NCAR | NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

- Early Career Science Highlight

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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SYMMETRIC ASYMMETRIC

2023 CEDAR Workshop, San Diego, CA

- **A journey to interhemispheric asymmetry**

UNIVERSITY OF TEXAS ARLINGTON

(Arlington, TX)

2015

2021

Present

NCAR | ADVANCED STUDY PROGRAM

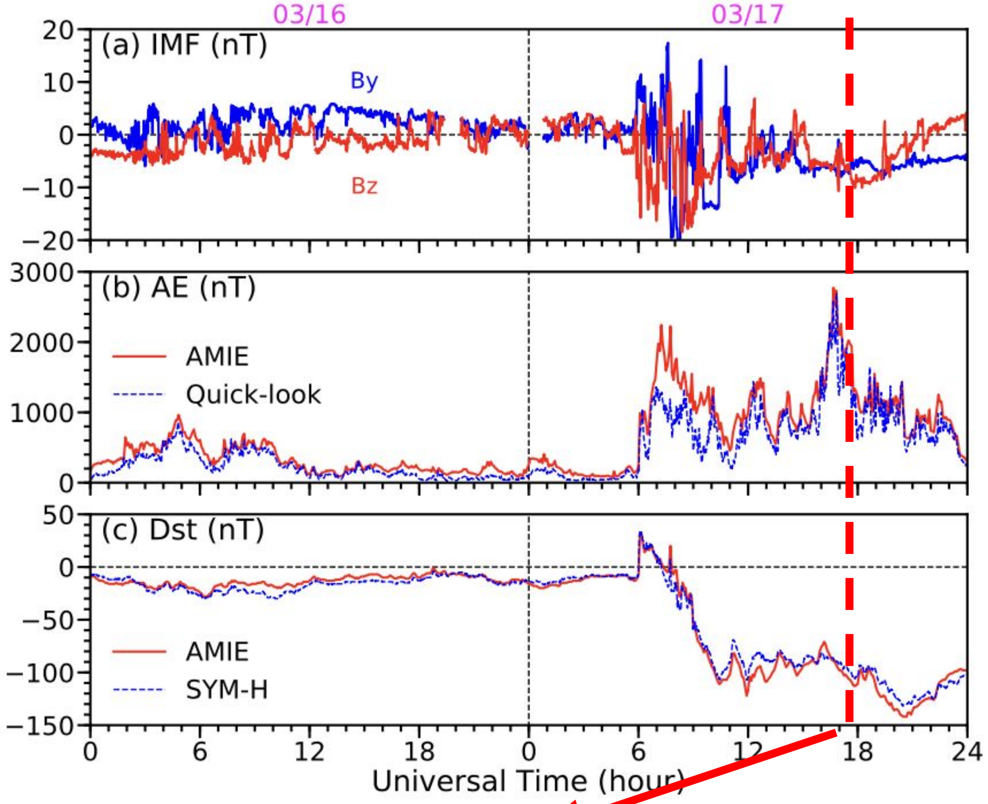
(Boulder, CO)

- 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

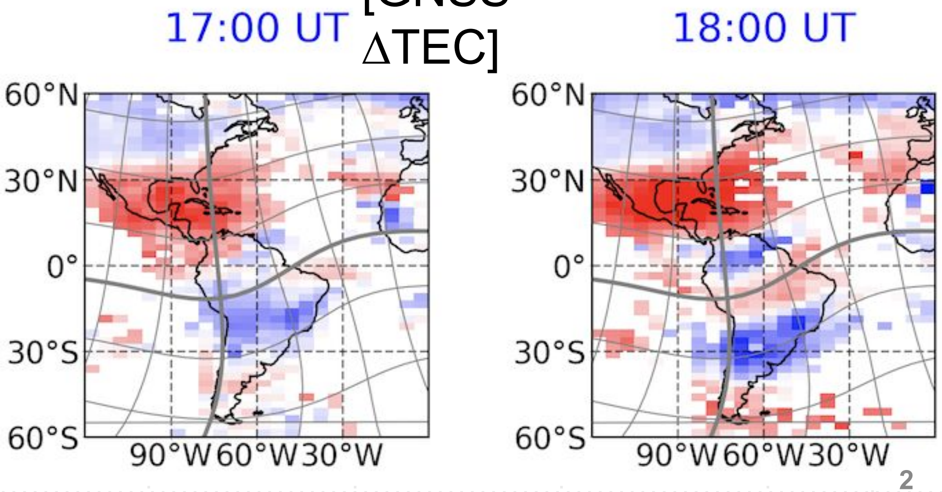
• Motivation

- 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



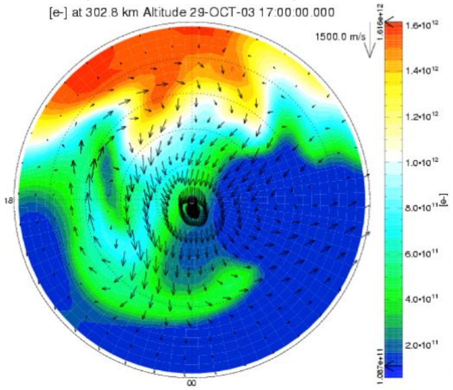
[GNSS ΔTEC]



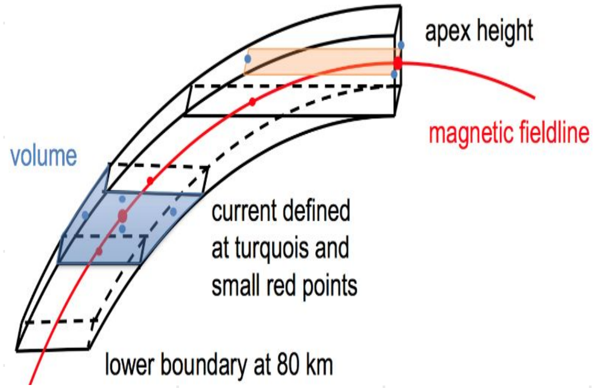
• Methodology

- 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)

GITM
[Ridley et al., 2006]

