Investigating the Storm-Time Response of the Ionosphere-Thermosphere (I-T) through Data Assimilation

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1. Introduction

Goal:

Advance physics-based data assimilation capabilities to specify I-T states, focusing on neutral density variability during a storm period

Motivation : Neutral observations have limited coverage, making it difficult to globally estimate the thermosphere. *Alternatively, we focus on assimilating indirect, plasma observations to directly estimate neutral and plasma states.*

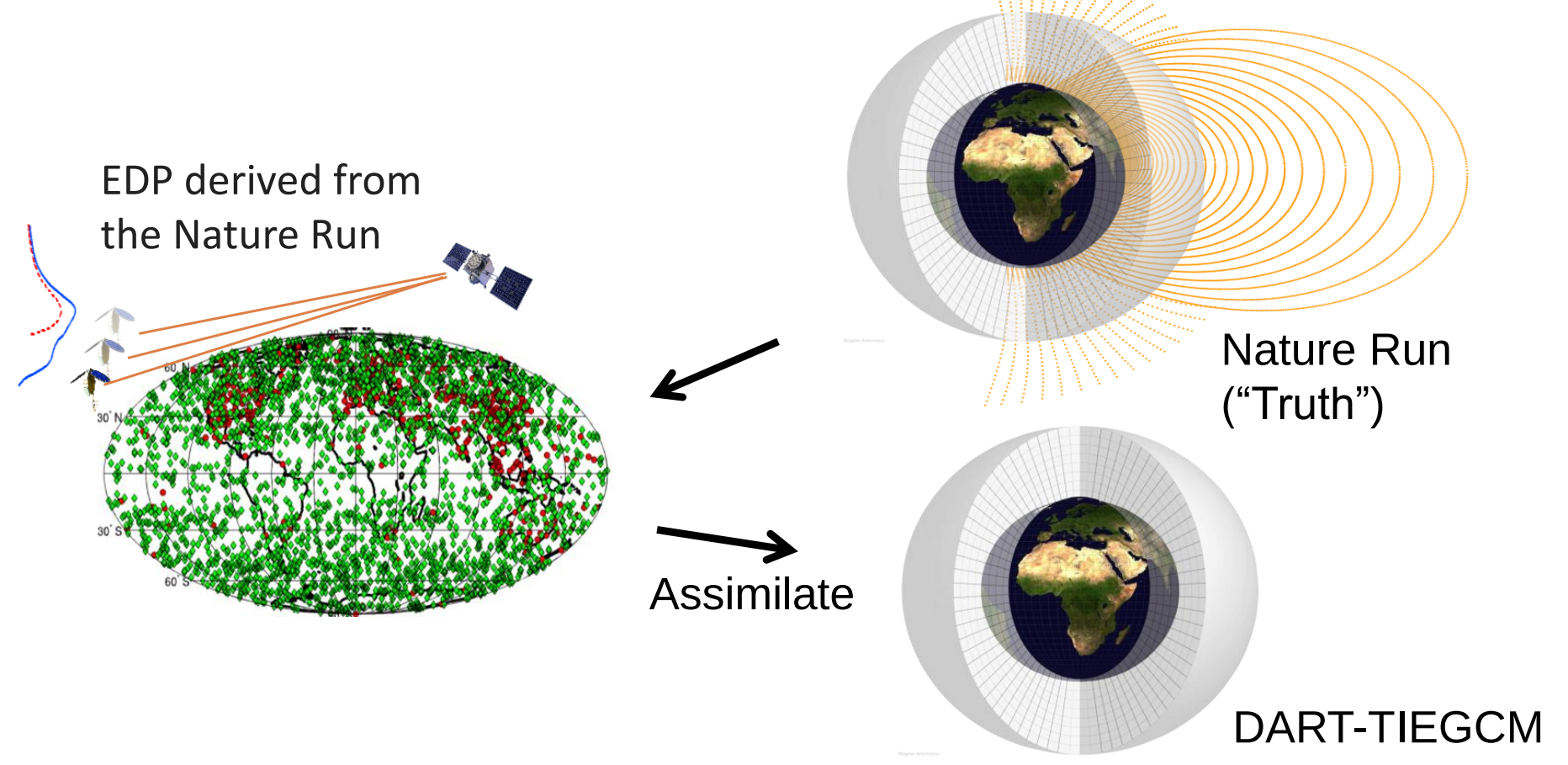


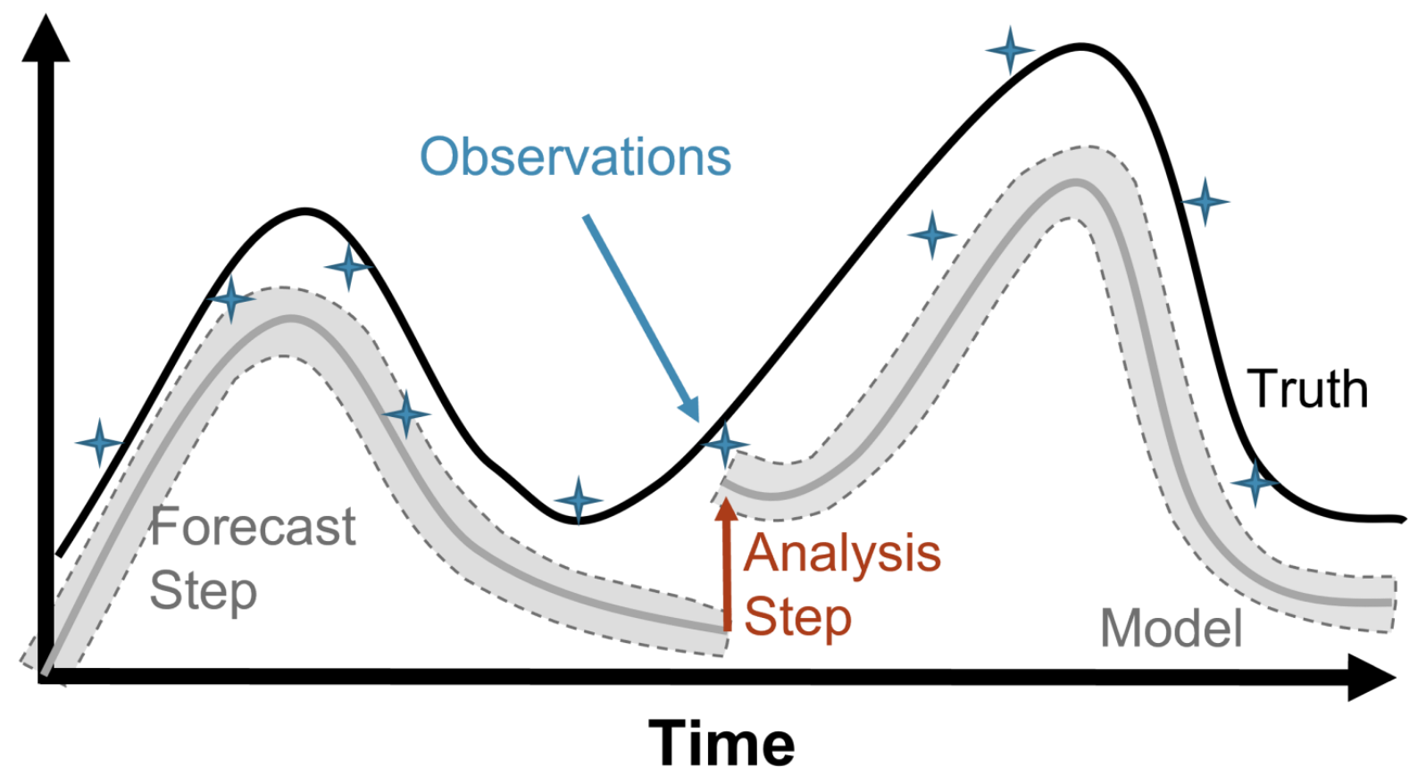
Fig. 1.1 – Assessment is shown in *Observing System Simulation Experiments* (*OSSEs*) and *Reanalysis*.

Method: Use the Ensemble Adjustment Kalman Filter (EAKF) from DART [3], a Monte Carlo data assimilation (DA) approach. We use *strongly coupled data assimilation* to update plasma and neutral states, $\boldsymbol{x}$, (neutral temperature and neutral winds), correcting model dynamics and energetics to improve the storm-time response. I-T system is largely driven by external forcing, $\boldsymbol{d}$.

1. **Forecast Step**
   Propagate states with non-linear, I-T coupled model dynamics, $\mathcal{M}$:
   $$p(\mathbf{x}_{k-1}, \mathbf{d}|Y_{k-1}) \xrightarrow{\mathcal{M}} p(\mathbf{x}_k, \mathbf{d}|Y_{k-1})$$
2. **Analysis Step**
   Bayesian update of states at time k:
   $$p(\mathbf{x}_k, \mathbf{d}|Y_k) \propto p(\mathbf{y}_k|\mathbf{x}_k)p(\mathbf{x}_k, \mathbf{d}|Y_{k-1})$$

Where observations $Y_k = \{\boldsymbol{y}_k, \boldsymbol{y}_{k-1}, \dots\}$
States $O(n) = 10^7$

Fig. 1.2 – Typical data assimilation cycle



Analysis Update - Direct-update of neutral states enabled through *strong I-T coupling*

