The tenth Workshop "Solar Influences on the Magnetosphere, Ionosphere and Atmosphere“,

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Electrical coupling of auroral ionosphere with lower atmospheric regions during SEP

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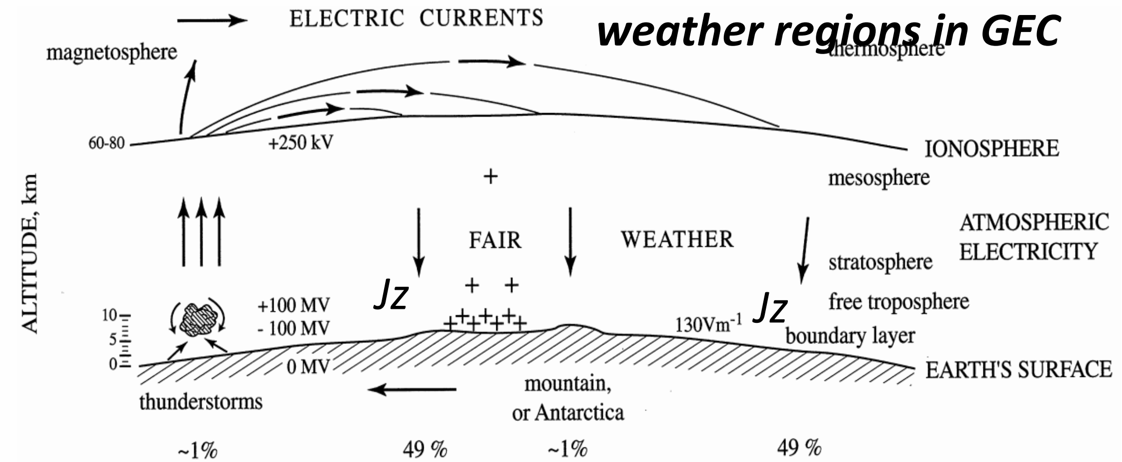
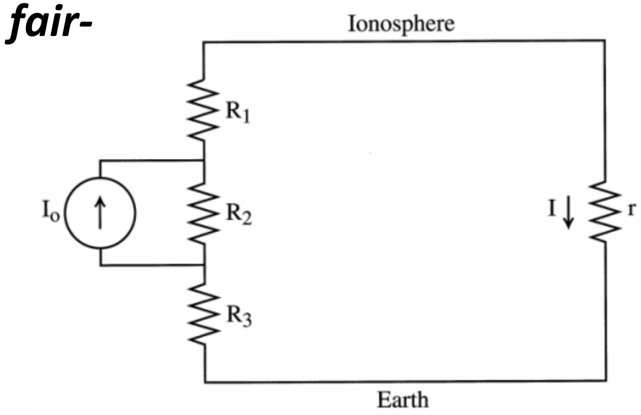
Influence of SPE on GEC and, in particular, on electric current Jz (which flows from ionosph

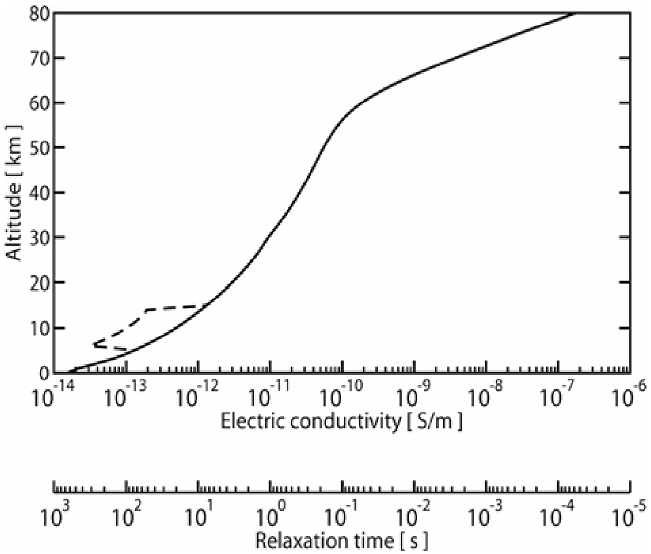
Ionosph-ground current Jz in fair-weather regions in GEC



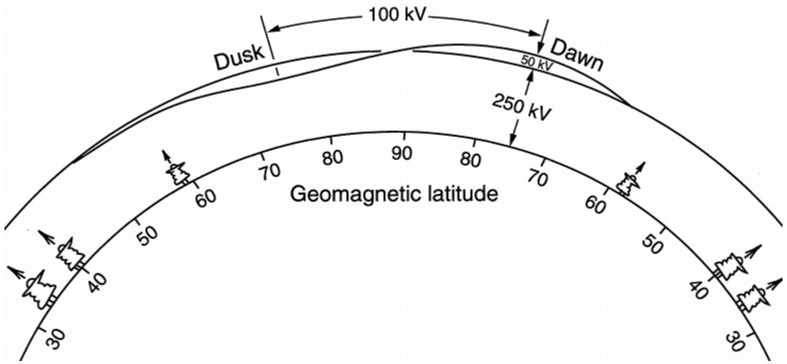


Equivalent electrical circuit. Column resist-s *r*, $R = \int dz/\sigma(z)$ by resp. height interval.

- Ionospheric potential relat.to surface: $V_I \sim 250$ kV
- Ionosphere-ground current $J_z = 1 - 4 \times 10^{-12}$ A/m^2 (typically 2 pA/m^2)