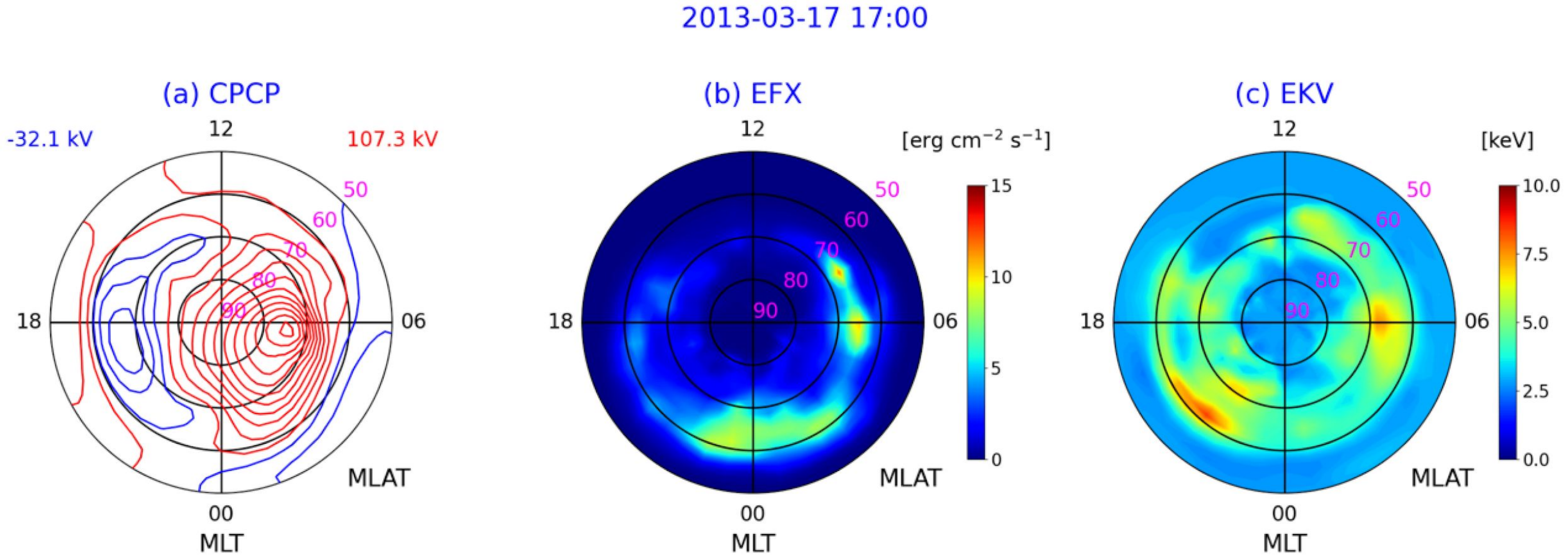


NCAR 3D electrodynamo solver
[Maute & Richmond, 2017]



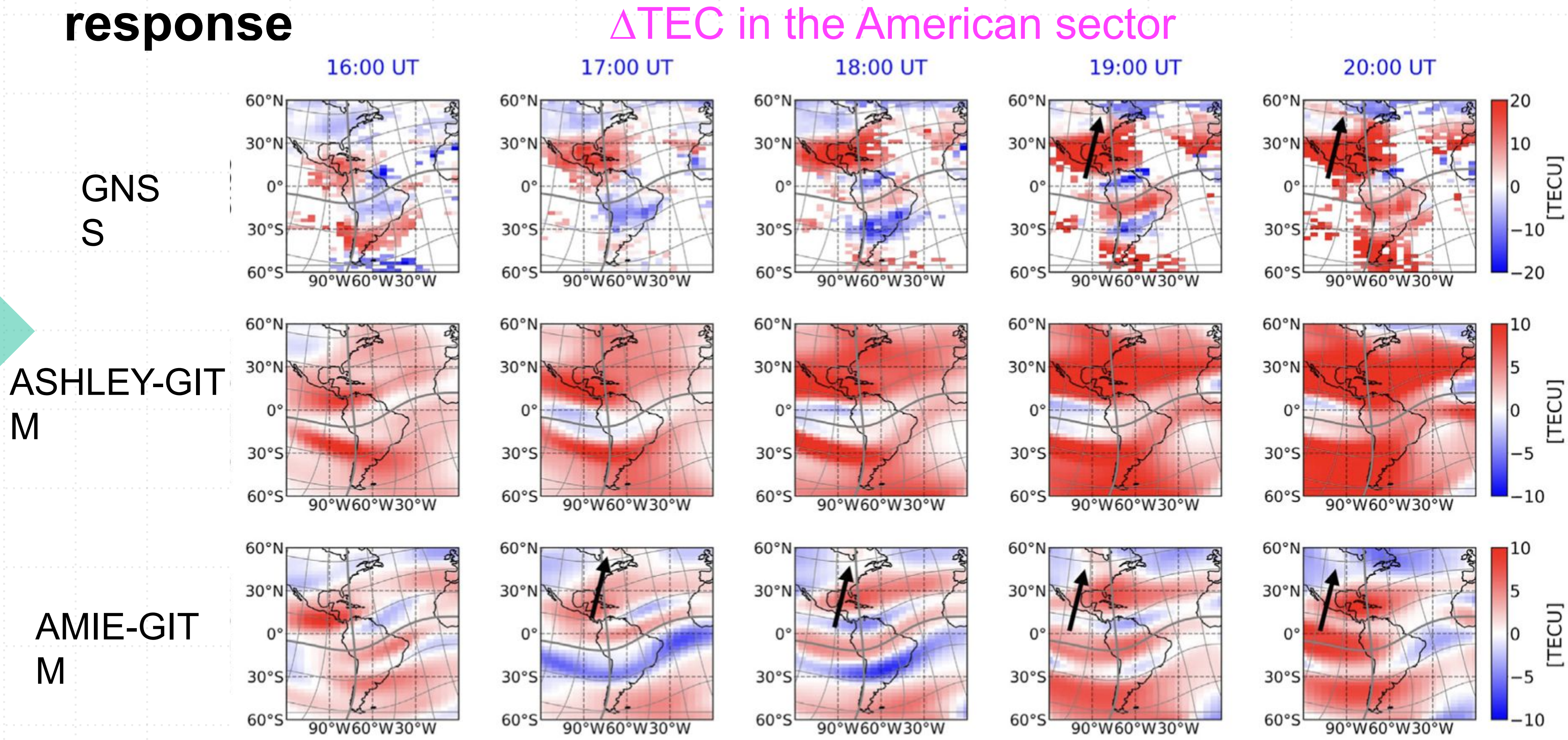
[Zhu et al., 2019, 2022]

• Assimilative Mapping of Ionospheric Electrodynamics (AMIE):



