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Observations Supporting Hypothesis for Global Electrical Circuit as Mediator between Solar Events and Weather

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Abstract.

Some of the few available experimental studies are discussed which demonstrate peculiarities of the local response of the global atmospheric electrical circuit (GEC) to major solar proton events (SPE), concerning conductivity, the fair-weather electric current J_z from ionosphere to ground, and the related field E_z. For more representative picture, these experiments include auroral and lower latitudes, as well as different altitudes: the ground level, stratosphere and mesosphere. The experimental data show typical peculiarities: although these are not fully understood yet, they can give a key to the global response of GEC to SPE. It is concluded that a relevant 3D dc model of GEC is necessary to determine factors and physical conditions which would lead to the locally observed characteristics.

Introduction

The aim of this work is to demonstrate the specific peculiar response of the global atmospheric electrical circuit (GEC) during major solar proton events (SPEs) seen from the available experimental studies performed in different atmospheric locations. These comprise measurements of the main electrical characteristics (conductivity σ, electrical field **E** and current density **J**) within several groups: a) at high and middle latitudes - balloon experiments at altitudes between 26 km and 31 km, as well as rocket measurements in stratosphere and mesosphere; b) ground-based measurements at high and low latitude. All these experimental studies demonstrate peculiar and large variations which cannot be predicted theoretically [*Farrell and Desch*, 2002]. Some factors are formulated in this work which can be responsible for the demonstrated peculiar behavior, together with their further analysis. The main future goal is to clarify the global-scale behavior of GEC during SPEs. Recent studies demonstrate that SEP can affect weather [*Veretenenko*, 2017], with GEC as hypothetical mediator between solar drivers and weather formation. According to the hypothesis [*Tinsley*, 2000] weather formation is affected by variations of the electric current J_z of few pA/m^2 which flows in GEC from the ionosphere to the surface in fair-weather regions where J_z influences creation of cloud and the atmospheric circulation.

Peculiarities demonstrated from experimental results in stratosphere

a) Measurements in Antarctic stratosphere during SPE'69 (GLE) on 20 January 2005

Fig.1 demonstrates data from GOES-10 for the solar proton flux during SPE'69 on 20.01.2005 (the upper-left panel), together with the simultaneously obtained balloon-borne data for the conductivity σ (the lower-left panel), the vertical electric field *Ez* (the upper-right panel), and the related current density *Jz* (the lower-right panel) in Antarctic stratosphere at coordinates between (70.9°S, 10.9°W) and (71.4°S, 21.5°W), and at altitude 30.9 - 33.2 km [*Kokorowsky et al.*, 2006; 2012]. Some of the peculiarities of the observed characteristics (not satisfactorily explained yet) are discussed by us here. Before the SPE onset at 06:51 UT σ, *Ez*, and *Jz* have typical values: σ is few $\times 10^{-10}$ S/m; the electric current *Jz* is downward, with mean value ~2 pA/m^2, however *Ez* and *Jz* are unusually dispersed. After SPE onset, till 13:48 UT: *i*) the conductivity σ increases due to ionization by protons with energies ~100 MeV - initially ~20 times or more; *ii*) *Ez* initially suddenly drops almost to zero, then *Ez* increases to its usual values; *iii*) *Jz* shows large variations to values about 5 times larger than usually. In the period

13:48-5:58 UT conductivity exceeds 5-10 times its usual values, and *Ez*, as well as *Jz* remain close to zero. After 15:58 UT *Ez* and *Jz* suddenly change their direction from downward to upward for at least 5 hours, yet *Jz* exceeds more than twice its typical value. This occurred together with the sudden increase of protons with energies <5 MeV which do not reach stratosphere. Also, a geomagnetic storm (12:00-18:00 UT; Kp= 4o, 5-), and a strong sub-storm from ~15:00 till ~18:00 UT (with AE~1200 nT) occurred. The current *Jz* remained reversed to upward for hours, yet exceeds more than twice its typical value (these last features are hard to explain). Although SPE'69 causes dramatic modification of conductivity σ in the middle atmosphere at high latitudes due to strong ionization, as demonstrated in Fig.2 [*Usoskin et al.*, 2014], the model results by the well-known oversimplified 1D model presentation of GEC by an equivalent circuit predicts that changes of *Jz* are <~5%; thus, this model does not predict the large and long-time variations in Fig.1.

