Impacts of Multi-scale Field-aligned currents (FACs) on the ionosphere-Thermosphere system: GITM simulation

[1]Qingyu Zhu, [1]Yue Deng, [2]Arthur Richmond, [3,4]Ryan McGranaghan, [2]Astrid Maute

[1]University of Texas at Arlington [2]High Altitude Observatory, National Center of Atmospheric Research

[3]CPAESS, University Corporation for Atmospheric Research [4]Jet Propulsion Laboratory

Email: qingyu.zhu@mavs.uta.edu

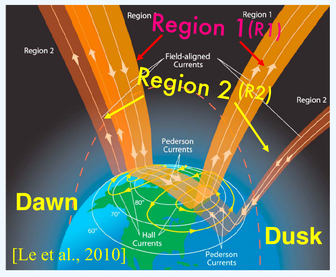
MITC-17

Abstract: In this study, FACs and ionospheric electric fields on different spatial scales are investigated through the analysis of FAC data from the Swarm satellites and electric field data from the DE2 satellite respectively, from all seasons and under all solar wind conditions and varying levels of solar activity. Distributions of the average and variable components of FAC and electric field are the main focuses of this study. We found that the mean patterns of the FAC and electric field are mainly contributed by the large-scale (wavelength: ⩾500 km) FAC and electric field. Unlike the average, variabilities of FAC and electric field are not negligible on mesoscale (wavelength: 100~500 km) and small scale (wavelength: 8~100 km), while the FAC variability shows a different scale dependence from the electric field variability. Specifically, for decreasing scale sizes, the FAC variability increases while the electric field variability decreases, suggesting that the strong FACs on small- and meso-scales do not necessarily correspond to strong ionospheric electric fields on those scales. Further, FAC variabilities on large- and meso-scales are included into the GITM and the corresponding impacts on Joule heating have been assessed. It was found that, for the conditions studied here, the large-scale FAC variability may significantly increase the Joule heating (~160% globally) and that the enhancement due to the mesoscale FAC variability is not negligible (~36% globally).

Introduction & Motivations

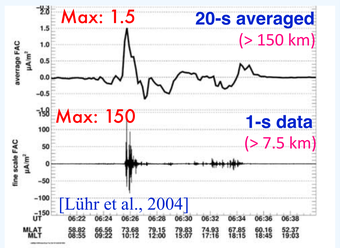
- **Field-aligned currents (FACs) are critical for the MIT coupling study:**
  - FACs are related to the ionospheric electrodynamics: $J_{\parallel} = -\nabla_{\perp} \cdot (\Sigma \cdot E_{\perp})$
  - Large-scale average FAC pattern is well-established (Typically, R1 + R2 currents)
  - Departures from the large-scale average pattern cannot be simply ignored:

    The magnitudes of small-scale FACs are much higher than those on larger scales.



A schematic of the FACs and ionospheric currents system, adapted from Le et al., [2010]

- **Motivations:**
  - The difference and relationship between FACs and ionospheric electrodynamics on different scales are still unclear:
    - Do the FACs and ionospheric electric fields tend to have similar scale dependence?
  - How would Joule heating estimation in GCMs be affected by the FACs on different scales?



(Top) 20-s averaged FAC and (Bottom) 1-s FAC measurements along a CHAMP polar crossing, adapted from Lühr et al., [2004]

Data and Model

Swarm Constellation
Three polar-orbiting satellites;
Alt: ~460 km (A,C); ~520 km (B)
Single-satellite Swarm A&C **FAC** data (01/2015~12/2016)

Compare behaviors on different scales

Dynamic Explorer (DE-2) satellite
Polar-orbiting; Alt: 300~1000 km
Electric fields are derived from ion-drift taken by RPA and IDM
Data range: 08/1981~03/1983

FAC

NCAR ionospheric electrodynamo model
[Maute and Richmond, 2016]
Solves for 3D ionospheric electric fields, currents and magnetic perturbations
Electrodynamo are solved in the APEX coordinates
[Richmond 1995]

Electric field

Winds & Conductivities

[Zhu et al., 2017]

