Ionospheric weather revealed by COSMIC missions with the GSI Ionosphere data assimilation system

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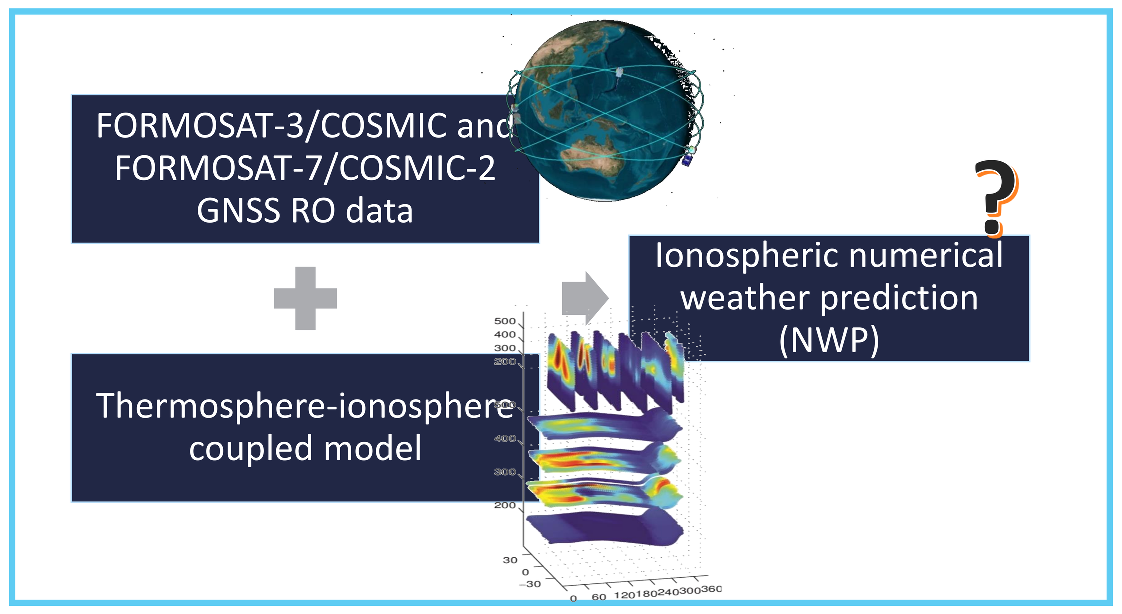
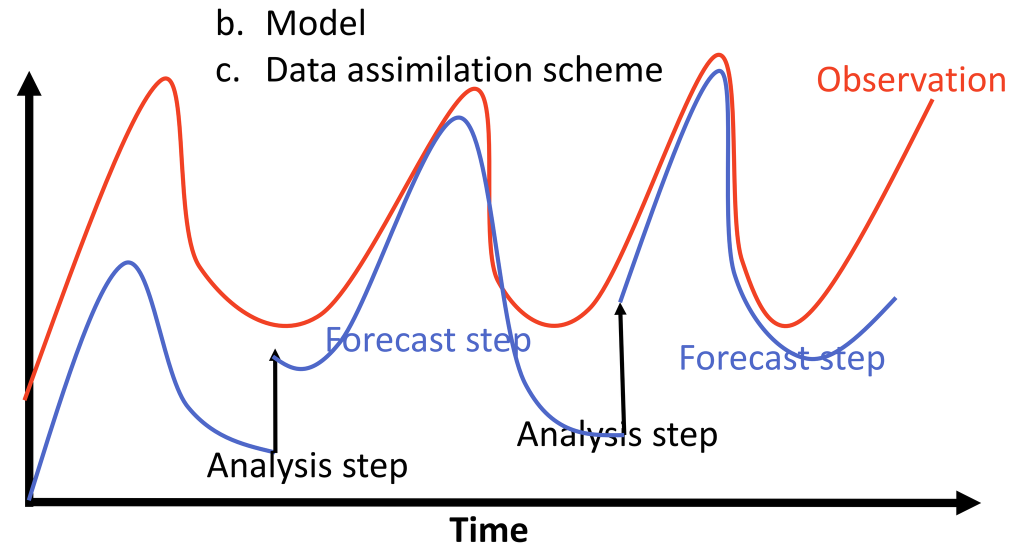
What is Ionospheric Data Assimilation?



