

Detecting Common Origin of Atmospheric Electric Responses during SEP

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Abstract.

Experimental investigations of the electric response of atmospheric regions at different latitudes during SEP systematically demonstrate for decades peculiar behavior of electric fields and currents, together with conductivity: these have extremely large and untypical variations. Here four such experiments in mesosphere, in stratosphere, and at surface, at high and low latitudes, are interpreted. These are: *i*) rocket-borne measurements of vertical electric field E_z in middle atmosphere at latitude 58.5°S during the major SEP 19-22 October 1989 accompanied by strong geomagnetic storm which show extremely large $E_z \sim 10$ V/m in mesosphere; *ii*) balloon-borne measurements in auroral stratosphere (31-33 km) during GLE 69 with unusually large variations and reversals of E_z ; *iii*) measurements of E_z at surface, both at: *a*) high, and *b*) low latitudes also demonstrating extremely large variations and change of its sign. It is shown here that results in case (*i*) are related to strong reduction of conductivity, seemingly due to formation and growth of aerosol particles during SEP. The specific behavior of electric fields and currents in the rest cases (*ii*, *iii*) can be considered as result of effective coupling between atmospheric regions at different altitudes and latitudes. The origin of perturbations anywhere is presented by SEP driven processes in mesosphere at high latitudes.

Experiments demonstrating effects of SEP on atmospheric electric characteristics

The aim of this paper is to give hypothetical explanation of the effects of major solar proton events (SPEs) on atmospheric electrical characteristics in different atmospheric regions (in mesosphere, stratosphere, and at ground level) which have been experimentally observed during several decades. We consider four experimental cases demonstrating extremely strong and unusual electric response in these regions at high and auroral latitudes (cases A-C given below), as well as at surface at low latitudes - case D. A short description follows:

Case A. During SPE on 19-22 October 1989 the profile of vertical electric field E_z is obtained in a rocket experiment at latitude 58.5°S over Southern Indian Ocean, on 21 October at 19:31 UT (Zadorozhny et al., 1998) when also strong geomagnetic storm takes place with index $K_p=8$ at the time of flight (during this day K_p reaches 8+). The E_z profile is shown in Fig.1a by thick line 1. E_z reaches extremely high values in mesosphere and upper stratosphere: $E_z=+12.2$ V/m at altitude $z=58$ km, and $E_z=-9.7$ V/m at $z=46$ km. Another striking fact is the change of sign of the electric field E_z : it points upwards above 50 km, and downwards below that height. There is no satisfying explanation of these features. For comparison, by usual conductivities close to 50 km, $2 - 6 \times 10^{-11}$ S/m, and fair-weather current -2 pA/m² E_z should be about -100 mV/m, i.e. at least two orders of magnitude smaller, and even well below that if accept that conductivity σ enhances due to strong impact ionization during SPE. It should be noted that the electric field peak values $E_{z\text{peak}}$ observed are the biggest ever measured in many tens of similar rocket experiments (Zadorozhny et al, 1998).

Case B. Balloon-borne measurements of electric characteristics in Antarctic stratosphere (31-33 km) on 20 January 2005 are in coincidence with SPE of very hard spectrum (GLE 69) (Kokorowski et al., 2006). During the day the balloon coordinates changes from (70.9°S , 10.9°W) to (71.4°S , 21.5°W). The geomagnetic conditions during SPE are: *i*) quiet from the SPE onset at $t_0=06:51$ UT until $t_1=14:00$ UT; *ii*) geomagnetic activity has an increase from 14:00 UT till the end of day; *iii*) strong geomagnetic substorm took place after $t_2=15:54$ UT. At times t_1 and t_2 also the protons of energies <5 MeV have sudden increase according to GOES-

10 data for the proton flux (Kokorowski *et al.*, 2006). The observed variations of vertical electric field E_z and of vertical current $J_z = \sigma E_z$ during the day are shown in Fig.2a,b. For the first ~ 1.5 hours after t_0 E_z is close to zero. Then, until time t_1 $E_z < 0$ becomes unusually large, so that the related current J_z exceeds the nominal fair-weather current J_{fw} more than three times. At time t_1 E_z jumps to about zero intensity and remains such until time t_2 . At t_2 E_z has another jump to large positive values such that J_z is well above J_{fw} , but now it points upwards until the end of the day. These features remain unexplained.

