Detecting Common Origin of Atmospheric Electric Responses during SEP

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Evidence for strong and peculiar response of atmospheric electricity to SPE

Many experimental measurements for several decades demonstrate too strong & unusual response of the atmospheric electrodynamics during major solar proton events (SPE).

- At different latitudes: high, middle, and low
- In different atmospheric regions: in mesosphere (rocket-borne data); stratosphere (balloon-borne or rocket-borne data); and at ground level

Basic characteristics of interest: i) Conductivity $\sigma$; ii) Vertical electric field $E_z$ & current $J_z$

Peculiar features (unexplained for the majority of experiments):
- Extremely large and unusual non-transient, as well as transient, variations of $E_z$ & $J_z$;
- Reversals of electric field $E_z$ and related current $J_z$ for hours (i.e. non-transient).

Global atmospheric electric circuit (GEC) - simple representation

Electric conductivity, S/m

El. current $J_{fw} \sim 2$-3 pA/m$^2$ from ionosphere down to the surface in fair-weather regions.

Hypothesis: The variations observed in each experimental case represent the response of GEC to the processes in mesosphere at high & auroral latitudes driven by SPE.
I.1. In mesosphere and upper stratosphere: during major SPE 19-22 October 1989

Rocket-borne data was obtained on 21.10.1989 at 19.31 UT, at latitude 58.5°S (Zadorozhny et al., 1998). SPE (one of those with biggest fluence for E<10 MeV) is accompanied by major geomagnetic storm on 20-21.10 (on 21.10 index Kp reached 8+; Kp=8 during rocket launch).

Vertical electric field Ez reaches extremely high values in mesosphere (unexplained)

\[ Ez = +12.2 \text{ V/m at altitude } z=58 \text{ km, and } -9.7 \text{ V/m at } z= 46 \text{ km} \]

For comparison, for usual conductivities 2-6 x10^{-11} S/m and fair-weather current –2 pA/m² \( E_z \) should be about -100 mV/m i.e. smaller at least by two orders of magnitude; and well below that, as result of enhanced conductivity \( \sigma \) due to strong impact ionization during SPE.

**Fig.1.** Profile of vertical electric field Ez from rocket-borne data at latitude 58.5° (South Indian Ocean) on 21.10.1989, 19:31 UT during major SPE of GLE event type, and major geomagnetic storm (Kp=8): thick line. Peak values of Ez are the largest ever measured in mesosphere; much bigger than those in case of second largest peaks measured on 12.10.1989 (thin line).

Series of measurements in different locations in mesosphere for decades show, for most of the cases, unusually large (and still unexplained) vertical electric fields of the order of magnitude of 1 V/m, but never that large.
Balloon-born measurements took place in Antarctic middle stratosphere at 31-33 km during SPE on 20 January 2005 (with very hard spectrum: GLE’69) \( (Kokorowski et al., 2006) \). Balloon coordinates: from \((70.9^\circ S, 10.9^\circ W)\) to \((71.4^\circ S, 21.5^\circ W)\).

**Geomagnetic conditions:**

- a) From SPE onset at 06:51 UT until 14:00 UT – quiet;
- b) Increased geomagnetic activity from 14:00 UT until the end of day;
- c) Strong geomagnetic substorm after 15:54 UT.

**Main features of vertical electric field \(E_z\) and current \(J_z\)**

1. Non-transient large variations;
2. \(J_z\) reaches more than twice larger values than usual;
3. \(E_z\) changes its direction for many hours;
4. \(E_z\) has two jumps coinciding with SW changes.

**Essential of the experimental results:**

1. High and auroral latitudes, stratosphere

**Fig.2.** Time variations of: a) conductivity \(\sigma\); b) vertical electric field \(E_z\).

**Unexplained features:**

1. Typical moderate variations of related current density \(J_z\sim 2\) pA/m\(^2\) are strongly impaired here.
2. Too large integrated el. current across the balloon altitude for each of two time periods ~08:30-14:00 UT and from 16:00 UT on. The origin of the large amount of the transited electric charge is unknown.
Ez at ground level: during three SPE of GLE type in 2001, on 14.04, 18.04, 04.11

Measurements of Ez in: i) Apatity, Russia (67.3°N, 33.2°E), geomag. latitude +63.8°; and ii) Vostok station, Antarctica (geomag.lat. -89.3°) on 14.04, Shumilov et al., (2015).