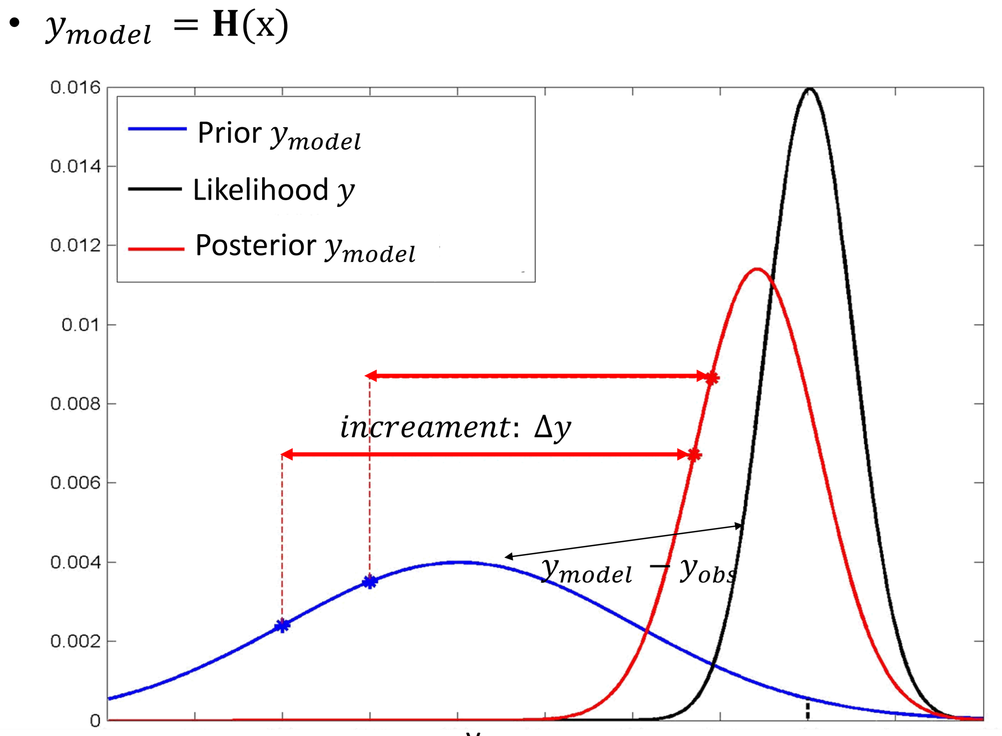
1. Data assimilation cycle

a. Observation
b. Model
c. Data assimilation scheme



2. Data assimilation scheme

- Basic ideal of deterministic update in the EnKF according to the Bayes' theorem
- $y_{model} = \mathbf{H}(\mathrm{x})$



- Ensemble Kalman Filter (EnKF)

$\bar{\mathbf{x}}_k^a = \bar{\mathbf{x}}_k^b + \mathbf{K}_k(y_k^o - \mathbf{H}_k\bar{\mathbf{x}}_k^b)$ – update of ensemble mean

$\mathbf{x}'^a_{k,n} = \mathbf{x}'^b_{k,n} + \widetilde{\mathbf{K}}_k(-\mathbf{H}_k\mathbf{x}'^b_{k,n})$ – update of each member

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

$$\mathbf{P}_k^b\mathbf{H}_k^T \sim \frac{1}{(N-1)}\sum_{n=1}^{N}(\mathbf{x}_{k,n}^b - \bar{\mathbf{x}}_k^b)[\mathbf{H}_k(\mathbf{x}_{k,n}^b - \bar{\mathbf{x}}_k^b)]^T$$

$$\mathbf{H}_k\mathbf{P}_k^b\mathbf{H}_k^T \sim \frac{1}{(N-1)}\sum_{n=1}^{N}[\mathbf{H}_k(\mathbf{x}_{k,n}^b - \bar{\mathbf{x}}_k^b)][\mathbf{H}_k(\mathbf{x}_{k,n}^b - \bar{\mathbf{x}}_k^b)]^T$$

