SAINT-PETERSBURG UNIVERSITY

As a manuscript

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IMPACT OF ENERGETIC PARTICLES ON THE EARTH'S ATMOSPHERE

Scientific specialty
1.3.1. Space physics, astronomy

SCIENTIFIC REPORT

for a degree

Doctor of Physical and Mathematical Sciences
(Russian)
Habilitation in Physical and Mathematical Sciences
(International)

Translation from Russian

Saint Petersburg
2023

Content

1. Introduction

The Earth's atmosphere is constantly under the influence of energetic charged particles that enter, or in other words, fall out into the ionosphere/atmosphere from the Earth's magnetosphere or interstellar space. Such particles are collectively known as energetic precipitating particles; they penetrate the Earth's atmosphere and can affect various atmospheric processes. Most of the energetic particles come from outer space, they are known as galactic cosmic rays, and are made up primarily of protons. During strong solar proton events and coronal mass ejections, protons of solar origin penetrate the Earth's atmosphere. An additional source of less energetic particles is the solar wind, which consists mainly of electrons that can be accelerated/trapped in the Earth's magnetosphere. Such particles precipitate into the atmosphere from various regions of the magnetosphere both under the influence of the solar wind and under the influence of internal magnetospheric processes and geomagnetic disturbances. Many processes and their dynamic variability lead to large variations in the spatial, temporal, and spectral distribution of precipitating particles. Spilling out into the atmosphere, energetic particles affect the entire atmosphere, creating atmospheric ionization rates, from the lower thermosphere / mesosphere through the stratosphere and troposphere to the Earth's surface. All precipitating energetic particles ionize neutral molecules (eg N_2 and O_2) in the Earth's atmosphere and produce reactive radicals such as N, NO, H and OH. The distribution of atmospheric ionization rates in space and time depends on the type of precipitating particles, on their interaction with variable heliospheric and geomagnetic fields. Despite this, the direct chemical effects are considered to be more or less the same and consist in the additional formation of hydrogen oxides ($HOx = H + OH + HO_2$) and nitrogen oxides ($NOx = N + NO + NO_2$), which can accelerate catalytic reactions and lead to ozone destruction. The dissertation explores various sources and energies of precipitating particles, such as galactic cosmic rays, solar protons associated with eruptive processes on the Sun, and precipitation of energetic electrons. All the mechanisms of the influence of energetic precipitating particles on the atmosphere, which are currently assumed, are studied, including the atmospheric ionization rates and their effect on ozone in the mesosphere and stratosphere, the effects on the global electric circuit and on aerosols. Special attention is paid to the study of the mechanism of the effect of electromagnetic radiation during class X solar flares on the ozone content in the atmosphere. The study of the role of energetic particles in the Earth's atmosphere is an interdisciplinary problem related to the study of the propagation of solar, galactic and magnetospheric energetic particles from the Sun to the lower layers of the Earth's atmosphere, and requires knowledge both in the field of space physics and astronomy, and in the sciences of the atmosphere and climate.

2. Tasks and results of the dissertation work

At the beginning of the 2000s, a breakthrough occurred in the study of processes in the chain of solar-terrestrial relations, due to a breakthrough in the development of chemical-climatic models that allow taking into account solar forcing through atmospheric ionization rates and studying their impact on ozone and the local climate of the Earth. However, the potential role of energetic particles in variations of atmospheric parameters is still poorly understood due to large uncertainties in atmospheric ionization rates associated with precipitating particle fluxes. Therefore, one of the objectives of the dissertation work is the development of numerical models of atmospheric ionization rates during precipitation of energetic particles associated with eruptive solar proton events, precipitation of energetic electrons from the magnetosphere, and variations in galactic cosmic ray fluxes. The next task is to carry out model calculations of atmospheric ionization rates and obtain numerical estimates of the role of atmospheric ionization rates in variations in the chemical composition of the polar atmosphere, in the destruction of mesospheric and stratospheric polar ozone, and the impact on the global electric circuit and on polar stratospheric aerosol. As a result, within the framework of the dissertation work, the following tasks are posed:

- Carrying out model studies of the propagation of monoenergetic electrons in the Earth's atmosphere, numerical calculation of atmospheric ionization rates during events associated with precipitation of energetic electrons, and assessment of their role in the destruction of polar ozone depending on the intensity of geomagnetic disturbances and seasons.
- Carrying out model studies of the propagation of monoenergetic protons in the Earth's atmosphere, numerical calculation of atmospheric ionization rates during GLE (Ground Level Enhancement) solar proton events and determination of their role in the formation of polar stratospheric aerosol.
- Carrying out model calculations and obtaining results in the form of numerical estimates of variations in the chemical composition of the polar atmosphere, including ozone, during decreases in atmospheric ionization rates associated with Forbush decreases in galactic cosmic rays.
- Carrying out model calculations of the parameters of the electric circuit depending on the processes in the magnetosphere and ionosphere, the rates of atmospheric ionization under the influence of precipitation of energetic particles. Carrying out model calculations and obtaining estimates of the degree of influence of electromagnetic radiation during solar flares on the chemical composition of the high-latitude atmosphere and ozone.

2.1. Brief description of the work performed by the applicant

- Setting tasks to be performed, performing research and obtaining scientific results.
- Model numerical calculations of atmospheric ionization rates during events associated with precipitation of energetic particles.
- Numerical estimates of the atmospheric response to events associated with precipitation of energetic particles using simulations and verification of the results using satellite data.

2.2. Brief description of the results obtained by the applicant

The conducted research and the results obtained represent a new direction of solar-terrestrial research created by the author, in collaboration with his colleagues and students: “Atmospheric ionization rates as the main link in the chain of solar-terrestrial relations necessary to study the impact of space weather and solar activity on the Earth’s atmosphere »:

I. Atmospheric ionization rates during events associated with precipitation of energetic electrons and assessment of their role in the destruction of polar ozone depending on the intensity of geomagnetic disturbances and the seasons

The dynamic interaction of the solar wind with the Earth's magnetosphere leads to the acceleration of energetic magnetospheric particles partially precipitating into the atmosphere. Precipitating populations of auroral electrons and energetic electrons from the radiation belts play an important role in atmospheric processes. The precipitation of electrons into the atmosphere occurs from different regions of the magnetosphere, due to various mechanisms. Energetic electrons with energies above tens of keV do not penetrate deeper than approximately 50 km into the atmosphere due to large ionization and radiation energy losses. However, energetic electrons generate X-ray bremsstrahlung, and this radiation can reach heights of about 20 km.

The precipitation of electrons covers the energy range from tens of keV to several MeV and lasts from fractions of a second to several hours, depending on geomagnetic disturbances. In order to correctly estimate the effects in the atmosphere during precipitation of energetic electrons, model studies of the propagation of monoenergetic electrons in the Earth's atmosphere were carried out taking into account bremsstrahlung [A13, A28, A30]. Two peaks of energy release in the atmosphere were identified. The first ionization peak is associated with direct ionization of primary relativistic electrons, and the second corresponds to bremsstrahlung. The papers [A13, A28, A30] present not only model tables of the propagation of monoenergetic electrons in the Earth's atmosphere, but also provide a developed technology for calculating atmospheric ionization rates during events associated with precipitation of energetic electrons. The developed technology for calculating the atmospheric ionization rates from the lower thermosphere to the lower stratosphere [A13, A28] made it possible to calculate the atmospheric ionization rates at different time intervals, during different levels of geomagnetic disturbance, using real spectra of energetic electron precipitation obtained from satellite and balloon observations [A1- A3, A4, A7, A16, A19, A23, A24, A26, A37]. It was shown that numerical calculations of atmospheric ionization rates under the influence of precipitation of energetic electrons into the ionosphere demonstrate strong variability and a strong dependence on geomagnetic disturbances at different altitudes of the atmosphere from 120 to 25 km [A1-A3, A18, A19, A23, A26]. After comparing the results of observations of the precipitation of energetic electrons on satellites and balloons, a criterion [A3] was proposed, according to which it is possible to control the ionization rates in the atmosphere at altitudes up to 20-25 km according to measurements on satellites. Using the criterion [A3] (according to satellite data, the flux of precipitating energetic electrons >800 keV should be >100 pfu), we estimated the number of days in a year when precipitation of energetic electrons would be observed in the lower stratosphere of the northern polar zone (geographical latitude 60°– 70°, longitude 0°–360°, McIlwain parameter L = 4–8).