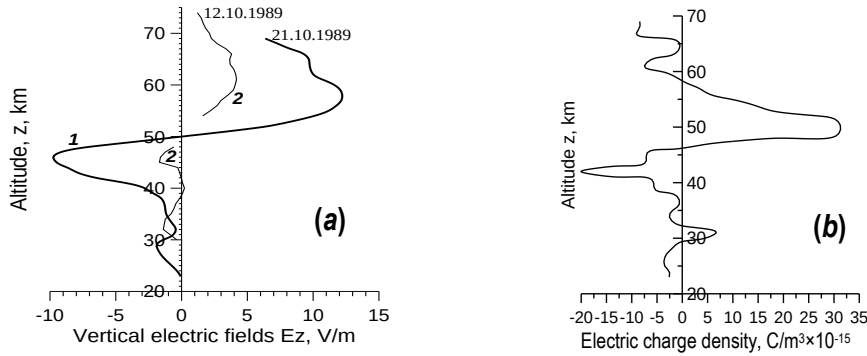


Fig.1. Profile of vertical electric field E_z from rocket-borne data at latitude 58.5° (Indian Ocean) on 21.10.1989, 19:31 UT during major SPE (GLE 69 event) and strong geomagnetic storm with $K_p=8$ (Zadorozhny *et al.*, 1998) (a). Profile of the electric charge density $\rho(z)$ derived from the profile of E_z by the use of Gauss's law (b).

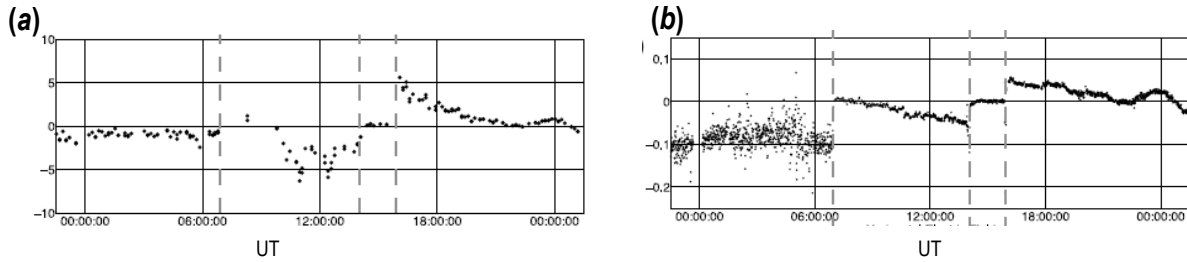


Fig.2. Time variations of the vertical electric field E_z (a) and vertical electric current density J_z (b) at 31-33 km altitude during GLE 69 (Kokorowski *et al.*, 2006). Dashed vertical lines correspond to times: $t_0=06:51$ of SPE onset, $t_1=14:00$ UT, and $t_2=15:54$ UT.

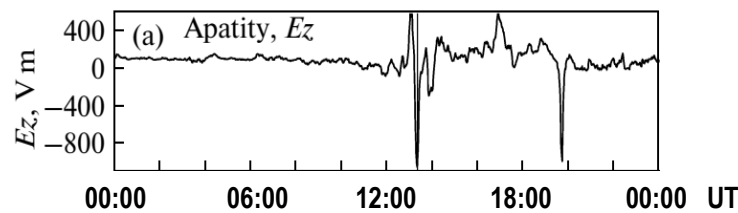


Fig.3. Time variations of the atmospheric electric field E_z at ground level in Apatity during SPE on 14 April 2001 (Shumilov *et al.*, 2015).