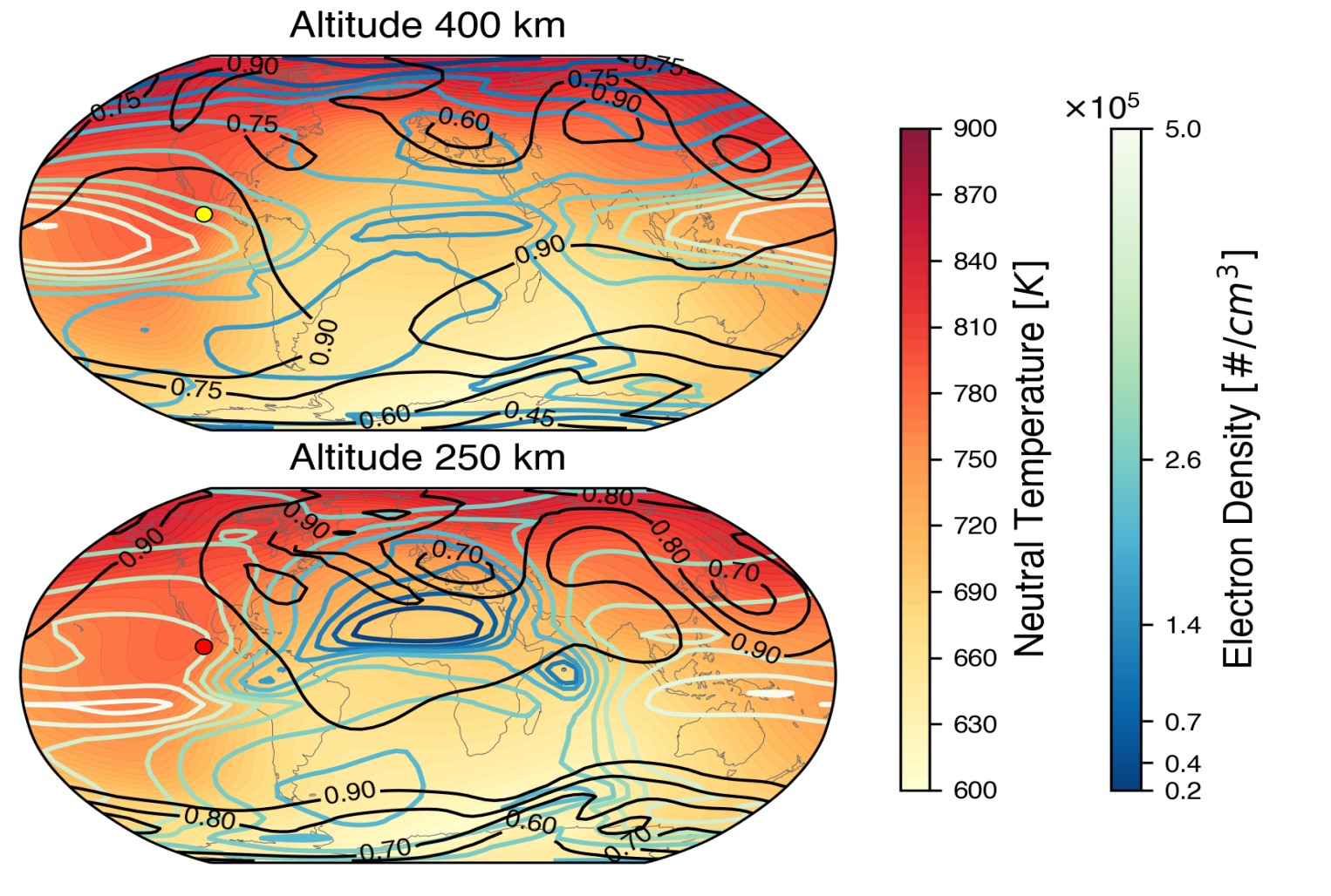


Fig. 1.3 – Multivariate covariance structures are generated by model dynamics. Correlations shown between electron density (NE) and neutral temperature (TN)

Acknowledgements

This work was supported by the National Aeronautics and Space Administration (NASA) under the FINESST Fellowship, as well as NSF award AGS 1848544, the NASA award 80NSSC21K1759, and the NOAA Office of Projects Planning and Analysis. The DART software was obtained from NCAR (http://www.image.ucar.edu/DAReS/DART). The TIEGCM software was obtained from High Altitude Observatory, NCAR (http://www.hao.ucar.edu/modeling/tgcm/tie.php). We acknowledge NCAR and UCAR for their community software and data support.

2. Model: DART-TIEGCM

Experiment Model: Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM). Altitudes $90 \sim 600$ km. Driven using geomagnetic forcing and daily F10.7 indices. Run alongside DART software.

2. Observations: Electron Density Profiles

Radio Occultation (RO) observations measure changes in GNSS radio signals as they pass through the ionosphere. Produces electron density profiles (EDPs) of the ionosphere. Hundreds available per hour.