Global Ionosphere Thermosphere Model (GITM)
[Ridley et al., 2006]
6 Neutral & 5 Ion Species
Ion and neutral density, velocity and temperature
Flexible grid resolution
Can have non-hydrostatic solutions

Result 1: FAC/electric field on different scales

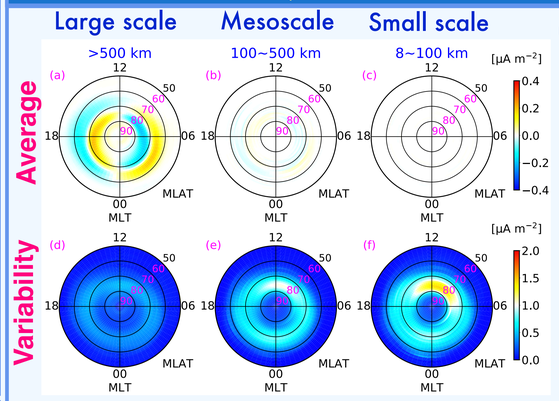


Fig 1. Distributions of average (Top) and variability (Bottom) of the FAC on (Left) Large scale (Middle) Mesoscale and (Right) Small scale. All results are presented in geomagnetic coordinates.

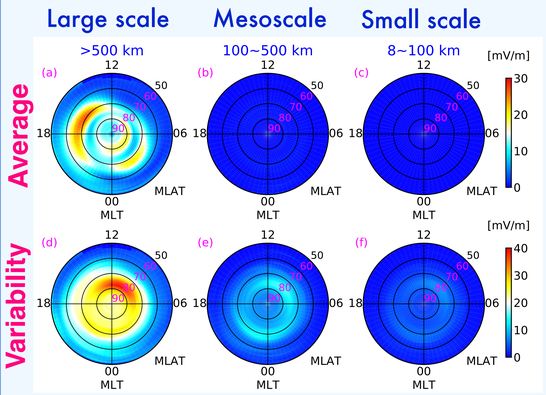


Fig 2. Distributions of average (Top) and variability (Bottom) of the electric field on (Left) Large scale (Middle) Mesoscale and (Right) Small scale. All results are presented in geomagnetic coordinates.

Data Analysis:
- Hanning Filter → FAC & electric field on different scales
- Binning:
  - 1° MLAT x 500 km MLT
  - All IMF, all seasons

← FAC:
- Average: Large scale dominates
- Variability: Increases with the decreasing scale size

(Variability = standard deviation)

← Electric field:
- Average: Large scale dominates
- Variability: Decreases with the decreasing scale size

FAC shows a different scale dependence from the electric field.

Result 2: Spectral analysis of the FAC and electric field

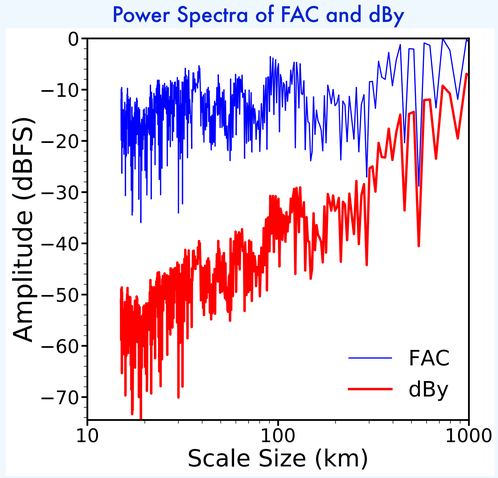


Fig 3. Power spectra of the FAC and E-W magnetic perturbation (dBy) along the same Swarm polar pass

Note:
dBy: Magnetic perturbation in the E-W direction
Power spectra: dBy ≃ Ex (N-S electric field)
[Weimer, 1985]

