

Examination of Extremely Big Mesospheric Electric Fields from Rocket-Borne Measurements on October 21 1989

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Abstract.

The profile of the vertical electric field E_z in the region 24 - 69 km obtained by rocket borne measurements on October 21 1989 over the South Indian Ocean [Zadorozhny et al., 1994] is examined. The experiment coincides with the major geomagnetic storm from October 20 and with GLE 43 event. The profile of E_z is characterized by well expressed peculiarities. E_z reaches extremely big maximums ($\sim 10 \text{ Vm}^{-1}$) of both polarities in the mesosphere and upper stratosphere. This peculiar profile of E_z is indication for gradual decrease of mesospheric conductivity as result of increase of aerosol density during the SEP event. Represented is an idea of a mechanism of aerosol density increase in the atmospheric regions of impact ionization. Our preliminary estimations show that the aerosol increase during GLE 43 according to the mechanism cause strong decrease of atmospheric conductivity which can explain the peculiar experimental results.

1. Introduction

Studied are the results of rocket-borne experimental measurements of the vertical component E_z of the electric field at altitudes 23 - 69 km conducted in South Indian Ocean at geographic coordinates (58°5S, 51°1E) on October 21 1989, at 19:31 UT (that is, close to the local midnight) [Zadorozhny et al., 1994]. The measurements are conducted during the major solar proton event (SPE) with ground-level enhancement from October 19 1989 (GLE 43). The SPE is characterized by extremely big flux of protons with energies $E_p < 14.5 \text{ MeV}$ for 56.5 hours after the onset of SPE [Marvin and Gorney, 1991]. The SPE is accompanied by a major geomagnetic storm from October 20 1989 with maximum planetary index of geomagnetic activity $K_p=8+$, and $K_p=8$ at the time of the rocket flight. The experimentally obtained profile of the vertical electric field E_z is shown in Fig.1 by solid curve [Zadorozhny et al., 1994]. Here a convention is used that downward E_z is positive, and vice/versa. The dashed curve shows the profile of density ρ of spatial electric charge. Peculiarities are revealed. While the electric field E_z is downward above 50 km altitude, it is upward below $z=50 \text{ km}$.

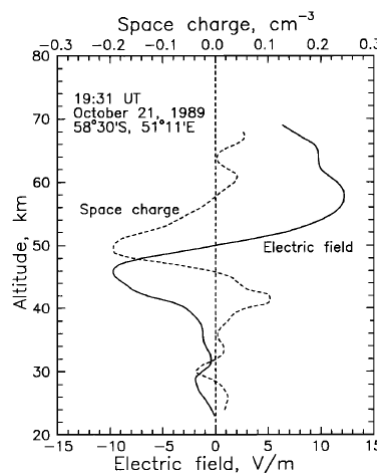


Figure 1. Profiles of the rocket-borne vertical electric field $E_z(z)$ (solid line), and of the density $\rho(z)$ of the electric spatial charge derived from Gauss's law (dashed line).

The reversal of E_z to upward contradicts to the direction of electric currents in the fair-weather regions of global atmospheric electric circuit (GEC) [Rycroft et al., 2008] where the current J_{FW} from the ionosphere to surface is downward. E_z reaches extremely big maximums of both polarities: $E_z=+12.3$ V/m at altitude $z=58$ km, and $E_z= -9.7$ V/m at $z=46$ km. For nighttime undisturbed profile of conductivity [Hale, 1984] $\sigma=2.5\times 10^{-8}$ Sm $^{-1}$ at altitude $z=58$ km, $\sigma=2\times 10^{-10}$ Sm $^{-1}$ at $z=46$ km; the electric current $J_z=\sigma E_z$ would be $J_z= +3.1\times 10^{-7}$ Am $^{-1}$ at $z=58$ km, and $J_z= -1.9\times 10^{-9}$ Am $^{-1}$ at $z=46$ km: J_z is larger by three to five orders of magnitude than J_{FW} . The discrepancy will be even larger if an enhancement of conductivity due to ionization is taken into account. Besides, the spatial electric charge density ρ in the layer 46 - 58 km is $\rho<0$. An explanation of these peculiarities is proposed.