Approximated by model ensemble

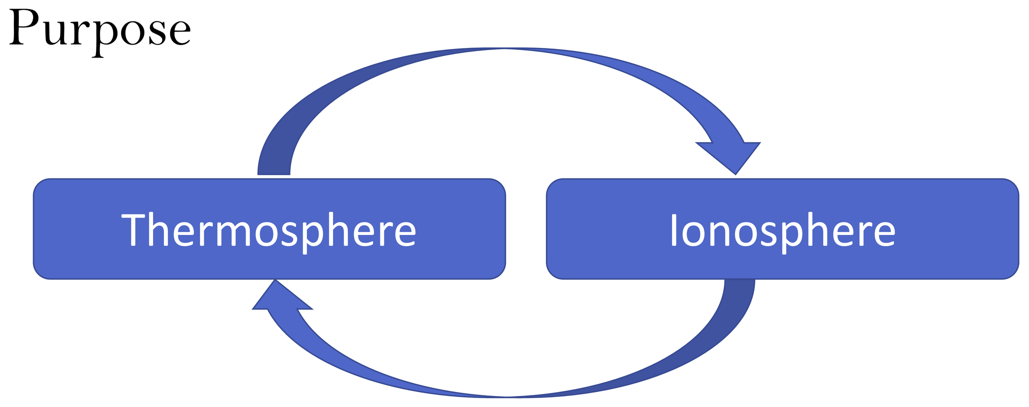
3. Model and Observation

Model	Neutral-Ion coupled model 1. TIE-GCM 2. GIP/TIE-GCM	**A. Evaluate the role of T-I coupling on ionospheric NWP**
Observation	COSMIC & COSMIC-2 Radio Occultation data 1. Electron Density Profile (EDP) 2. Slant Total Electron Content (sTEC)	**B. Evaluate the role of sTEC on ionospheric NWP**

C. Ionospheric specification revealed by GSI Ionosphere (real data assimilation)

(A) Model - Evaluate the role of T-I coupling on ionospheric NWP

1. Purpose



$$\frac{\partial N}{\partial t} = Q - L - \nabla\cdot(N\boldsymbol{v})$$

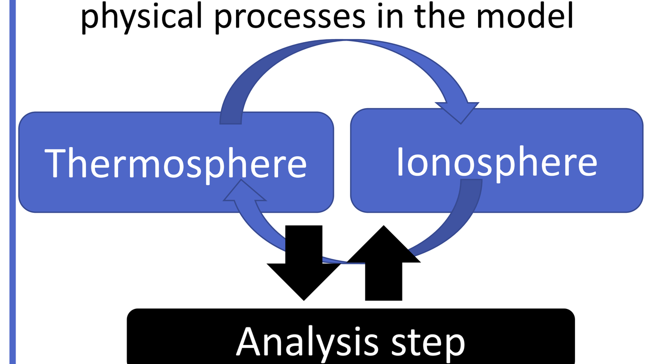
N: Plasma density
Q: production rate (dominated by photoionization)
L: loss rate (dominated by chemical processes in the ionosphere)
$\boldsymbol{v}$: plasma drift velocity

2. Experiment Design

a. Observation: COSMIC EDP
b. Model: TIE-GCM
c. Data assimilation scheme: EnKF (DART)
d. Experiment: Observing System Simulation Experiment (OSSE)