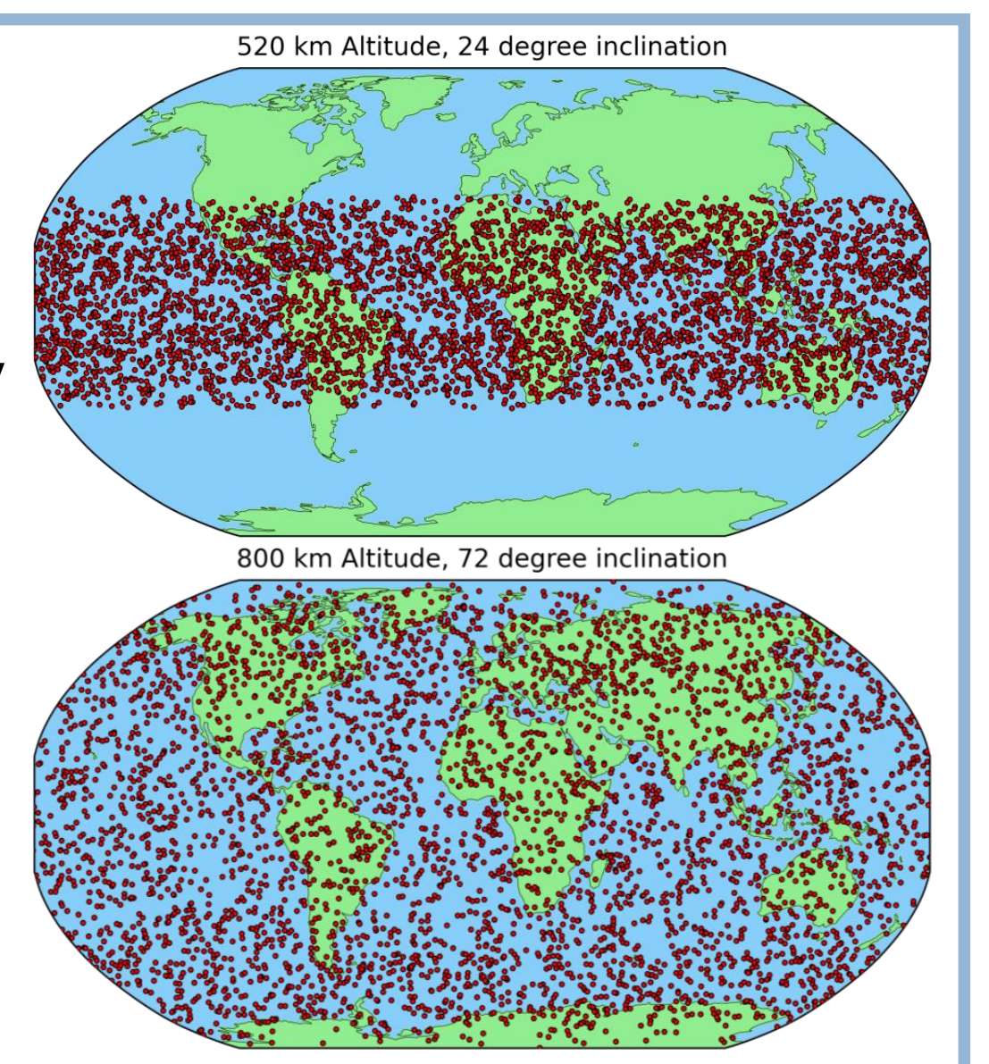


Fig. 2.1 – Example RO tangent point EDPs coverage for a full day

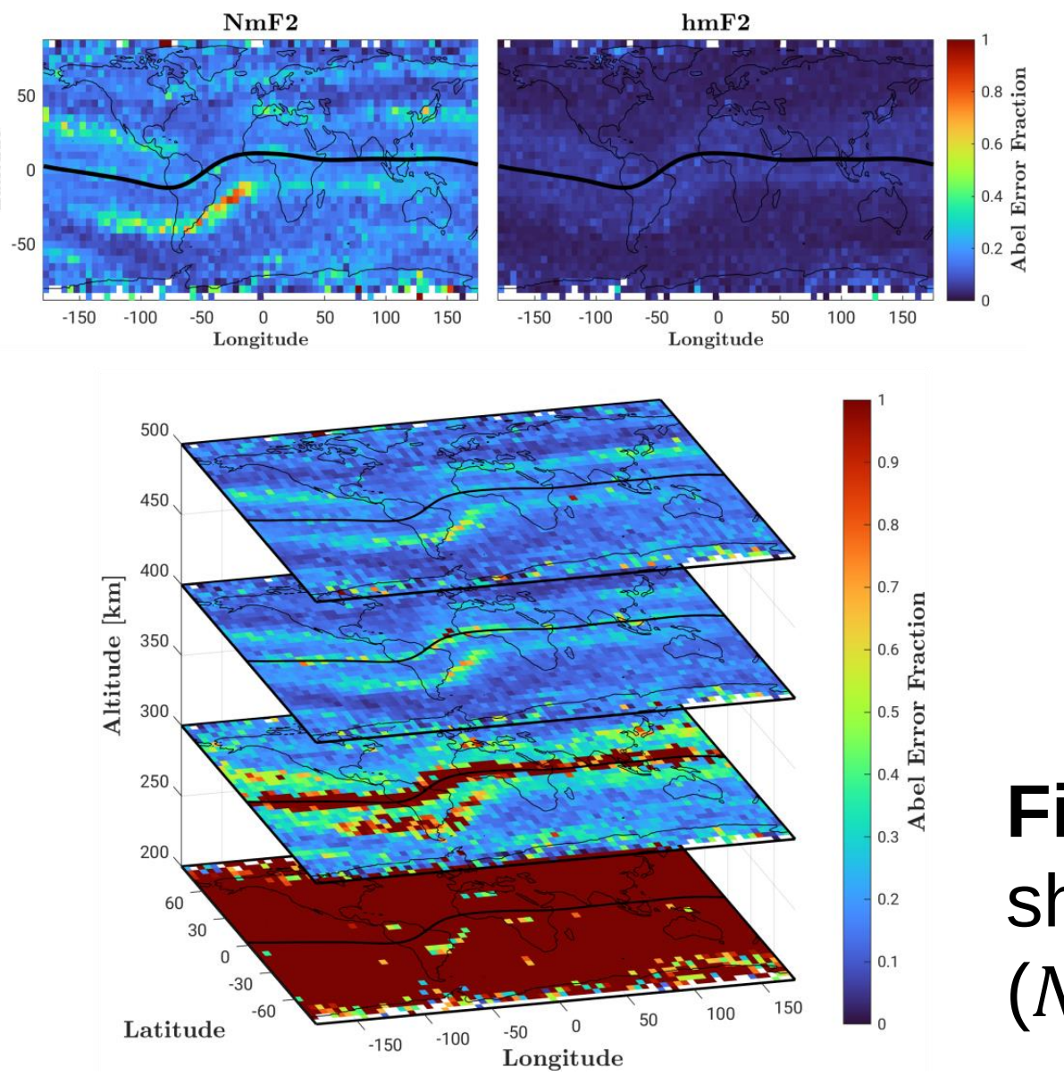
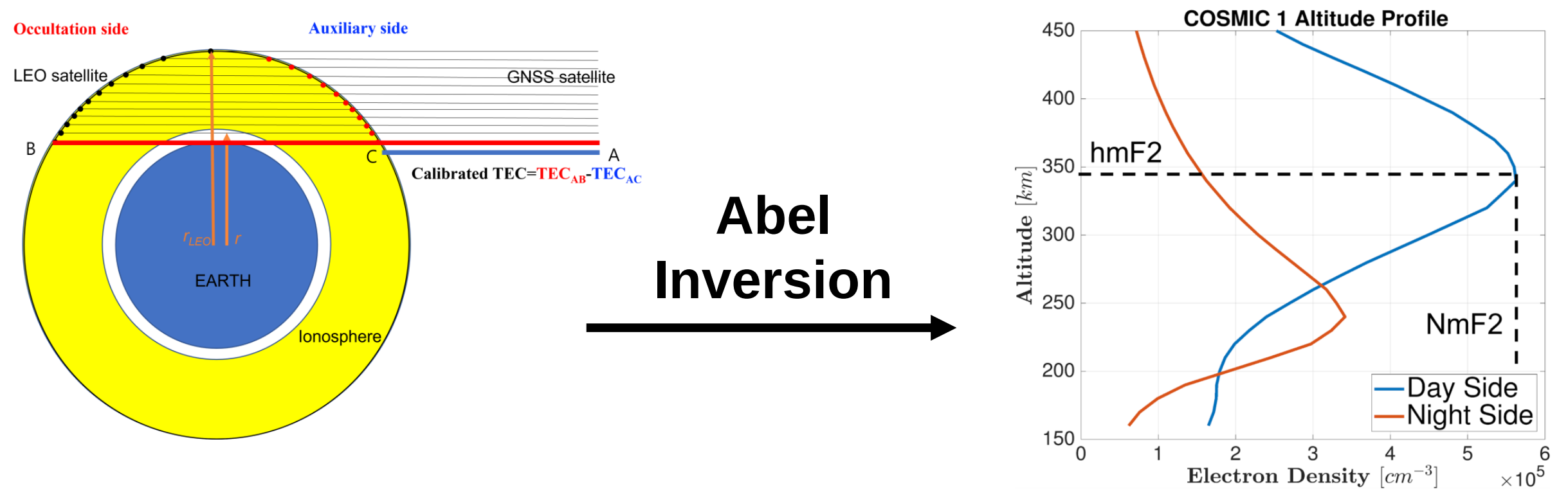


Fig. 2.2 – Calculated EDP errors, shown for 4 altitudes and peak NE ($NmF2$) and its height ($hmF2$)

Fig. 2.3 – Abel inversion retrieval procedure of total electron content (TEC). Relies on spherical symmetry assumption with associated errors



References

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[2] Dietrich, N., Matsuo, T., Lin, C.-Y., diLorenzo, B., Lin, C., C.-H., Fang, T.W. (2024). Evaluating Radio Occultation (RO) Constellation Designs using Observing System Simulation Experiments (OSSEs) for Ionospheric Specification. *Space Weather, Under Review.*
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3. OSSE Results (Plasma State Specification)

In this study, we inform future RO constellations design and DA integration in *comprehensive* OSSEs (*Dietrich et al., 2024*).

