Preliminary results from a comprehensive analysis of low-latitude ionospheric electrodynamics variability using data assimilation

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Goal and motivation

The goal is to conduct a quantitative data-driven and first-principles-based investigation to improve the understanding of the variability of the dayside, low-latitude, and global-scale ionospheric electrodynamics.

- Estimating the uncertainty and variability of energy sources and evaluating their impact on the ionosphere to get a better understanding of ionospheric variability.
- Data assimilation can help quantify the effects of these energy sources by combining multiple types of observations and first-principles models.
- COSMIC electron density and C/NOFS ion velocity data are assimilated into the TIE-GCM to provide a comprehensive vision of variability of ionospheric electrodynamics.

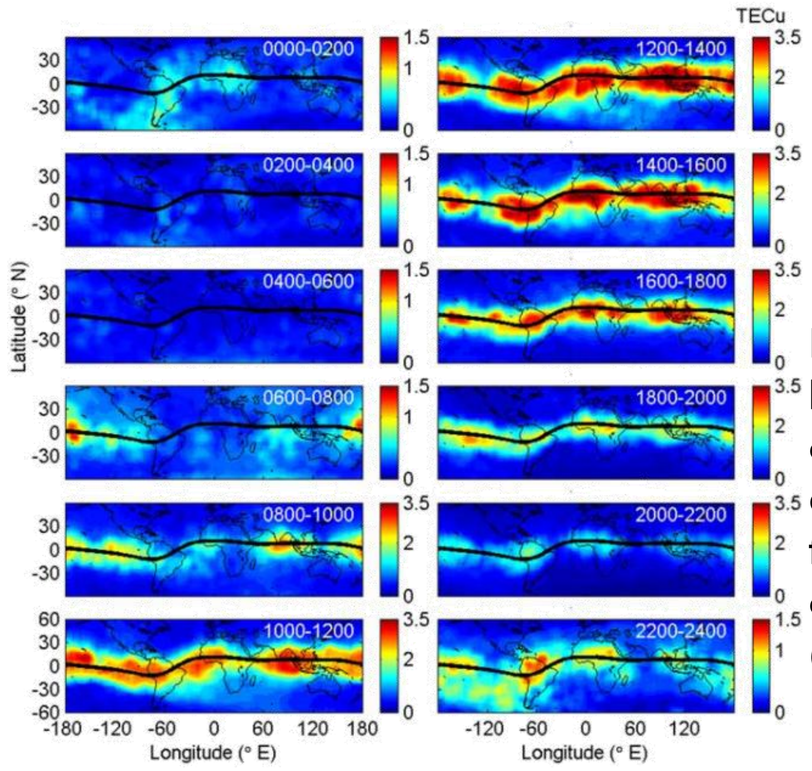

Figure 1. Local time and longitudinal dependence of equatorial F region electron density derived from measurements obtained by COSMIC. (Image created: Lin et al. [2007])

Data Assimilation–Ensemble Adjustment Kalman Filter (EAKF) in Data Assimilation Research Testbed (DART)

