Investigating interhemispheric asymmetries in the ionospheric response using “realistic” high-latitude electrodynamic forcings

A case study for the 2013 St Patrick’s Day storm

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• A journey to interhemispheric asymmetry

• Understanding asymmetries could be lifesaving (e.g., skiing)

• Understanding the interhemispheric asymmetry in the I-T system could help us better mitigate adverse effects caused by space weather in the NH & SH
• Motivation

The 2013 St Patrick’s Day geomagnetic storm
  • Intense storm occurred around March equinox
  • Negative storm effects in the typical EIA peak regions near the end of the main phase
  • Stronger negative storm effect in the SH at 17 and 18 UT

What is the cause of the interhemispherically asymmetric negative storm effects at low latitudes?
  • Data analysis + numerical simulation
• **Methodology**

- **GNSS TEC data**
- **Global Ionosphere Thermosphere Model**
  - 3D non-hydrostatic model
  - Coupled with the NCAR 3D electrodynamo solver
  - High-latitude forcings:
    - **ASHLEY**: Empirical models of electric potential and electron precipitation (Zhu et al., 2021)
    - **AMIE**: Assimilative patterns of electric potential and electron precipitation (Richmond and Kamide, 1988)
• Assimilative Mapping of Ionospheric Electrodynamics (AMIE):

• AMIE: an **optimal estimation** of high-latitude electrodynamc fields based on a variety of ground-based and space-based measurements

  • Horizontal magnetic perturbations (217 stations for this event + AMPERE)
  • Ion drifts (DMSP + SuperDARN)
  • Electron precipitation (DMSP SSUSI)
• Impact of high-latitude forcing on the ionospheric response

ΔTEC in the American sector

- AMIE-GITM simulation general captures the ionospheric response and overperforms the ASHLEY-GITM simulation.

Necessity of using realistic high-latitude forcings
• Ionospheric response at 70° W

• Simulation results are generally consistent with the observation.
  • Can capture the IHA in the negative storm effect between 17 and 19 UT
• Ionospheric response at 70°W

\[ \frac{\partial N}{\partial t} = (\text{Production} - \text{Loss}) + \text{Trans}_{E\times B} + \text{Trans}_{\text{wind}} + \text{Trans}_{\text{diff}} \]

- Term analysis to the ion continuity equation
- Transport related to neutral winds mainly contributes to the ionospheric response at 70°W.
• **Cause of the negative storm effect**

- TAD signals appear in the meridional winds

- Meridional winds and vertical shear of meridional winds contribute to the negative storm effect.

- Move plasma downward
- Electron density decreases
- Compression
  - Adiabatic; Constant T
  - Electron density increases

- Magnetic field line
  - **16 UT**
  - Equator
  - Pole

**MLAT 15S**

**Δ Electron density**

**Δ Meridional wind**

**Alt**

**Universal Time, 03/17**

**[m/s]**

[0, 200, 400, 600] [0, -200, -400, -600]
• Cause of asymmetric negative storm effects

- Disturbance meridional winds are weaker in the NH.
- Weaker meridional winds in the NH are responsible for weaker negative storm effect.
• Cause of asymmetric negative storm effects

- Generation, propagation and interaction of TADs are different in the different hemispheres.

- Joule heating deposited in different hemispheres shows significant IHAs

□ IHAs in TADs
• Realistic high-latitude forcings are crucial:
  • Creating AMIE patterns is time-consuming

• Can we be a little bit lazier?
  Yes?
  AMPERE FAC data are available → Drive GCMs
  • **AMPERE FAC**: fitting results of the magnetic perturbation measurements by Iridium satellites
  • **FAC-driven**: Solves for global electric potential using FAC inputs along with the neutral winds and conductance from GCMs

• How does FAC-driven simulation behave?
• Impact of high-latitude forcing on ionospheric responses

- AMIE-driven
- FAC-driven

- Joule heating are different between the AMIE-driven and FAC-driven simulations
- FAC-driven simulation cannot well reproduce asymmetric negative storm effects
- Impact of high-latitude forcing on ionospheric responses

- **FAC-driven simulation:**
  - Disturbance meridional winds are stronger/weaker in the NH/SH.
  - Opposite to the AMIE-driven simulation.
The observed ionospheric response in the American sector can be well reproduced in the AMIE-driven GITM simulation but not in the ASHLEY-driven simulation.

