Enhancing Thermospheric Specification via Ensemble Data Assimilation

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Overview

Goal: Improve the specification of physics-based model initial conditions to maximize the predictability of the ionosphere-thermosphere (I-T) system

Approach: Employ ensemble data assimilation methods with abundantly available observation data

The upper atmosphere is controlled by external forcing ($\boldsymbol{d}$) and initial conditions ($\boldsymbol{x}$), here we focus on direct state estimation to improve forecast skill in aims to capture smaller scale features

1. Forecast Step

Propagate with model dynamics:

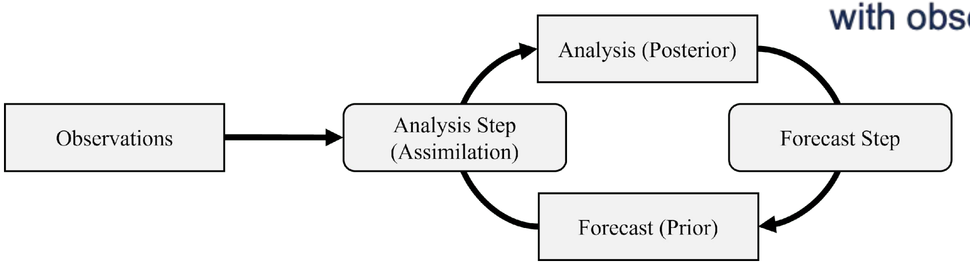
$$p(\boldsymbol{x}_{k-1}, \boldsymbol{d}_{k-1} | Y_{k-1}) \rightarrow \mathrm{p}(\mathbf{x}_{\mathrm{k}}, \mathbf{d}_{\mathrm{k}} | \mathrm{Y}_{\mathrm{k-1}})$$

2. Analysis Step

Bayesian update:

$$p(\boldsymbol{x}_k, \boldsymbol{d}_k | Y_k) \propto p(\boldsymbol{y}_k | \boldsymbol{x}_k) p(\boldsymbol{x}_k, \boldsymbol{d}_k | Y_{k-1})$$

with observations $Y_k = y_k, y_{k-1}, \ldots$

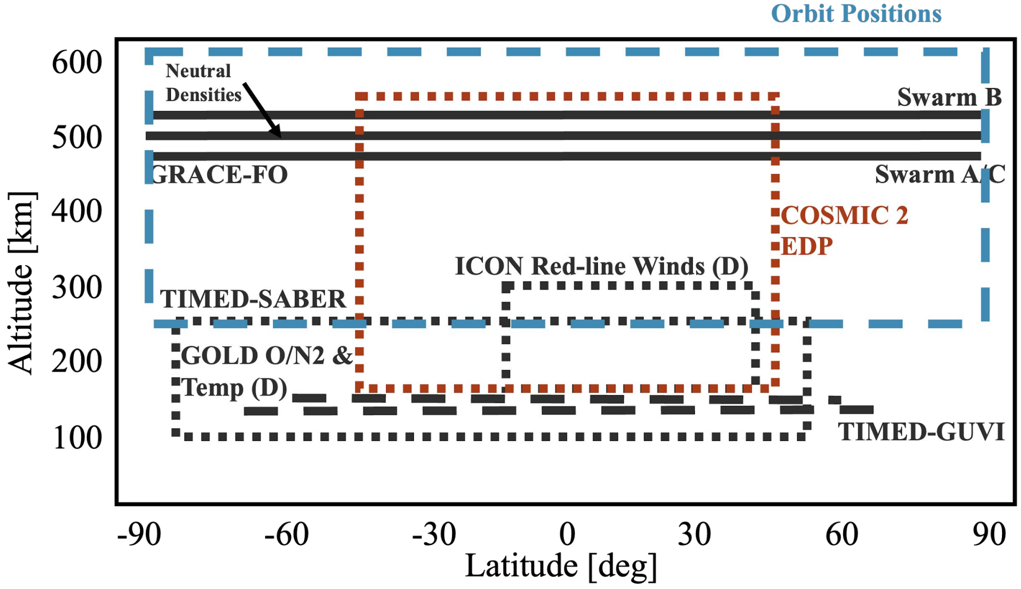


Motivation

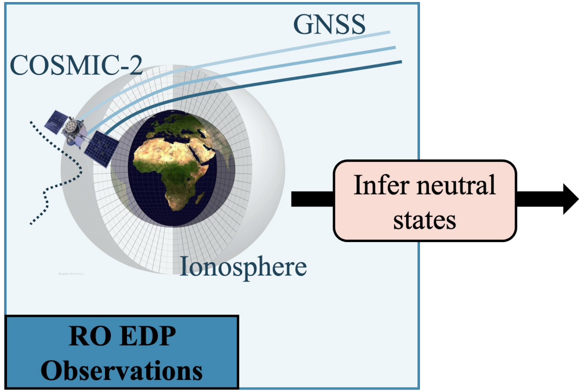
Upper atmosphere observations – considerable gaps in direct neutral state observations

Two approaches:

1) Assimilating *radio occultation (RO) plasma observations*
2) Assimilating *orbit position observations*



Data coverage of satellite observations for in-situ (solid), altitude profiles (dotted), and height integrated (dashed). (D) denotes dayside only observations.