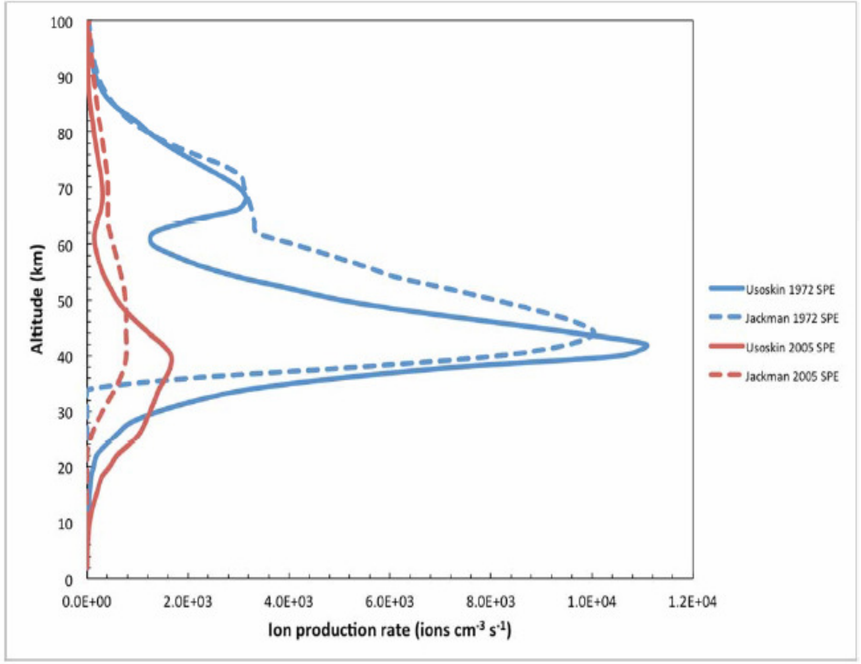


Atmospheric conductivity profile σ(z)

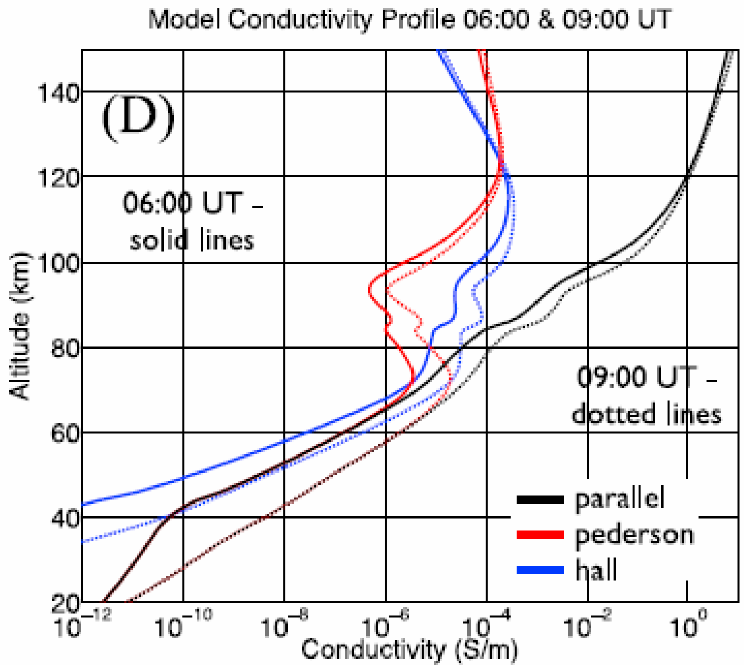


Trans-polar potential difference in auroral ionosphere ~20 to >~150 kV

Ionization effects of solar proton events (SPE) in atmosphere



Profiles of ionization rate ***q*** for two SPS woth GLE, resp. on 04.08.1972 (blue curves) and SPE-69 on 20.01.2005 (red curves) acc. to models of Usoskin (solid curves) and Jackman (dashed curves).



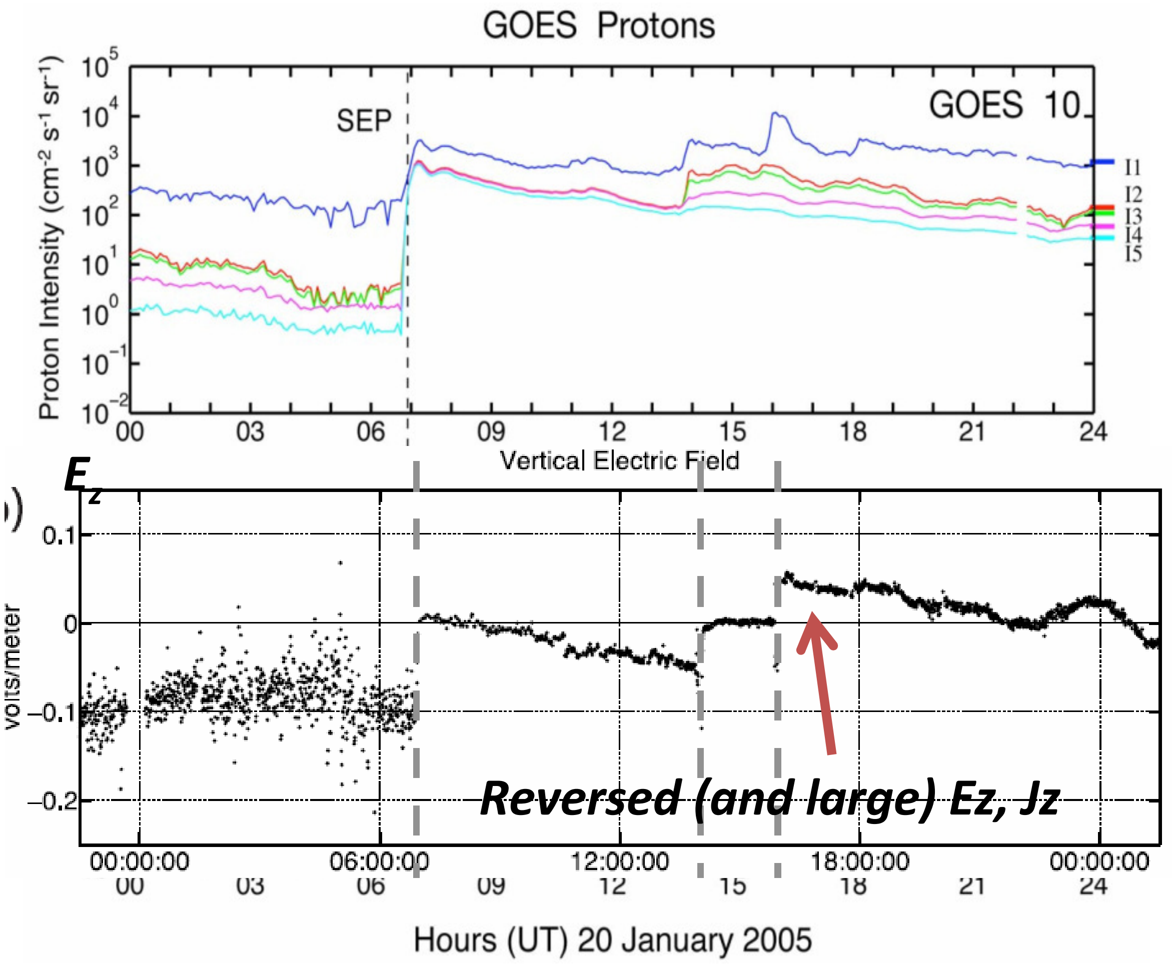
Model profiles of conductivity: field-aligned σ_0 (brown curves), Pedersen σ_P (red), Hall σ_H (blue) before (solid) and during (dashed lines) SPE-69 (20.01.2005) (Kokorowski et al., 2012).