Using the developed technology for calculating atmospheric ionization rates [A13, A28] during events associated with precipitation of energetic electrons, estimates were made of the degree of mesospheric ozone destruction depending on the season, location and intensity of atmospheric ionization rate variations under the influence of precipitation of energetic electrons [A1, A4 , A11, A18, A24, A26, A27, A31-A32]. In autumn and spring, the maximum depletion of mesospheric polar ozone can reach 20% during moderate and strong geomagnetic activity. Polar mesospheric ozone cannot be destroyed by precipitation of energetic electrons in summer in the presence of UV radiation. In winter, the maximum depletion of mesospheric polar ozone can reach up to 80% during strong geomagnetic disturbances. A linear dependence of the maximum depletion of mesospheric ozone in different seasons depending on the rate of atmospheric ionization during precipitation of energetic electrons during geomagnetic disturbances is obtained.

II. Atmospheric ionization rates during GLE (Ground Level Enhancement) solar proton events and determination of their role in the formation of polar stratospheric aerosol

The main sources of protons in the Earth's atmosphere are cosmic rays, which can be of galactic, solar or heliospheric origin. The dominant components of cosmic rays are protons, about 10% (according to the number of particles) are He nuclei (α-particles), and the remaining nuclei are less than 1%. Galactic cosmic rays, constantly arriving from outside the solar system, consist of protons with energies between approximately 107 eV and 1021 eV. Solar cosmic rays, or energetic solar particles, appear sporadically in near-Earth space due to explosive energy releases from the Sun, and can have energies up to about 10 GeV. Solar cosmic rays (>90% protons) are associated with fast powerful energy releases on the Sun - solar flares and/or coronal mass ejections. The energy spectrum of energetic solar protons covers more than 4 orders of magnitude in energy and more than 8 orders of magnitude in intensity. The most energetic fluxes of solar protons (over 1000 MeV) can initiate a nucleon-electromagnetic cascade in the atmosphere, leading to nucleon and muon components potentially detected by ground-based detectors (neutron monitors). Such eruptive solar proton events are distinguished as a separate class/type of GLE (ground level enhancement) events. The ionization effect from GLE events is important only in the polar atmosphere, where it can be significant in the stratosphere (about 25-30 km) during large GLEs. In order to correctly estimate the effects in the atmosphere during precipitation of energetic protons, model studies of the propagation of monoenergetic protons in the Earth's atmosphere were carried out. The model of propagation in the atmosphere of monoenergetic solar protons from 10 MeV to hundreds of GeV and the associated atmospheric ionization rates and spectra of energetic proton fluxes during eruptive solar proton events of the GLE (ground level enhancement) type are presented in [A38-A40, A8, A21, A25, A29]. Articles [A39-A40] present not only model tables of the propagation of monoenergetic electrons in the Earth's atmosphere, but also provide a developed technology for calculating atmospheric ionization rates during events associated with precipitation of energetic protons during large GLE events.

Using the developed technology for calculating atmospheric ionization rates [A39-A40] during GLE events associated with precipitation of energetic protons, the role of atmospheric ionization rates in the formation of polar stratospheric aerosol was determined [A32, A34-A36]. A combination of at least two factors can lead to the formation of stratospheric aerosol: 1) a significant, at least about twofold, increase in the ionization rate in the polar stratosphere and 2) a winter season without UV and with a low temperature sufficient for the formation of polar stratospheric clouds [A34 - A37, A39 - A41, A43 - A46].