Nature Run (Truth): WAM-IPE
(Source of synthetic EDPs, retrieved using Abel inversion)

Experiment Model: DART-TIEGCM

Period: St. Patrick's Day Storm (March 13-18, 2015)

➢ *We find greater spatial coverage leads to improved specification at altitudes above 300 km, and lower altitude constellations providing higher observation counts.*

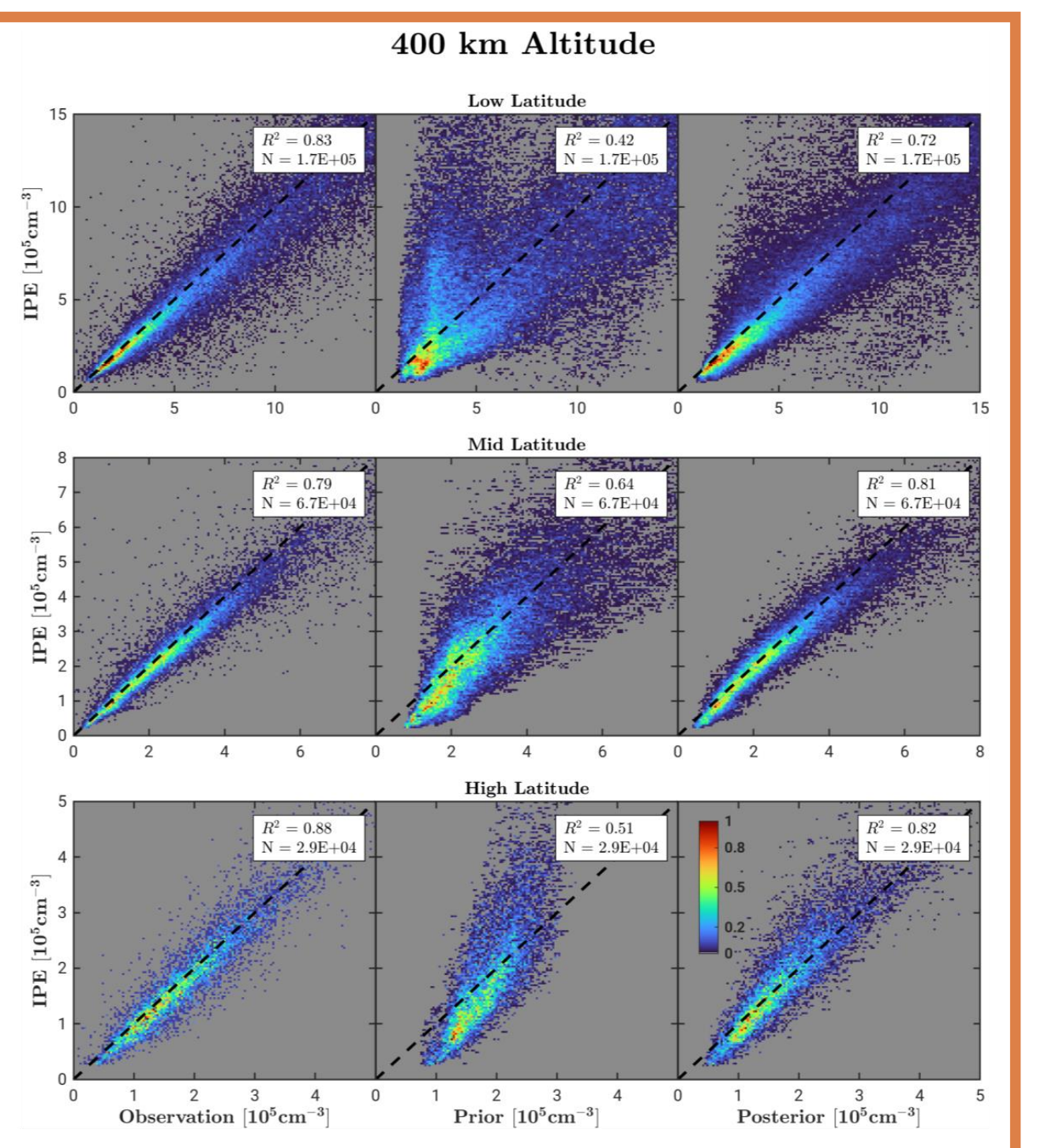


Fig. 3.1 – Observation comparison of prior and posterior states, showing improved agreement between models