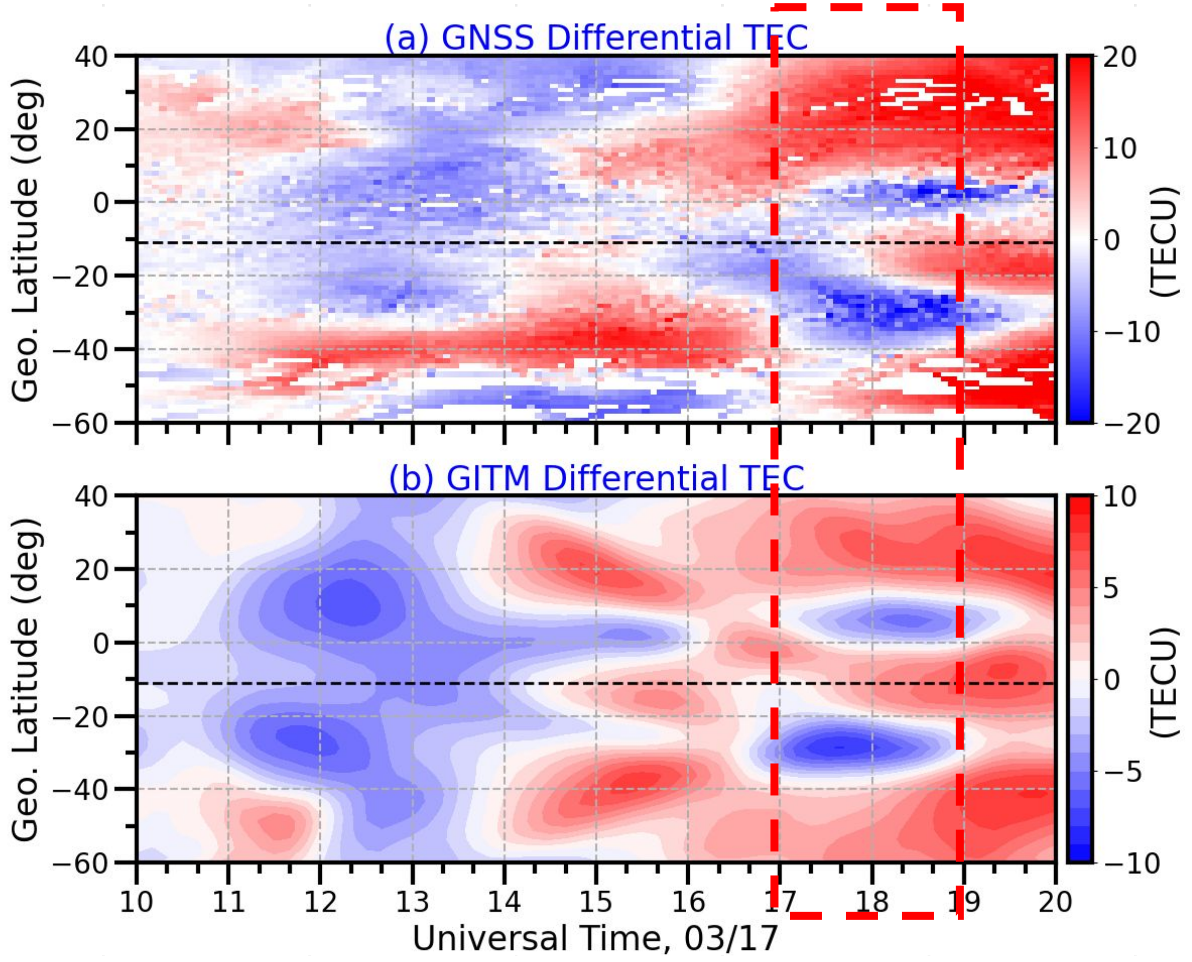
- AMIE: an **optimal estimation** of high-latitude electrodynamic fields based on a variety of ground-based and space-based measurements
  - Horizontal magnetic perturbations (217 stations for this event + AMPERE)
  - Ion drifts (DMSP + SuperDARN)
  - Electron precipitation (DMSP SSUSI)

- **Impact of high-latitude forcing on the ionospheric response**



- AMIE-GITM simulation general captures the ionospheric response and overperforms the ASHLEY-GITM simulation. □ Necessity of using realistic high-latitude forcings

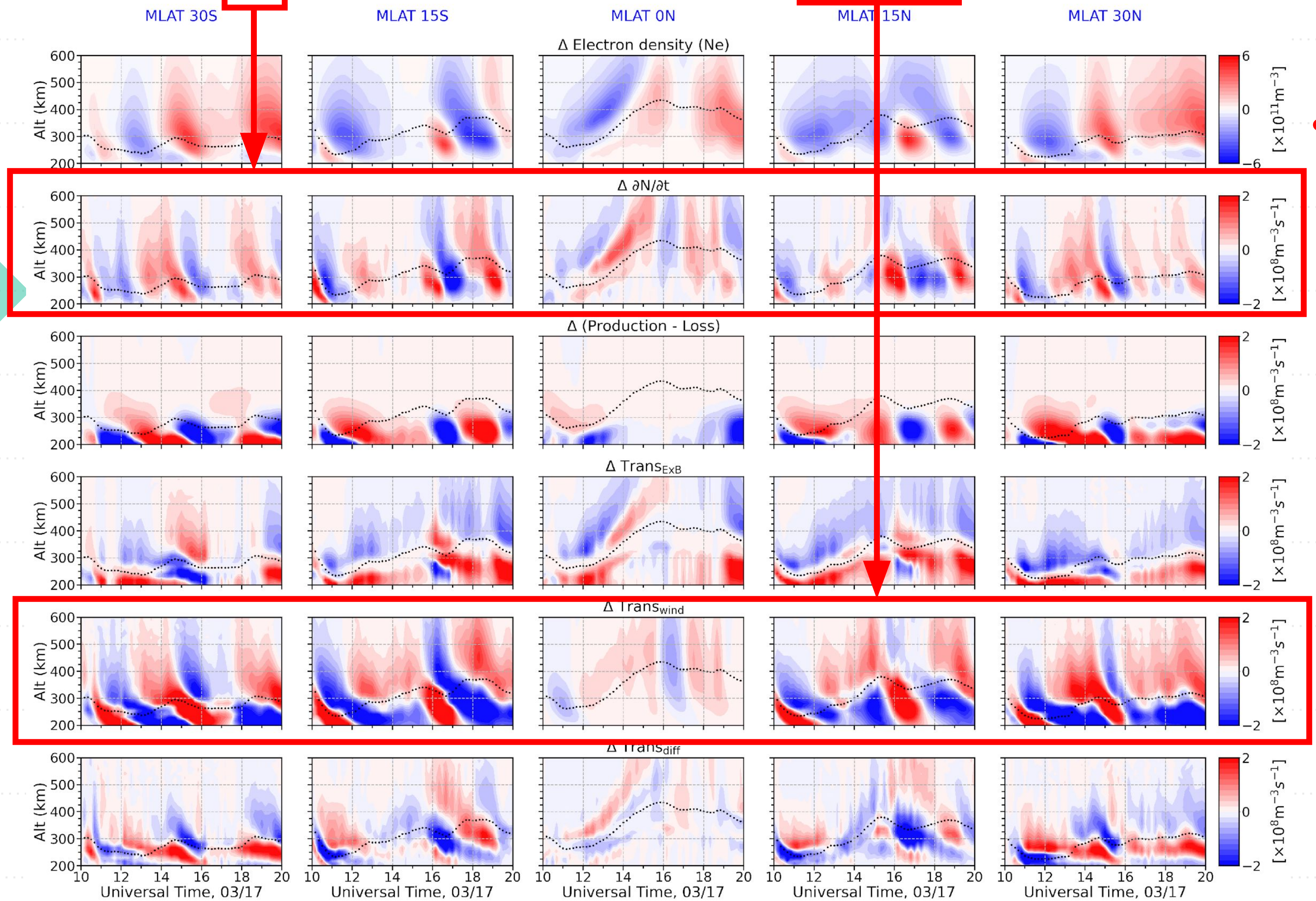
• Ionospheric response at 70° W



- Simulation results are generally consistent with the observation.
  - Can capture the IHA in the negative storm effect between 17 and 19 UT