} **DART/TIEGCM**

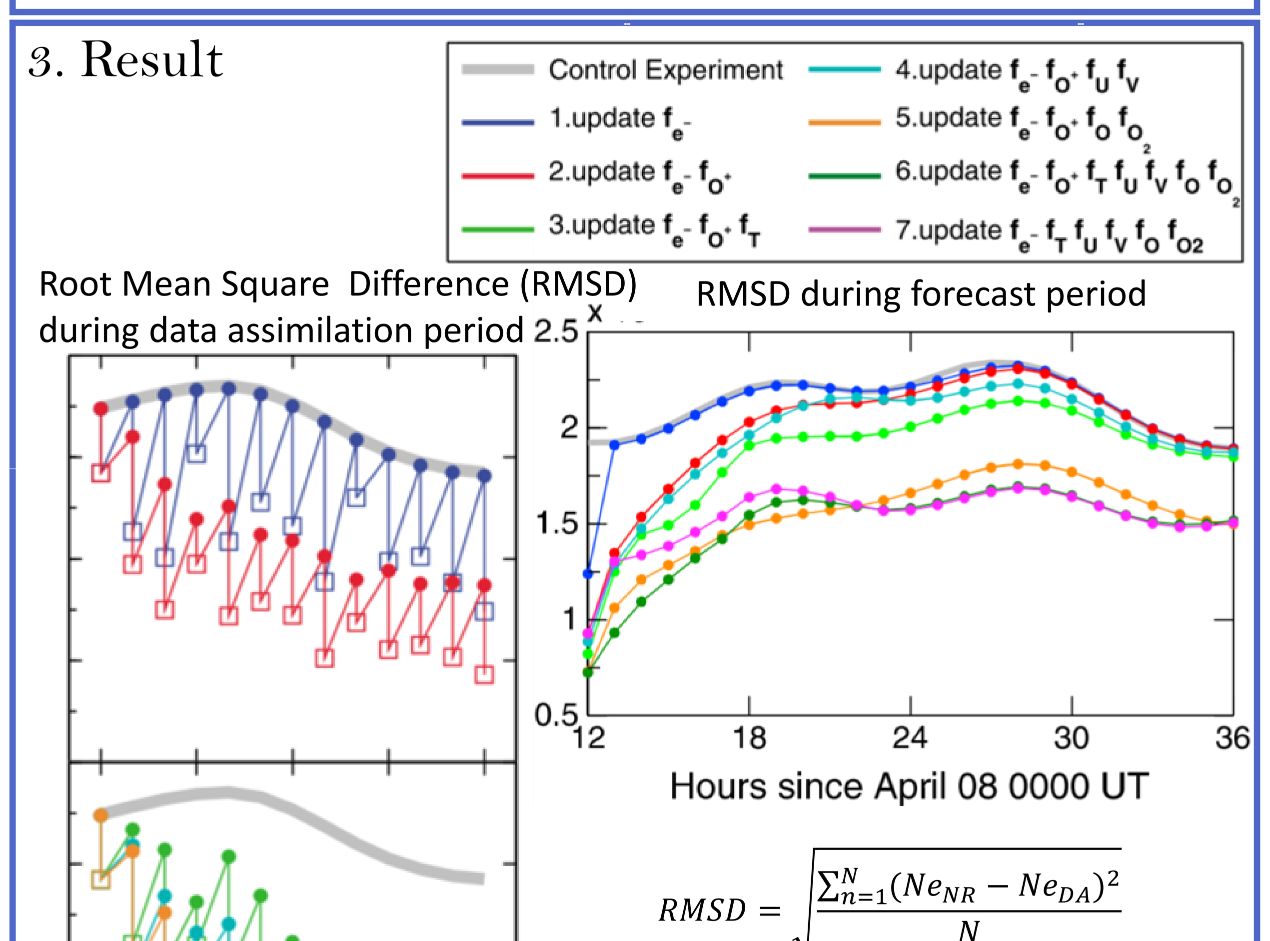
Weak Coupling
Un-updated variables evolve along with updated variables through physical processes in the model



Strong Coupling
Variables **x** are update according to observation information

Exp.	State vector
1	x= $[f_{e^-}]$
2	x= $[f_{e^-}; f_{O^+}]$
3	x= $[f_{e^-}; f_{O^+}; f_T]$
4	x= $[f_{e^-}; f_{O^+}; f_U; f_V]$
5	x= $[f_{e^-}; f_{O^+}; f_O; f_{O_2}]$
6	x= $[f_{e^-}; f_{O^+}; f_T; f_U; f_V; f_O; f_{O_2}]$
7	x= $[f_{e^-}; f_T; f_U; f_V; f_O; f_{O_2}]$

3. Result



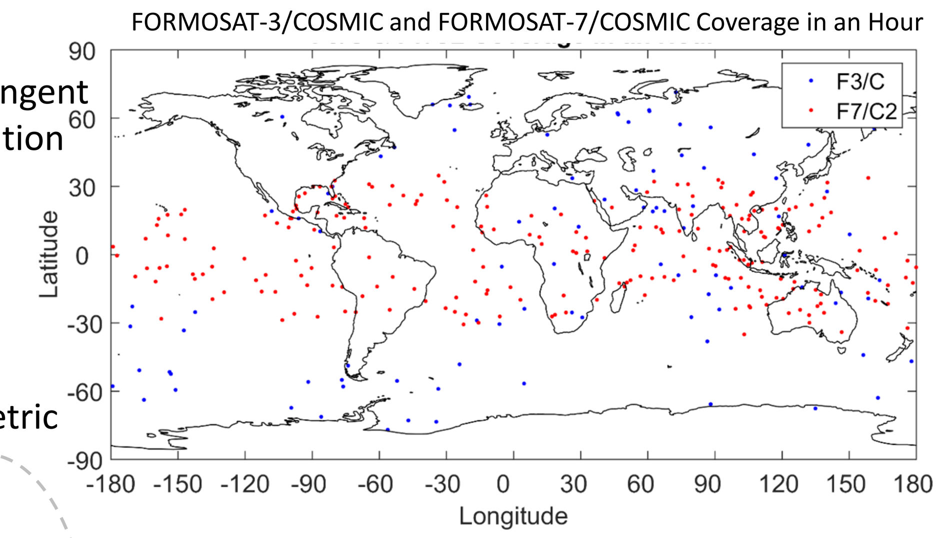
$$RMSD = \sqrt{\frac{\sum_{n=1}^{N}(Ne_{NR} - Ne_{DA})^2}{N}}$$