Variations of Ez observed are between about -1 and +1 kV/m (typically, Ez~100 V/m)

Unexplained Peculiarities: i) Unusually large variations; ii) non-transient reversals of Ez.

We have examined several hypothetic mechanisms to explain these data - no success!

The new idea is that the observed variations of Ez & Jz are mutually consistent via GEC.
Essential of the experimental results. II.1. Low latitudes, ground-level

Measurements of atmospheric electric field Ez at surface in CASLEO, Argentine (31.8°S, 69.3°W), at 2552 m altitude, for 15 major SPEs, Tacza (2018).

According to our point of view, the observed deviations in electric field Ez represent the response of GEC to SPE, or, more precisely, its response to effects of SPE in mesosphere at high and auroral latitudes.

Fig. 4. Results for atmospheric electric fields (AEF) during 15 major SPEs.

The average absolute deviation (in V/m) of AEF Ez from mean diurnal curve for Ez is shown.

Unambiguously, SPEs lead to significant deviations of Ez from its mean value.

The cutoff rigidity is 9.8 GV. Hence, the deviation hardly can be explained by a direct effect of energetic proton flux.

II.2. Middle latitudes, ground-level

Similar results have been obtained at low (Cobb, 1967) and middle (Reiter, 1978) latitudes.

Proton channels: 1) 4.2-8.7; 2) 8.7-14.5; 3) 15-44; 4) 39-82; 5) 84-200; 6) 110-500; 7) 640-850 MeV (Dashed curve is for electrons >2 MeV. Vertical line indicates launch time 19:31 UT.

Proton fluence for energies 1-10 MeV is among the highest ever observed.
Factors determining height distribution of relaxed protons in atmosphere

Stopping altitudes of energetic protons (dashed line) and electrons (solid line) as function of their energy.

Proton cutoff rigidity at 450 km by different values of Kp index, Rodgers et al.(2006)

- Each energetic proton that penetrates into atmosphere enters also an extra elementary positive charge \( q_e = 1.6 \times 10^{-19} \) into it.
- This extra charge cannot enter back the magnetosphere due to low energy of its (any) carrier.
- Hence, uncompensated positive spatial charge \( Q_{PT} = q_e n \) is being accumulated below about 150 km during SPE where \( n \) is the number of penetrated protons.
- Its neutralization can occur by precipitated electrons of same quantity from magnetosphere.
Analysis of rocket-borne measurements in auroral mesosphere on 21 October 1989

Even if very small part of this charge enters the atmosphere, it would be yet much larger than the charge in GEC from tropospheric sources evenly distributed at the globe: \( \sim 10^{-10} \text{ C/m}^2 \)

Hence, the uncompensated charge injected into atmosphere should be taken into account!

The problem of redistribution of electric charges in the atmosphere thus arises.

**Oversimplified model:** Uncompensated electric positive charges injected at the stopping altitude corresponding to protons initial energy, are transported then upwards towards increasing conductivity to the base of magnetosphere at \( \sim 150 \) km altitude. But the uniformly distributed charges at this altitude would have no effect on GEC below!

\[
\begin{align*}
\text{Integral Fluence for } 19-31.10 \text{ (cm}^{-2}) &; \text{ & Equivalent positive charge } Q_{PT} \\
>1 \text{ MeV} & \quad >5 \text{ MeV} \quad >10 \text{ MeV} \quad >30 \text{ MeV} \quad >60 \text{ MeV} \quad >100 \text{ MeV} \\
\text{pfu} & \quad 1.03 \times 10^{11} \quad 3.89 \times 10^{10} \quad 1.92 \times 10^{10} \quad 4.26 \times 10^9 \quad 1.23 \times 10^9 \quad 4.65 \times 10^8 \\
Q_{PT}, \text{ C/m}^2 & \quad 1.65 \times 10^{-4} \quad 6.24 \times 10^{-5} \quad 3.07 \times 10^{-5} \quad 6.82 \times 10^{-6} \quad 1.97 \times 10^{-6} \quad 7.44 \times 10^{-7}
\end{align*}
\]
Fig. 6. From the profile of vertical electric field $E_z$ at the time of rocket launch time (a) we derive the profile of electric charge density $\rho$ (b) from Gauss’s law $\text{div} \mathbf{E} = \rho / \varepsilon_0$, $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m is permittivity.