Approach #1

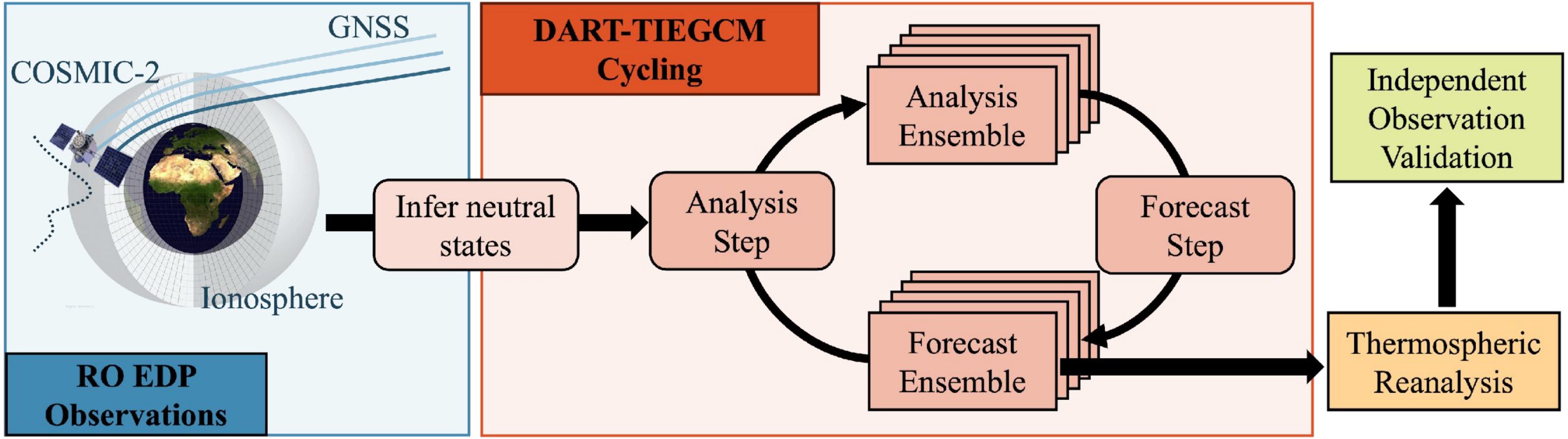
SPECIFYING NEUTRAL STATES USING ABUNDANT PLASMA OBSERVATIONS

Project Overview

Objective: Build towards developing a reanalysis of a geomagnetic storm event

Approach: Leverage radio occultation electron density profiles (EDPs) to constrain neutral states in the Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM), using the Ensemble Adjustment Kalman Filter (EAKF).

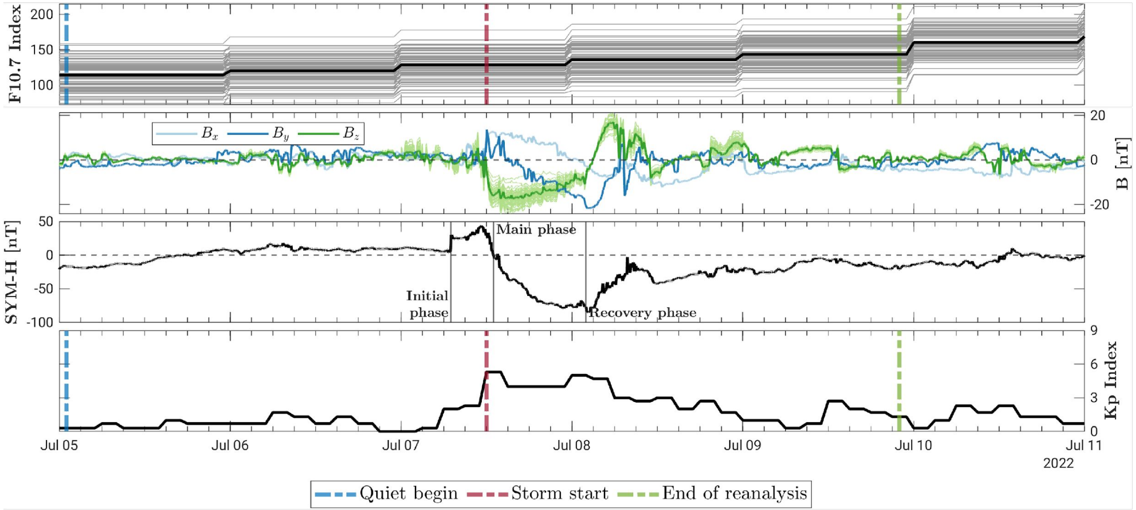
- Apply during isolated storm case



Specifying Neutral States using Abundant Plasma Observations

Experiment Period

- **Period**: July 5th - July 10th , 2022 ($-85\ Dst$ on. July 7th)
- **Experiment model**: TIEGCM 2.5° res
  (Qian et al., 2014)
- **Filter**: EAKF (Anderson, 2001)
- **Observations**: COSMIC-2 EDPs
  - 6,000 profiles per day at low- to mid-latitudes
- **Updated state vector**: $[\boldsymbol{f}_{e^-}; \boldsymbol{f}_{O^+}; \boldsymbol{f}_{Tn}]$
- **Ensemble**: 90 members, initialized with



Ensemble initialization:

1) Solar irradiance (F10.7 index)
2) Geomagnetic forcing (solar wind)
3) Lower atmosphere (GSWM)
4) Internal processes (O-O+ collision frequency)

Addressing observation errors

1) Quality control
2) Outlier thresholding

Specifying Neutral States using Abundant Plasma Observations

Storm Experiment Verification

Rejection rates:

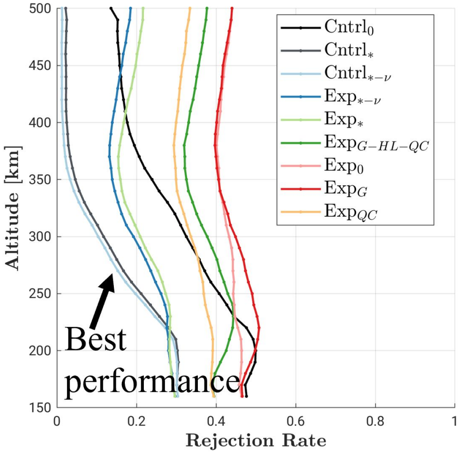
a) Control (no DA) - 10%

b) Experiment (with DA) - 20%

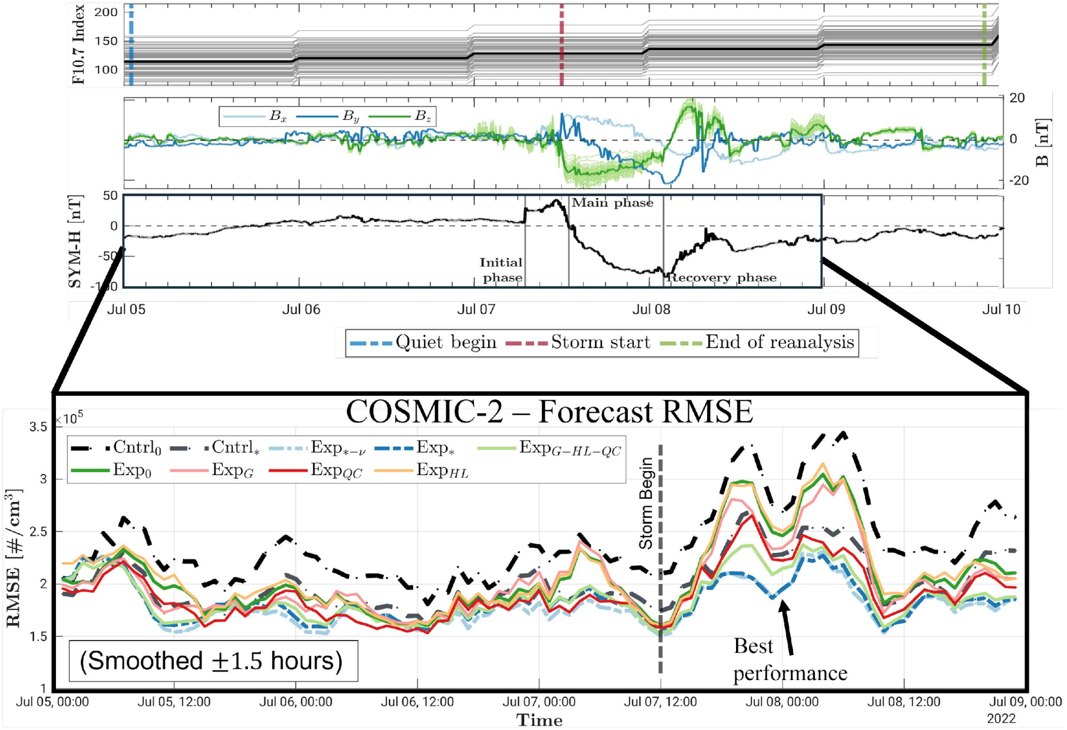
Forecast EDP RMSEs show a 20% improvement

$\rightarrow Exp_{*-Storm}$ is the chosen “reanalysis”

Obs rejection rate



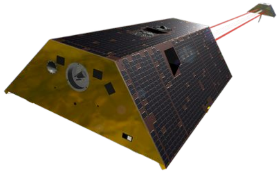
Storm: July 7th, 2022 (peak -85 Dst)



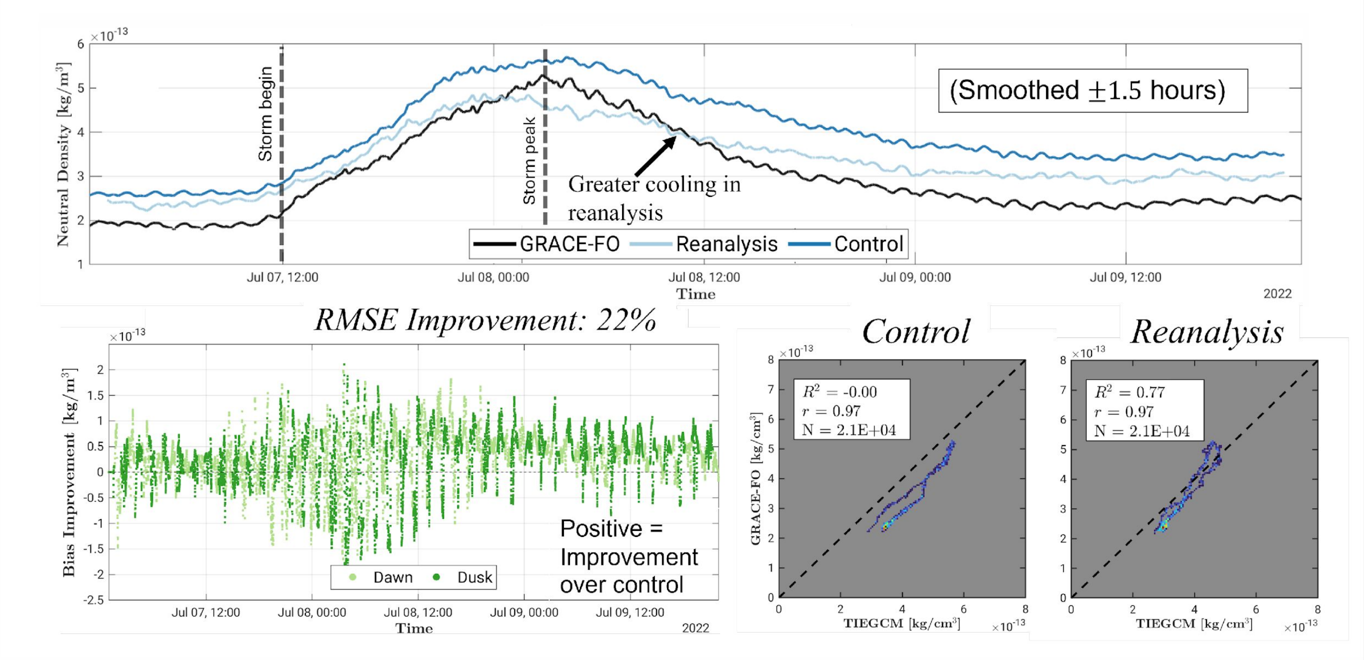
Specifying Neutral States using Abundant Plasma Observations