III. Atmospheric ionization rates during Forbush decreases of galactic cosmic rays and determination of their role in variations in the chemical composition of the atmosphere

Sporadic outbursts of solar energy, solar flares and/or coronal mass ejections, are usually accompanied by strong disturbances, often caused by coronal mass ejections propagating through the interplanetary medium. When such a disturbance passes near the Earth, it results in a suppression of the intensity of galactic cosmic rays, known as the Forbush diminution. The main feature of the Forbush decrease is a sharp (lasting several hours) decrease in the intensity of galactic cosmic rays caused by the passage of a disturbance, followed by a gradual, almost exponential, recovery, which can take several days or even weeks. A typical Forbush decrease is about 4–5% (up to 20%) observed with ground-based neutron monitors.

Using the developed technology for calculating atmospheric ionization rates [A39-A41] associated with precipitation of energetic protons, the atmospheric ionization rates during Forbush decreases of galactic cosmic rays are calculated and estimates of the degree of ozone destruction and ozone depleting groups (HOx and NOx) are made. Analysis of the Forbush decreases in galactic cosmic rays in January 2005 showed that on January 18 and 21, the worldwide network of neutron monitors recorded a significant decrease in the count rate. The Forbush decrease caused by the interplanetary disturbance on January 18, 2005 was a strong 15% decrease in the flux of galactic cosmic rays, and on January 21, 2005, the Forbush decrease was about 10%. It was shown in [A15] that due to the decrease in ionization rates caused by

Forbush depressions, the family of hydrogen oxide (HOx) radicals loses about half of its concentration over the polar nighttime stratosphere in winter. At the same time, a stable response in the nitrogen family (NOx) and stratospheric ozone is not detected, as is the effect of Forbush decreases in galactic cosmic rays in summer in the southern polar stratosphere [A15].

IV. Variations in the parameters of the electric circuit depending on the processes in the magnetosphere and ionosphere, the rates of atmospheric ionization under the influence of precipitation of energetic particles

Precipitation of energetic particles affects not only the chemical composition of the atmosphere and aerosols, but also the parameters of the electrical circuit. Therefore, at the next stage of studying the impact of energetic particles on the Earth's atmosphere, it became necessary to give a numerical estimate of the change in the parameters of the electric circuit depending on the processes in the magnetosphere, ionosphere, and atmospheric ionization rates under the influence of precipitation of energetic particles. It was shown in [A20] that atmospheric ionization rates during extreme solar proton events lead to a significant increase in fair weather currents on a global scale, and the magnitude of the effects depends on the location and can exceed the background value by more than 10 times at high latitudes. It was proved in [A12, A14] that precipitation of energetic electrons during geomagnetic disturbances modulates the Schumann resonance at high latitudes and affects the global electron content during geomagnetic disturbances. The parameters of the global electrical circuit can also be associated with magnetospheric processes [A5, A9-A10, A22], therefore, in [A5], an attempt was made to estimate the degree of influence of fluctuations of the By component of the interplanetary magnetic field on surface meteorological parameters through the global electrical circuit of the atmosphere above the Polar Regions. However, the model numerical results do not confirm the connection of surface temperature and pressure with the influence of the Bu component of the interplanetary magnetic field through the global electrical circuit of the atmosphere [A5].