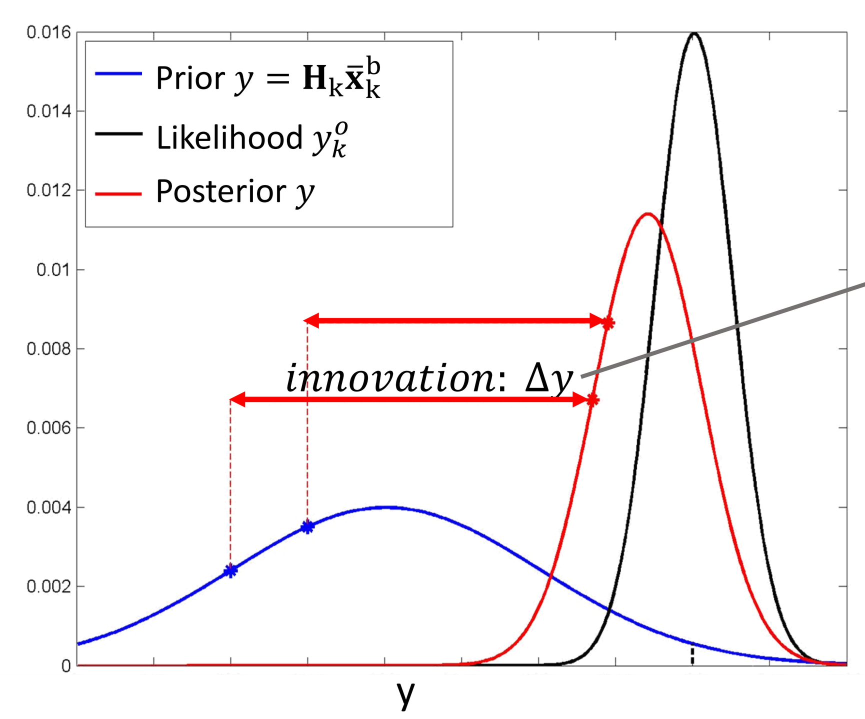

Figure 2. Illustration of how EAKF derived from Bayes' rule

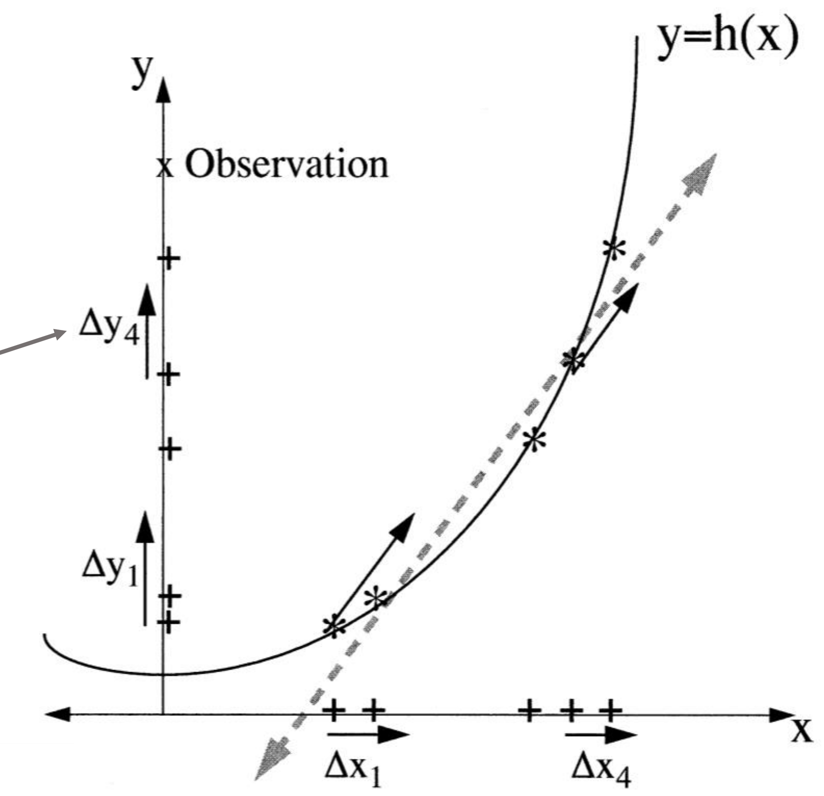

Figure 3. In EAKF, **unobserved model state variable (e.g. neutral winds)** from model (the TIE-GCM) can be updated by **observation (e.g. C/NOFS ion velocity)** according to the model and observation uncertainty. (Image created: Anderson [2002])

$$\bar{\mathbf{X}}^a = \bar{\mathbf{X}}^b + \mathbf{K}(\mathbf{y}^o - \mathbf{H}(\bar{\mathbf{X}}^b))$$

$$\mathbf{X}_n^a - \bar{\mathbf{X}}^a = (\mathbf{X}_n^b - \bar{\mathbf{X}}^b) + \tilde{\mathbf{K}}(-\mathbf{H}(\mathbf{X}_n^b - \bar{\mathbf{X}}^b))$$

$$\mathbf{K} = [\rho^b \circ (\mathbf{P}^b\mathbf{H}^T)][\rho^b \circ (\mathbf{H}\mathbf{P}^b\mathbf{H}^T + \mathbf{R})]^{-1}$$