- We analyze the main layer $L_P$ of positive charge around 50 km and the total positive charge $Q_{LP}$ in it. This layer is hypothetically fed by the uncompensated positive charges injected during SPE. Any precipitation of protons from magnetosphere have no significant contribution to layer $L_P$.

- Layer $L_P$ is in quasi-steady state at the flight time since the decay of proton flux is very slow ($\sim 7\%$ per hour), and no other sources affect it. The conductivity $\sigma$ in $L_P$ satisfies then:

$$Q_{LP} / t_P = J_P$$

(1)

where $J_P(z) = F_P(z)q_e$ is the source current of newly injected uncompensated positive charges; $F_P(z)$ is the proton flux reaching altitude $z$), and $t_P$ is the relaxation time, $t_P = \varepsilon_0 / \sigma$. 
The source current $J_p$ is derived from the proton flux parameters (Fig. 5) by assumption that at the top of atmosphere ($\sim100$ km) the same flux as that measured at Lagrange point (such approximation has been used also by other authors).

With columnar charge density in $L_p$ $Q_{LP} \sim 10^{-10}$ C m$^{-2}$ and $J_p \sim 10^{-14}$ A m$^{-2}$ for the layer $L_p$, a rough approximation of conductivity $\sigma_{LP}$ in the layer $L_p$ around 50 km yields:

$$\sigma_{LP} = \frac{J_p \varepsilon_0}{Q_{LP}} \sim 10^{-15} \text{ S/m}$$

(2)

This incredibly low conductivity is necessary to avoid fast relaxation of the charge $Q_{LP}$. Such paradoxically low conductivity, if only relevant, could be due to presence of aerosol particles. Similar conclusion is made by Zadorozhny (2001), Holzworth and Goldberg (2004).

Similar large reduction of conductivity by several orders of magnitude has been derived from measurements of $E_z$ in NLC in mesopause by Holzworth and Goldberg (2004) (Fig. 7). They obtained for conductivity there $\sim 4 \times 10^{-13}$ S/m, i.e. decreased by several orders of magnitude.

Fig. 7. Vertical electric field measured in a noctilucent cloud around $\sim81$ km altitude (Holzworth and Goldberg, 2004). Conductivity is decreased by several orders of magnitude, which is due to aerosol particles, according to authors.
Main phases of creation and growth of aerosol particles. We suppose that during major SPE aerosol particles (APs) are being created and grow to larger particles; they also can carry multiple electric charge (up to 10\(^{-7}\)).

Physics of aerosol in stratosphere and mesosphere is not well developed yet.

**Presumed properties of layer of aerosol particles (APs) during strong SPE**

- Growth and multi-charging of APs during SPE;
- Grown up APs are stable and their mobility is very low;
- APs control mesospheric and stratospheric conductivities during SPE: these decrease strongly in time: hence, columnar resistance within an aerosol layer would increase;
- A significant portion of the uncompensated positive charge is being accumulated in the middle atmosphere forming a layer LP of positive charge which is descending in time.
Hypothetic model of redistribution of unsatisfied electric charges (when no EEP takes place)

**Fig. 8.** Representation of link in GEC between ionosphere and surface at high & auroral latitudes during SPE.

- Columnar resistances in the upper stratosphere, mesosphere and mesopause increase during SPE.
- Layer $L_P$ of uncompensated positive charge is built and developed together with the gradual increase of columnar resistances $r_{P1} + r_{P2}$ and $r_N$. Layer $L_N$ of negative charge is induced above layer $L_P$ due to the conductivity gradient.
- Relaxation of the charge $Q_P$ occurs through the upward $J_U$ and downward $J_D$ currents. $J_U$ and $J_D$ are superimposed to fair-weather current $J_{FW}$.
- If $r_{P2} + r_N > ~ r_{HT} + r_{P1}$, the downward current $J_D$ is significant;
- $J_{FW}$ decreases with increase of resistances.