The extremely big electric fields E_z in mesosphere and upper stratosphere mean decrease of conductivity σ by several orders of magnitude (the alternative assumption for reciprocal increase of electric current J_z does not seem plausible). We show that such decrease of mesospheric conductivity σ can be gradually completed on a definite phase of SPE together with a simultaneous increase of aerosol density S related to the ionization by energetic protons. The direct effect of ionization, the increase of conductivity is realized on an earlier phase. Later this effect is being masked by the reverse effect of increasing aerosol density on conductivity.

2. Hypothetic mechanism of aerosol creation and conductivity decrease during SPE

Considered are atmospheric processes during SEP events which can cause gradual decrease of conductivity in atmospheric regions Reg_p in both hemispheres where the proton cutoff rigidity does not exceed 1 MeV. Each region Reg_p includes the magnetic pole and invariant latitudes λ , $|\lambda|>|\lambda_B|$, where λ_B depends on the geomagnetic activity. Rodger et al. (2006) obtain $|\lambda_B|$ as function of Kp index (their Fig.4, and Eq.(2)); $|\lambda_B|\approx 56^\circ$ for Kp=8. The rocket launch is at invariant latitude $\lambda_{RE}= -59.5^\circ$, that is, it is well inside the region Reg_p .

In this paper described is an idea of a mechanism of aerosol production in regions Reg_p during SPE which causes decrease of atmospheric conductivity σ . There are indirect experimental confirmations: demonstrated has been significant increase of aerosol density in lower and middle stratosphere [Shumilov et al., 1996; Mironova et al., 2012] for few days after GLE events. The mechanism proposed here includes creation, growth, multiplication, and transportation of aerosol particles (AP) in regions Reg_p . We assume that initially APs can be created at altitudes ~ 70 -120 km from cosmic (meteoric) smoke particles (MSP) [Hedin et al., 2014; Rapp, 2000]. A MSP with size of few nanometers can serve as a nucleus which grows into an AP by attachments of ions. While a growing particle is small (with radius $r_A < \sim 4$ nm) it is critical and can degrade. By reaching radius $r_A > 4$ nm an AP reaches stability. To clarify the idea of the mechanism of aerosol creation and of a causative decrease of the conductivity in Reg_p , the following system of equations of ionization is considered:

$$dn_{e,i}/dt = q - L_R - L_{Ae,i} \quad (1)$$

Here n_e and n_i are the densities of electrons and ions. L_R and $L_{Ae,i}$ are competing terms of losses of electrons and ions. $L_R = \alpha n_e n_i$, α is the coefficient of electron-ion recombination. L_A is the term of losses of electrons and ions as result of their attachment to aerosol particles.

$$L_{Ae,i} = B_{e,iA} n_{e,i} \quad \text{where} \quad B_{e,iA} = \sum_{r_A, k_A} \beta_{e,i}(r_A, k_A) S(r_A, k_A) \quad (2)$$

Here $S(r_A, k_A)$ is the density of APs with radius r_A and k_A charges with the respective sign.

The proposed mechanism is based on the assertion that the terms $L_{Ae,i}$ increase quasi-exponentially with time t for specific set of parameters. While L_{As} becomes much bigger than

L_{RS} $n_{e,i}$ and conductivity $\sigma = q_e(\mu_e n_e + \mu_i n_i)$ decrease quasi-exponentially. Here $q_e = 1.6 \times 10^{-19}$ C is the elementary charge, $\mu_{e,i}$ is the coefficients of electron and ion mobility.

We use the theory of attachment of an electron or ion to an AP developed by Hoppel (1985), Hoppel and Frick (1986), Rapp (2000). According to this theory the interaction of an electron or ion with a big particle (neutral or charged) is determined by the potential $\phi = \phi_C + \phi_P$ where ϕ_C corresponds to Coulomb interaction, and ϕ_P – to the image force of the polarization interaction. Hoppel (1985); Hoppel and Frick (1986) estimate the coefficients $\beta_{e,iA}$ of attachment of a ion/ electron to a big spherical particle with radius r_A and charge k_A (k_A is for the number of elementary charges and their polarity) as functions of r_A and k_A : $\beta_{e,iA}(r_A, k_A)$ increase with r_A , as well as with $|k_A|$ when AP is neutral or oppositely charged. These properties determine acceleration of the growth of APs with time t .