Case C. The response of the atmospheric electric field at surface (AEF) E_z (here downward direction is accepted to be positive) in Apatity, Russia (67.3°N , 33.2°E) at geomagnetic latitude $+63.8^\circ$ has been examined by Shumilov *et al.* (2015) to three SPE in 2001 of GLE type: on 14.04, 18.04, and 04.11, respectively. Fig.3 shows variations of AEF E_z during SPE on 14 April 2001. The time period from $t_1=14:10$ UT (at the rise phase of SPE) is considered, since after time t_1 the effect of this last on E_z dominates over other factors which affect AEF E_z before t_1 .

AEF E_z reaches its first maximum $E_z \sim 330$ V/m at 14:15 UT. Then, variations of E_z are close to 100-150 V/m for about two hours. After 16:40 UT AEF E_z increases to its absolute peak value of almost 600 V/m reached at 17:50 UT. Later E_z varies within limits 0-300 V/m until 19:30 UT, and after that it has a sharp jump to large negative value (more than 1 kV/m) reached at 19:45 UT. After this peak, until the end of the day E_z varies between 0 and 100 V/m most of time, although sometimes E_z becomes negative.

Case D. Response of AEF E_z measured at surface at low latitudes to intense SPEs, which have significant proton flux above 100 MeV, is studied in CASLEO, Argentine (31.8°S, 69.3°W) at 2552 m altitude (Tacza *et al.*, 2018). The proton cutoff rigidity at CASLEO is 9.8 GV. Measurements of AEF E_z at surface are conducted during 15 SPEs in the time period from 21 March 2011 until 18 April 2014. Solar proton events are only included in the experiment which satisfy requirements for fair-weather conditions (no lightning activity or strong wind are present) and for low geomagnetic activity ($K_p < 4$). The fluence of these 15 SPEs is within the limits $2.8 \times 10^3 - 3.2 \times 10^5$ protons $\text{cm}^{-2} \text{ day}^{-1} \text{ sr}^{-1}$. SPE on 17 May 2012 with the highest fluence is marked here as SPE*. Average deviation ΔE_z of AEF E_z from the monthly standard diurnal curve for the AEF is examined with following results:

Time from SPE onset, hours	0 - 3	3 - 6	6 - 9	9 - 12	12 - 15	15 - 18	18 - 21
ΔE_z , V/m	2.0	8.9	6.8	7.5	7.2	5.0	-1.8

E_z has well expressed positive deviation (up to $\sim 15\%$) during first 18 hours, and only small negative deviation during the succeeding three hours. These deviations are significant. Particularly for SPE* with the largest fluence (on 17 May 2012) the deviation ΔE_z is also significant, however it behaves otherwise in time, as demonstrated in Fig.4. Variations of E_z (shown by black curve) are compared to the monthly standard AEF curve. As opposed to the common case, AEF E_z shows first (for 4.5 hours) a negative deviation (up to $\sim 15\%$) from the monthly standard curve, and then a positive deviation (up to $\sim 40\%$) for the next 7 hours.

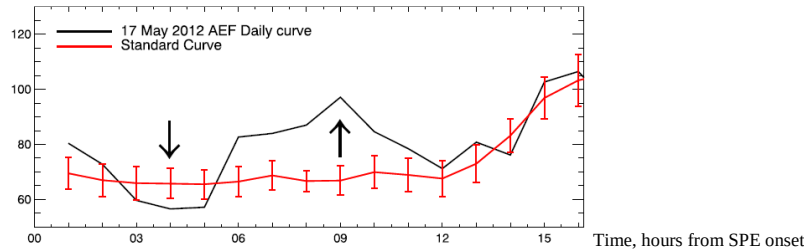


Fig.4. AEF E_z hourly values for the day of SPE (black curve) and the monthly standard curve (red) with respective error bars of one standard deviation (1σ) (Tacza *et al.*, 2018).

Unambiguously, SPEs causes significant deviations of AEF E_z from its average value. Because of the high cutoff rigidity (9.8 GV) these deviations hardly can be explained by a direct effect of energetic protons. Cobb (1967) observes similar AEF response at low latitudes to solar flares (which seemingly have produced SEP events).