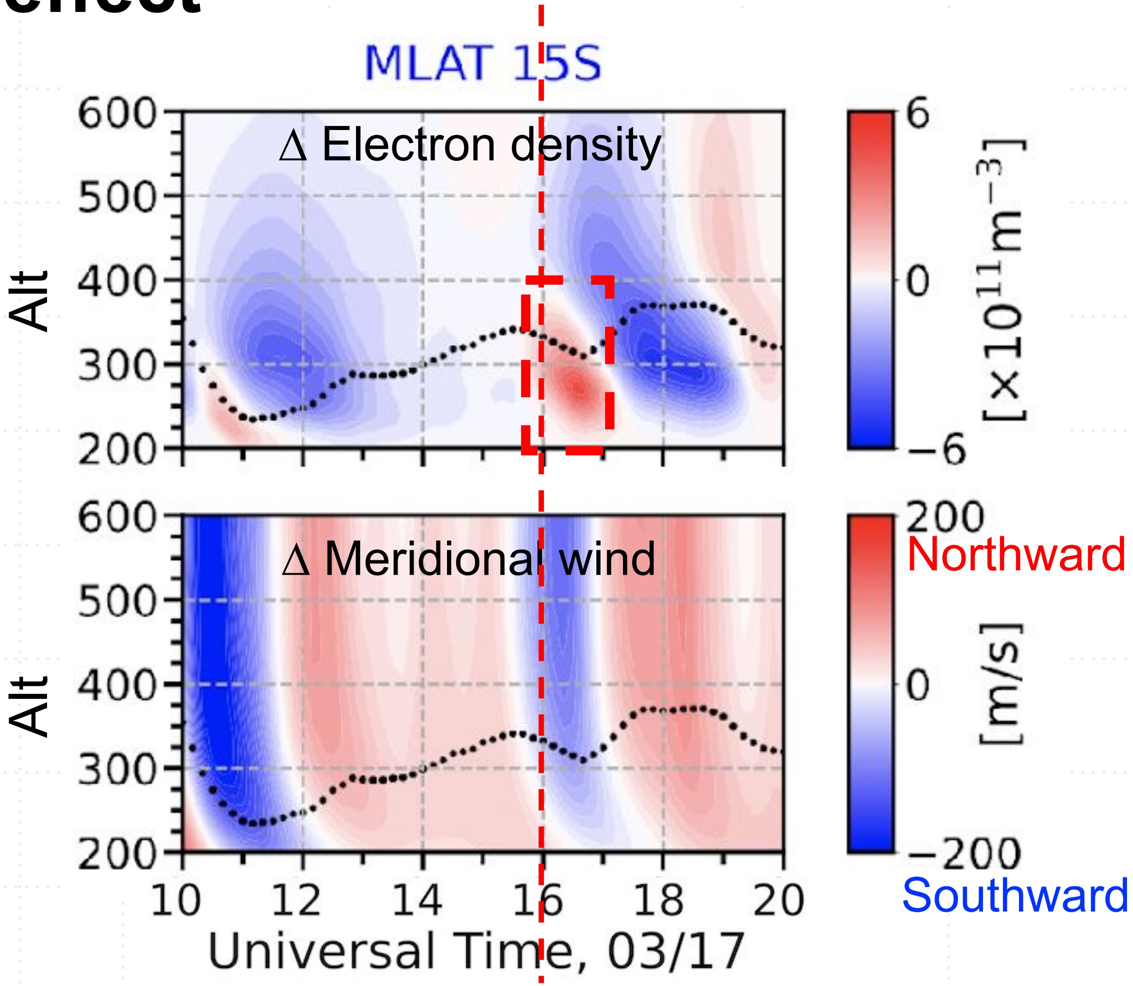
• Ionospheric response at 70° W

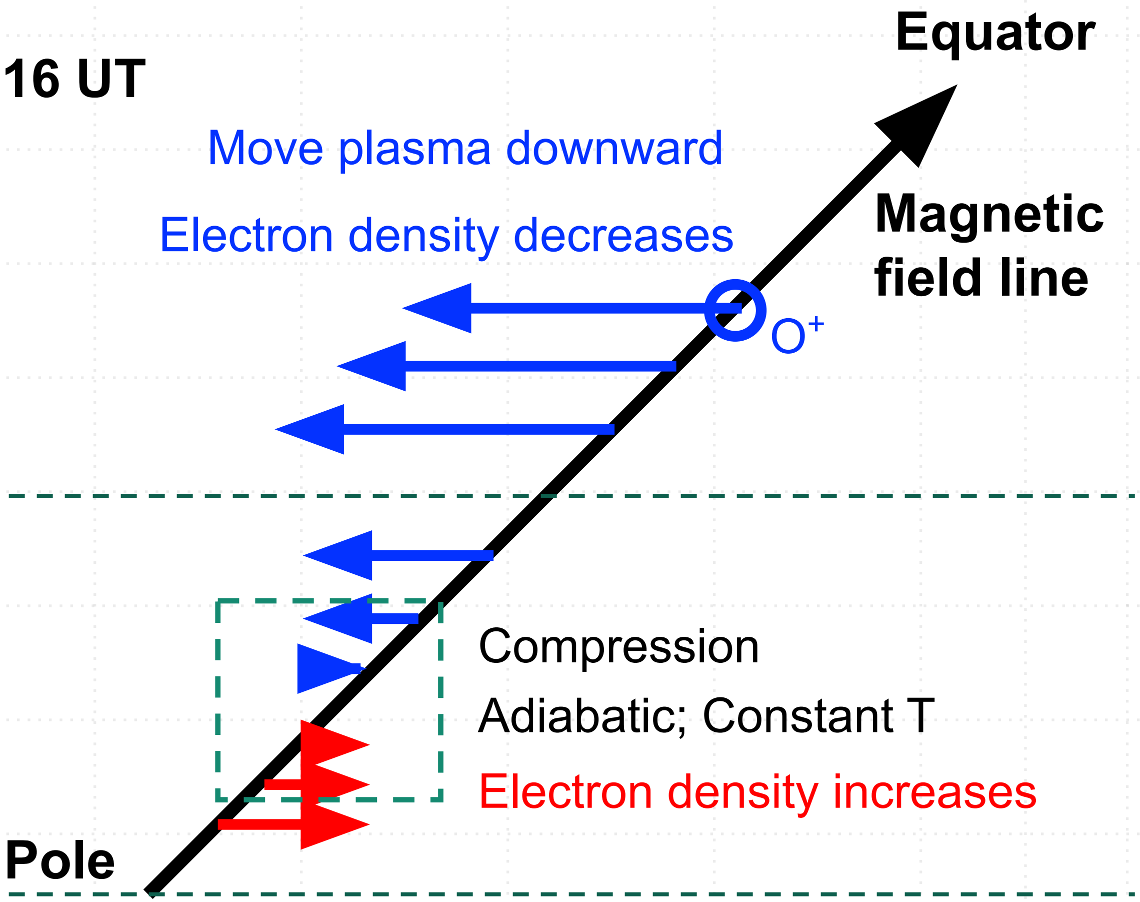
$$\frac{\partial N}{\partial t} = (Production - Loss) + Trans_{E\times B} + Trans_{wind} + Trans_{diff}$$