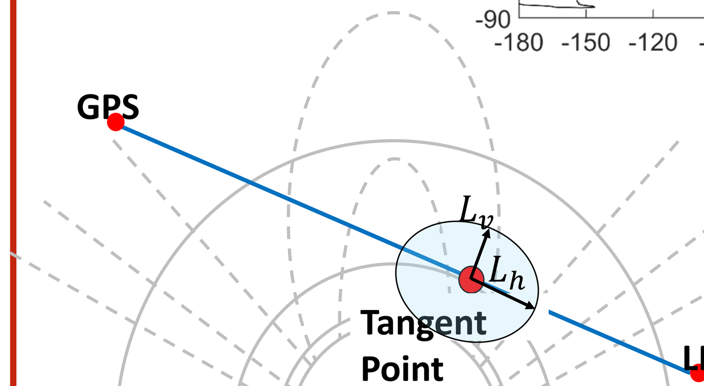
1. By incorporating ion-neutral coupling into the EnKF, the ionospheric electron density specification and forecasting can be considerably improved.
2. Thermospheric composition is the most significant state variable affecting the ionospheric specification and forecasting.
3. Estimation of unobserved thermospheric variables by the EnKF has a much longer lasting impact on the ionospheric forecast (>24 hours) than estimation of ionospheric variables (2 to 3 hours).
4. In the TIE-GCM, the effect of assimilating electron densities is not completely passed to the forecast step unless the densities of ion species are estimated.

(B) Data – Evaluate the role of RO sTEC on ionospheric NWP

1. Purpose

sTEC – Not local (use tangent point as observation location)
EDP – Local data
Need to assume electron density distribution is spherical symmetric





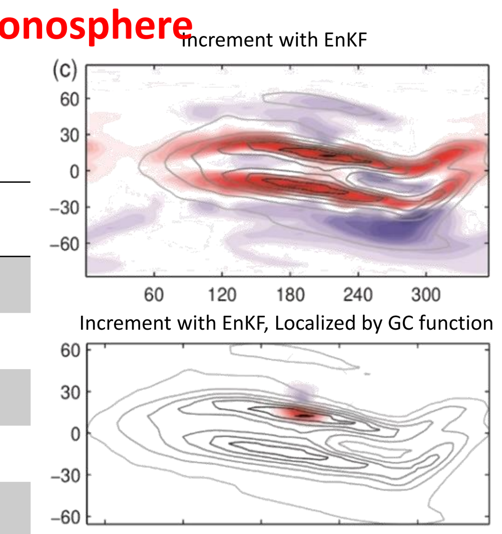
ρ=GC(r)
r : normalized distance
L_h: horizontal localization length scale
L_v: vertical localization length scale