Interpretation of experimental results in case A

The stopping altitude z_{ps} of energetic protons entering the atmosphere depends by quasi-logarithmic law on their initial energy E_p , as shown below:

E_p , MeV	0.3	1	5	10	30	50	100
z_{ps} , km	100	89	72	63	48	39	30

Any proton which penetrates into the middle atmosphere injects an elementary positive charge $q_e = 1.6 \times 10^{-19}$ C which cannot leave the atmosphere since its carriers have no sufficient energy

to enter the magnetosphere. Thus, uncompensated positive spatial charge is being accumulated in the atmosphere during a SPE. This charge would remain uncompensated until a precipitation of electrons of the same quantity which would neutralize the atmosphere. While not neutralized the uncompensated positive charges would redistribute within the atmosphere in order to reach balance. In a case of undisturbed conductivity, these charges would run upwards to the base of the magnetosphere (~ 150 km) where they would distribute evenly, with no contribution to atmospheric electrical characteristics. However, it is demonstrated here that this is not always the case, because of strong conductivity disturbance in middle atmosphere at high latitudes related to formation and growth of aerosol particles. Enhancement of stratospheric aerosol due to SPEs has been observed (*Shumilov et al.*, 1996).

The specific E_z profile in Fig.1a indicates for presence of layers of positive, as well as negative spatial charges of large density ρ . These last are estimated here from the Gauss's law $\text{div}\mathbf{E}=\rho/\epsilon_0$, where $\mathbf{E}$ is the electric field, $\epsilon_0=8.85\times 10^{-12}$ F/m is permittivity. dE_z/dz is the only significant term in $\text{div}\mathbf{E}$, hence, the charge density ρ is determined as

$$\rho = \epsilon_0 dE_z/dz. \quad (1)$$

Fig.1b demonstrates the profile of ρ obtained from the profile of E_z shown in Fig.1a. Further we analyze the main layer L_P of positive charge around 50 km and the columnar positive charge Q_{LP} in it. Layer L_P is hypothetically fed by uncompensated positive charges injected together with energetic protons during SPE. This layer is assumed to be in quasi-steady state at time of the rocket experiment since: i) any precipitations of protons or electrons from the magnetosphere would have no contribution to L_P ; ii) the decay of proton flux is monotonic and stably slow for many hours before and after the experiment: only $\sim 7\%$ per hour, as follows from energetic proton flux data by GOES-7 (*Marvin and Gorney*, 1992). In quasi-steady state the conductivity in layer L_P satisfies the equation:

$$Q_{LP}/t_R = J_{\text{prot}}, \quad (2)$$

where $J_{\text{prot}}(z) = q_e F_{\text{prot}}(z)$ is the source current into L_P formed by the uncompensated positive charges newly injected by stopping protons; $F_{\text{prot}}(z)$ is the flux of protons whose stopping altitude is z ; $t_R(z)$ is the charge relaxation time at altitude z : $t_R(z) = \epsilon_0/\sigma(z)$. The source current J_{prot} into the layer is obtained from GOES-7 data for the energetic proton flux (*Marvin and Gorney*, 1992), by assumption of identity between proton flux at the top of atmosphere (~ 100 km) and that measured at GOES-7 (this assumption is used also by other authors). With account to the results of *Rodger et al.*, (2006) for proton cutoff rigidity as function of Kp index, all protons of energies >1 MeV enter the atmosphere by Kp=8 at the geomagnetic latitude of the rocket experiment, $\Lambda=-62.7^\circ$.

With columnar charge density Q_{LP} in layer L_P , $Q_{LP}\sim 10^{-10}$ Cm $^{-2}$ and source current $J_{\text{prot}}\sim 10^{-14}$ Am $^{-2}$ into L_P , the estimation of conductivity σ_{LP} within layer L_P (47-58 km) yields:

$$\sigma_{LP} = J_{\text{prot}}\epsilon_0 / Q_{LP} \sim 10^{-15} \text{ S/m} \quad (3)$$

This is extremely low conductivity by which fast relaxation of the charge Q_{LP} would be avoid. It could be hypothetically achieved by presence of aerosol particles of needed density and size. For example, extreme reduction of conductivity in a noctilucent cloud in summer mesopause is found by *Holzworth and Goldberg* (2004).