$$\mathbf{P}^b\mathbf{H}^T \sim \frac{1}{N-1}\sum_{n=1}^{N}(\mathbf{X}_n^b - \bar{\mathbf{X}}^b)[\mathbf{H}(\mathbf{X}_n^b - \bar{\mathbf{X}}^b)]^T$$

$$\mathbf{H}\mathbf{P}^b\mathbf{H}^T \sim \frac{1}{N-1}\sum_{n=1}^{N}[\mathbf{H}(\mathbf{X}_n^b - \bar{\mathbf{X}}^b)][\mathbf{H}(\mathbf{X}_n^b - \bar{\mathbf{X}}^b)]^T$$

$$\mathbf{P}^a = (\mathbf{I} - \mathbf{K}\mathbf{H})\mathbf{P}^b = \left(\mathbf{I} - \tilde{\mathbf{K}}\mathbf{H}\right)\mathbf{P}^b\left(\mathbf{I} - \tilde{\mathbf{K}}\mathbf{H}\right)^T = \mathbf{Z}^b[\mathbf{I} - \mathbf{Z}^{bT}\mathbf{H}^T(\mathbf{H}\mathbf{Z}^b\mathbf{Z}^{bT} + \mathbf{R})^{-1}\mathbf{H}\mathbf{Z}^b]\mathbf{Z}^{bT}$$

$\mathbf{A} = \left(\mathbf{I} - \tilde{\mathbf{K}}_k\mathbf{H}\right)$ - adjustment matrix A computed by SVD

Moderate storm in March 2009

- Experiment Period: UT 00 to 04 of 12 Mar. 2009
- Observation: C/NOFS CINDI IVM ion velocity
- Model state variables: TIE-GCM ion drifts and neutral winds

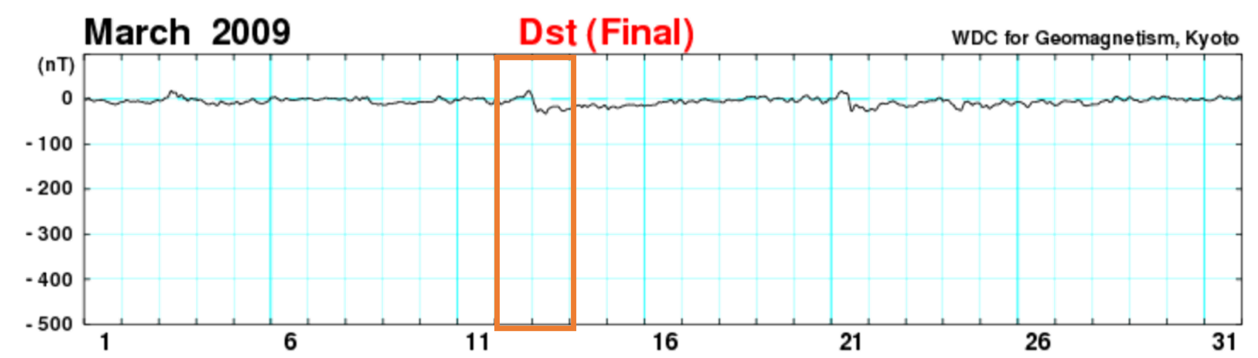

Figure 6. Dst index during March 2009. (Image created: world Data Center for Geomagnetism, Kyoto, http://wdc.kugi.kyoto-u.ac.jp/index.html)