V. Effects of electromagnetic radiation during solar flares on the chemical composition of the high-latitude atmosphere and ozone

The state of the Earth's atmosphere depends on various external cosmic and solar factors [A33, A42, A47], including not only precipitating energetic particles of solar, galactic or magnetospheric origin, but also solar radiation. Therefore, at the stage of studying the effects in the atmosphere associated with ionization rates, it was decided to test and evaluate the degree of impact of solar radiation during flare activity on the ozone-depleting groups HOx, NOy, and ozone. In [A6, A17], based on model calculations, an assessment is made of the degree of impact of solar radiation during the solar flare activity in September 2017 on ozone-depleting components and the ozone layer in the Earth's atmosphere. For this, two largest solar flares of class X of the 24th solar cycle were selected: the X9.3 flare on September 6 and the X8.2 flare on September 10, 2017. For model numerical estimates, we used data on radiation fluxes in the entire wavelength spectrum up to 190 nm from solar flares in early September 2017. The odd nitrogen family and the odd hydrogen group were chosen as the main ozone-depleting components of the atmosphere. It was shown in [A6, A17] that the hydrogen group (HOx) is only slightly affected by flare activity over equatorial and polar latitudes. No statistically significant response was found in the HOx family. When analyzing the response of the odd nitrogen family (NOy), it was shown that solar radiation during two solar flares on September 6 and 10, 2017 increased the concentration of NOy up to 40% in the mesosphere in regions of equatorial latitudes.

It is important to note that solar flares in early September 2017 led to a significant increase in the concentrations of reactive nitrogen oxides. However, this increase did not affect the change in the ozone content in the tropical stratosphere, since the destruction of ozone by nitrogen oxides in the upper mesosphere is inefficient and there are no stable downward movements that can carry excess NOx down into the stratosphere. Thus, it can be concluded that ozone changes caused by processes associated with the impact of electromagnetic radiation on the Earth's atmosphere during solar flares, if they occur, will occur only during more intense solar flares than those of September 2017. Changes in the chemical composition of the atmosphere in the polar regions are small and not statistically significant [A6, A17].

The performance of dissertation research by the applicant, over the past 10 years, as part of the implementation of research projects, was supported by the following funds:

- Russian scientific foundations:

- RSF Project No. 20-67-46016 “Extreme Space Weather Events: Environmental Impact Assessment” (2020 - 2022 –PI)

- RFBR international project No. 20-55-12020 NNIO_a “Precipitation of high-energy electrons into the atmosphere: assessment based on balloon observations and model calculations (H-EPIC)” (2020 - 2022 – PI)

- RFBR project No. 19-35-90134 PhD students, “Influence of cosmic factors on processes in the global electrical circuit” (2021-2019 – head of PhD, PI)

- RFBR project No. 20-0500450 A “Day and night mechanism of atmospheric oxygen glows consistent with night hydroxyl emission in the mesosphere and lower thermosphere” (2021-2020 – PP, 2022 –PI)

- RFBR project No. 17-55-10014 KO_a “The impact of atmospheric electricity on weather and climate caused by clouds and precipitation” (2018 - 2019 – PP)

- Megagrant “Forecasting the state of the ozone layer using modeling and measurements of the composition of the atmosphere”, Agreement No. 075–15-2021-583 dated 06/03/2021 between the Ministry of Science and Higher Education of the Russian Federation and St. Petersburg State University (2021-2023 - the main PP)

- Foreign scientific foundations:

- 2018-2019 - ISSI project (International Space Science Institute)
"Relativistic Electron Precipitation and its Atmospheric Effect (ISSI Bern and ISSI Beijing)" Role: Team/Project Leader

• 2013-2015 – ISSI project (International Space Science Institute)
"Specification of ionization sources affecting atmospheric processes"
Role: Team/Project Leader

• 2010-2012 – project of ISSI (International Space Science Institute).
"Investigation of the influence of cosmic rays on atmospheric processes"
Role: Team/Project Leader

• 2011-2015 – COST ES1005 (TOCKA) project “Towards a more complete assessment of the impact of solar variability on the Earth's climate”.
Role: team member and co-leader of the working group "Atmospheric effects of energy particles"

• 2016-2020 – COST CA15211 project (ELECTRONET)
"Atmospheric electricity network: connection to the Earth system, climate and biological systems"
Role: team member