SPE causes increase of conductivity in high-latitude atmosphere

- Little in the high troposphere: usually up to few tens of percent
- In stratosphere and above: up to two orders or more

Effects of SPE on fair-weather current Jz and relative el.field Ez

Experimental results in high-lat stratosphere (Kokorowski et al., 2006)



GOES-10 proton energy channels I1-I5 for <1, 5, 10, 30, 50 MeV (Kokorowski et al., 2012).

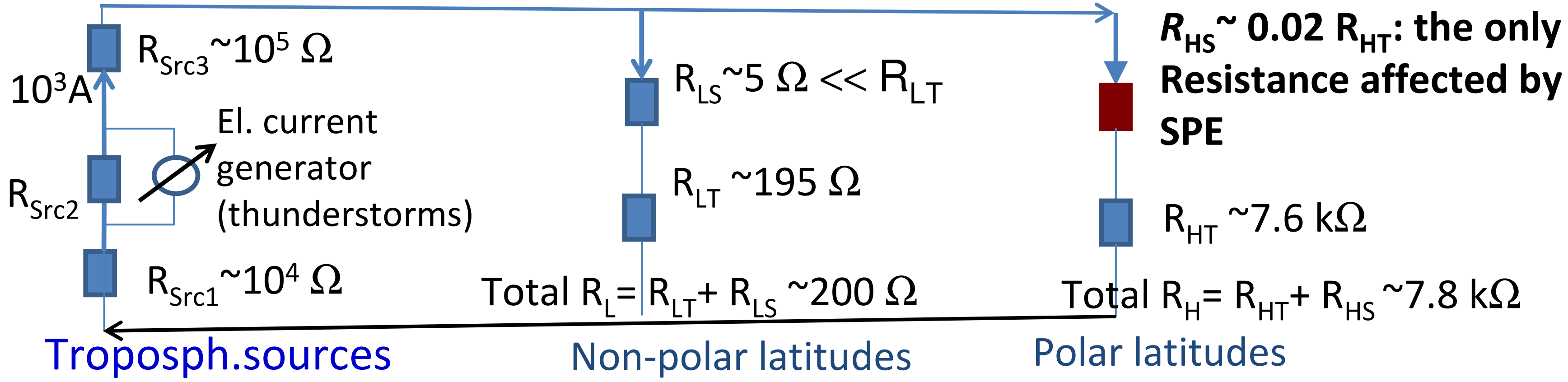
Vertical electric field *Ez* at height 31-33 km from balloon flying from (70.9°S, 10.9°W) to (71.4°S, 21.5°W). Local conductivi-ty σ increased 5-20 times.

Most striking feature: as response to SPE, *Ez* reverses its direction to upward (not transiently), and is too large. Similar features shows current Jz. Similar peculiarities are also demonstrated experimentally during SPE.

Unexplained features of el.current Jz in polar stratosphere

- Jz exceeds twice or more its typical value of 2 pA/m^2
- Jz reverses to upward for hours and remain large in later phase of SPE
- Jz shows also another peculiarities – a subject of another study
- Similar peculiarities have been observed also in other cases of SPE

Theoretical estimation of GEC response to SPE



R_{Src3}~10^5 Ω

10^3A

El. current generator (thunderstorms)

R_{Src2}

R_{Src1}~10^4 Ω

R_{LS}~5 Ω << R_{LT}

R_{LT} ~195 Ω

Total R_L= R_{LT}+ R_{LS} ~200 Ω

R_{HS}~ 0.02 R_{HT}: the only Resistance affected by SPE

R_{HT} ~7.6 kΩ

Total R_H= R_{HT}+ R_{HS} ~7.8 kΩ

Troposph.sources

Non-polar latitudes

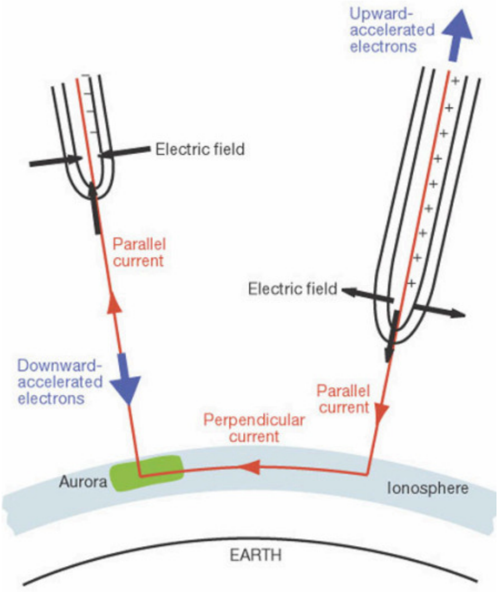
Polar latitudes

SPE affects conductivity, hence resistances in equivalent el. circuit Only resistance R_{HS} (of stratosphere and above at high latitudes) is changed significantly due to the cut-off rigidity factors. Since R_{HS}<<R_H current Jz in GEC will change up to ~5% (Farell and Desh (2002),Tinsley (2007)

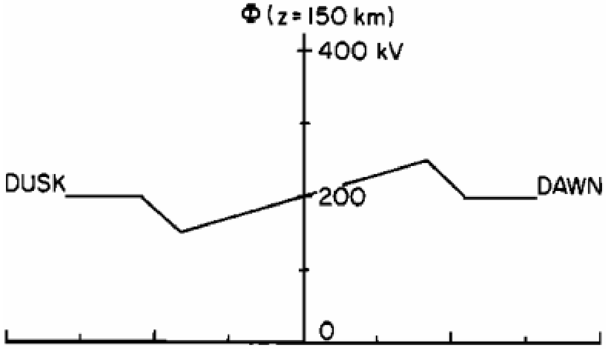
To solve discrepancy between experiments and modeling, we suggest that:

At high lat-s $J_z = J_{TS} + J_{IS}$. Here J_{TS}, J_{IS} are currents from tropospheric and from ionospheric sources. J_{IS} is an agent of SW-GEC coupling via FAC

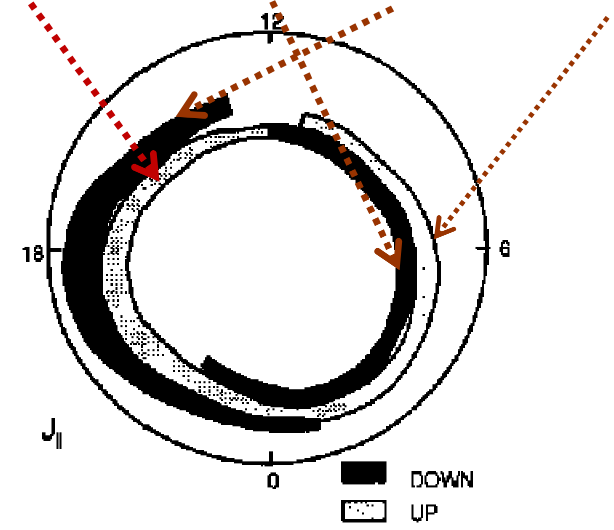
Field-aligned currents (FAC) and related phenomena in auroral ionosphere



System of FAC in auroral ionosphere: the closure currents principally flow in E-region

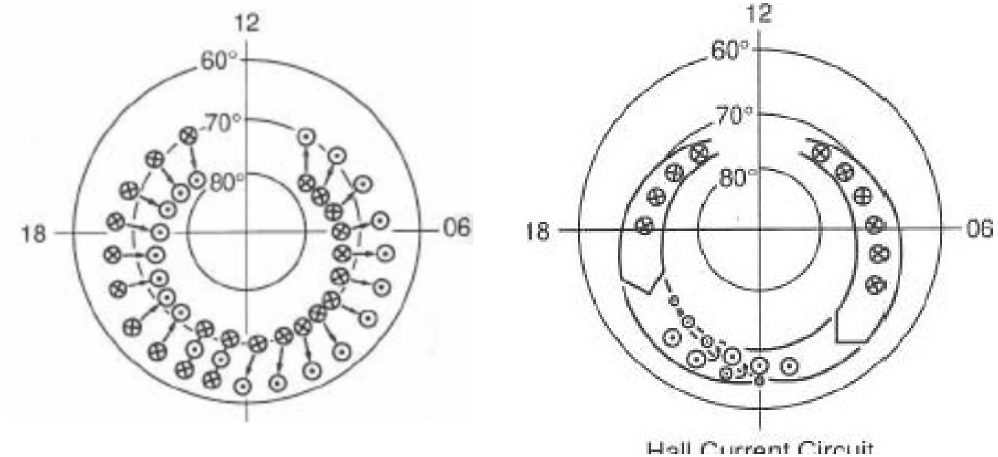


Trans-polar difference of el.potential in auroral ionosphere (non-uniform disribution)



Region 1, 1-3 MA

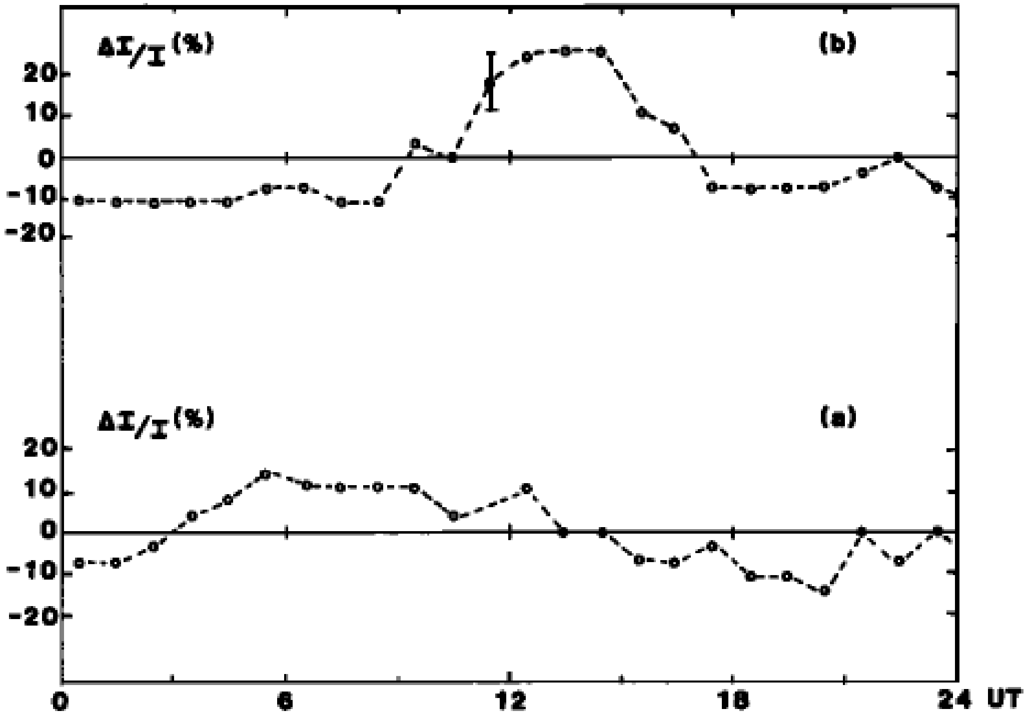
Region 2 <~ R1



Systems of Pedersen (left) and Hall (right) currents in auroral ionosphere.

Relationships betw. trans-polar potential and GEC at high lat-s

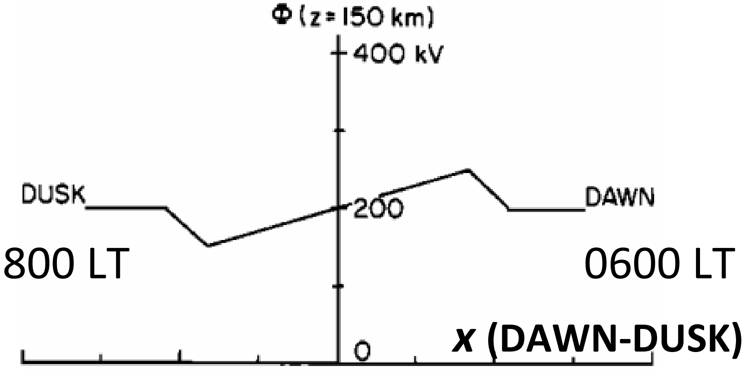
Supporting experiments in auroral stratosphere (*D'Angelo et al.,1982*)



Data for Jz are from 10 balloon experiments (1200 hours) with East-West drift (from 16°E to 95°W) at constant geogr. lat ~69.5° and geomag.lat. from 66° to 81°; altitude 30- 25 km. Diurnal Jz curve by $Kp \leq 2$ agrees with Carnegie and Markson curves.