Storm Experiment: Neutral Density Validation

Improved agreement with GRACE-FO neutral densities (contains small-scale structures) – 20% RMSE reduction



GRACE-FO samples ~500 km at dawn (local time 6) and dusk (local time 19)

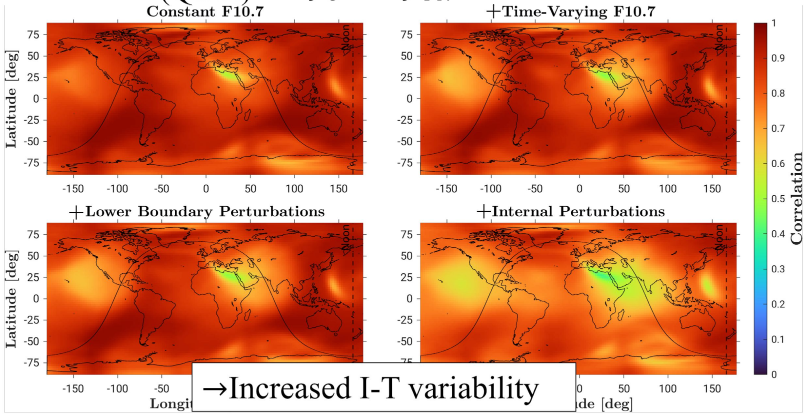


Background Covariance: Plasma → Neutral State Correlations

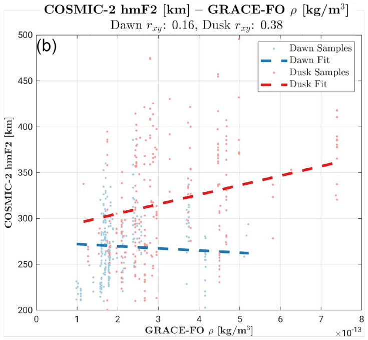
There is an increase in the model variability (shown by background correlation) with added model perturbations

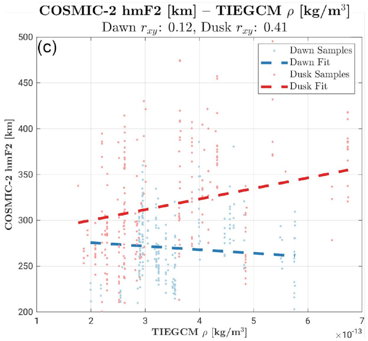
Locally averaged correlations:

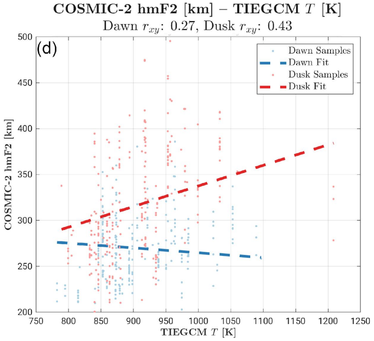
(Quiet) $f_{e^-} \rightarrow f_{TN}$



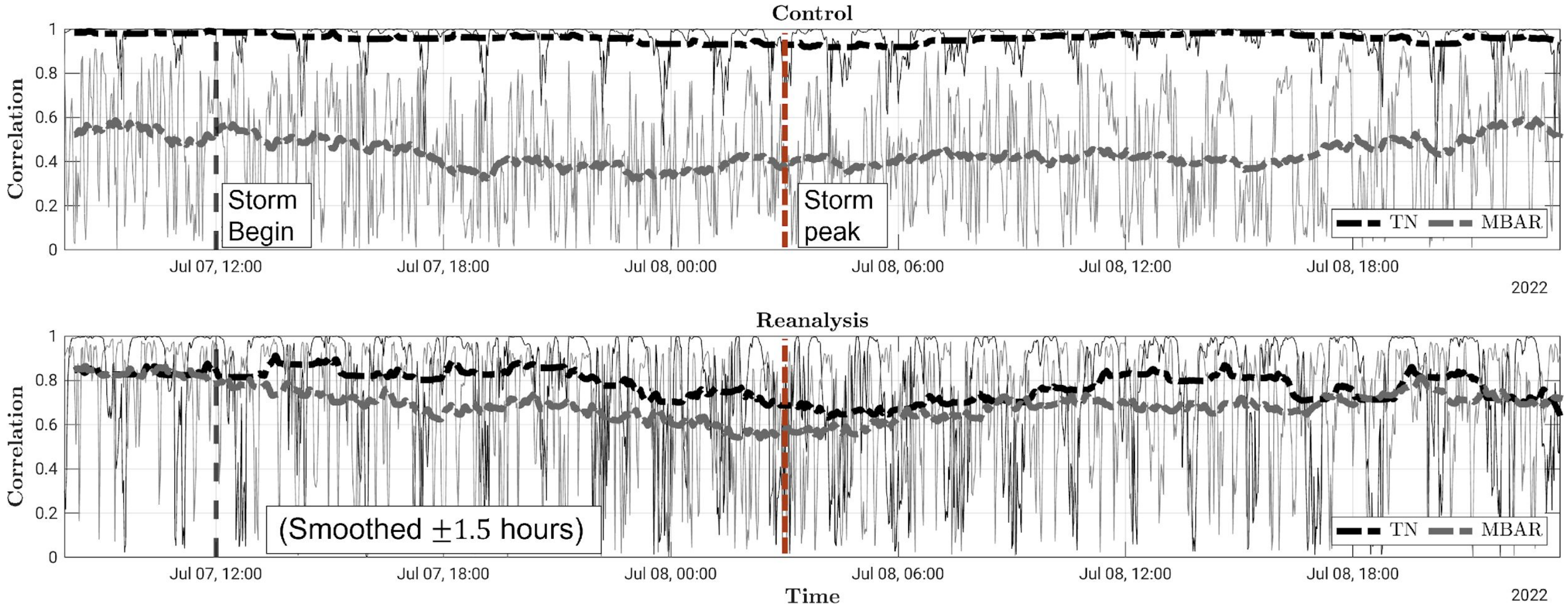
The dusk LT show higher correlations between EDPs and neutral. The TIEGCM matches these correlations.







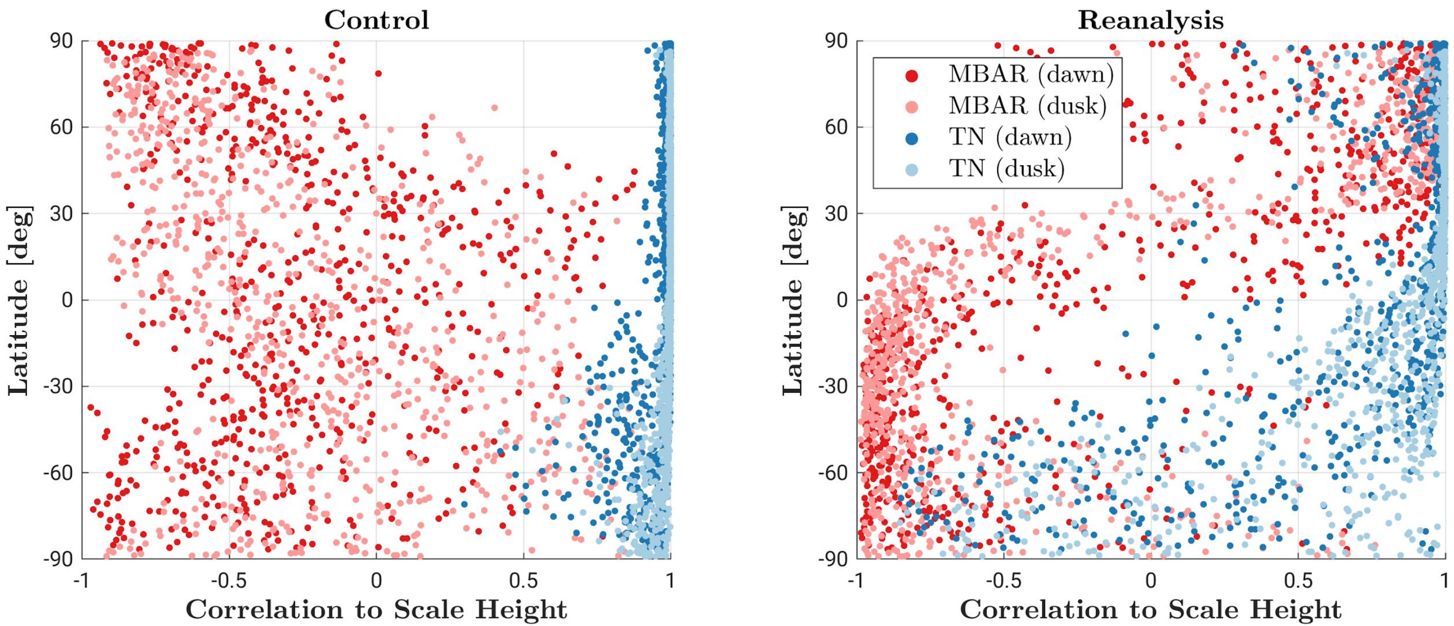
How is the neutral density estimate controlled in the reanalysis? Looking at neutral state correlations to scale-height



Data assimilation neutral density adjustments can be explained by neutral temperature (TN) and composition (MBAR) change – MBAR and TN have more equal contributions to variability

Scale height correlations: MBAR and TN → scale height

We see a strong latitude dependence in the correlations that is very apparent in the reanalysis