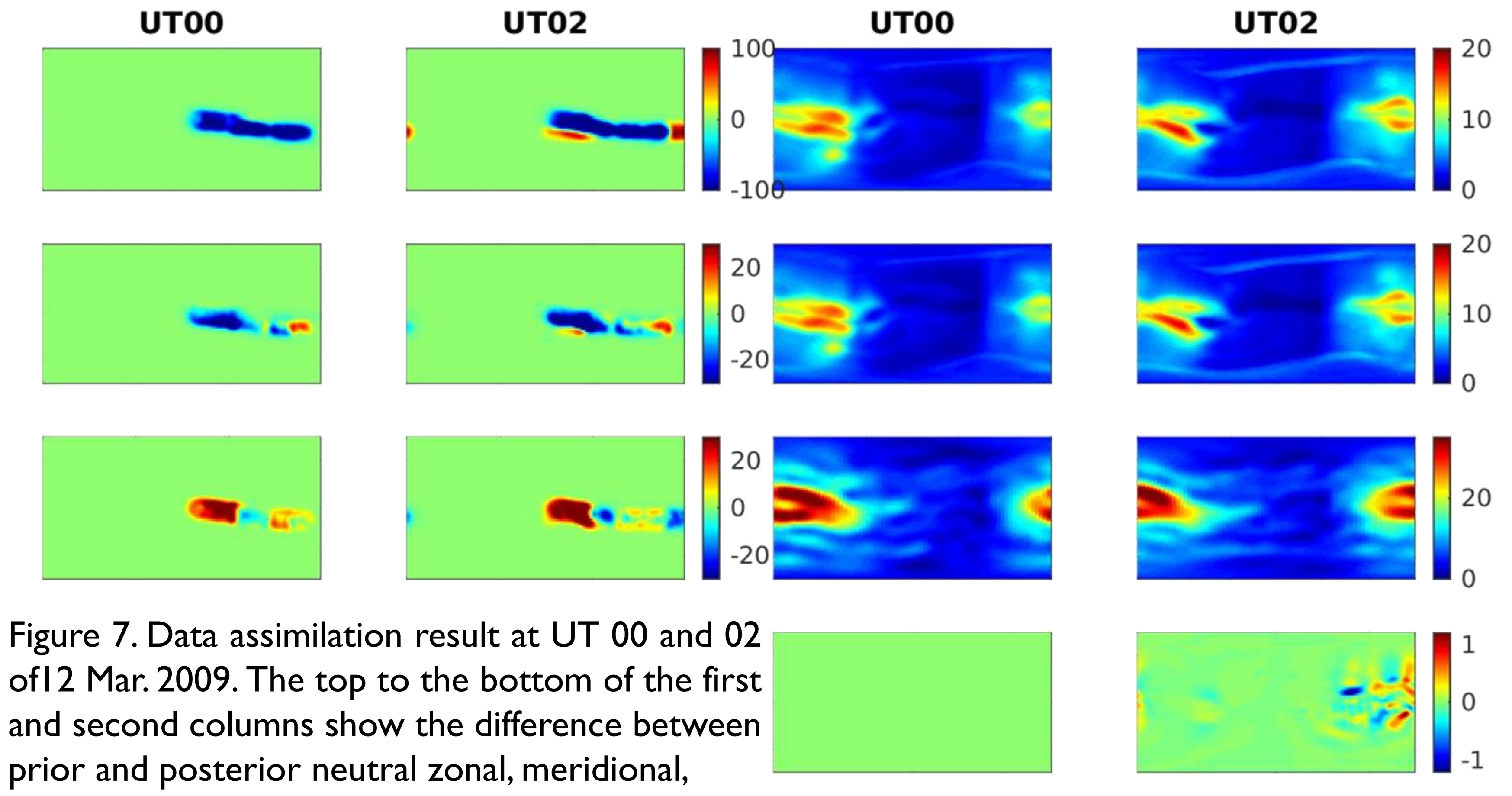

Figure 7. Data assimilation result at UT 00 and 02 of12 Mar. 2009. The top to the bottom of the first and second columns show the difference between prior and posterior neutral zonal, meridional, and vertical winds, respectively. The top to the bottom of the third and fourth columns show the TEC w/o the impact of data assimilation, TEC w/ the impact of data assimilation, CODE GIM, and difference between the TEC w/ and w/o the impact of data assimilation, respectively.

Challenge 1. How to generate ensemble that reflects realistic uncertainty of model forecasts?

The model ensemble is generated by perturbing:

1. Solar irradiance – F10.7 index

F10.7 index is perturbed according to Gaussian distribution with standard deviation and mean given from the variance and mean from 12 to 18 March 2009.

2. Forcing from the magnetosphere– Assimilative Mapping of Geospace Observations

According to Matsuo and Richmond [2008], high-latitude ionospheric convection is given by using the Assimilative Mapping of Geospace Observations and is perturbed according to a multivariate normal distribution with the mean and covariance estimated from assimilative mapping results from 12 to 18 March 2009.