- Other external organizations:

Contracts for research “Atmospheric effects of precipitation of energetic electrons from the outer radiation belt: Part I and Part II” between St. Petersburg State University and SINP MSU, fulfillment of tasks under the interdisciplinary Russian Science Foundation project No. 22-62-00048 (2022-2023 - PI)

3. The main provisions submitted by the applicant for defense

A new area of solar-terrestrial research has been created: "Atmospheric ionization rates as the main link in the chain of solar-terrestrial relations necessary to study the impact of space weather and solar activity on the Earth's atmosphere", based on the provisions submitted for defense:

1. Model estimates of the propagation of monoenergetic electrons in the atmosphere from 30 keV to several MeV during the precipitation of energetic electrons of magnetospheric origin into the ionosphere. Technologies for calculating atmospheric ionization rates from the lower thermosphere to the lower stratosphere using satellite and balloon observations. Numerical calculations of atmospheric ionization rates under the influence of precipitation of energetic electrons into the ionosphere, which demonstrate strong variability and strict dependence on geomagnetic disturbances at different atmospheric altitudes from 120 to 25 km [A1-A4, A7, A13, A16, A18-A19, A23-A24, A26, A30, A37].

2. Using model calculations of atmospheric ionization rates based on satellite and balloon observations, estimates were made of the degree of mesospheric ozone destruction depending on the season, location, and intensity of atmospheric ionization rate variations under the influence of energetic electron precipitation. In autumn and spring, the maximum depletion of mesospheric polar ozone can reach 20% during moderate and strong geomagnetic activity. Polar mesospheric ozone cannot be destroyed by precipitation of energetic electrons in summer in the presence of UV radiation. In winter, the maximum depletion of mesospheric polar ozone can reach 80% during strong geomagnetic disturbances. A linear dependence of the maximum depletion of mesospheric ozone in different seasons depending on the rate of atmospheric ionization during precipitation of energetic electrons during geomagnetic disturbances has been obtained [A1-A3, A4, A7, A11, A13, A16, A18-A19, A23-A24, A26, A27-A28, A30-A32, A37].

3. Model estimates of propagation of monoenergetic solar protons in the atmosphere from 10 MeV to hundreds of GeV and technologies for calculating atmospheric ionization rates during eruptive solar proton events of the GLE type (ground level enhancement). Based on model calculations of atmospheric ionization rates during eruptive solar proton events of the GLE type, the role of atmospheric ionization rates in the formation of polar stratospheric aerosol is determined. A combination of at least two factors can lead to the formation of stratospheric aerosol: 1) a significant, at least approximately twofold, increase in the ionization rate in the polar stratosphere

and 2) a winter season without UV and with a low temperature sufficient for the formation of polar stratospheric clouds [A8, A21, A25, A29, A34 - A37, A38 - A40, A43 - A46].

4. On the basis of model calculations of atmospheric ionization rates during the Forbush decreases of galactic cosmic rays, estimates were made of the degree of destruction of ozone and ozone depleting groups (HOx and NOx). Due to the decrease in ionization rates caused by Forbush depressions, the hydrogen oxide (HOx) family of radicals loses about half of its concentration over the polar nighttime stratosphere in winter. At the same time, a stable response in the nitrogen family (NOx) and stratospheric ozone is not detected, as well as the effect of Forbush decreases in galactic cosmic rays in summer in the southern polar stratosphere [A15, A39 - A41].

5. With the help of model studies, an assessment was made of changes in the parameters of the electrical circuit depending on the processes in the magnetosphere, ionosphere and the rates of atmospheric ionization under the influence of precipitation of energetic particles. Atmospheric ionization rates during extreme solar proton events lead to a significant increase in fair weather currents on a global scale, and the magnitude of the effects depends on the location and can exceed the background value by more than 10 times at high latitudes. Precipitation of energetic electrons during geomagnetic disturbances modulates the Schumann resonance at high latitudes and affects the global electron content during geomagnetic disturbances. At the same time, the study of the influence of fluctuations of the By component of the interplanetary magnetic field through the global electric circuit did not confirm a noticeable effect on surface meteorological parameters. [A5, A9 - A10, A12, A14, A22].