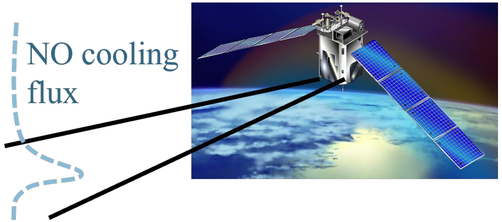


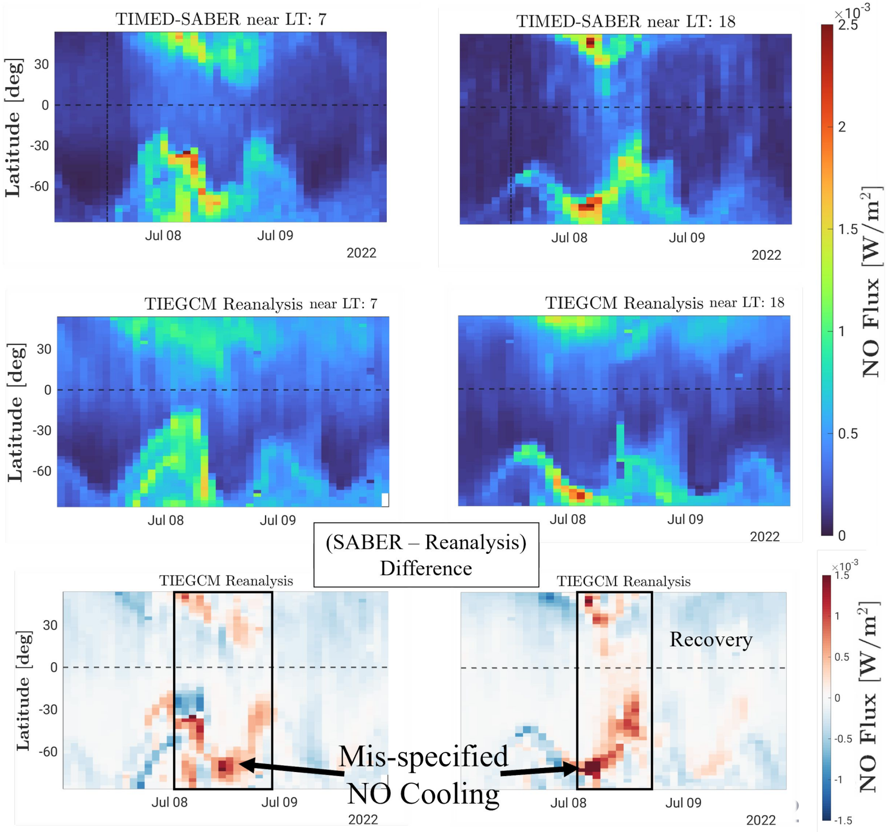
Specifying Neutral States using Abundant Plasma Observations

Storm recovery: comparison with TIMED-SABER NO cooling

We only see a slight impact on NO cooling fluxes from the DA on (peak at alts ~130 km)

- RO EDP retrievals worsen at these altitudes
- Potentially weaker dynamical correlations





Recovery timescales, assuming an exponential recovery rate:

GRACE-FO	10.9 hours
Control	12.9 hours
Reanalysis	11.9 hours

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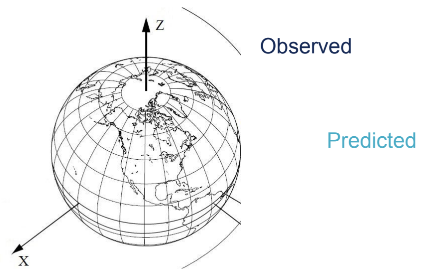


Approach #2

SPECIFYING NEUTRAL STATES USING ABUNDANT ORBIT POSITION OBSERVATIONS

Approach

Approach: Use available satellite position data in low Earth orbit (LEO) to directly constrain thermospheric states in NEPTUNE-LETKF

Satellite position data are abundantly available and don't require dedicated science missions

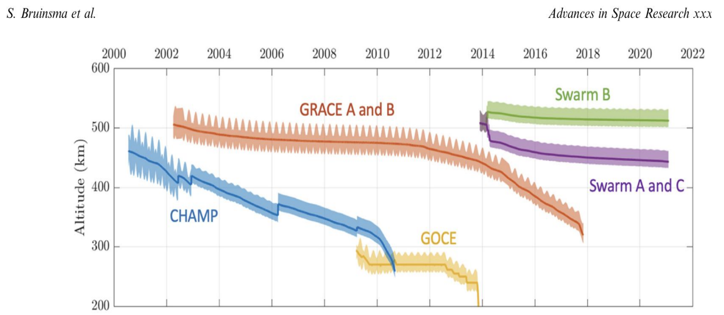
- Includes constellations Starlink and Spire, TLE data, JPsOC tracked positions

Question whether we can extract smaller-scale structures using abundant "noisy" satellite position data

- Can at least fix global scale biases at ~400-500 km altitude
- Using a model (NEPTUNE) the represents smaller scale structures and variability

Atmospheric drag equation:

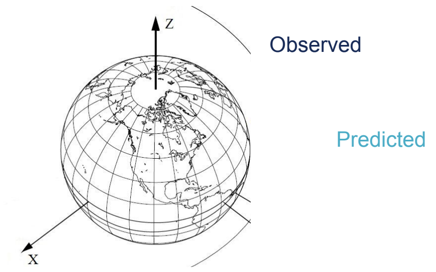
$$a_{aero} = \frac{1}{2} C_D \frac{A}{m} \rho v^2$$



Density observations from accelerometers are best, but are only from science missions:

Data Assimilation Approach

- **Experiment model:** NEPTUNE (surface – 500 km)
- **Filter**: ETKF
  - (Future: LETKF in JEDI Framework)
- **Observations**: Orbit position observations
- **Cycling:** [1 – 24 hours]
  - Question of retrieving integrated signal
- **Ensemble:** ~80 members
  - Only has perturbations from the lower atmosphere
- **Experiment period:** April 13th, 2020



Approach: Simulation experiments to learn how to best constrain thermospheric states with integrated orbit observations.