- 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**

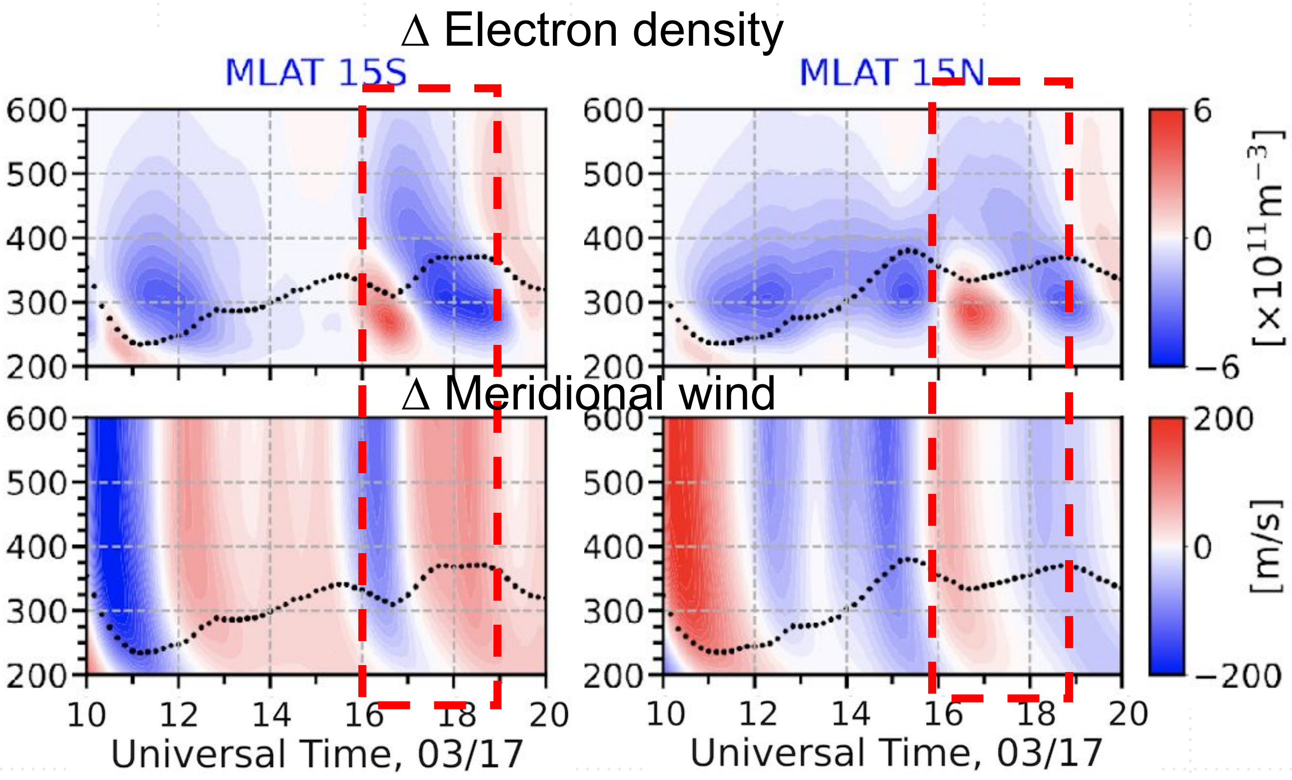




- TAD signals appear in the meridional winds

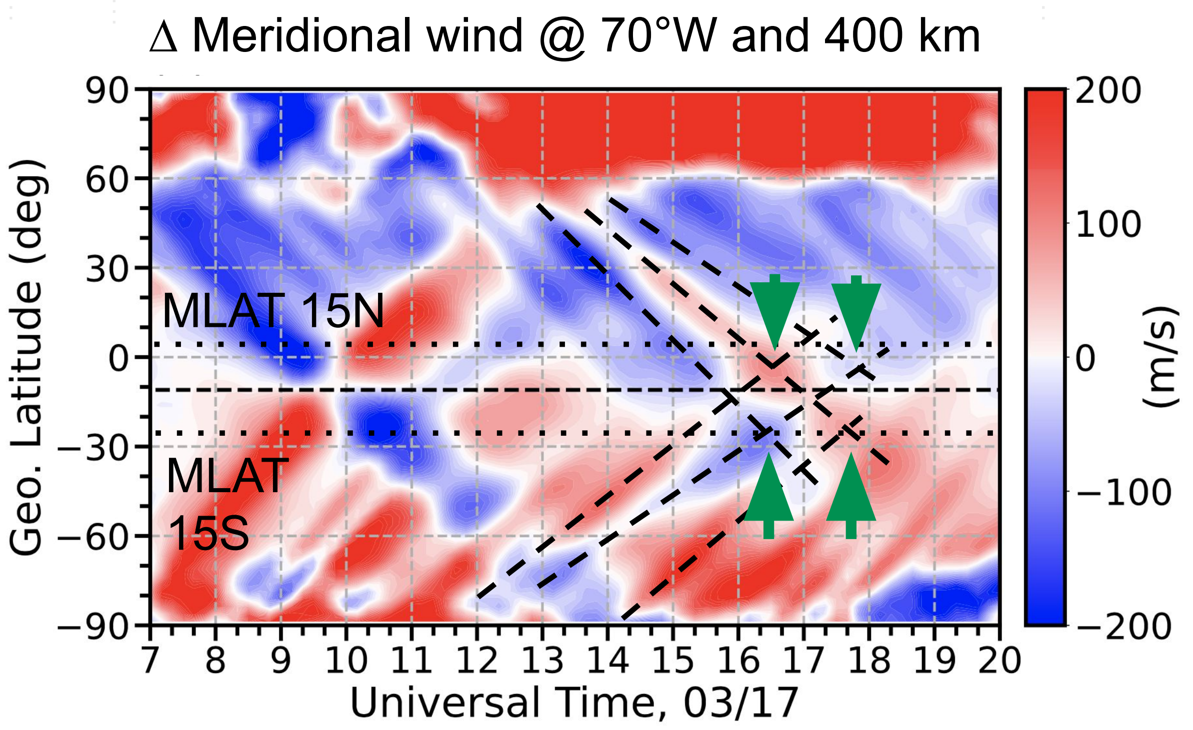
- Meridional winds and vertical shear of meridional winds contribute to the negative storm effect.

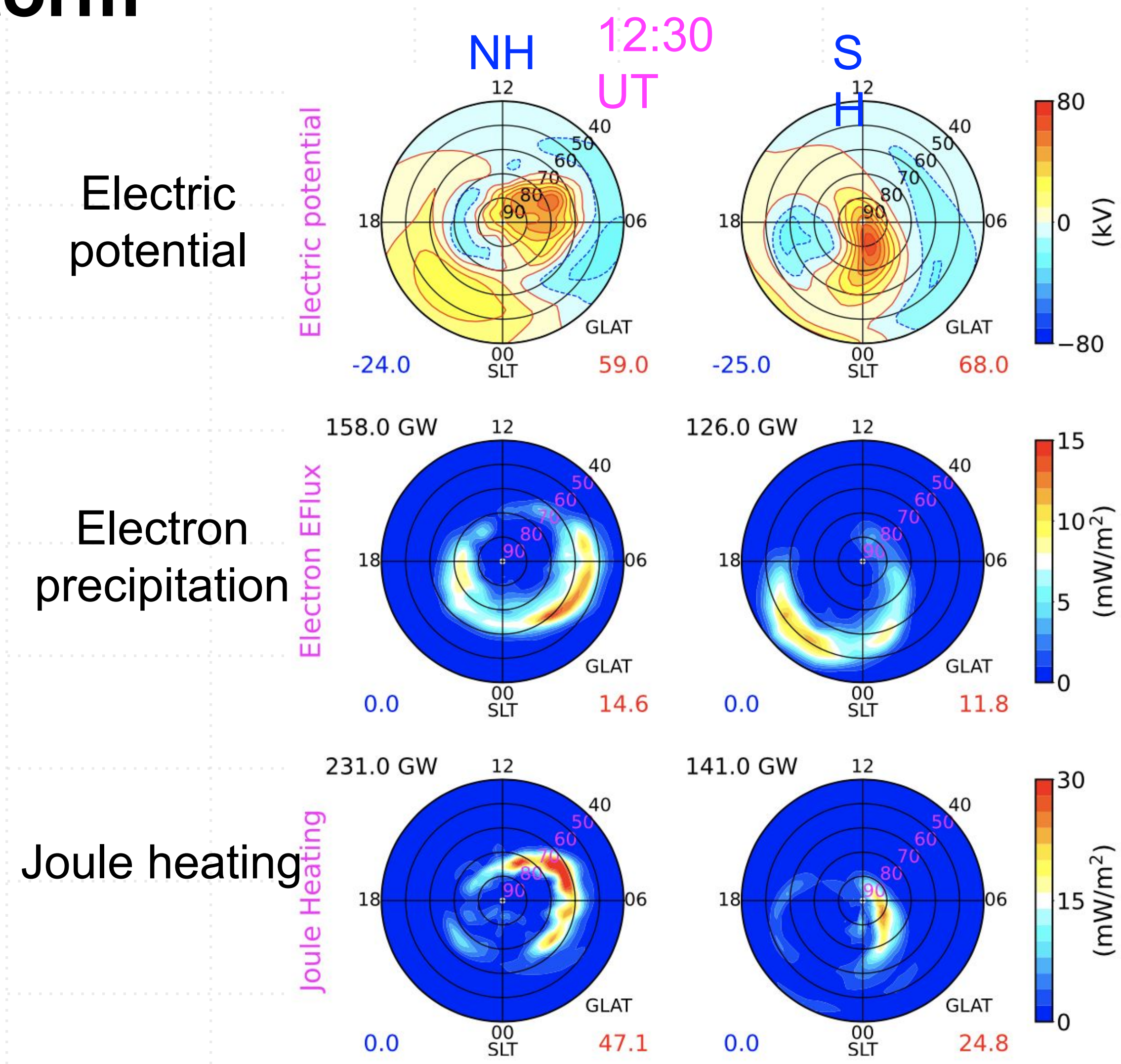
- **Cause of asymmetric negative storm effects**