6. With the help of model studies, an assessment was made of the degree of influence of electromagnetic radiation during solar flares on the chemical composition of the atmosphere and ozone. Electromagnetic radiation from class X solar flares can lead to a significant increase in the concentration of nitrogen oxide (NOx) families at equatorial latitudes. However, this increase does not affect the change in the ozone content in the tropical stratosphere. Changes in the chemical composition of the atmosphere in the Polar Regions are small and not statistically significant [A6, A17].

4. List of applicant's publications in chronological order

A1. Mironova I, Grankin D, Rozanov E. Mesospheric Ozone Depletion Depending on Different Levels of Geomagnetic Disturbances and Seasons. *Atmosphere*. 2023; 14(8):1205. https://doi.org/10.3390/atmos14081205

A2. Makhmutov V., Maurchev E., Bazilevskaya G., Mironova I. Development of a method for reconstructing the energy spectra of precipitating electrons from measurements in the atmosphere. Geomagnetism and Aeronomy, 2023, 63, 5, 638–643. doi:10.31857/S0016794023600564

A3. Mironova I, Bazilevskaya G, Makhmutov V, Mironov A, Bobrov N. Energetic electron precipitation via satellite and balloon observations: their role in atmospheric ionization. *Remote Sensing*. 2023; 15(13):3291.
https://doi.org/10.3390/rs15133291

A4. Grankin D, Mironova I, Bazilevskaya G, Rozanov E, Egorova T. Atmospheric Response to EEP during Geomagnetic Disturbances. *Atmosphere*. 2023; 14(2):273.
https://doi.org/10.3390/atmos14020273

A5. Karagodin A, Rozanov E, Mironova I. On the possibility of modeling the IMF B_y-weather coupling through gec-related effects on cloud droplet coalescence rate. *Atmosphere*. 2022; 13(6):881. https://doi.org/10.3390/atmos13060881

A6. Pikulina P, Mironova I, Rozanov E, Karagodin A. September 2017 Solar Flares Effect on the Middle Atmosphere. *Remote Sensing*. 2022; 14(11):2560. https://doi.org/10.3390/rs14112560

A.7. Mironova I., Sinnhuber M., Bazilevskaya G., Clilverd M., Funke B., Makhmutov V., Rozanov, E., Santee M. L., Sukhodolov T., and Ulich T. Exceptional middle latitude electron precipitation detected by balloon observations: implications for atmospheric composition. *Atmos. Chem. Phys.* 2022.; 22, 6703–6716, https://doi.org/10.5194/acp-22-6703-2022

A.8. Usoskin, I., Koldobskiy, S., Kovaltsov, G., Mishev, A., Mironova I. Strongest directly observed Solar Proton Event of 23-Feb-1956: Revised reference for the cosmogenic-isotope method. *Proceedings of Science*, 2022; 395. 1319.
https://doi.org/10.22323/1.395.1319

A.9. Mironova I, Füllekrug M, Kourtidis K and Mareev E. Editorial: atmospheric electricity. *Front. Earth Sci*., 2022;10:853584. doi: 10.3389/feart.2022.853584

A.10. Mironova, I., Karagodin, A., Rozanov, E. Sensitivity of Surface Meteorology to Changes in Cloud Microphysics Associated with IMF By. *Springer Proceedings in Earth and Environmental Sciences* 2022; pp. 413-420.