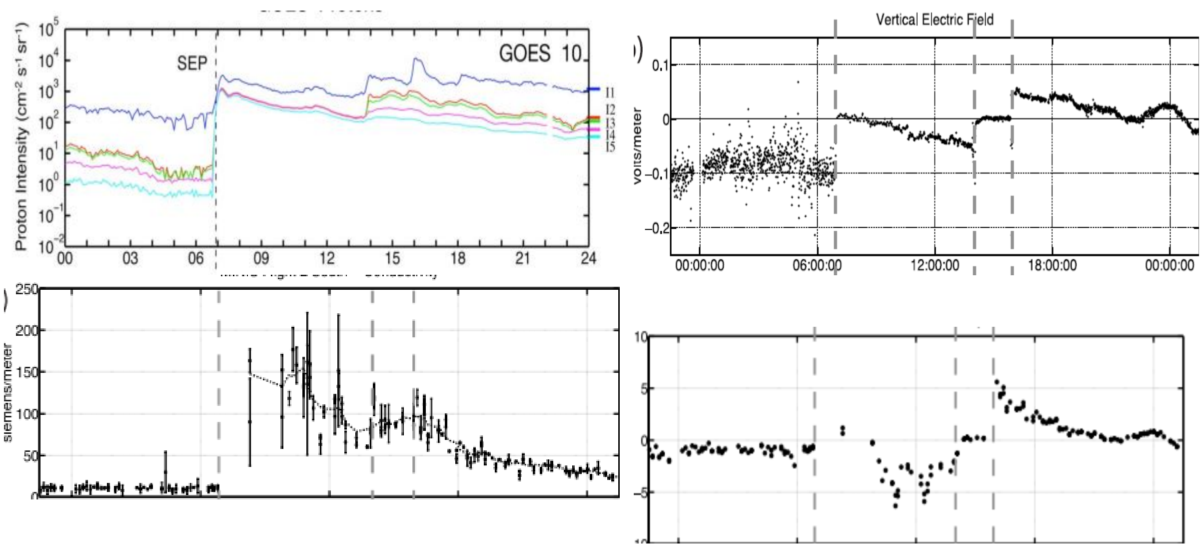

Fig.1. Data from GOES-10 for the integral proton intensity energies for channels > 1, 10, 30, and 50 MeV (the upper-left panel); simultaneous measurements of conductivity σ (the lower-left panel); vertical electric field Ez (the upper-right panel); and the vertical current density Jz (the lower-right panel) computed from σ and Ez [Kokorowski et al., 2006; 2012].

Similar model estimations are obtained also by [*Farell and Desh*, 2002], in contradiction with experimental data for E_z and J_z.

b) Measurements in stratosphere at middle latitudes during SPE on 16 February 1984

During SPE (with GLE) on 16 Feb.1984 the electric characteristics σ, *Ez*, and *Jz* were obtained on a balloon payload EMA-8 with coordinates (44.6°S, 142.7°E), Λ=-56.3° [*Hozlworth et al.*, 1987]. Data obtained are presented in Fig.2. This SPE occurred in short time period (~ one hour). Simultaneously was obtained data from identical payload EMA-7 located on lower latitude (Λ=–48.8°) which indicated no effect of SPE on σ, *Ez*, and *Jz*. Both σ and *Ez* increased initially (σ enhanced more than twice); *Jz* also increased (2.2 times). Peculiarities of perturbations of σ, *Jz*, and *Ez*, though smaller and in shorter time, resemble those demonstrated in Fig.1**.** These perturbations are also in contradiction with modeling [*Farrell and Desch*, 2002], and are even more striking than in the former case, since they take place at latitude with much higher cutoff rigidity (> 1 GV).

