesosphere ion production during strong geomagnetic storms can various from 10^6 to 10^{12} ion pairs per gram per second.

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References

1. Mironova, I. A., Aplin, K. L., Arnold, F., Bazilevskaya, G. A., Harrison, R. G., Krivolutsky, A. A., Nicoll, K. A., Rozanov, E. V., Turunen, E., & Usoskin, I. G.: Energetic particle influence on the Earth's atmosphere. Space Science Reviews, 194, 1–96 (2015).
2. Rozanov, E.V.: Effect of Precipitating Energetic Particles on the Ozone Layer and Climate. Russ. J. Phys. Chem. B 12, 786–790 (2018).
3. Matthes K., Dudok T., Lilensten J.: Earth's climate response to a changing Sun. EDP Science, Les Ulis, 267–272 (2015).
4. Mironova I, Kovaltsov G, Mishev A, Artamonov A.: Ionization in the Earth's Atmosphere Due to Isotropic Energetic Electron Precipitation: Ion Production and Primary Electron Spectra. Remote Sensing, 13 (20), 4161 (2021).
5. Mironova I., Artamonov A., Bazilevskaya G., Rozanov E., Makhmutov V., Mishev A., Karagodin A.: Ionization of the polar atmosphere by energetic electron precipitation retrieved from balloon measurements. Geophysical Research Letters, 46, 990–996 (2019).
6. Mironova I., Bazilevskaya G., Kovaltsov G., Artamonov A., Rozanov E., Mishev A., Makhmutov V., Karagodin A., Golubenko K.: Spectra of high energy electron precipitation and atmospheric ionization rates retrieval from balloon measurements. Science of The Total Environment, 693, 133242 (2019).
7. Bazilevskaya, G., Logachev, Y., Vashenyuk, E. et al.: Solar proton events in solar activity cycles 21–24. Bull. Russ. Acad. Sci. Phys. 79, 573–576 (2015).
8. https://sites.lebedev.ru/ru/DNS_FIAN/479.html, last accessed 2023/07/03.
9. Makhmutov, V. S., Bazilevskaya, G. A., Stozhkov, Y. I., Svirzhevskaya, A. K., & Svirzhevsky, N. S.: Catalogue of electron precipitation events as observed in the long duration cosmic ray balloon experiment. Journal of Atmospheric and Solar-Terrestrial Physics, 149, 258–276 (2016).

10. Bazilevskaya G., Kalinin M., Krainev M., Makhmutov V., Stozhkov Y., Svirzhevskaya A., Svirzhevsky N., Gvozdevsky B.: Temporal characteristics of energetic magnetospheric electron precipitation as observed during long-term balloon observations. Journal of Geophysical Research: Space Physics, 125, e2020JA028033 (2020).
11. https://www.gfz-potsdam.de/en/section/geomagnetism/data-products-services/geomagnetic-kp-index, last accessed 2023/07/03.
12. Grankin D, Mironova I, Bazilevskaya G, Rozanov E, Egorova T. Atmospheric Response to EEP during Geomagnetic Disturbances. Atmosphere, 14(2), 273 (2023).