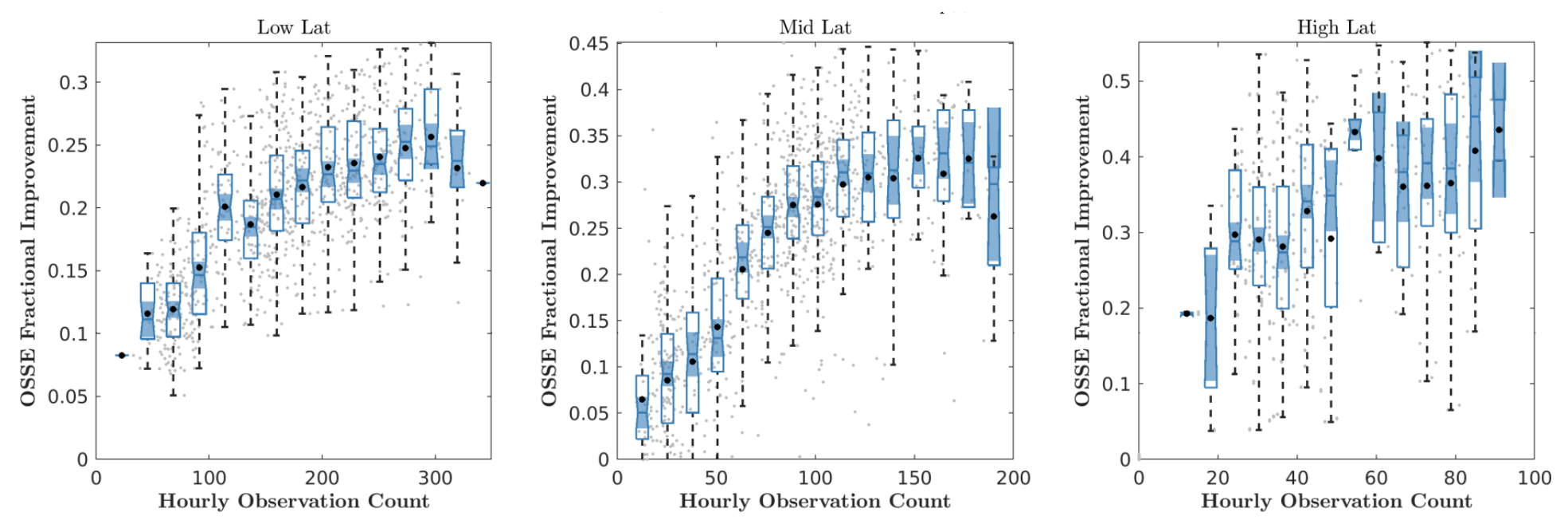
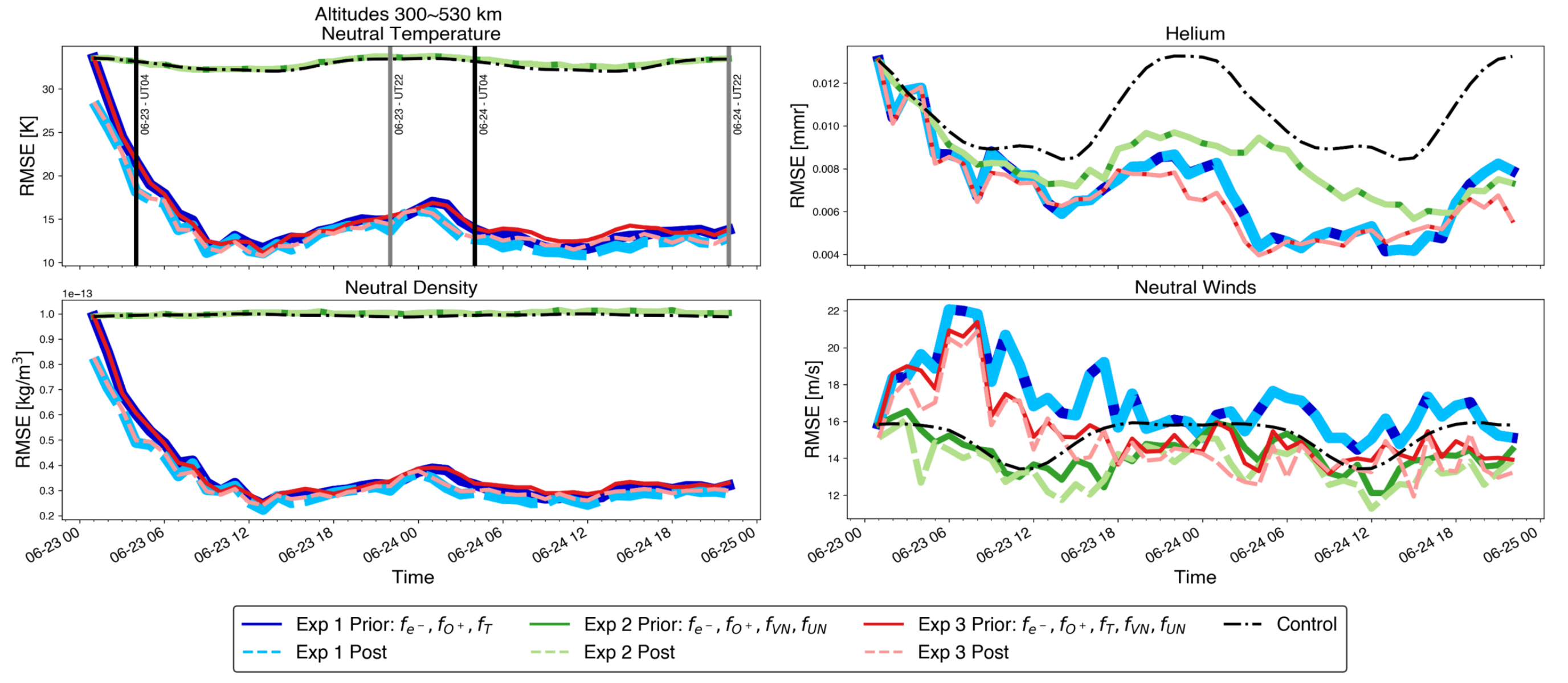


Fig. 3.2 – EDP impact reaches a potential performance limit. where Fractional Improvement = $(RMSE_{cntrl} - RMSE_{exp})/RMSE_{cntrl}$

4. OSSE Results (Neutral State Specification)

In OSSEs, we demonstrate the capability of EDPs to estimate neutral temperature and neutral winds through direct-updates (*Dietrich et al., 2022*). High correlations are found between $hmF2$ and temperature

Fig. 4.1 – Root mean square errors (RMSE) improvements for temperature (70%), neutral density (70%) and neutral winds (20%)