- 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**





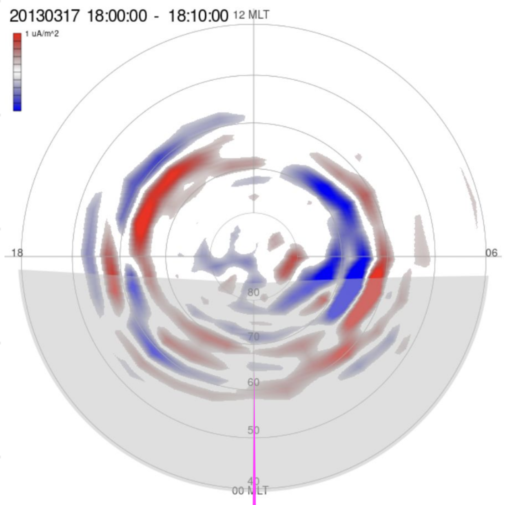
- Generation, propagation and interaction of TADs are different in the different hemispheres.

- Joule heating deposited in different hemispheres shows significant IHAs □ IHAs in TADs

- **Realistic high-latitude forcings are crucial:**
  - Creating AMIE patterns is time-consuming

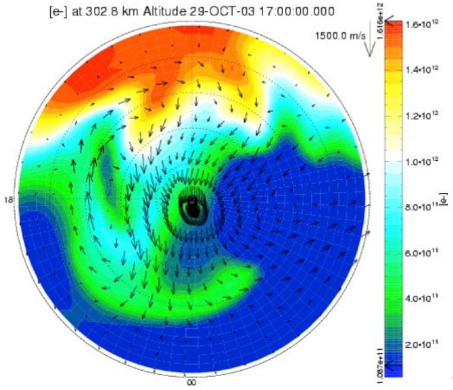
- **Can we be a little bit lazier? Yes?**
  - AMPERE FAC data are available Drive GCMs
    - **AMPERE FAC**: fitting results of the magnetic perturbation measurements by Iridium satellites
    - **FAC-driven:** Solves for global electric potential using FAC inputs along with the neutral winds and conductance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

AMPERE FAC (https://ampere.jhuapl.edu/)

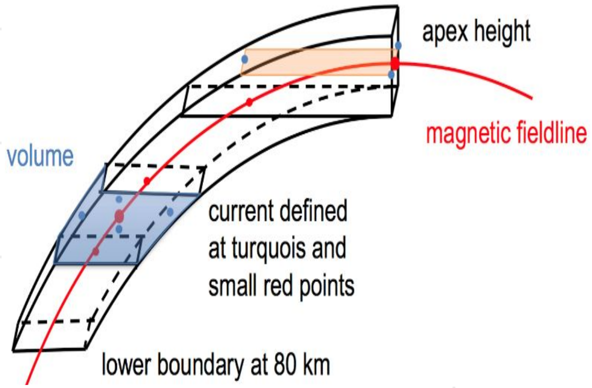


Input

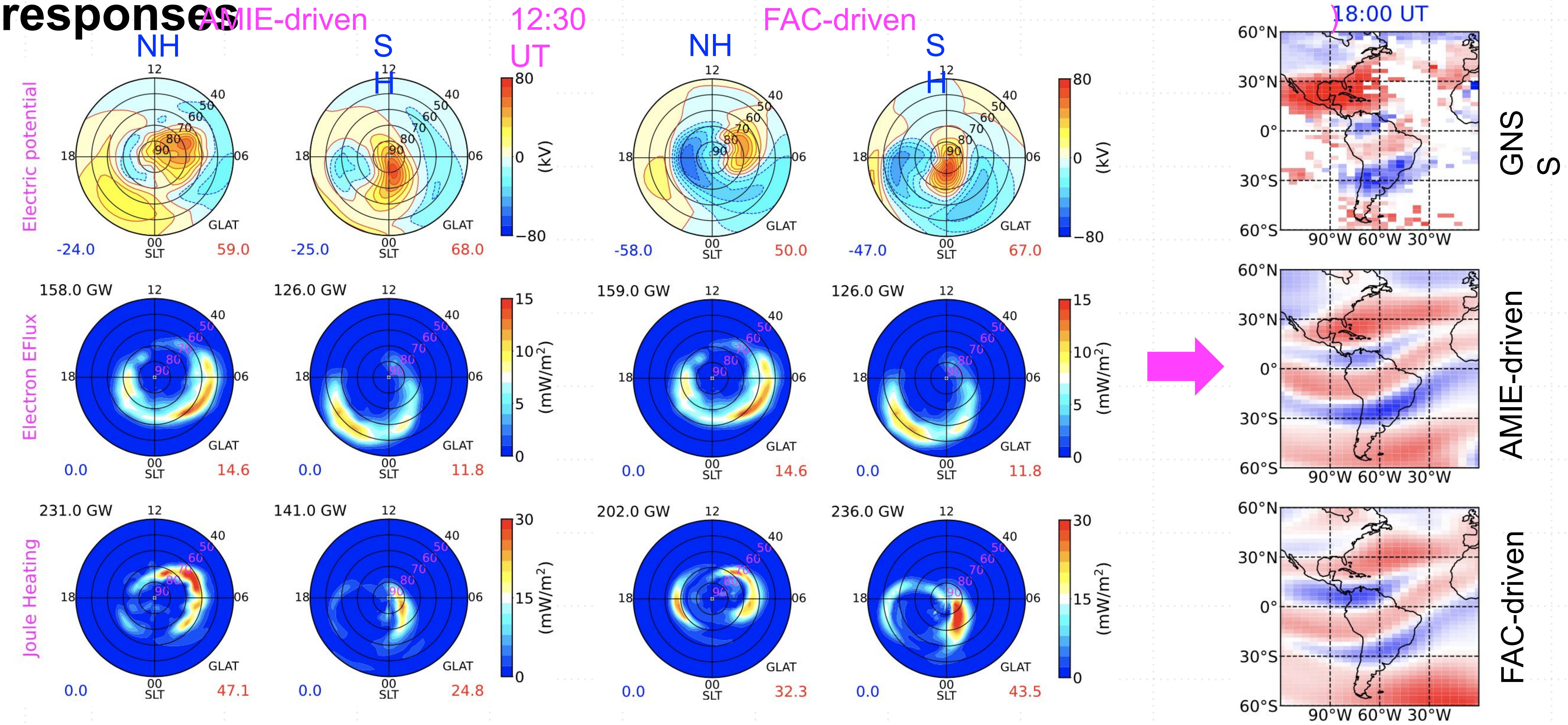
GITM [Ridley et al., 2006]