3. Forcing from the lower atmosphere – TIME-GCM + MERRA

According to Häusler et al., [2014], lower boundary conditions (winds and temperature) are given by Modern-Era Retrospective Analysis for Research and Application (MERRA)-driven TIME-GCM and are perturbed according to Gaussian distribution with covariance and mean computed from TIME-GCM output from 12 March to 29 April 2009.

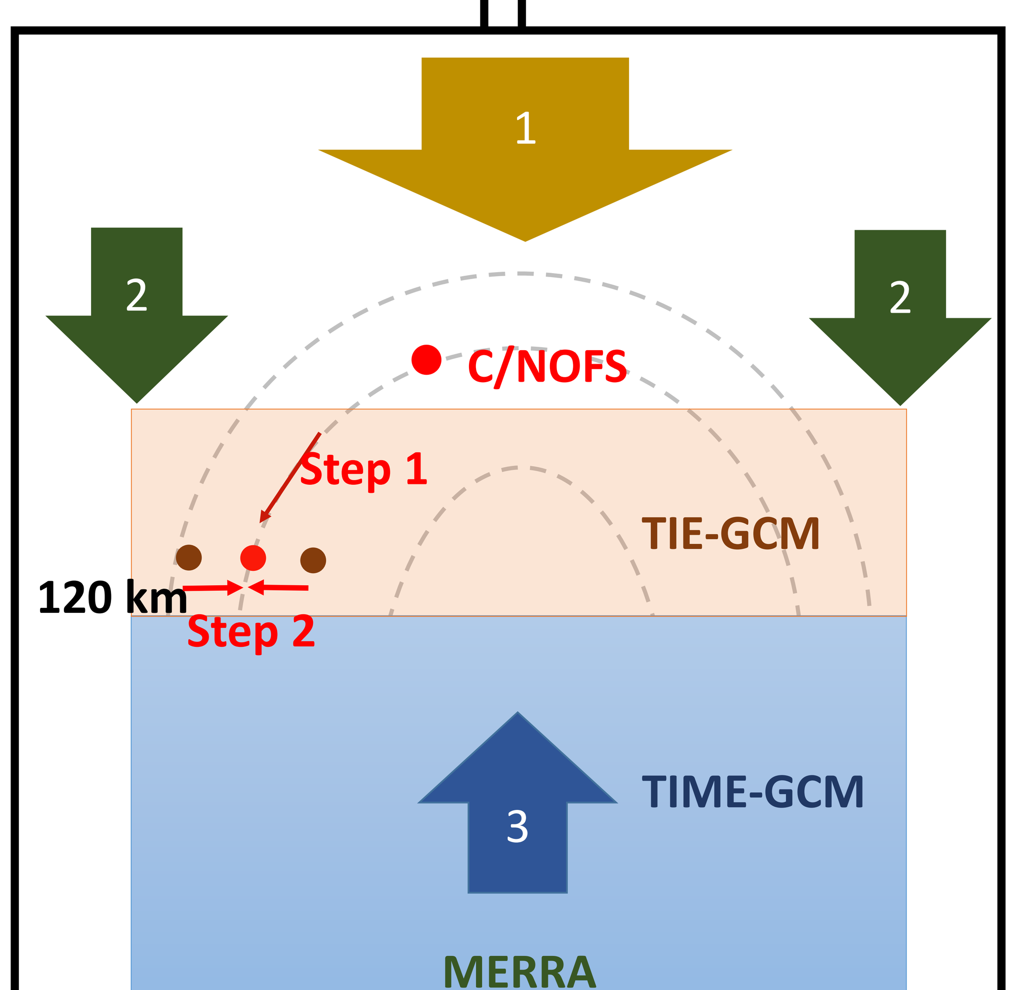

Figure 4. Illustration of how to generate model ensemble and how to compute the innovation of observed variable.

Challenge 2. How to compute the innovation $y_{model} - y_{obs}$?