The estimation of columnar resistance r_L of the layer L_P 47-58 km of thickness $\Delta z=11$ km yields $r_{LP} = \Delta z/\sigma_{LP} \sim 10^{19}$ Ωm^2 - more than one order of magnitude larger than the columnar resistance r_0 of region 0 - 20 km which is the total resistance under by undisturbed conditions.

These results demonstrate the following structure of the electrical ionosphere-surface link at high formed until the rocket experiment. The layer L_P of positive spatial charge around the

altitude $z_B=50$ km is formed, where altitude z_B separates regions of upward electric field E_z above z_B and downward E_z below z_B . Layer L_P contains large uncompensated positive spatial electric charge Q_{LP} fed by arriving protons and relaxing through the electric currents J_U above z_B (upward), and J_L below z_B (downward) as shown in Fig.5. Also, altitude $z_{PN}=58$ km separates layer L_P and an upper layer L_N of negative spatial charge which is induced due to the conductivity gradient. The electric currents J_U and J_D are superimposed to the downward fair-weather current J_{fw} which is ~ 2 pA.m $^{-2}$ under quiet conditions, but can be strongly diminished during SPE due to reduced conductivity σ_M in middle atmosphere. Respectively, three columnar resistances: i) r_{PL} between ~ 30 km and altitude z_B , ii) r_{PU} between z_B and z_{PN} , and iii) r_N above z_{PN} gradually increase during SPE together with growth of aerosol particles.

Electric field variations in regions below layer L_P are determined by the vertical current $J_z=J_D+J_{fw}$, and thus of interplay between group of parameters PARS: the altitudes z_B and z_{PN} , the charge Q_{LP} , and resistances r_{PL} , r_{PU} and r_N . The experiment is conducted long time (54.5 hours) after the onset of SPE when aerosol characteristics determine very large resistances r_{PL} and r_{PU} , and thus, negligible currents J_{fw} , J_D and J_z . In opposite, at earlier phases of SPE the parameters PARS could determine increase of J_z compared to its value before SPE.

Interpretation of experimental results in cases B and C

We consider first case B. From time $t_0=06:51$ until $t_1\sim 08:40$ UT resistances r_{PL} , r_{PU} and r_N are too small to affect the vertical electric field E_z ; yet, due to highly increased conductivity (up to 20 times), $E_z\sim 0$. At time period $t_1 - t_2$ resistances r_{PL} and r_{PU} enlarge moderately; changes of parameters PARS lead to increase of current J_D and decrease of J_{fw} , so that current $J_z\sim J_D$ increases as result. The jump of E_z from large negative values to ~ 0 at $t_2=14:00$ UT is possibly caused by sudden enlargement of resistance $r_{PU} + r_N$ due to change in protons <5 MeV. The second jump at $t_3=15:56$ UT (the substorm onset) may be caused by strong EEP, eventually leading to change of polarity of layer L_P , and hence, of current J_D .

Variations of AEF E_z in case C have similarity with those in case B: they both are controlled by electric current J_D .

Interpretation of experimental results in case D

The uncompensated positive charge in layer L_P at high latitudes is redistributed to lower latitudes through currents in global atmospheric electrical circuit (GEC) as represented in Fig.5: these currents are J_D (downward, at high latitudes), J_S (through surface), and J_{LT} which is an upward current at lower latitudes and contributes to the positive spatial charge Q_{TC}