NCAR 3D electrodynamo solver [Maute & Richmond, 2017]

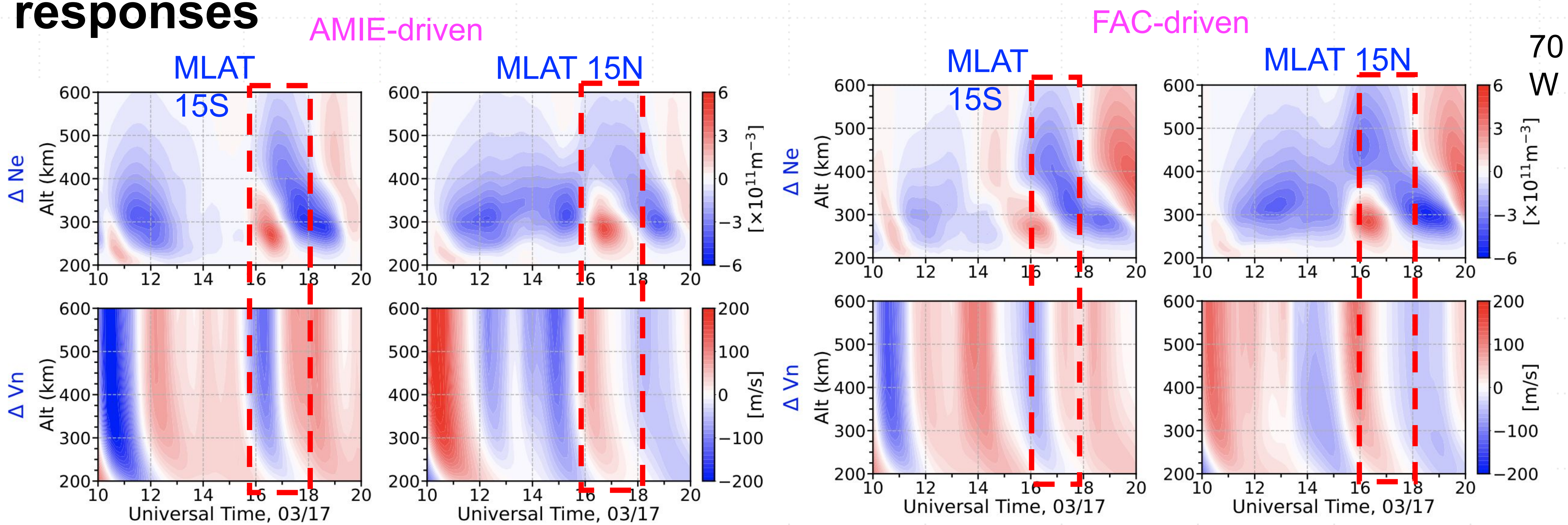


• Impact of high-latitude forcing on ionospheric responses



- 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.

Summary

- 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:
Zhu, Q., Lu, G., Deng, Y. (2022). doi: 10.3389/fspas.2022.916739
Zhu, Q., Lu, G., Maute, A., Deng, Y., & Anderson, B. (2022). doi: 10.1029/2022SW003170

Thanks!

Backup (1): FAC-driven method in GITM

- **Step 1: Calculate high-latitude (>50° MLAT) electric potential (Φ^{R}) using FAC in each hemisphere (N: NH; S: SH)**

$$\frac{\partial}{\partial \phi_m}\left[\frac{\Sigma_{\phi\phi}^{N/S}}{\cos\lambda_m}\frac{\partial \Phi^{RN/S}}{\partial \phi_m} + \Sigma_{\phi\lambda}^{N/S}\frac{\partial \Phi^{RN/S}}{\partial|\lambda_m|}\right] + \frac{\partial}{\partial|\lambda_m|}\left[\Sigma_{\lambda\phi}^{N/S}\frac{\partial \Phi^{RN/S}}{\partial \phi_m} + \Sigma_{\lambda\lambda}^{N/S}\cos\lambda_m\frac{\partial \Phi^{RN/S}}{\partial|\lambda_m|}\right] = R\left[\frac{\partial K_{m\phi}^{DN/S}}{\partial \phi_m} + \frac{\partial (K_{m\phi}^{DN/S}\cos\lambda_m)}{\partial|\lambda_m|}\right] + J_{mr}^{N/S}R^2\cos\lambda_m$$

$$\nabla\cdot(\boldsymbol{\Sigma}\cdot(\mathbf{E})) \qquad -\nabla\cdot(\boldsymbol{\Sigma}\cdot(\mathbf{U}\times\mathbf{B})) \qquad -\mathrm{J}_{\parallel}$$