Considered are two phases of growth of an AP. On the first phase small APs grow by attachment of ions only. The growth of APs on this phase is realized by repeating of two main processes: A1) Attachment of a free electron to a big neutral ($k_A=0$) particle (MSP or AP) with radius r_A ; A2) Attachment of a positive ion to a negatively charged big particle. With the increase of r_A attachments of electrons to negatively charged APs ($k_A < 0$) are typical too (Rapp, 2000). The second phase concerns large multi-charged APs – they grow by attachment of ions, as well as of small MSPs, or of cluster molecules with $k_A \leq 0$ by polarization interaction between particles.

The behaviour of any critical AP is described as a probabilistic process. If p_S is the probability of a critical AP to grow to a stable one (with radius r_{AS}) then $1-p_S$ is the probability that an AP degrades before reaching stability. We assume that a degrading AP is fully destroyed with probability p_D , and is split into two smaller APs with probability $1-p_D$. The density S_C of critical APs is a function of time, $S_C(t)$:

$$S_C(t) = S_{C0} \exp(t/t_C) \quad \text{where} \quad t_C = N_{AP} / (2B_{iA}P) \quad (3)$$

In (3) S_{C0} is the initial density of critical APs, N_{AP} is the mean number of the ions which compose an AP, $P = (1-p_S)(1-2p_D)$. (3) shows that $S_C(t)$ increases if $p_D < 0.5$.

An estimation of decrease of the conductivity is approximate due to the numerous uncertainties. If $p_D < 0.5$ B_{iA} (2) increases fast so that L_{Ai} can become much bigger than L_R within the few hours after the onset of SPE. In such case almost all ions produced during SPE until time t_{RE} (in 56.5 hours) attach to APs. The total number of ions per cm^3 N_i produced in this time is roughly estimated by adaptation of results for the profile of electron production rate $q(z)$ during GLE 69 as function of the cutoff rigidity for protons [Velinov et al., 2013, their Figs.6-8]. Since the integrated flux of protons with energies < 10 MeV for GLE 43 is bigger than the one for GLE 69 we obtain for $z \sim 80$ km that N_i is of the order of 10^{10} cm^{-3} , and $S_C = N_i / N_{AP}$. B. For quasi-equilibrium state at time t_{RE} terms dn_i/dt and L_R in Eq.(1) are negligible. We obtain from Eq.(1) that n_i can be as low as few units per cm^3 for $\beta_{iA} \sim 10^{-6} \text{ cm}^{-3}\text{s}^{-1}$ [Hoppel and Frick, 1986]. Then, the modified ion conductivity $\sigma_{Mi} = q_e \mu_i n_i$ will be $\sim 5 \times 10^{-13} - 10^{-12} \text{ Sm}^{-1}$ by unmodified ion mobility $\mu_i = 1.4 \times 10^4 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$. However, there are additional factors: i) the effect of big APs is not taken into account for which the coefficient β_{iA} can be 10 times larger; ii) the ion mobility μ_i can suffer significant decrease due to big AP density S . These and other factors determine additional decrease of σ_{Mi} by up to two orders of magnitude, or even more.

A key parameter for estimation of the level of decrease of the electron conductivity σ_e is the electron-AP attachment coefficient $\beta_{eA}(r_A, k_A)$. Rapp (2000) obtains that β_{eA} is between $10^{-4} \text{ cm}^{-3}\text{s}^{-1}$ for small r_A , k_A , and $\beta_{eA} \sim 10^{-2} \text{ cm}^{-3}\text{s}^{-1}$ for big r_A , k_A for electrons with thermal energies – this determines insufficient decrease of σ_e . Free electrons produced by ionization by protons of energies > 1 MeV are with much bigger initial energy. This can lead

to changes in cross-sections for the considered reactions; respectively, bigger β_{eA} . The decrease of σ_e can be then of the order of the decrease of σ , due to electron depletion known as electron bite-outs [Friedrich et al., 2011].