Step 1. Using Python Satellite Data Analysis Tookit (PysatMagVect) to map the ExB drift from C/NOFS location to 120 km altitude according to the APEX coordinate with the assumption of equal-potential along geomagnetic field.

Step 2. Interpolating TIE-GCM ExB drift horizontally from model grid to the mapping point at 120 km altitude.

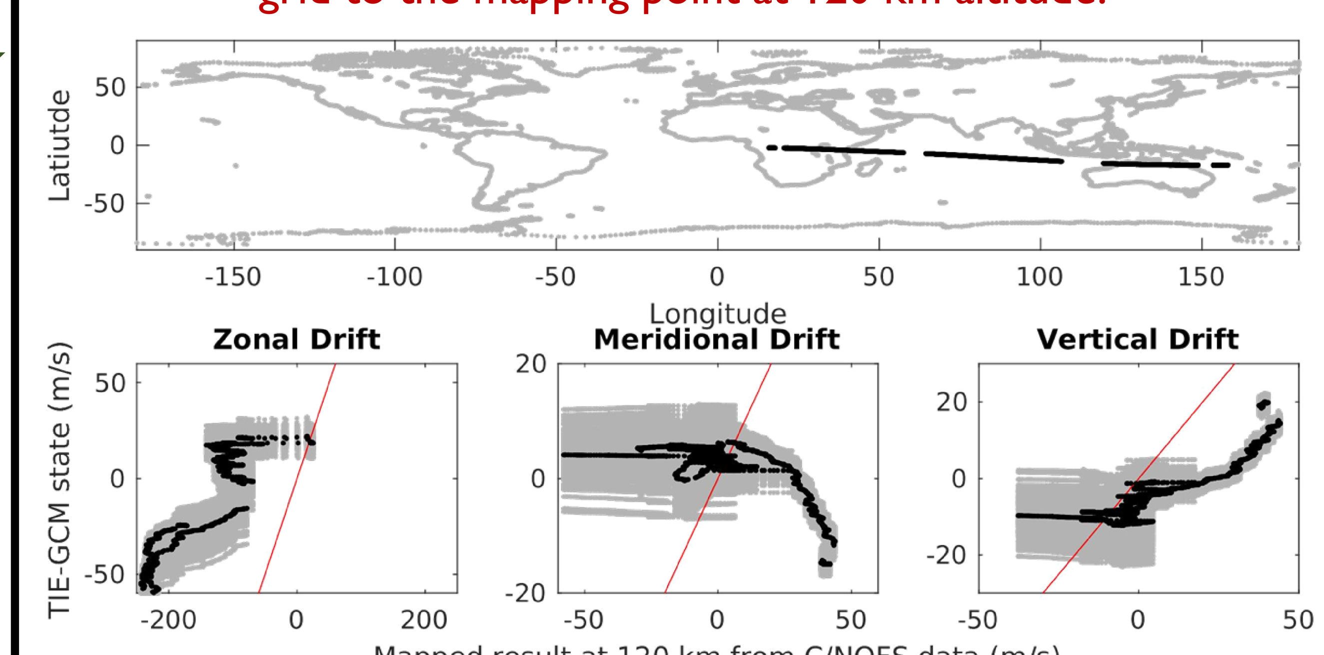

Figure 5. Comparison of plasma drifts from TIE-GCM and ion velocities from C/NOFS. Top panel shows the orbit of C/NOFS satellite around UT 0000 of 12 March 2009. Black dots in bottom panels show the comparison of the ensemble mean of TIE-GCM drift and drift mapping from C/NOFS ion velocity to 120 km altitude. Grey dots in the bottom panels show that for each ensemble member.

Summary and future work

- In comparison to C/NOFS ion velocity observations, TIE-GCM ensemble simulations underestimate equatorial plasma drift velocities especially in the zonal direction. A more comparison is needed to assess the model biases.
- C/NOFS ion velocity observations can be assimilated into the DART/TIE-GCM to correct the winds around the equatorial region.
- COSMIC electron density data will be assimilated to improve the nowcasting of the day-to-day variability of ionospheric equatorial electrodynamics.
- Further physical constraints need to be considered to improve the forecasting of the day-to-day variability of ionospheric equatorial electrodynamics.

References

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