2. Experiment Design

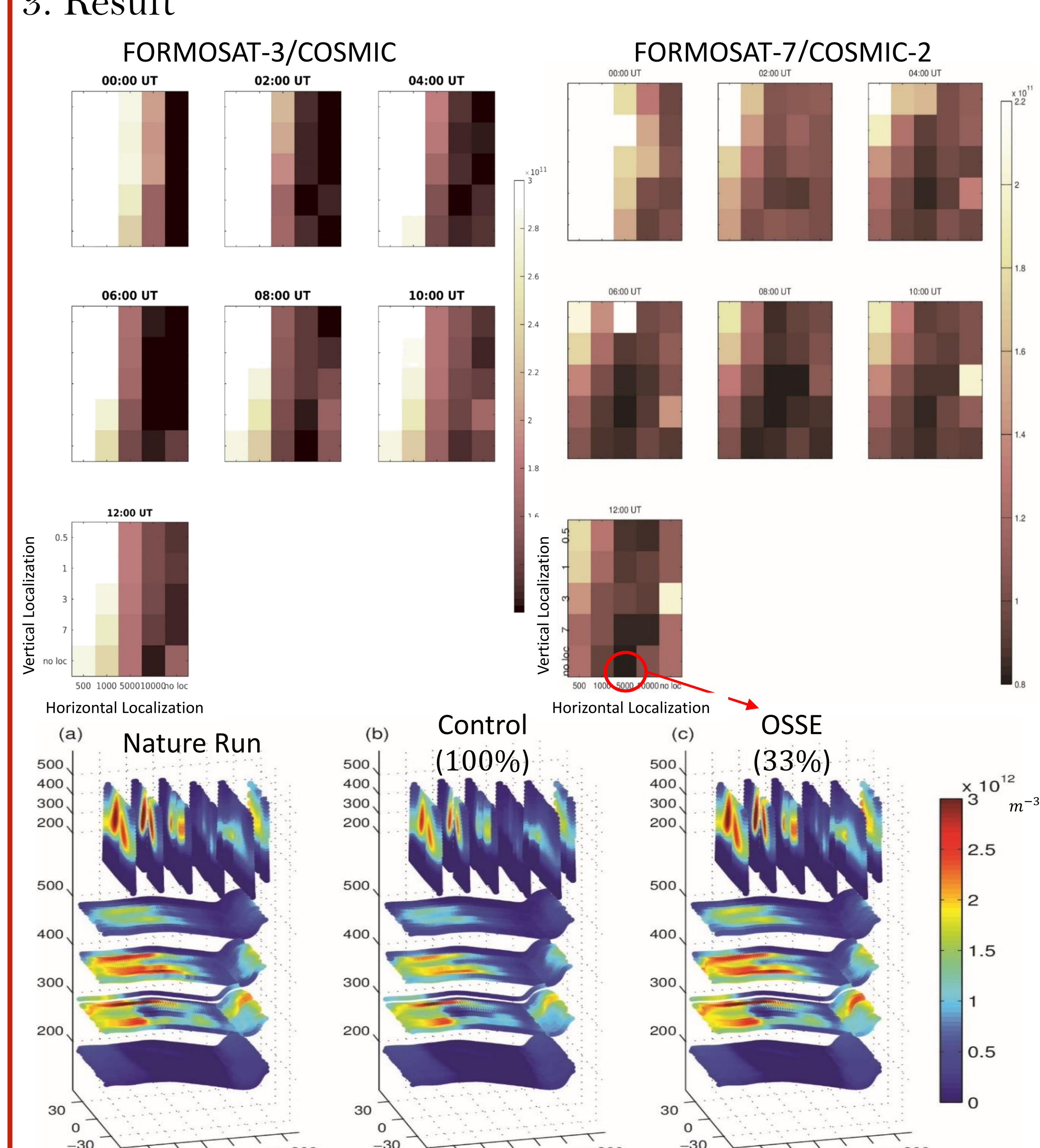
a. Observation: COSMIC & COSMIC-2 RO sTEC
b. Model: GIP/TIE-GCM
c. Data assimilation scheme: EnKF (GSI)
d. Experiment: OSSE

} **GSI Ionosphere**

L_v (ln(mb))	L_h (km)
0.5	500
1	1,000
3	5,000
7	10,000
No localization	No localization