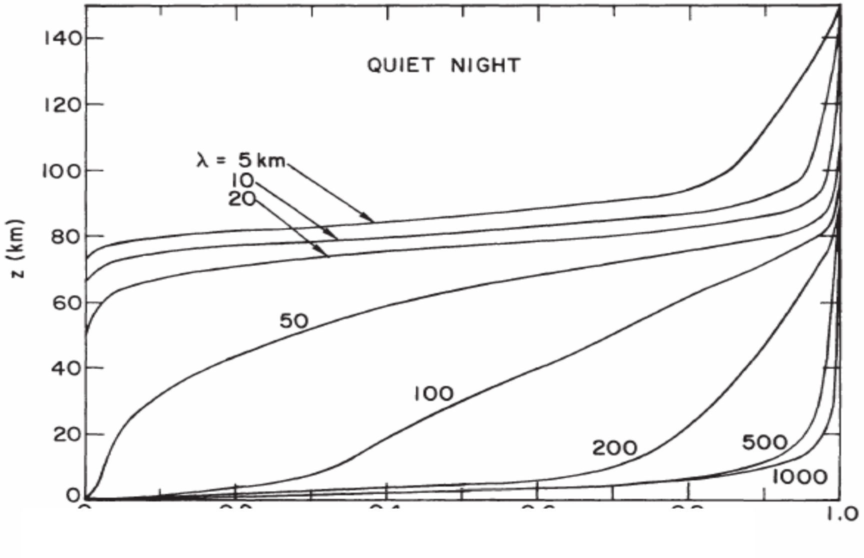
Fig. Deviation of Jz (in %) under disturbed conditions ($Kp>2$) from the curve for Jz by undisturbed conditions: (***a***) first two days of flights (closer to 16°E); (***b***) last two days of flights (closer to 95°W). Deviations up to 20% of *Jz* are observed whose sign correlates with direction of FAC above: positive when LT is closer to sunrise, and negative for LT closer to sunset.

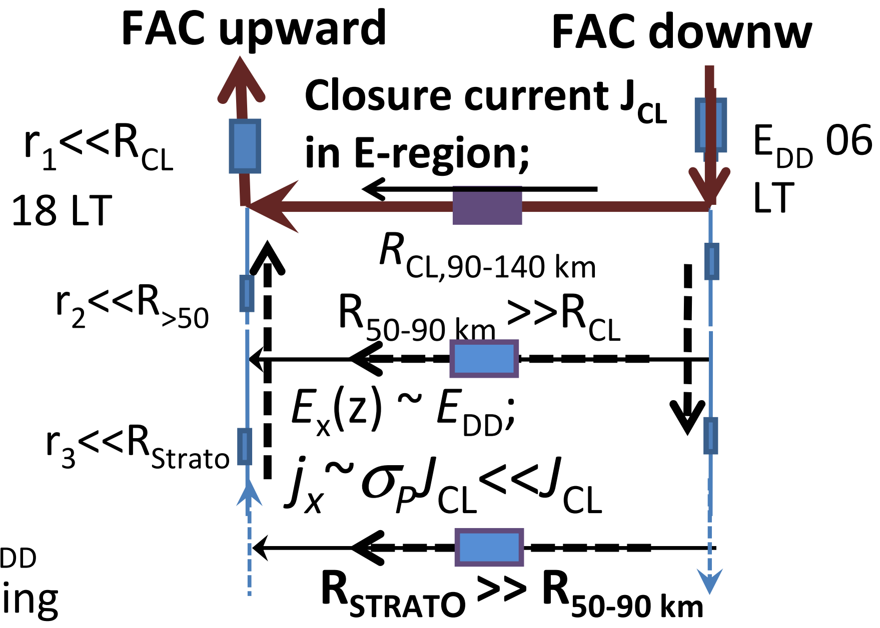
Supporting model studies (Park, 1976, Dejnakarintra et al.,1987)



El.potential Φ in auroral ionosphere

Downward mapping of trans-polar electric field E_{DD} (dawn-dusk) below auroral structures of Φ. Mapping factor f_M: $E_x(z) = \boldsymbol{f_M} E_{DD}(150\text{ km})$.





FAC upward

FAC downw

Closure current J_{CL} in E-region;

$r_1 << R_{CL}$

18 LT

E_{DD} 06 LT

$R_{CL,90\text{-}140\text{ km}}$

$r_2 << R_{>50}$

$R_{50\text{-}90\text{ km}} >> R_{CL}$

$E_x(z) \sim E_{DD}$;

$r_3 << R_{Strato}$

$j_x \sim \sigma_P J_{CL} << J_{CL}$

$\mathbf{R_{STRATO} >> R_{50\text{-}90\text{ km}}}$

Extension of FAC below ionosphere – represented schematically.

Equivalent result: Below 90 km closure currents J_{C1} flow also through resist-s $R_{50\text{-}90\text{ km}}$, R_{Strato}: $J_{C1} \propto \sigma_{mesosph.}$ $J_{C2} \propto \sigma_{Strato}$. $J_{C1,2} << J_{CL}$, but still can play role in GEC.

Contribution of FAC to currents of GEC – 2D model estimations of J_{IS}

Model Domain: 0-150 km by height

Distribution of FAC J_B at 150 km

n^{th} layer: $\sigma_{0n} = const,\ \sigma_{Pn} = const$

$n-1^{th}$ layer: $\sigma_{0n-1},\ \sigma_{Pn-1} = const$

Closure of FAC: principally above 90 km; small portion penetr-s to lower alt-s

Conductivity profile of specific σ_0, Pedersen σ_P, Hall σ_H: step-wise approx-n

2^{nd} layer: $\sigma_{02} = \sigma_{P2} = const$

1^{st} layer: $\sigma_{01} = \sigma_{P1} = const$

At ground: $Z_0 = 0$: $u \equiv 0$

- *Source Equation in 0-150 km:*

$$\nabla \cdot J = 0,\ J = [\sigma]E,\ E = -\nabla u \quad \text{(Eq.1)}$$

J – electric current density vector;
E – electric field; *u* – el.potential
[σ] – conductivity tensor,
Below 65 km $\sigma_P = \sigma_0$, $\sigma_H << \sigma_0$

- *Boundary Conditions*:

i) $u(z=0) = 0$; *ii*) FAC= J_B at 150 km:
$J_B>0$ for downward currents; $J_B<0$ for upward currents.