Simultaneously with its growth an AP created above ~ 80 km is transported to lower altitudes (depending on the AP's radius r_A) by gravitational sedimentation on the timescale of SEP. Big APs can descend to the mesosphere and upper stratosphere and be accumulated there. Processes of their further growth by attachment and of multiplication will lead to quasi-exponential increase of their density S , and to respective decrease of conductivity.

3. Modifications of atmospheric electric parameters in region R_p

The decrease of modified conductivity σ_M to values $\sigma_M < \sim 10^{-11} \text{ Sm}^{-1}$ at altitudes $z > z_{M0} = 35$ km determines vertical electric current inside region Reg_p . The total vertical electric current J_z is:

$$J_z = J_{FW} + J_p + J_T. \quad (4)$$

Here $J_{FW} = V_I / R_C$ is the electric current from the ionosphere to surface in fair-weather regions of GEC, $V_I \sim 250$ kV is the ionospheric potential, R_C is the columnar resistance. The electric current J_p is generated because of the unbalanced distribution of uncompensated elementary positive charges in GEC injected into atmosphere together with the energetic solar protons [Tonev, 2024]. J_T is a transient electric current generated of redistribution of spatial electric charges. Electric current J_p satisfies the equation:

$$dJ_p(z)/dz = 10^4 q_e D(E_{ps}(z)) [dz/dE_{ps}(z)]^{-1} \quad (5)$$

with boundary condition $\Delta J_p = J_p(z=120 \text{ km}) - J_p(z=0) = 10^4 q_e F_p$. D is differential spectrum of the proton flux, and F_p is the integrated proton flux above the atmosphere. $E_{ps}(z)$ is the initial energy of protons which lose their energy (stop) at altitude z . Eq.(5) shows that the direction of J_p is changed at an altitude z_p : J_p flows upwards at $z > z_p$, and downward at $z < z_p$. The experimental profile of E_z (Fig.1) shows that z_p is located at 50-60 km altitude.

While the decrease of σ_M in an upper part of region Reg_p (above an altitude $z_{Mmax} \sim 60$ km) is controlled mainly by attachments and growth of APs, below z_{Mmax} it depends mainly on gravitational sedimentation of APs on the timescale of GLE 43 which declines towards lower altitudes. The combined effect of processes of attachment, splitting, and sedimentation of APs on σ_M will be strongest at $z_{Mmax} = 58$ km with maximum decrease of σ_M . These processes have no effect at altitude $z_{M0} \sim 35$ km: $\sigma_M(z=z_{M0})$ remains unmodified. This determines a negative conductivity gradient $d\sigma_M/dz < 0$ in the layer L_{NC} [z_{M0} , z_{Mmax}]. When the electric current J_z is downward, negative spatial charge with density $\rho(z) < 0$ will be accumulated in [z_{M0} , z_{Mmax}] according to the following expression:

$$\rho(z, t) = \rho_0(z) [1 - \exp(-(t - t_0)/\tau_R(z))] \quad \text{where} \quad \rho_0 = -J_z d\tau_R(z)/dz < 0 \quad (6)$$

Here $\tau_R(z) = \epsilon_0 / \sigma_M(z)$ is the electric charge relaxation time at altitude z , $\epsilon_0 = 8.85 \times 10^{-12} \text{ Fm}^{-1}$ is the vacuum permittivity. Eq.(6) is derived from Maxwell's equations for quasi-static case. This result explains presence of the layer [46 - 58 km] with negative spatial electric charge. As it is shown below, the positive density ρ in the layer [35 - 46 km] is result of strong variability of the transient electric current J_T at altitudes of relatively big conductivity.