- Importance of using “realistic” high-latitude forcings

- Traveling atmospheric disturbances (TADs) are important for the ionospheric response in the American sector.
  - The IHA in the TADs ▸ The IHA in the negative storm effects at low latitudes

- FAC-driven GITM simulation cannot well reproduce the asymmetric negative storm effects during this event.
  - May be caused by inconsistency between the FAC and conductance

References:
• Backup (1): FAC-driven method in GITM

- Step 1: Calculate high-latitude (>50° MLAT) electric potential ($\Phi^R$) using FAC in each hemisphere (N: NH; S: SH)

\[
\frac{\partial}{\partial \phi_m} \left[ \frac{\Sigma^{N/S}_\phi \Phi^{R,N/S}_\phi}{\cos \lambda_m \partial \phi_m} + \Sigma^{N/S}_\phi \frac{\partial \Phi^{R,N/S}_\phi}{\partial |\lambda_m|} \right] + \frac{\partial}{\partial |\lambda_m|} \left[ \Sigma^{N/S}_\lambda \frac{\partial \Phi^{R,N/S}_\phi}{\partial \phi_m} + \Sigma^{N/S}_\lambda \cos \lambda_m \frac{\partial \Phi^{R,N/S}_\phi}{\partial |\lambda_m|} \right] = R \left[ \frac{\partial K^{D,N/S}_{m \phi}}{\partial \phi_m} + \frac{\partial (K^{D,N/S}_{m \phi} \cos \lambda_m)}{\partial |\lambda_m|} \right] + J^{N/S}_{m_r} R^2 \cos \lambda_m
\]

\[\nabla \cdot \left( \Sigma \cdot (E) \right) \]

\[-\nabla \cdot \left( \Sigma \cdot (U \times B) \right)\]

\[-J_{\parallel}\]

- High-latitude electron precipitation pattern is derived from the AMIE technique:
- Modifying the electron precipitation pattern by ground-based magnetic perturbation measurements and DMSP SSUSI data
- The neutral wind dynamo is included

- Step 2: Calculate global electric potential ($\Phi$) using high-latitude (>50° MLAT) electric potential ($\Phi^R$)

\[
p \frac{\partial}{\partial \phi_m} \left[ \frac{\Sigma^T \phi \Phi}{\cos \lambda_m \partial \phi_m} + \Sigma^T \phi \frac{\partial \Phi}{\partial |\lambda_m|} \right] + p \frac{\partial}{\partial |\lambda_m|} \left[ \Sigma^T \phi \frac{\partial \Phi}{\partial \phi_m} + \Sigma^T \phi \cos \lambda_m \frac{\partial \Phi}{\partial |\lambda_m|} \right] - (1 - p) \Phi^R \cos \lambda_m \Phi = p R \left[ \frac{\partial K^{D,T}_{m \phi}}{\partial \phi_m} + \frac{\partial (K^{D,T}_{m \phi} \cos \lambda_m)}{\partial |\lambda_m|} \right] - (1 - p) \Phi^R \cos \lambda_m \Phi^R
\]

- ($\sigma^R$: reference conductivity; $p$: spatial varying parameter) $\rightarrow$ Penetration electric field
Backup (2): AMIE-driven vs FAC-AMIE:}

Generation, propagation and interaction of TADs are different in the AMIE-driven and FAC-AMIE simulations.
Backup (3): Impact of conductance on FAC-driven simulations

Empirical model (ASHLEY) Calculated based on FAC using the Robinson et al. (2020) formula

- Joule heating can be significantly affected by the choice of the conductance