Features of vertical electric fields in mesosphere and stratosphere

In a series of rocket experiments above Heiss Island (80°37N, 58°03E) and above southern Indian Ocean [*Zadorozhny et al.*, 1998] found unusually large (~1 V/m) vertical electric field

Ez in the mesosphere which still remain unexplained. Fig.3 demonstrates profiles of *Ez* in three cases above Indian Ocean. On 21.10.1989 19:31 UT, at (58.5°S, 51.1°E), Λ=62.7°S the electric field *Ez* (presented by thick solid line) reached much larger peak in mesosphere (12.2 V/m) than in all other cases (the second largest peak *Ez* was for 12.10.1989 shown in Fig.3 by dashed line). The first case on 21.10 coincided with both strong solar proton event and major geomagnetic storm (with Kp=8) which cause the enhancement of *Ez*.

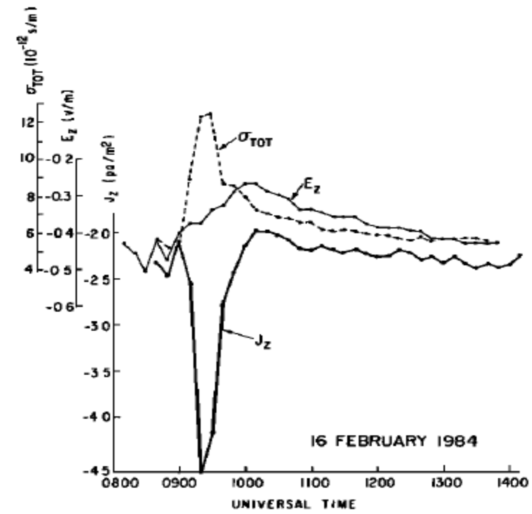

Fig.2. Conductivity σ_{TOT}, vertical electric field E_z and current density $J_z=\sigma E_z$ during SPE on 16 Feb.1984 from balloon-borne measurements at 26 km altitude, at (44.6°S, 142.7°E), Λ=–56.3°.

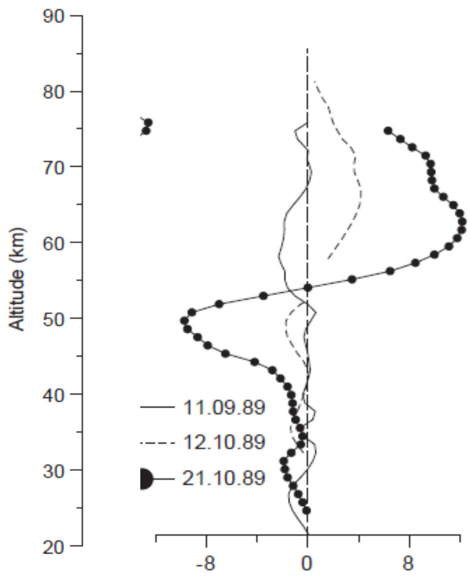

Fig.3. Vertical electric fields Ez measured in Southern Indian Ocean in 1989 on: 11 September 20:15 UT at (52.4°S, 41.07°E) (thin solid line); 12 Oct. 18:30 UT at (57.1°S, 45.0°E) (dashed line); 21 Oct., 19:31 UT at (58.5°S, 51.1°E) (thick solid line). First two cases are during quite geomagnetic conditions. The last case is during a major geomagnetic storm (Kp=8) and GLE.

The following peculiarities are observed: *i*) Paradoxically large and still unexplained electric fields *Ez* are observed in mesosphere and stratosphere in large number of cases; in Southern hemisphere *Ez* peaks are often much bigger than those in Heiss Island (80.6°N); *ii*) usually, direction of the vertical electric field *Ez* changes at ~50 km, but while on 11.09 *Ez* points to downward above 50 km and to upward below, in the other two cases it is upward above 50 km and downward below. The positive and the negative *Ez* peaks have comparable values. The source of the large electric fields in mesosphere is under debate. [*Zadorozhny et al.*, 1998], etc. suggested as hypothetical factors effects of charged aerosol particles and decreased conductivity.