4. Explanation of the reversal of E_z to upward direction below 50 km altitude

Below $z = 50$ km the vertical electric field E_z is directed upwards ($E_z < 0$, $J_z < 0$). This seems to contradict to the fact that $J_{FW} > 0$, and $J_p > 0$. This situation can be explained by generation of

big upward transient current J_T . The reason can be even small fluctuations of the geomagnetic field during the major geomagnetic storm. Such fluctuations can lead to significant changes of the cutoff rigidity for protons at invariant latitude λ_{RE} since λ_{RE} is close to λ_B . According to Rodger et al. (2006) (their Fig.4, and Eq.(2)) a small decrease of index Kp corresponds to big increase of the cutoff at latitude $\lambda = \lambda_{RE}$. The result of a sudden increase of cutoff rigidity will be strong change in the height distribution of electric current J_P in (5).

Characteristics are derived first for a time period of equilibrium before the time t_0 of the cutoff change. The flux of protons with energies $E_p > 1$ MeV at the top of the atmosphere is obtained to be $\sim 6 \times 10^2 \text{ cm}^{-2} \text{ s}^{-1}$ by the use of exponential extrapolation of GOES-7 data for protons with energies $E_p > 4.2$ MeV at time t_{RE} of the rocket flight. This yields $\Delta J_P \sim 10^{-12} \text{ Am}^{-2}$. If accept that the average modified conductivity between ~ 50 km and ~ 90 km is $\sigma_M \approx 4 \times 10^{-13} \text{ Sm}^{-1}$ (according to our estimations above, and those by Holzworth et al. (2004) for noctilucent clouds) the columnar resistance $R_C = V_i / J_{FW}$ increases twice (from $\sim 10^{-17} \Omega \text{ m}^2$ to $\sim 2 \times 10^{-17} \Omega \text{ m}^2$), and J_{FW} decreases also twice, $J_{FW} \sim 10^{-12} \text{ Am}^{-2}$. Hence, the strongly decreased conductivity at altitudes $z > 58$ km determines before t_0 that electric current J_P has a big contribution to J_z below in (4) (about 50%). The quasi-constant downward electric current J_z causes accumulation of negative spatial charge with density $\rho(z) < 0$ between $z_{M0} = 35$ km and $z_{Mmax} = 58$ km according to (6).

The sudden increase of the cutoff rigidity at time t_0 will cause a decrease of ΔJ_P , and redistribution of J_P by altitude z , so that below $z = 58$ km the contribution of J_P in (4) can become negligible. Because of the big contribution of J_P in the total electric current J_z before time t_0 J_z will suddenly decrease to $J_{zd} = C J_z$ by tens of percent. This big change will lead to redistribution of spatial charges in layer L_{NC} after t_0 . Their density $\rho(z, t)$ is expressed below.

$$\rho_r(z, t) = [\rho_{r0}(z) - \rho_0(z)] [1 - \exp(-\Delta t / \tau_R(z))] + \rho_0(z), \quad \rho_{r0}(z) = C \rho_0(z). \quad (7)$$

Here $\Delta t = t - t_0$. Transient electric current $J_T(z, t)$ is generated at altitudes $z < z_{PR}$ is a result of this spatial charge redistribution. We obtain the height profile $J_{T0}(z) = J_T(z, t)$ at $t = t_0$ when J_T has maximum contribution in (4). For this goal the profile of modified conductivity $\sigma_M(z)$ in layer L_{NC} is represented by exponential function: $\sigma_M(z) = \sigma_0 \exp [(z_{M0} - z) / H_M]$ where $\sigma_{M0} = \sigma(z = z_{M0})$, $H_M > 0$ is scale height. The profile $J_{T0}(z)$ is expressed, as follows:

$$J_{T0}(z) = \int_z^{z_{Mmax}} \frac{d\rho_r(z, t=0)}{dt} dz = -J_{z0}(z_{Mmax} - z) / H_M < 0 \quad (8)$$

Here Eq.(8) shows that at the time $t = t_0$ of the cutoff change the transient electric current $J_T(z)$ exceeds $|J_{z0}| = |J_{FW} + J_P|$ at altitudes $z < z_{PR} - H_M$, that is: a) $J_z(z, t_0)$ becomes zero at altitude $z_0 = z_{PR} - H_M$; b) $J_z(z, t)$ is upward ($J_z < 0$) at altitudes below z_0 . $|J_T(z, t)|$ decreases quasi-exponentially by $t > t_0$, and the altitude z_0 (at which J_z changes its sign) descends with time. The upward direction of the vertical electric field $E_z = J_z / \sigma_M$ below 50 km is explained by (8). These results confirm that the altitude z_P of change of direction of J_P is located above 50 km, and the columnar resistance at $z > z_P$ is comparable to the one below z_P .