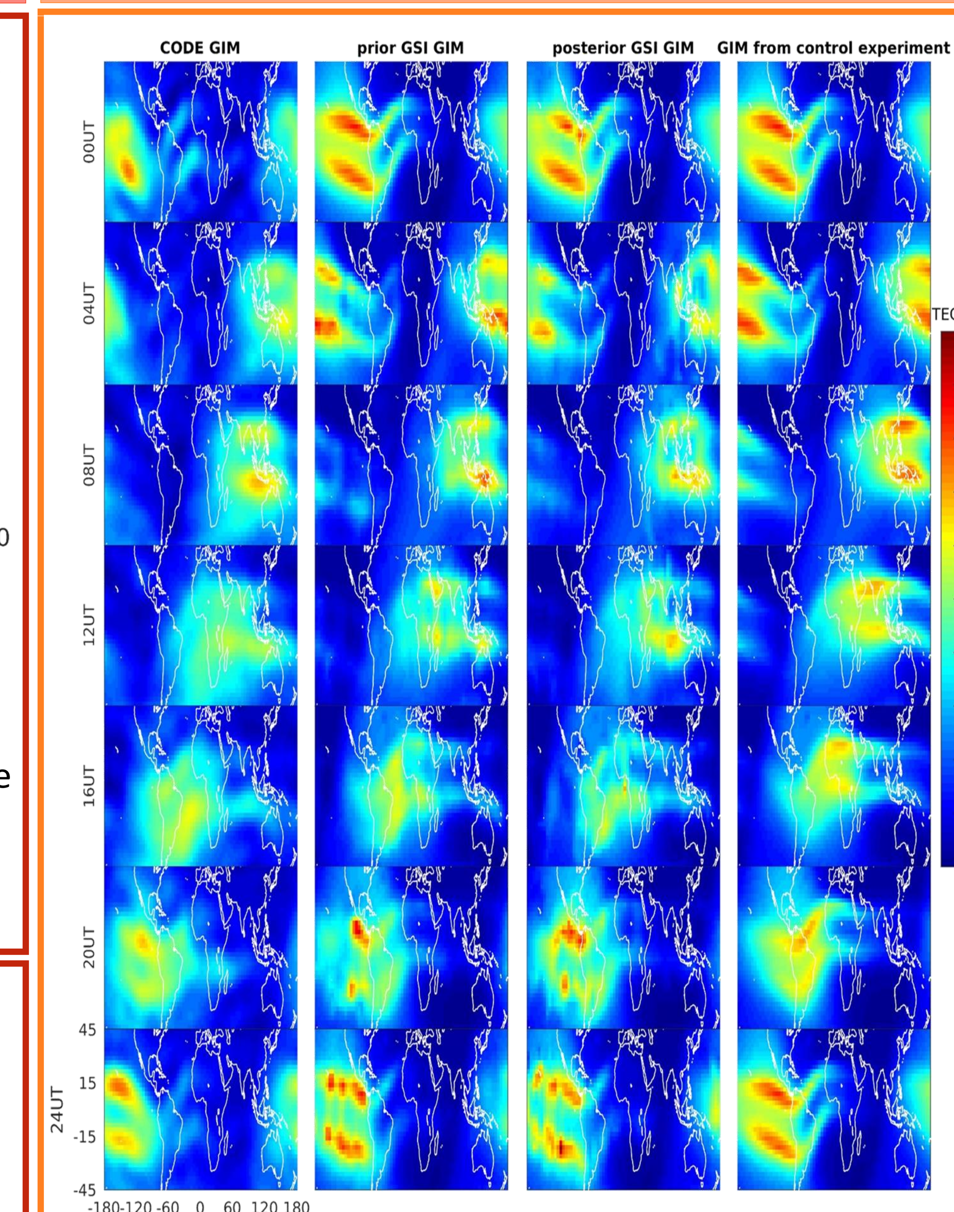


3. Result



1. The GSI Ionosphere can improve the low- and mid-latitude ionospheric specification.
2. For FORMOSAT-3/COSMIC RO sTEC, Localizing the impact of observations around the tangent points in the horizontal direction with a length scale of 10,000 km is effective in improving assimilation analysis quality.
3. For FORMOSAT-7/COSMIC-2 RO sTEC, the horizontal localization length scale of 5000 km is effective in improving assimilation analysis quality.

(C) Ionospheric specification revealed by GSI Ionosphere



a. Observation: COSMIC RO sTEC
b. Model: GIP/TIE-GCM
c. Data assimilation scheme: EnKF (GSI)
d. Experiment: Data Assimilation

} **GSI Ionosphere**

1. The capability of the GSI Ionosphere to reproduce realistic ionospheric feature has be demonstrated by real FORMOSAT-3/COSMIC RO sTEC data assimilation.
2. Accumulation of observation information can help improving ionospheric monitoring.
3. The GSI Ionosphere can effectively correct the model state variables globally but has issues with local adjustment. These issues can be resolved by increasing the data volume, implying the great potential of improving ionospheric NWP by using FORMOSAT-7/COSMIC-2 data in the future.

Conclusions

A. A neutral-Ion coupled model can help improve ionospheric specification and forecasting.

B. GSI Ionosphere are able to assimilate sTEC and improve ionospheric specification.

C. The GSI Ionosphere reveals a capability of monitoring and predicting ionospheric weather by assimilating real data.

Reference

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