Behavior of potential difference *Ez* at surface during SPEs

a) High latitudes (Kola Peninsula) during two major SPEs in 2001

Measurements of air-earth current (AEC) *Jz* and the potential difference (PD) *Ez* at ground level at high latitudes have been realized in very few places and for limited periods of time. Fig.4 demonstrates observed variations of *Ez* in Apatity (Kola Peninsula, Russia) at geomagnetic latitude 63.3° during two major SPE (with GLE) in 2001: SPE-1 on 18 April, and SPE-2 on 4 November [*Kasatkina et al*., 2009]. In both cases CMEs took place. The following features are valid: 1) Variations of *Ez* strongly enhance after the beginning of SPE; (*Ez* can enhance up to ~1 kV/m); 2) For both SPEs the behavior of *Ez* in the first and the second phase of a SPE is quite different: in the first phase *Ez* varies strongly, yet remains positive; in the second phase *Ez* becomes sometimes negative; its negative peaks can be as large as positive ones.

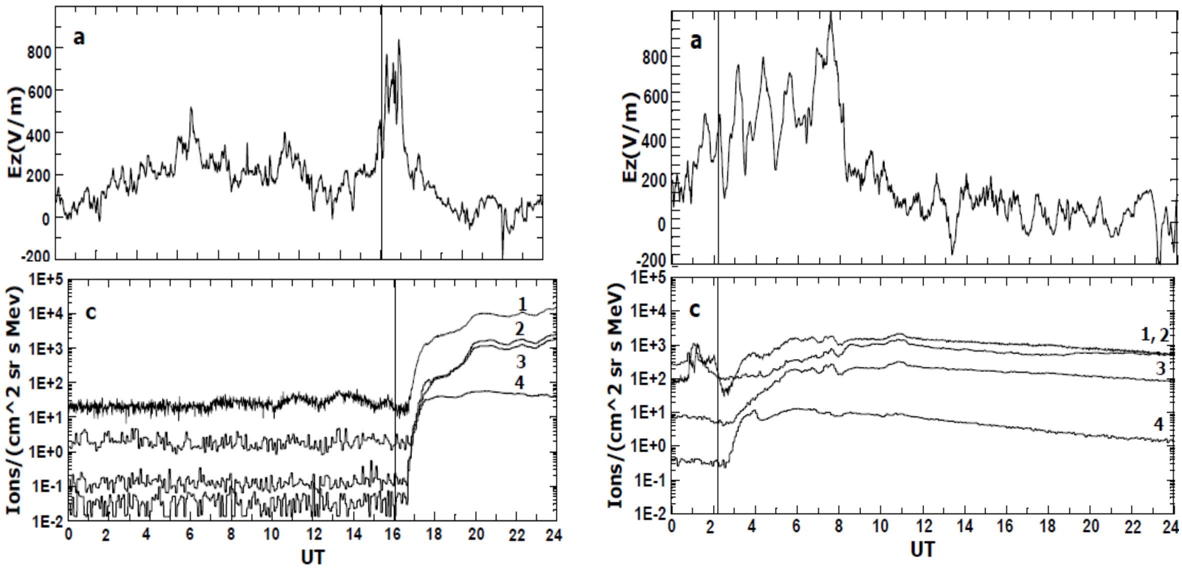

Fig.4. Potential difference Ez at surface in Apatity during SPE-1 on 18.04.2001 (left upper panel) and SPE-2 on 04.11.2001 (right upper panel). The two lower panels show the integral proton intensity energies for channels > 1, 10, 30, and 50 MeV (marked by numbers from 1 to 4 for SPE-1 and SPE-2, respectively. The vertical line marks the flare onset.

b) Low latitudes

Fig.5 demonstrates ground-level variations of the potential difference E_z, (denoted here as atmospheric electric field, AEF) at low latitudes: in CASLEO, Argentina (31.8°S, 69.3°W) at 2552 m altitude during SPE (GLE) on 17.05.2012 [*Tacza et al*., 2017]. Data for E_z in the upper and the lower panels shown by black lines are obtained respectively from measurements at two stations, CAS1 and CAS2. The red lines in both panels show the average electric field E_{za}. Data show significant and typical deviations for a period of ~10 hours from the SPE onset at 0 UT. During the first phase (for 3.5 – 4 h) E_z is well smaller than E_{za}; then, for the next 5-6 hours, E_z becomes well larger than E_{za}, as indicated by arrows. Similar features take place also for a group of 8 solar proton events: during the first phase of SPE the measured electric field E_z is lower than its average value for few hours, and the relation is opposite in the second (somewhat longer) phase of SPE. This pattern of E_z during SPE at low latitudes is 'reversed' compared to that high latitudes (although the last is stronger expressed). This indicates that the global-scale reaction of GEC to SPE is of interest.