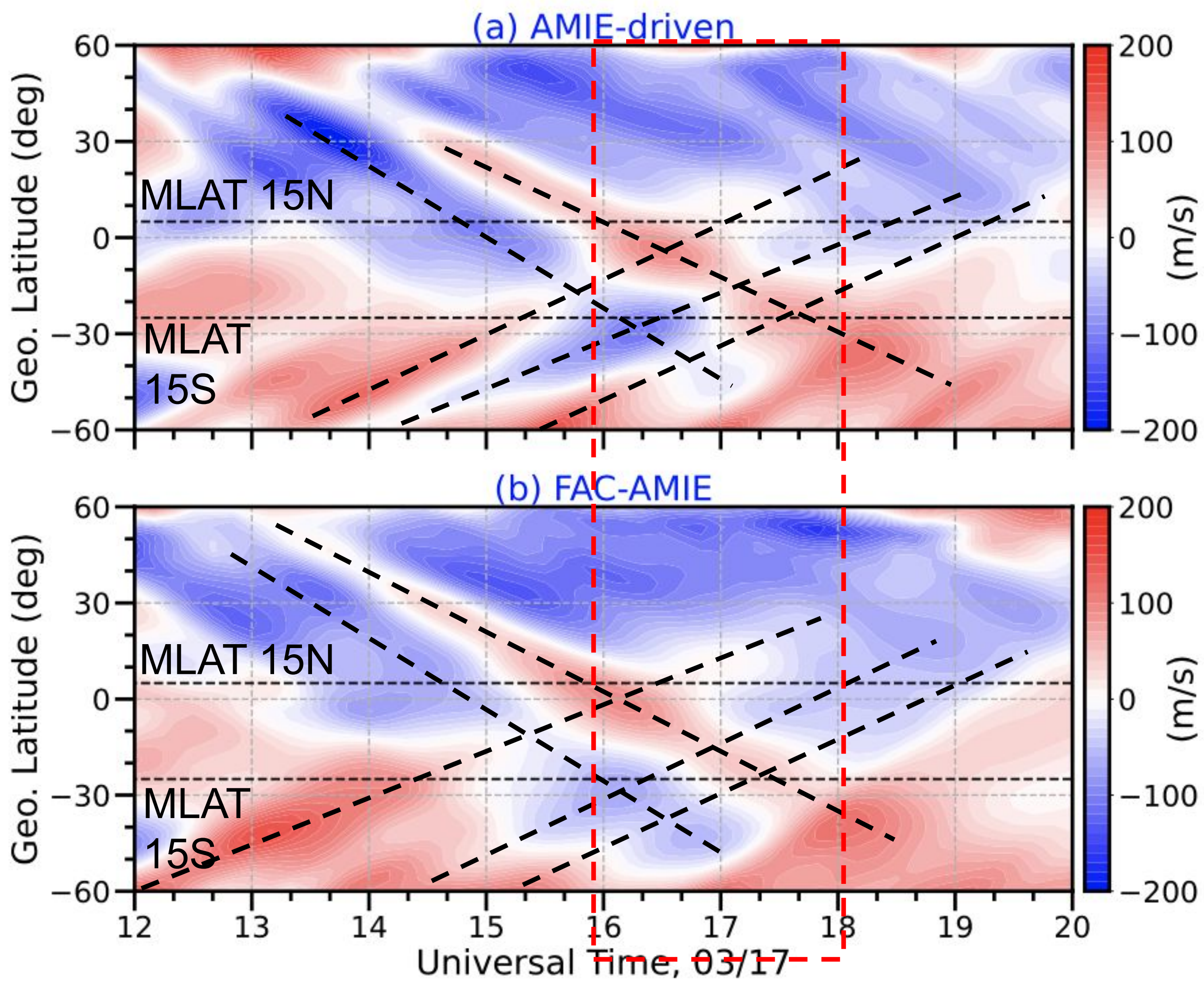
  - High-latitude electron precipitation pattern is derived from the AMIE technique:
    - Modifying the electron precipitation pattern by ground-based magnetic perturbation measurements and DMSP SSUSI data
  - The neutral wind dynamo is included

- **Step 2: Calculate global electric potential (Φ) using high-latitude (>50° MLAT) electric potential (Φ^{R})**

$$p\frac{\partial}{\partial \phi_m}\left[\frac{\Sigma_{\phi\phi}^{T}}{\cos\lambda_m}\frac{\partial \Phi}{\partial \phi_m} + \Sigma_{\phi\lambda}^{T}\frac{\partial \Phi}{\partial|\lambda_m|}\right] + p\frac{\partial}{\partial|\lambda_m|}\left[\Sigma_{\lambda\phi}^{T}\frac{\partial \Phi}{\partial \phi_m} + \Sigma_{\lambda\lambda}^{T}\cos\lambda_m\frac{\partial \Phi}{\partial|\lambda_m|}\right] - (1-p)\sigma^R R\cos\lambda_m\Phi = pR\left[\frac{\partial K_{m\phi}^{DT}}{\partial \phi_m} + \frac{\partial (K_{m\phi}^{DT}\cos\lambda_m)}{\partial|\lambda_m|}\right] - (1-p)\sigma^R R\cos\lambda_m\,\Phi^{\mathrm{R}}$$

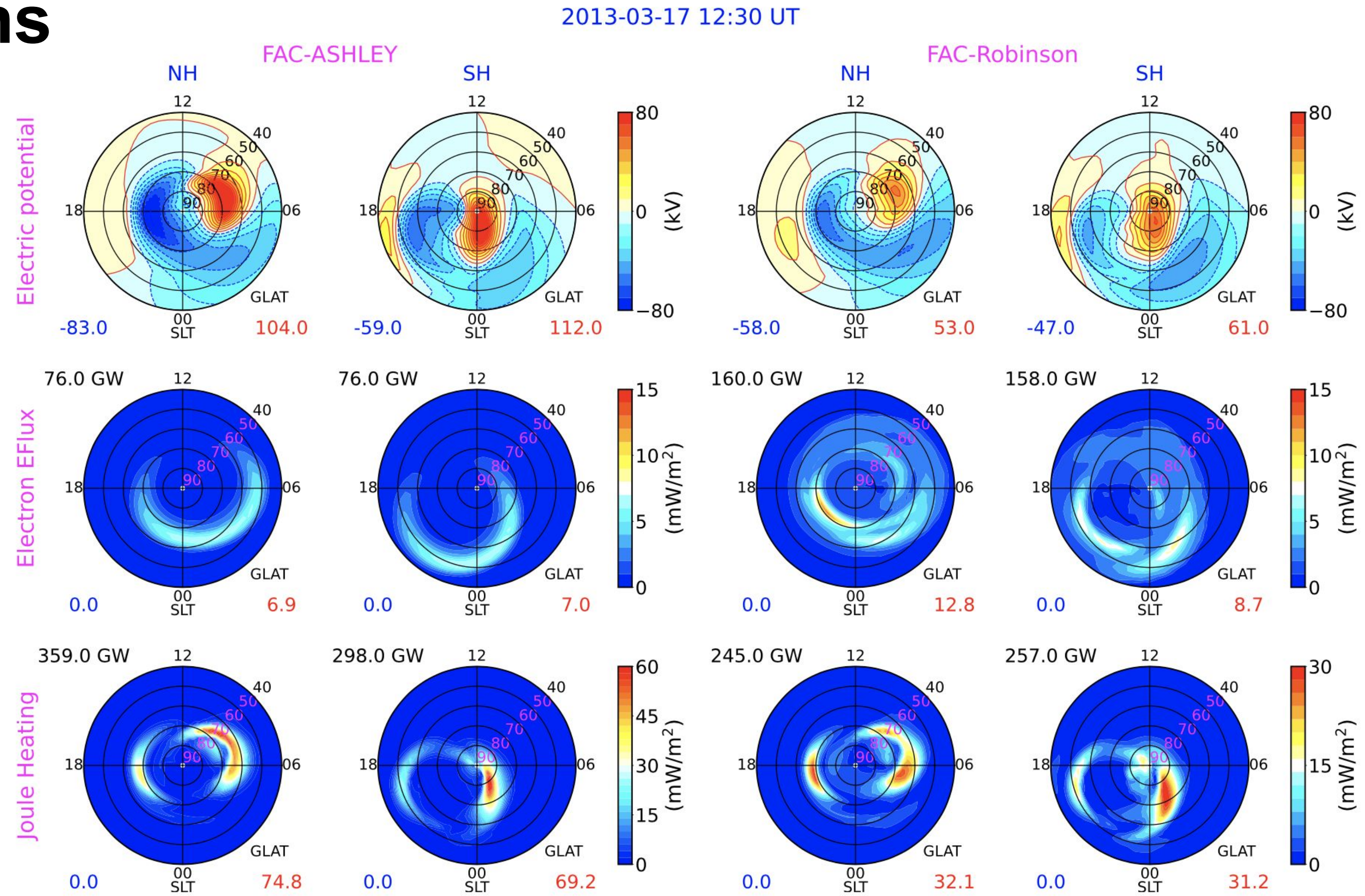
  - (σ^R: reference conductivity; p: spatial varying parameter) → Penetration electric field

• Backup (2): AMIE-driven vs FAC-AMIE: TAD



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

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