Within filter, we will assimilate the difference in the predicted satellite position from its observed state:

$$y^{obs} = h(x, \rho) + \varepsilon$$

- The LETKF can readily use this orbit time-integrated information

Orbit propagation through NEPTUNE neutral density ensemble

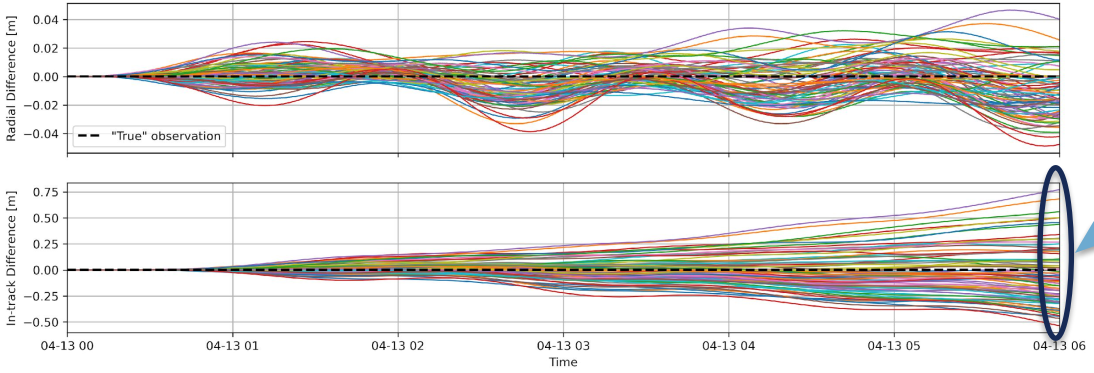
Forward Model: Orbit propagator predicting satellite position:

$$[\boldsymbol{r};\ \boldsymbol{v}]_{t_2} = h([\boldsymbol{r};\boldsymbol{v}]_{t_1}, \rho)$$

Where orbital dynamics included are:

$$\boldsymbol{a}([\boldsymbol{r};\boldsymbol{v}],\boldsymbol{\rho}) = -\frac{\mu}{r^3}\boldsymbol{r} + \boldsymbol{a}_{gravity}(\boldsymbol{r}) + \boldsymbol{a}_{drag}(\boldsymbol{r},\boldsymbol{v},\rho) + \boldsymbol{a}_{third-body}(\boldsymbol{r}) + \boldsymbol{a}_{SRP}(\boldsymbol{r})$$

Propagating simulated orbit (~430 km alt) gives the resulting orbit position errors

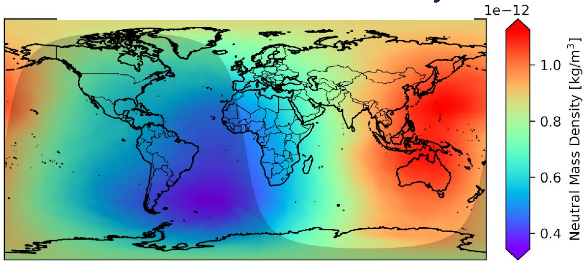


Currently assimilating in-track these in-track position errors

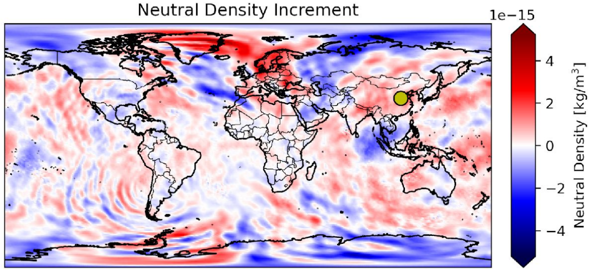
Specifying Neutral States with Orbit Positions

Pre-preliminary Increments: single observation update of neutral density with ETKF