5. Conclusions

Studied are the rocket-borne extremely large vertical electric fields E_z in mesosphere measured during GLE 43 and the major geomagnetic storm from October 20 1989 [Zadorozhny et al., 1994]. E_z reaches about 10 Vm^{-1} both in downwards (at 58 km altitude) and in upward (at $z = 46$ km) directions. These results demonstrate dramatic decrease of conductivity (by three to five orders of magnitude). In order to explain these peculiarities proposed is a hypothetic mechanism of creation of aerosol particles of extremely high density S during solar proton events which can cause such conductivity decrease. There are

experimental indirect confirmations of aerosol production during SPEs. The mechanism of aerosol production in atmospheric regions of reach of energetic protons which is proposed is based on the theory of ion-aerosol attachment. The approximate estimations show that during GLE 43 conductivity in the mesosphere can gradually decrease at least down to 10^{-12} Sm^{-1} . The proposed hypothetical mechanism is developed from the one used by Tonev (2022, 2024), Tonev and Asenovski (2023) explain peculiar, yet typical response of GEC in middle stratosphere, as well as at ground level at high latitudes to series of GLE events documented by Holzworth et al. (1987), Kokorowski et al. (2006), Shumilov et al. (2016).

An explanation is proposed of the reversal of the vertical electric field E_z below 50 km altitude into upward direction. This reversal is explained as result of even small fluctuations in the geomagnetic field. It can be caused by upward transient electric current generated due to suddenly unbalanced spatial electric charges.