← dBy (Ex) ↘ as scale ↘
FAC is roughly constant

Discrepancy between FAC ($J_{\parallel}$) & ionospheric electric field ($E_{\perp}$):

$$J_{\parallel} = -\nabla_{\perp} \cdot (\Sigma \cdot E_{\perp})$$

Assume:
- Div Hall current is zero
- Pedersen conductance is uniform
- Electric field is in the x direction

$$J_{\parallel} = -\Sigma_P \frac{\partial E_x}{\partial x}$$

From the dimensional analysis:

$$|J_{\parallel}| \propto \frac{|E_x|}{L} \Rightarrow |E_x| \propto |J_{\parallel}| L$$

L: scale size

$|E_x|$ ↘ with L if constant $|J_{\parallel}|$

On mesoscale & small scale Strong $J_{\parallel}$ ≠ Strong $E_{\perp}$

Result 3: GITM simulation: Impacts on Joule heating

Simulation summary:

GITM	5° GLON x 1° GLAT, $F_{10.7}$=100 sfu, September Equinox; Particle precipitation: Fuller-Rowell & Evans [1987], HP=10 GW;
NCAR IEM	3.6° MLON x variable grid sizes in MLAT (~0.6° at 60 ~80° MLAT)
Runs	Run1: FAC average; Run2: FAC average + large-scale variability; Run3: FAC average + mesoscale variability;

3.1 Outputs from Run 1

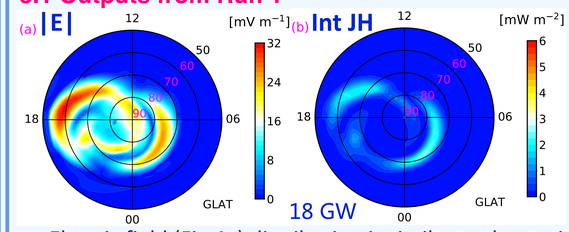


Fig 4. (a) Electric field magnitude and (b) Height-integrated Joule heating from Run 1. All results are presented in geographic coordinates.

- Electric field (Fig 4a) distribution is similar to the statistical results (Fig 2a);

3.2 Impacts on Joule heating after including the FAC variability

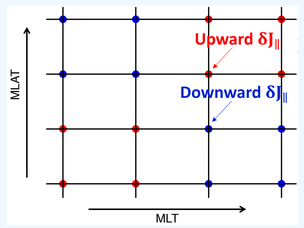


Fig 5. Schematic diagram to illustrate the inclusion of FAC variability

← Inclusion of FAC variability:
- Flip the sign of the FAC variability every few adjacent grid points in MLAT and MLT directions
- Larger spatial separations for the large-scale variability than mesoscale variability (Result 2)
- Determine the best separations once the simulated electric field variability is most comparable with the statistical results (Fig 2)

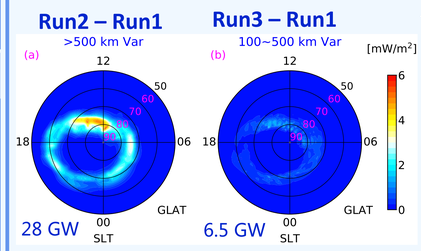


Fig 6. Height-integrated Joule heating enhancement after including (a) large-scale and (b) mesoscale FAC variabilities. All results are presented in geographic coordinates.

← Contribution of FAC Variabilities on different scales to Joule heating:

Large-scale FAC Var (Fig 6a)	↗~160% globally ↗ ~5 mW/m² near the noon
Mesoscale FAC Var (Fig 6b)	↗~36% globally ↗ ~1 mW/m² near the noon

Contribution from the mesoscale FAC variability is not negligible.

Summary

➡ FAC and ionospheric electric field on different scales:
- FAC variability increases with the decreasing scale while the electric field variability decreases with the decreasing scale;
- Strong small-scale and mesoscale FACs do not necessarily mean strong ionospheric electric fields on those scales.

➡ Impacts of multiscale FAC variabilities on Joule heating:
- Large-scale FAC variability can significantly increase Joule heating;
- Contribution from the mesoscale FAC variability cannot be ignored.

CHECK IT OUT! Zhu et al., (2019) Impacts of Multiscale FACs on the Ionosphere -Thermosphere System: GITM Simulation, JGR.

Acknowledgement: NSF and AFOSR MURI