Region 0-150 km is fragmented into *n* layers; σ_0, σ_P, σ_H = const in each layer. If *n* is large (*n* =75 used), conductivity profile is accurately approximated

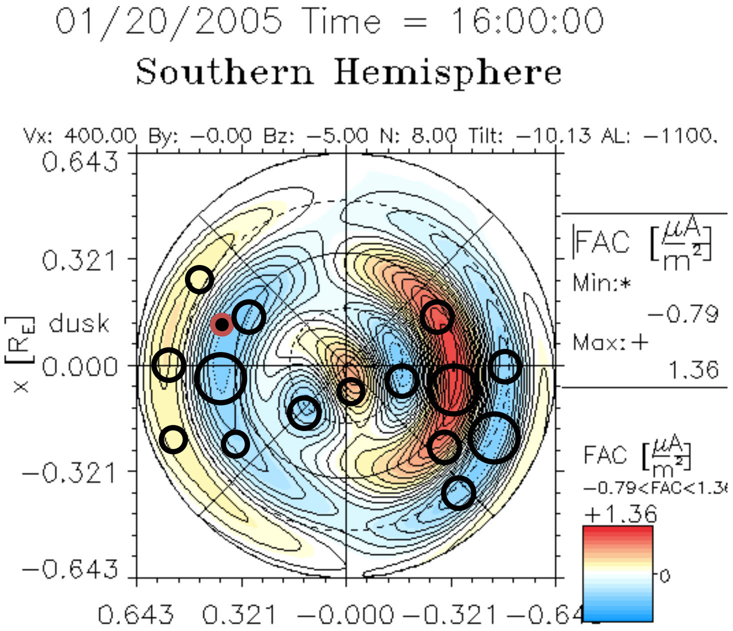
Assumptions:

- Steady-state conditions: valid for slow FAC changes.
- Vertical geomagn. field lines.
- Distrib-n of FAC at 150 km (J_B) taken from Weimer model.

$J_B>0$ where FAC flow upward; $J_B<0$ for downward FAC.

Contribution of FAC to currents of GEC – 2D model estimations - 2 -

Boundary condition at altitude 150 km: FAC distribution $j_B(r)$ from Weimer model



FAC distribution during later phase of SPE-69 (1600 LT). The empty circles are sample FAC sources. Black circle is balloon position.

Distribution of FAC is approx-d by a set of n_{FAC} sample FAC sources. Two types of i-th sample distribution are used:

1) $$j_{Bi}(r_i + r) = j_{Bi0}\exp(-r / r_{Si})$$

2) $j_B(r_i + r) = j_{B0i}$ by $r \le r_{Si}$, $j_B(r) = 0$ by $r > r_{Si}$

where j_{B0i} and r_{Si} are parameters.

Requirements:

1) Total currents of each polarity are equal;

2) The total downward currents of Weimer model and of approximation used are equal

3) j=0 at geom.lat-s below 50° g.lat: based on assumption for symmetry between both geomagnetic hemispheres..

On *20.01.2005,* 15-18 UT

AE$_{max}$ >1200 nT (substorm)

Kp 2+ 2o 2o 3o 4o 5- 3o 3o

Minor geomag.storm (15-18 UT)

Contribution of FAC to GEC – estimations of Jz by 2D modeling - 3 -

Conductivity profiles used

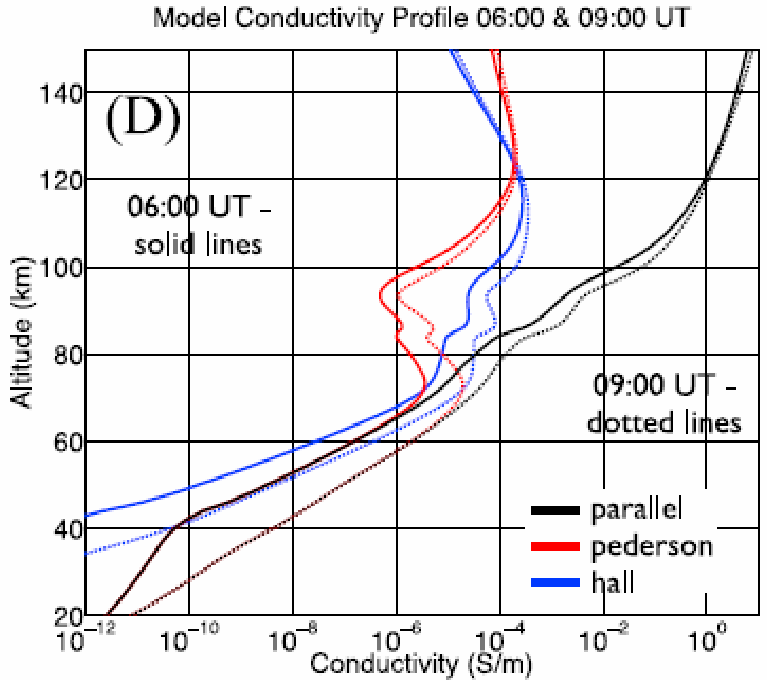


Fig.a. Conductivity profiles adopted in modeling for a round region at high latitudes with a sample FAC source in its center (from Kokorowski et al., 2012).