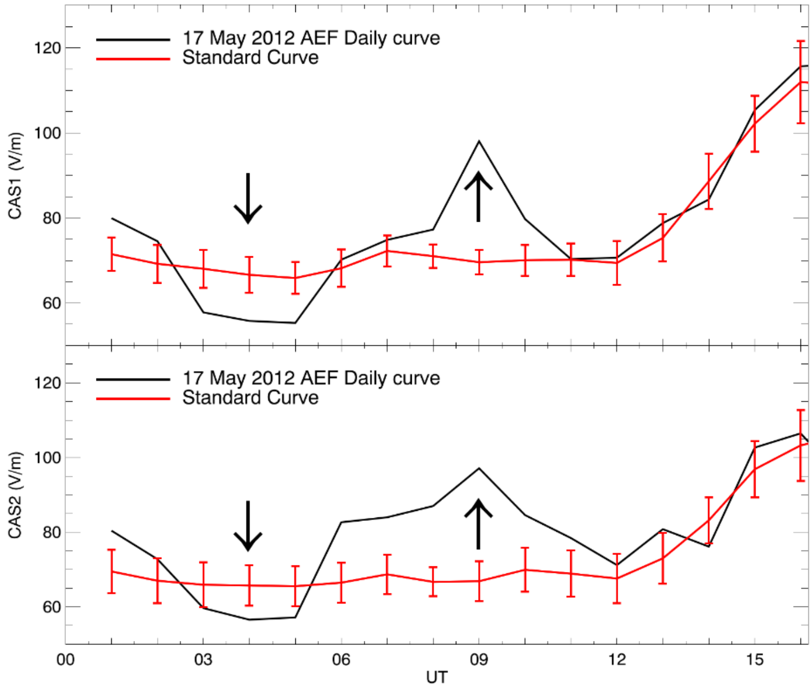

Fig.5. Atmospheric electric field (AEF) measured at CASLEO, Argentina (31.798°S, 69.295°W) at 2552 m altitude, during GLE on 17 May 2012 [Tacza et al., 2017].

Factors hypothetically possible to enforce effects of SPE on GEC

All considered here results in Figures 1-5 demonstrate that the response of GEC to a SPE is much stronger and specific than predicted by modeling [Farrell and Desch, 2002]. For a possible explanation, four factors are considered in this work as hypothetically responsible for the specificity of the considered measurements.

Factor 1. Increase of conductivity σ in middle atmosphere at high latitudes by enhanced ionization by solar proton flux.

Factor 2. More effective electrical coupling of auroral ionosphere with GEC during SPE due to enhanced conductivity in middle atmosphere at high latitudes. Even penetration of a tiny part J_{IS} of FAC (say, ~10^{-6}) into the middle atmosphere (due to larger conductivity during SPE) could be significant as superposed current in GEC. The total ionosphere-to-ground current *Jz* would be then $J_z = J_{TS} + J_{IS}$ where J_{TS} is the current from tropospheric sources [*Tonev*, 2018]. The relation between the geomagnetic activity and the current density J_z in auroral stratosphere has been first supported experimentally by balloon-borne data series [*D'Angelo et al.*, 1982].

Factor 3. A series of studies demonstrate that SPE can produce aerosol particles in the stratosphere [*Mironova et al.*, 2014] and thus can cause decrease of the conductivity.

Factor 4. Penetrating energetic solar protons during SPE could create regions with charged particles, leading to formation of electric fields.

In order to take into account, the possible effects of these factors on the electric characteristics new more adequate models of GEC (2D and 3D, as well as steady-state and quasi-statistic) have to be developed as future tasks.

Conclusions

1. Peculiar variations of the vertical electric field Ez and related current density Jz are observed during major SPEs at different altitudes and latitudes which are not explained in terms of equivalent electrical circuit. The responsible mechanisms should be searched.
2. Four factors are formulated which can play role in creation of the observed specific and large local variations in GEC during SPE.
3. Development is needed of 2D and/or 3D model of GEC with account to Factors 1-4.

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