References

- Friedrich, M., Rapp, M., Plane, J. M. C., Torkar, K. M. (2011). Bite-outs and other depletions of mesospheric electrons. *Journal of Atmospheric and Solar-Terrestrial Physics*, Vol. 73, pp. 2201–2211. DOI: 10.1016/j.jastp.2010.10.018.
- Hale, L. C. (1984). Middle atmospheric electrical structure, dynamics, and coupling. *Advances in Space Research*, Vol. 4, pp. 175–186. DOI: 10.1016/0273-1177(84)90283-7.
- Hedin, J., Giovane, F., Waldemarsson, T., Gumbel, J., et al. (2014). The MAGIC meteoric smoke particle sampler. *Journal of Atmospheric and Solar-Terrestrial Physics*, Vol. 118, pp. 127–144. DOI: 10.1016/j.jastp.2014.03.003.
- Holzworth, R. H., Norville, K. W., Williamson, P. R. (1987). Solar flare perturbations in stratospheric current systems. *Geophysical Research Letters*, Vol. 14, No. 8, pp. 852–855. DOI: 10.1029/GL014i008p00852.
- Holzworth, R. H., Goldberg, R. A. (2004). Electric field measurements in noctilucent clouds. *Journal of Geophysical Research: Atmospheres*, Vol. 109, D16203. DOI: 10.1029/2003JD004468.
- Hoppel, W. A. (1985). Ion-aerosol attachment coefficients, ion depletion, and the charge distribution on aerosols. *Journal of Geophysical Research*, Vol. 90, No. D4, pp. 5917–5923.
- Hoppel, W. A., Frick, G. M. (1986). Ion-aerosol attachment coefficients and the steady-state charge distribution on aerosols in a bipolar ion environment. *Aerosol Science and Technology*, Vol. 5, No. 1, pp. 1–21. DOI: 10.1080/02786828608959073.
- Kokorowski, M., Sample, J. G., Holzworth, R. H., Bering, E. A., Bale, S. D., Blake, J. B., et al. (2006). Rapid fluctuations of stratospheric electric field following a solar energetic particle event. *Geophysical Research Letters*, Vol. 33, L20105. DOI: 10.1029/2006GL027718.
- Marvin, D. C., Gorney, D. J. (1991). Solar proton events of 1989: Effects on spacecraft solar arrays. *Journal of Spacecraft and Rockets*, Vol. 28, No. 6, pp. 713–719. DOI: 10.2514/3.26304.
- Mironova, I. A., Usoskin, I. G., Kovaltsov, G. A., Petelina, S. V. (2012). Possible effect of extreme solar energetic particle event of 20 January 2005 on polar stratospheric aerosols: Direct observational evidence. *Atmospheric Chemistry and Physics*, Vol. 12, pp. 769–778. DOI: 10.5194/acp-12-769-2012.
- 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. (2015). Energetic particle influence on the Earth’s atmosphere. *Space Science Reviews*, Vol. 194, pp. 1–96. DOI: 10.1007/s11214-015-0185-4.
- Rapp, M. (2000). Capture rates of electrons and positive ions by mesospheric aerosol particles. *Journal of Aerosol Science*, Vol. 31, No. 11, pp. 1367–1369. DOI: 10.1016/S0021-8502(00)00030-6.
- Rodger, C. J., Clilverd, M. A., Verronen, P. T., Ulich, T., Jarvis, M. J., Turunen, E. (2006). Dynamic geomagnetic rigidity cutoff variations during a solar proton event. *Journal of Geophysical Research: Space Physics*, Vol. 111, A04222. DOI: 10.1029/2005JA011395.
- Rycroft, M. J., Harrison, R. G., Nicoll, K. A., Mareev, E. A. (2008). An overview of Earth’s global electric circuit and atmospheric conductivity. *Space Science Reviews*, Vol. 137, Nos. 1–4, pp. 83–105. DOI: 10.1007/s11214-008-9368-6.
- Shumilov, O. I., Kasatkina, E. A., Henriksen, K., Vashenyuk, E. V. (1996). Enhancement of stratospheric aerosols after solar proton event. *Annales Geophysicae*, Vol. 14, pp. 1119–1123. HAL: hal-00316221.
- Shumilov, O. I., Kasatkina, E. A., Frank-Kamenetsky, A. V. (2015). Effects of extraordinary solar cosmic ray events on variations in the atmospheric electric field at high latitudes. *Geomagnetism and Aeronomy*, Vol. 55, pp. 666–674. DOI: 10.1134/S0016793215050151.

- Tonev, P. T. (2022). Peculiar atmospheric electric field response at high latitude to three major SEP events in 2001 and possible interpretation. *Proceedings of the Fourteenth Workshop “Solar Influences on the Magnetosphere, Ionosphere and Atmosphere”*, pp. 77–82. DOI: 10.31401/WS.2022.proc.13.
- Tonev, P., Asenovski, S. (2023). Hypothetic atmospheric response to SEP explaining peculiar electric fields and currents at high latitudes. *Proceedings of the Fifteenth Workshop “Solar Influences on the Magnetosphere, Ionosphere and Atmosphere”*, pp. 125–131. ISSN 2367-7570. DOI: 10.31401/WS.2023.proc.
- Tonev, P. (2024). Hypothetic explanation of peculiar atmospheric electric response to SEP at high latitudes: Experimental evidence. *Proceedings of the Sixteenth Workshop “Solar Influences on the Magnetosphere, Ionosphere and Atmosphere”*, pp. 94–99. DOI: 10.31401/WS.2024.proc.14.
- Velinov, P. I. Y., 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*, Vol. 3, A14. DOI: 10.1051/swsc/2013036.
- Zadorozhny, A. M., Kikhtenko, V. N., Kokin, G. A., Tuchkov, G. A., Tyutin, A. A., Chizhov, A. F., Shtirkov, O. V. (1994). Middle atmosphere response to the solar proton events of October 1989 using the results of rocket measurements. *Journal of Geophysical Research: Atmospheres*, Vol. 99, No. D10, pp. 21059–21069. DOI: 10.1029/93JD03194.