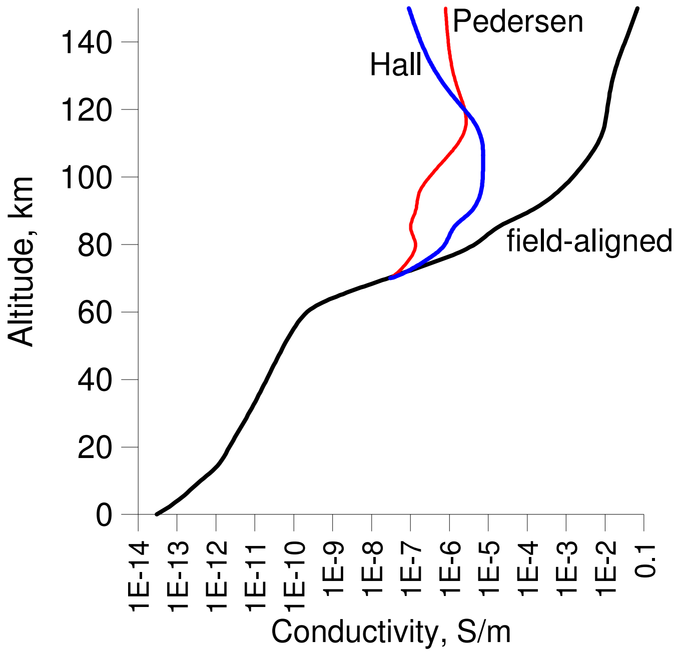


Fig.b. Averaged profile for the rest modeled region (adapted from Tinsley, Zhou, 2006, and ionosphere conductivity model

We expect that Jz from the auror. Ionosphere penetrates in region with higher conductivity in Fig.a (during SPE) much better than in regions with much lower conductivity in Fig.b.

I. Simplified estimations of current J_{IS} in stratosphere

Assumptions (for oversimplified first estimations)

- Flat ground;
- Uniform conductivity profile anywhere (taken from Kokorowsky et al., 2012 for auroral latitudes).
- Single sample FAC source

Cylindrical coordinates (r, φ, z) used.

Equation for potential u in a layer:

$$\sigma_P\left(\partial^2 u/\partial r^2 + 1/r\,\partial u/\partial r\right) + \sigma_0\,\partial^2 u/\partial z^2 = 0$$

- From Fig: J_{IS} in stratosphere has horizontal scale tens of thousands km: comparable to or larger than the earth dimension

- The total J_{IS} from sample sources of diff.polarity is small compared to J_{TS}

- The results are unphysical. Global-scale modeling is required

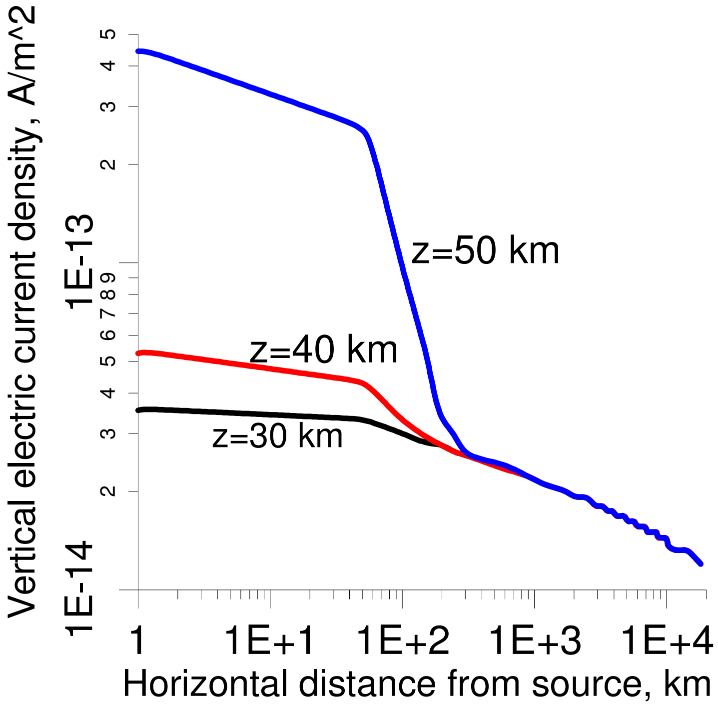
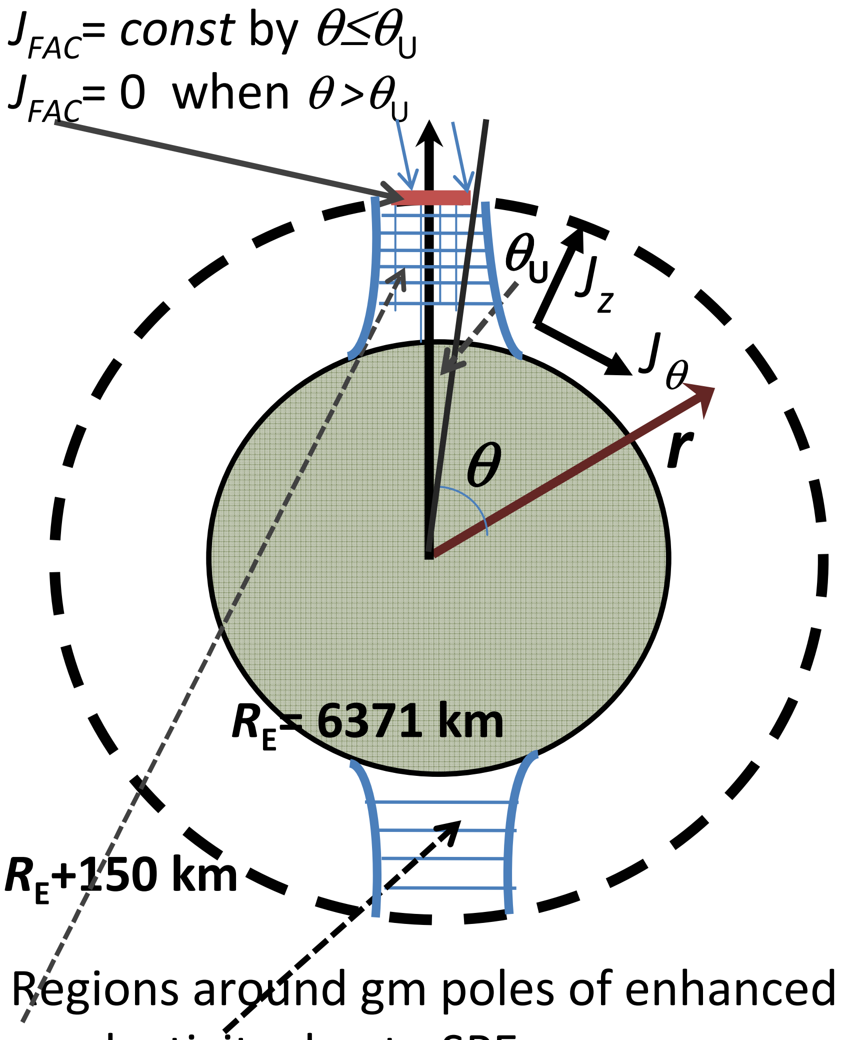


Fig. Current J_{IS} at 30-50 km as function of horiz. distance r from a sample FAC source of type 1 with parameters: j_{Smax}=1 μA/m^2, r_S=100 km. J_S= 63 kA

II. Estimations of current J_{IS} in stratosphere: single sample FAC source

Current J_{IS} below a single sample FAC source (in 0 -150 km) is determined in global scale for the earth. Conductivity profiles: as in Fig.a during SPE 15° around the FAC source (Kokorowski et al, 2012); as in Fig.b elsewhere.