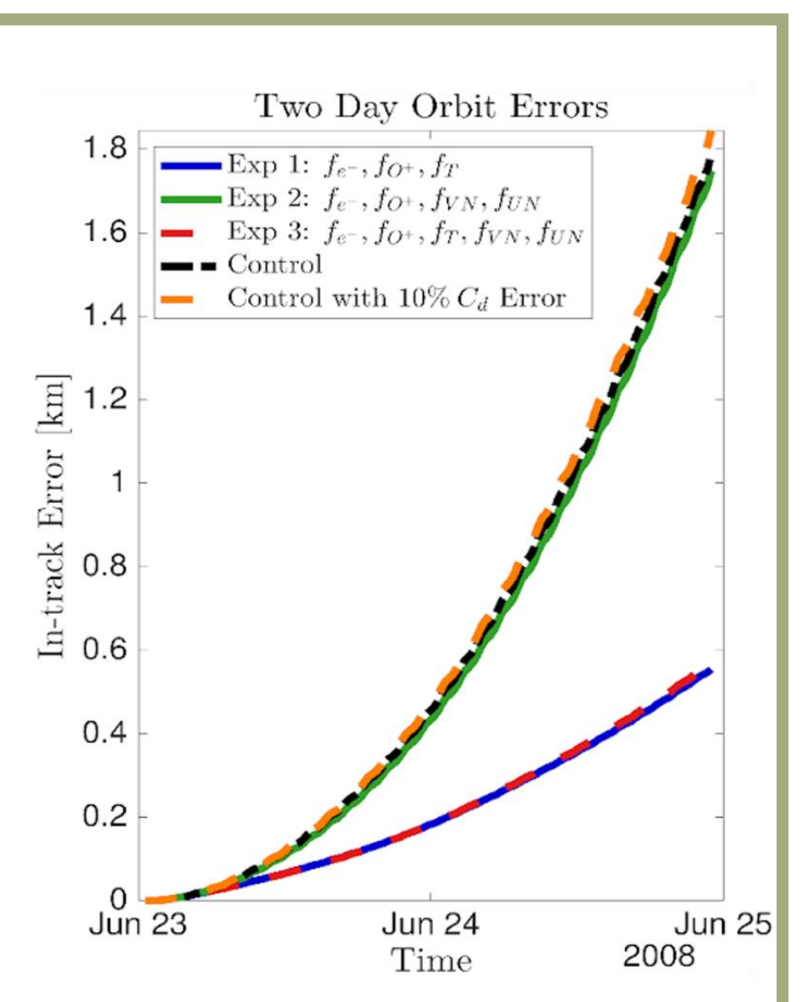


Fig. 4.2 – Improve in-track orbit position errors by 70% with neutral density.
Drag equation:

$$\boldsymbol{a} = \frac{\mu}{r^3}\boldsymbol{r} + \boldsymbol{a}_{J_2} - \frac{C_d A}{m}\rho v \boldsymbol{v}$$

5. Storm-Time Reanalysis

In this study, we aim to specify model dynamics and energetics to improve representation of the storm-response ($-80\ Dst$).

1. Assimilate COSMIC-2 ($\pm 40°$ lat) EDPs
2. Directly update neutral temperature
3. **Objective:** *Improve the magnitude and time-scale of the neutral density response*

Fig. 5.1 – Improved agreement of TIEGCM reanalysis with GRACE-FO (dusk-side, $\sim 500\ km$ alt), neutral density keogram