For large downward electric field $E_z$ in stratosphere and lower the requirements are:

1) The columnar charge density $Q_{LP}$ is large enough;
2) $r_{P2} + r_N > ~ r_{HT} + r_{P1}$. 

$r_{HT} \sim \text{const}$ is tropospheric columnar resistance; $r_{P1}, r_{P2}$ & $r_N$ are strongly varying columnar resistances.
Analysis of measurements in Antarctic stratosphere on 20.01.2005 (Kokorowski et al., 2006), first phase: $t_0=06:51 – t_2=14:00$ UT (quiet geomagnetic conditions)

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**Fig. 8.** Data during first phase, 06:51-14:00 UT

- From $t_0=06:51$ until $t_1=08:40$ UT the vertical electric field $E_z$ is small and mostly positive. The inverse direction of $E_z$ is result of protons of energies $\sim 100$ MeV which penetrate below the balloon whose charges then form an upward current $J_{HEP}$ which is larger than the decreased fair-weather current $J_{FW}$.

- At time period $t_1 - t_2$ the downward current $J_D$ enlarges and $J_{FW} \ll J_D$ due to the enhanced charge $Q_{LP}$ and increased columnar resistances $r_{P2}$ and $r_N$.

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**Link between surface & ionosphere in GEC at high latitudes. Increase of current $J_D$ begins at $t_1$.**
Analysis of measurements in Antarctic stratosphere (Kokorowski et al., 2006), second phase after 14:00 UT (geomagnetically disturbed)

**Fig. 9.** Second phase: 14:00 – 00:00 UT

- With the increase of geomagnetic activity at $t_2 = 14:00$ UT the vertical electric field $E_z$ jumps from extremely large negative values to almost zero, possibly, due to weak electron precipitation which imports negative charge descending towards layer $L_P$.

- The second jump at $t_3 = 15:56$ UT (the substorm onset) is caused, possibly, by stronger EEP. Layer $L_P$ is filled with negative charges $Q_N$ which increases and descends quickly. Aerosol particles are controlling charge carriers. Before 15:56 UT the current $J_U$ below $L_P$ is small yet, and compensated by the fair-weather current. At 15:56 UT intensified recharging of layer $L_P$ occurs, and an upward current $J_U > 0$ surface-to-stratosphere is quickly generated.
Interpretation of AEF Ez variations at surface for SPE 14.04.2001 (Shumilov, 2015)

**Fig.10.** Ground-level electric field Ez in: a) Apatity ($\Lambda=+63.8^\circ$) on 14.04.2001 and b) Vostok, Antarctica ($\Lambda=-89.8^\circ$); c) GOES-10 integral fluxes: 1) electrons >2 MeV; 2)-4): protons >1 MeV, >10 MeV, >100 MeV.

**Ez behavior resembles that in stratosphere Figs.8-9**
- Relatively small Ez for the first two hours is due to initial gradual growth and charging of APs in stratosphere and mesosphere;
- After that, increase of Ez to untypically large values is due to increase of downward current JD from the upper stratosphere to surface, as in Fig.8;
- Transient reversal of Ez reaching ~ -1 kV/m, could be due to EEP or REP, similarly to Fig.9.
- The increase of Ez up to almost +1 kV/m at Vostok station possibly represents the GEC response to effects of EEP at auroral latitudes.
Coordinates: (31.8°S, 69.3°W); altitude: 2552 m asl.