$J_{FAC}= const$ by $\theta \le \theta_U$

$J_{FAC}= 0$ when $\theta > \theta_U$

Regions around gm poles of enhanced conductivity due to SPE

Spherical coordinates used (r,θ,φ).

Equation for u in a layer:

$$\sigma_0\left[\frac{\partial^2 u}{\partial r^2}+\frac{2}{r}\frac{\partial u}{\partial r}\right]+\sigma_P\left[\frac{\partial^2 u}{\partial \theta^2}+\cot\theta\,\frac{\partial u}{\partial \theta}\right]=0$$

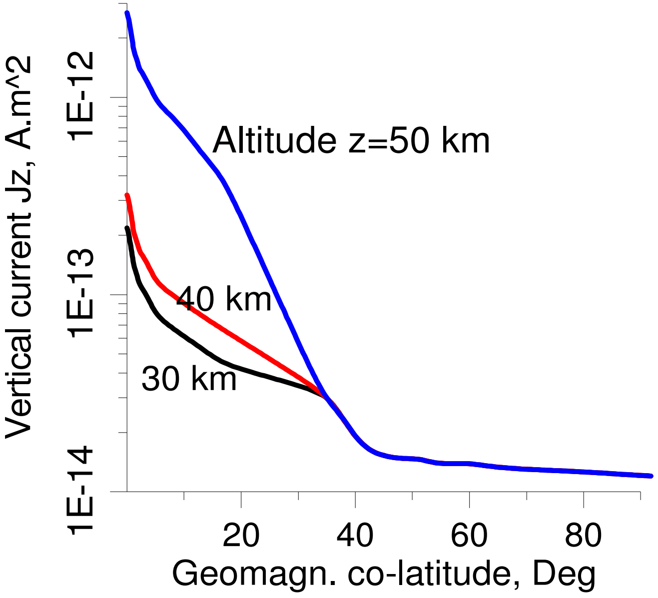


Fig. J_{IS} at 30-50 km as function of θ from single sample FAC source of type 2 with parameters: j_{Smax}=1 μA/m², r_S= 60 km J_S= 1 kA

Contribution of FAC to GEC (by current J_{IS}) during SPE 69

Jz in stratosphere below FAC structure (roughly approximated) during SPE-69 on 20 January 2005) determined by global-scale modeling. Conductivity profiles: as in Fig.a during SPE 15° around the FAC source (Kokorowski et al, 2012); as in Fig.b elsewhere.

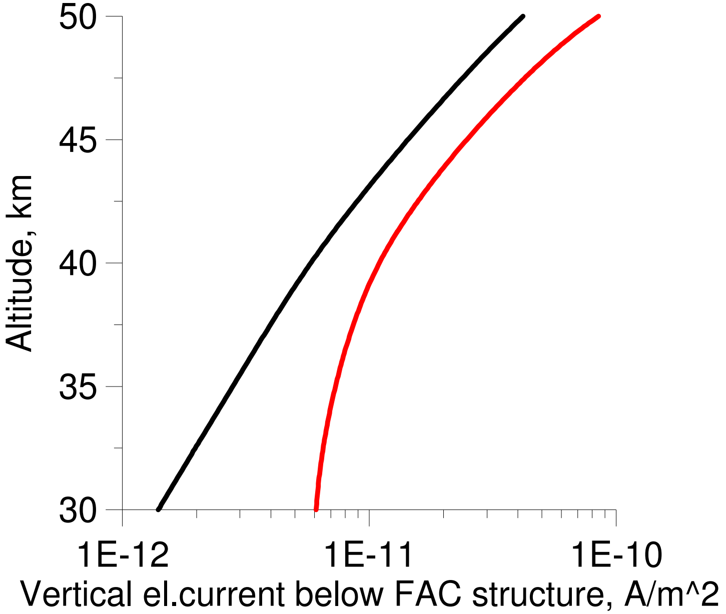


Fig. Profiles of J_{IS} in the upper stratosphere 30-50 km for two different position of the balloon related to FAC structure. Red profile is for a balloon position horizontally mapped closer to point of maximum upward FAC density

Density of total vertical current Jz is:

$$J_z = J_{TS} + J_{IS}$$

For J_{TS}=-2 pA/m^2 (typical value) current J_z at 32 km will be close to 0 for the black profile of J_{IS} and 4 pA/m^2 for the red profile. This agrees with measured values. At 40 km altitude Jz will be 4 and 8 pA/m^2, resp.; at 50 km Jz will be even much larger. This is result of enhancement of conductivity at high lat-s during SPE69.

The approximation by the 2D model used may be not very good due to assumptions and representations used. 3D global-scale modeling is desirable.

Conclusions

- It is shown by modeling that the electrical coupling between ionosphere and stratosphere at high latitudes becomes effective during solar proton events due to easier downward penetration from auroral ionosphere of electric currents.

- The field-aligned currents in auroral Ionosphere can lead to formation of electric currents in the meso- and stratosphere which are significant related to currents in global atmos.electrical circuit from tropospheric sources.

- The more effective coupling during SPE is result of significant enhancement of middle atmosphere conductivity;

- The model results agree with experimental balloon results of electrical characteristic at 31-33 km in Antarctica during SPE on 20 January 2005. The model results can explain the extreme enlargement of current Jz and the reversal of its direction observed in the later phase of SPE69.

- Variations of Jz during SPE, thus predicted, could be important in formation of weather, according to theory of Tinsley.

- Development of 3D model for the ionosphere-atmosphere electrical coupling is needed in order to obtain more accurate predictive results.

THANK YOU