Mean background NEPTUNE neutral density

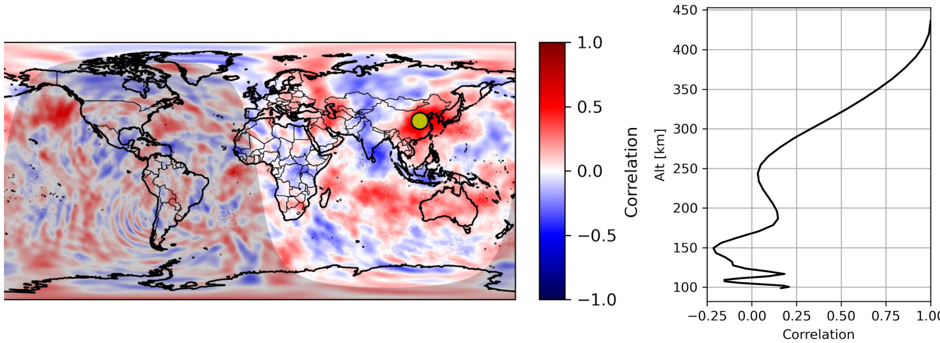


Assimilating in-track orbit position observations

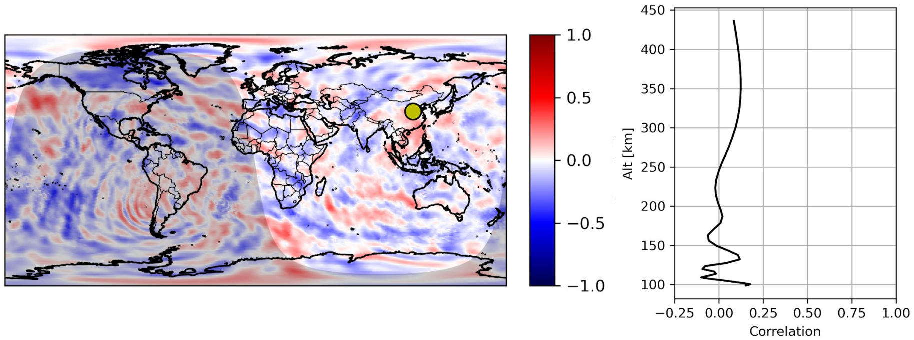


(Note: ensemble perturbations are only from the lower atmosphere)

Correlation *(grid point neutral density -> neutral density)*



Correlation *(Satellite pos -> neutral density)*



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Conclusions

Using plasma observations (RO EDPs) to constrain neutral states

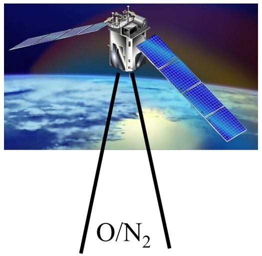
- Demonstrates usefulness of plasma observations to improve representation of neutral densities
  - RMSEs reduced by 20% compared with GRACE-FO and improved storm recovery
- See mixed results for compositions and cooling lower in thermosphere
  - There are challenges to validate a reanalysis – must get lucky that satellites are sampling the same latitudes & local times
- In support of towards future thermospheric reanalysis – transparent for scientific insights
  - Specification of global models enables better observation comparisons
- It is important to consider what the DA impact is on the model: is it physical? Are the results realistic?
  - Ensemble methods strongly rely on ensemble covariance

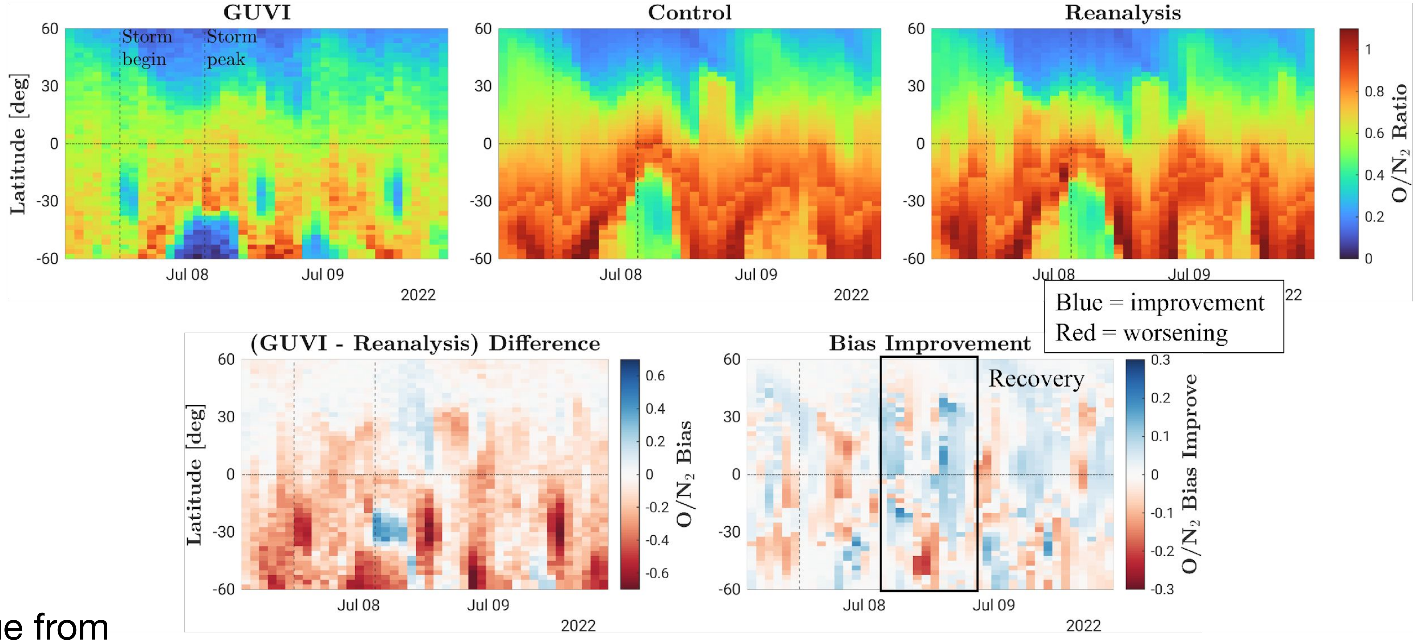
Using orbit position observations to constrain neutral states

- Very preliminary results, under active development, but promising
- Can see small-scale correlations from NEPTUNE's lower atmospheric forcing
- Investigating the best space to assimilate these data

Extra Slides

TIMED-GUVI Validation – Mixed results improving and worsening biases





Samples dawn LTs (6-10)

Composition is altered due from neutral temperature coupling