A.11. Makhmutov, V.S., Bazilevskaya, G.A., Mironova, I.A. *et al.* Atmospheric Effects during the Precipitation of Energetic Electrons. *Bull. Russ. Acad. Sci. Phys.* 85, 1310–1313 (2021). https://doi.org/10.3103/S1062873821110228

A.12. Klimenko, M.V., Klimenko, V.V., Bessarab, F.S., Mironova, I.A., Rozanov, E.V. On possible causes of positive disturbance of global electronic content during a complex heliogeophysical event on september 2017. *Cosmic Research*. 2021; 59(6). 456–462 doi: 10.1134/S0010952521060046

A.13. 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*. 2021; 13(20):4161. https://doi.org/10.3390/rs13204161

A.14. Bozóki T, Sátori G, Williams E, Mironova I, Steinbach P, Bland EC, Koloskov A, Yampolski YM, Budanov OV, Neska M, Sinha AK, Rawat R, Sato M, Beggan CD, Toledo-Redondo S, Liu Y and Boldi R. Solar cycle-modulated deformation of the earth–ionosphere cavity. *Front. Earth Sci.* 2021; 9:689127. https://doi.org/10.3389/feart.2021.689127

A.15. Mironova I, Karagodin-Doyennel A and Rozanov E. The Effect of Forbush Decreases on the Polar-Night HOx Concentration Affecting Stratospheric Ozone. *Front. Earth Sci.* 2021; 8:618583. doi: 10.3389/feart.2020.618583

A.16. Grankin D. V., Mironova I. A., Rozanov E. V. Polar winter mesospheric ozone depletion during energetic electron precipitation. *Proc. SPIE*. 2021; 11916. 119167Z. https://doi.org/10.1117/12.2603373

A.17. Pikulina P. O., Mironova I. A., Rozanov E. V., Sukhodolov T. V., and Karagodin A. V. Response of the upper atmosphere to irradiance increase after the solar flare on 6 September 2017. *Proc. SPIE* . 2021; 11916.1191680.
https://doi.org/10.1117/12.2603374

A.18. Mironova I., Sinnhuber M., Rozanov E. Energetic electron precipitation and their atmospheric effect. *E3S Web of Conferences*. 2020; 196. doi:10.1051/e3sconf/202019601005

A.19. Yakovchuk O. and Mironova I. Energetic Particle Precipitation during Extreme Space Weather Events. *E3S Web of Conferences*. 2020; 196. doi:10.1051/e3sconf/202019601006

A.20. Golubenko, K., Rozanov, E.,Mironova, I., Karagodin, A., Usoskin, I. Natural sourcesof ionization and their impact onatmospheric electricity. *Geophysical Research Letters*. 2020; 47, e2020GL088619.https://doi.org/10.1029/2020GL088619

A.21. Usoskin, I. G., Koldobskiy, S. A., Kovaltsov, G. A., Rozanov, E. V., Sukhodolov, T. V., Mishev, A. L., Mironova, I. A. Revisited reference solar proton event of 23February 1956: Assessment of thecosmogenic-isotope method sensitivityto extreme solar events. *Journal of Geophysical Research: Space Physics*. 2020; 125, e2020JA027921.
https://doi.org/10.1029/2020JA027921

A.22. Karagodin, A., Rozanov, E., Mareev, E., Mironova, I., Volodin, E., & Golubenko, K. The representation of ionospheric potential in the global chemistry-climate model SOCOL. *Sci. Total. Environ.* 2019; 697, 134172.
https://doi.org/10.1016/j.scitotenv.2019.134172

A.23. 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. *Sci. Total. Environ.* 2019; *69*, 133242. https://doi.org/10.1016/j.scitotenv.2019.07.048

A.24. Golubenko, K., Mironova, I., Rozanov, E. Impact of middle range energy electron precipitations on polar winter ozone losses. *E3S Web of Conferences*. 2019; 127. doi:10.1051/e3sconf/201912701005

A.25. Krivolutsky, A.A., Repnev, A.I., Mironova, I.A. *et al.* Results of Russian studies of the middle atmosphere in 2015–2018. *Izv. Atmos. Ocean. Phys.* 2019; 55, 537–551. https://doi.org/10.1134/S0001433819060069

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