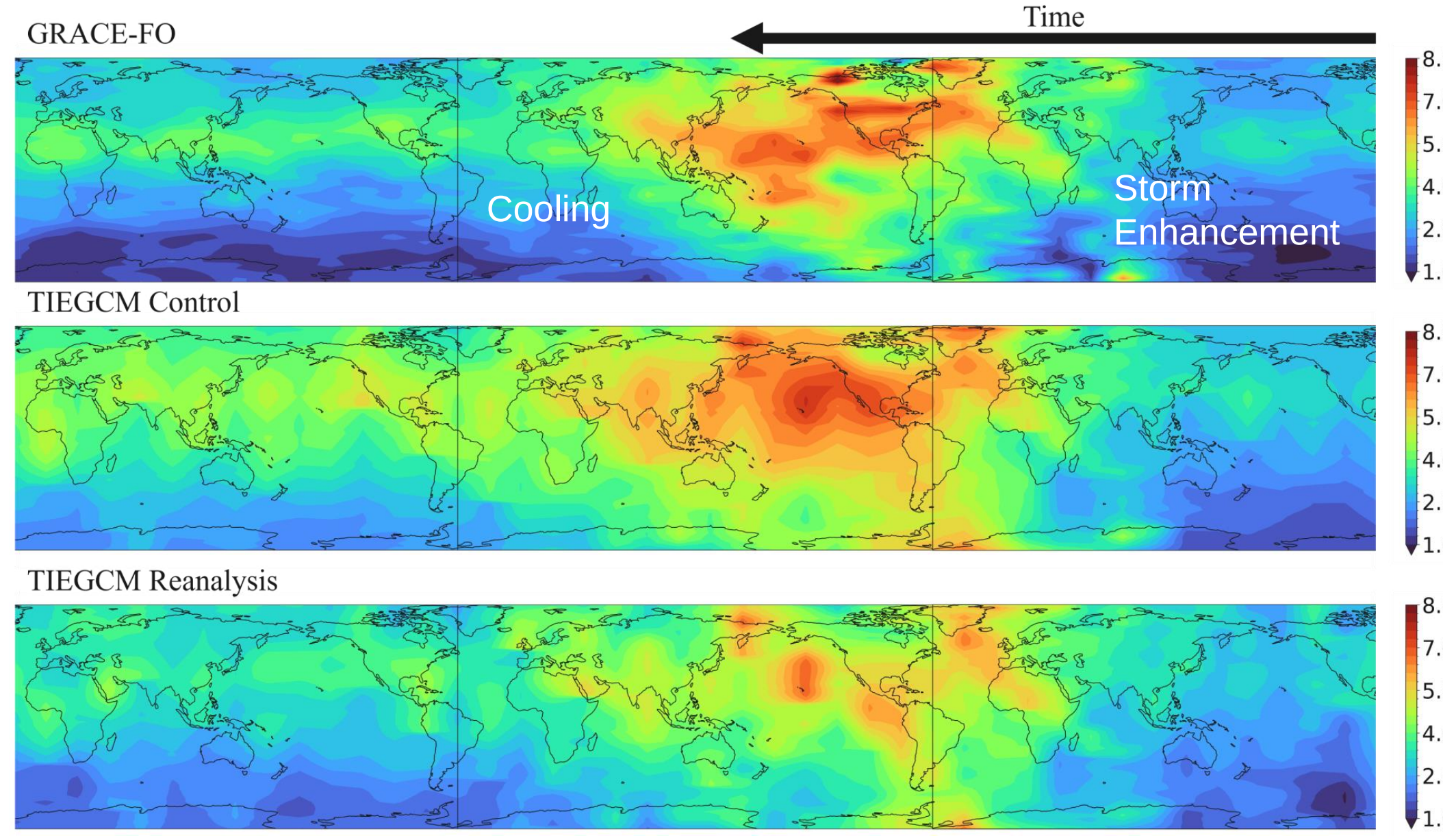
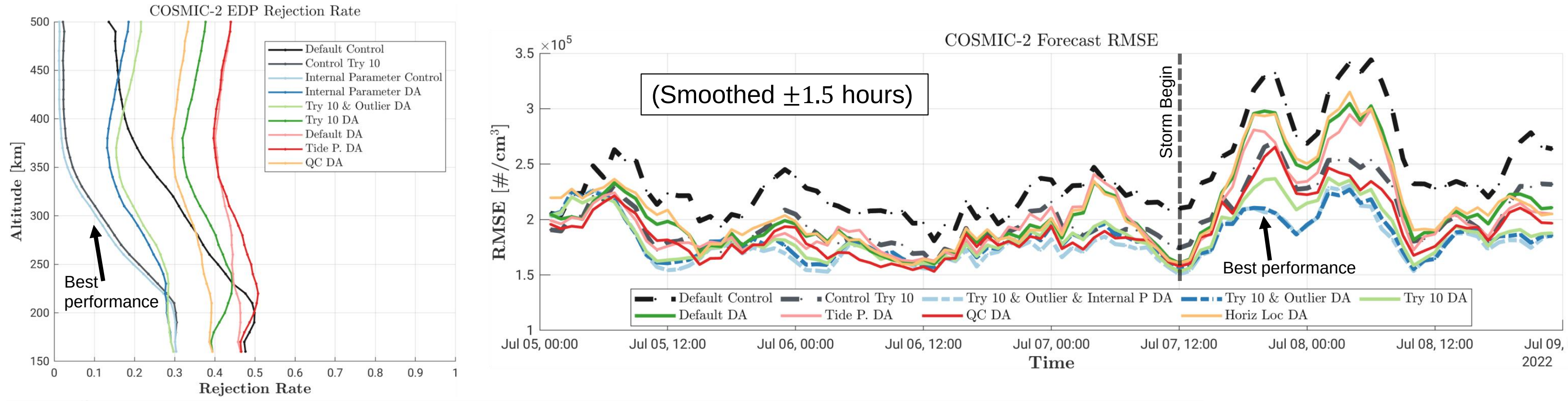


Fig. 5.2 – Reanalysis tuning with *DA features* (QC, localization, outlier control) and *ensemble initialization* (Tides and $O - O^+$ collision factor) improves RMSEs and obs-model agreement



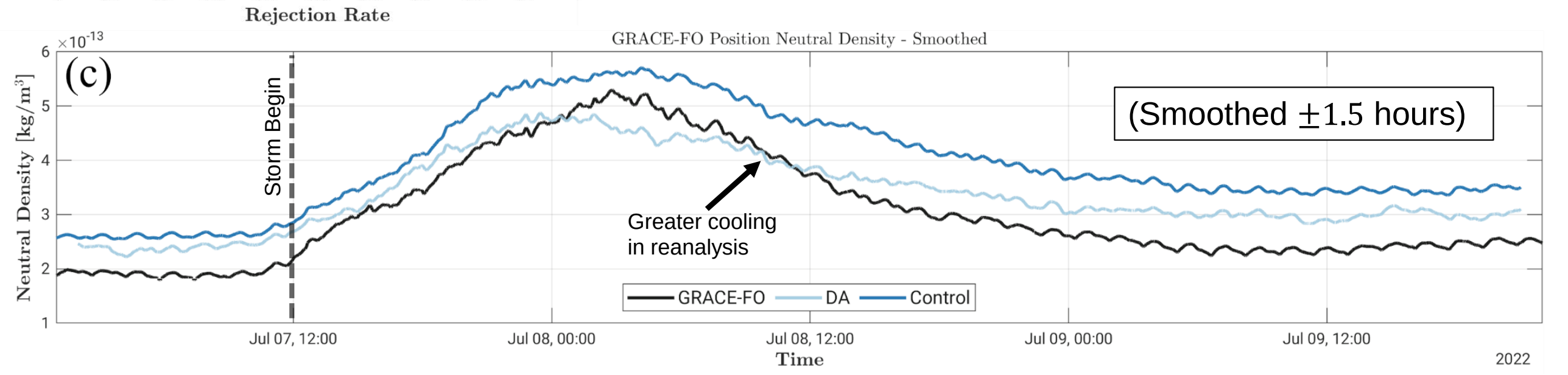


Fig. 5.3 – The TIEGCM reanalysis better matches GRACE-FO post-storm behavior (NO cooling)

6. Conclusions

1. We assess hypothetical RO constellations in comprehensive OSSEs to inform future design and use of EDPs for ionospheric specification, with greater spatial coverage from lower altitude constellations providing the best performance (*Dietrich et al., 2024*).
2. In *Dietrich et al., 2022*, we demonstrate the ability of EDPs to directly estimate neutral temperature and neutral winds using strongly coupled data assimilation. Enables neutral density estimation and we show improved orbit position errors (both improved by 70%).
3. In a real storm-event reanalysis, we assimilate COSMIC-2 EDPs and improve TIEGCM post-storm cooling, possibly by emulating greater NO cooling.