List of 15 Solar Proton Events Examined

<table>
<thead>
<tr>
<th>Year</th>
<th>Start Date/Time (UT)</th>
<th>Proton Fluence (protons/cm(^2) day sr)</th>
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<td>8.4e + 03</td>
</tr>
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<td>2011</td>
<td>23 September/02:00</td>
<td>7.7e + 03</td>
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<td>1.6e + 05</td>
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<td>17 May/02:00</td>
<td>3.2e + 05</td>
</tr>
<tr>
<td>2012</td>
<td>12 July/17:00</td>
<td>3.7e + 03</td>
</tr>
<tr>
<td>2012</td>
<td>19 July/07:00</td>
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<td>18 April/13:00</td>
<td>1.3e + 04</td>
</tr>
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Picked up is the SPE on 17.05.2012; it has the largest fluence.
Average deviation of AEF Ez for 14 SPE (without marked one) from diurnal curve

Features: Increase of $\Delta E_z$ (up to 15%) for the first ~17 hours from the beginning of SPE. Then, only slight (~5%) and short (~3 hours) decrease can be seen.
Deviations of atmos. el. Field $E_z$ at CASLEO during SPE 17 May 2012 (Tacza et al. 2018)

**Fig.11b.**

- Energetic proton flux for protons $>10$ MeV, $>50$ MeV, and $<100$ MeV from GOES-11 measurement data (upper panel).

- Atmospheric electric field $E_z$ at ground level; data is from stations CAS1, CAS2 at altitude 2552 m asl. (two lower panels). The mean diurnal curve of $E_z$ is shown in red, and $E_z$ during during SPE – in black.

**Properties:** As opposed to previous case, $E_z$ has first a negative deviation from the standard diurnal curve up to $\sim 15\%$ for 4.5 hours, then a positive deviation increase (up to $\sim 40\%$) for next 7 hours.
Interpretation of electric field $E_z$ deviations as response of GEC to SPE

**Fig. 12.** Model representation of GEC. The uncompensated positive charge in layer $L_p$ at high latitudes is redistributed to lower latitudes by currents $J_D$ (downward, at high latitudes), $J_S$ (through surface) and $J_{LT}$ (upward, at lower latitudes) which contribute at lower latitudes to induced tropospheric spatial charge $Q_{TC}$. Key characteristics are the positive charge $Q_p$ and resistances $r_{P1}$, $r_{P2}$, $r_N$ which increase in time during SPE. They determine the upward current $J_{LT}$. For weaker SPEs $J_{LT}$ at low latitudes is less than the enhancement of $J_{FW}$ due to the increase of ionospheric potential; the result is increase of $J_z$ and $E_z$. Stronger SPEs cause first, in opposite, an increase of $J_z$ and of charge $Q_{TC}$. At later phase $Q_{TC}$ is relaxed partially and contributes for the increase of $J_z$. 
CONCLUSIONS

- Large electric fields ~10 V/m measured in mesosphere at auroral latitudes during major SPE are hypothetically considered as result of development of aerosol layers in which the electric conductivity gradually decreases to very low values.

- During major SPE significant uncompensated positive electric charge can be accumulated in mesosphere and stratosphere. As result, downward current $J_D$ to the surface can arise.

- Unexpectedly large and quite untypical non-transient variations of the vertical electric field $E_z$ and related current $J_z$ in the middle stratosphere at auroral latitudes during major SPE can be result of the downward current $J_D$ when no EEP occurs.

- Four phases detected in electric field variations in Antarctic stratosphere during GLE69 are consistent with the hypothetically predicted processes in mesosphere.

- Electric field variations at surface at auroral latitudes can be explained in similar way.

- Experimentally observed large and untypical variations of the electric field and current in different atmospheric regions and at different latitudes represent GEC response to processes in high-latitude mesosphere driven by SEP.

- SEP-driven hypothetical processes of aerosol creation and growth in mesosphere and upper stratosphere at high and auroral latitudes, is important factor in physico-chemical atmospheric processes, particularly concerned to small constituents.

- Large variations of electric currents in the troposphere possibly affect weather formation.

- The presented hypothetic considerations indicate GEC as effective mediator between sun and atmospheric physico-chemical processes.
THANK YOU