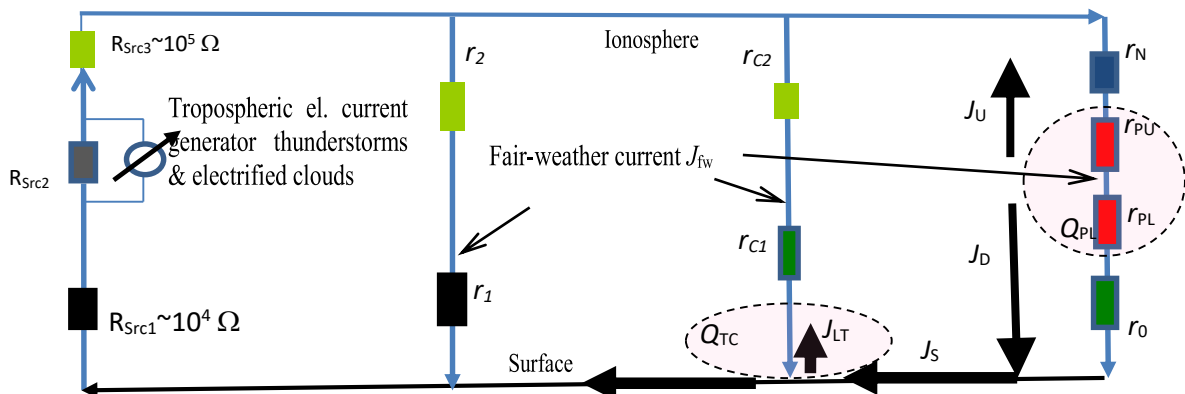


Fig.5. Model scheme of GEC affected by SEP. The four vertical links connecting ionosphere and surface represent currents which flow in regions: i) of tropospheric electric generator; ii) of fair-weather conditions at low and middle latitudes; iii) in particular, of CASLEO location; iv) at high and auroral latitudes where SEP lead to modification of parameters PARS.

induced in the boundary layer. Current J_{LT} is proportional to J_D which is determined by parameters PARS. Each of the 15 SPEs in case *D* has much smaller fluence than that in case *A* in time interval from SPE onset until the experiment. That is why the electric current J_D during these 15 SPEs is not reduced to ~ 0 (as in case *A* due to extreme $r_{PL}+r_{PU}+r_N$).

The fair-weather current J_{fw} at low latitudes increases during SPE (changes by $\Delta J_{fw}>0$) consistently with its decrease at high latitudes. The 14 SPEs whose fluence is less than that of SPE* at their earlier phase (within ~ 21 hours from their onset) cause relatively smaller increase of resistances r_{PL} , r_{PU} and r_N , and produce smaller positive charge Q_{LP} in layer L_P , compared to SPE*, thus determining relatively smaller currents J_D , respectively J_{LT} . For these SPEs $J_{LT} < \Delta J_{fw}$. This determines positive deviation of AEF E_z at low latitudes, since there $J_z = J_{fw} + J_{LT}$. The short and small negative deviation of E_z at a latter phase corresponds to restoration of characteristics of high-latitudinal atmosphere taking part before the SPE onset.

The results in Fig.4 related to SPE* correspond to generation of relatively large currents J_D and J_{LT} in an initial phase of SPE*, so that $J_{LT} > \Delta J_{fw}$, and hence the deviation of the current $J_z = J_{fw} + J_{LT}$ is negative in that phase. On the other hand, current J_{LT} causes significant enhancement of the charge Q_{TC} . At a latter phase J_D diminishes, possibly, as result of increase of the resistance $r_{PL}+r_{PU}+r_N$ well above r_0 , and current J_{LT} changes its polarity (becomes negative) consistently with decrease of charge Q_{TC} to its initial magnitude. This determines an increase of the total current $J_z = J_{fw} + J_{LT}$ for the time of restoration of parameters of the link corresponding to high latitudes.

Conclusions

1. Large electric fields ~ 10 V/m measured in mesosphere at auroral latitudes during major SEP are hypothetically considered as result of development of aerosol layers and injection of uncompensated positive electric charge.
2. Processes of aerosol growth in mesosphere and upper stratosphere at high latitudes driven by SEP cause severe decrease of conductivity and control the redistribution of uncompensated positive charge within the atmosphere.
3. Response of atmospheric regions at different latitudes to major SEP is realized through effective coupling between them which is controlled by processes in the mesosphere at high and auroral latitudes.

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