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THERMOSPHERE-IONOSPHERE OBSERVING SYSTEM SIMULATION EXPERIMENTS

This work is part of the ESA Swarm-SWITCH (Space Weather in the Ionosphere-Thermosphere Cal/val Hub) project. The Swarm-SWITCH is a tool for monitoring the weather in the thermosphere-ionosphere using in-situ satellite observations and models, which can be accessed via **spaceweather.knmi.nl/viewer**.

Multi-instrument in-situ sampling from satellite constellations provides critical data to better understand and manage the impact of space weather on the thermosphere-ionosphere system. In the Swarm-SWITCH, we conduct observing system simulation experiments (OSSEs) to evaluate a thermosphere-ionosphere data assimilation framework. Simulation experiments using a proxy truth (nature run) to assess the impact of a realistic observing system are known as OSSEs. OSSEs provide important guidance for the effective integration of observing systems into data assimilation frameworks and for the assessment of forecast skill. Here we present experiments using synthetic electron and neutral measurements from Swarm and future geospace dynamics constellation (GDC) missions.

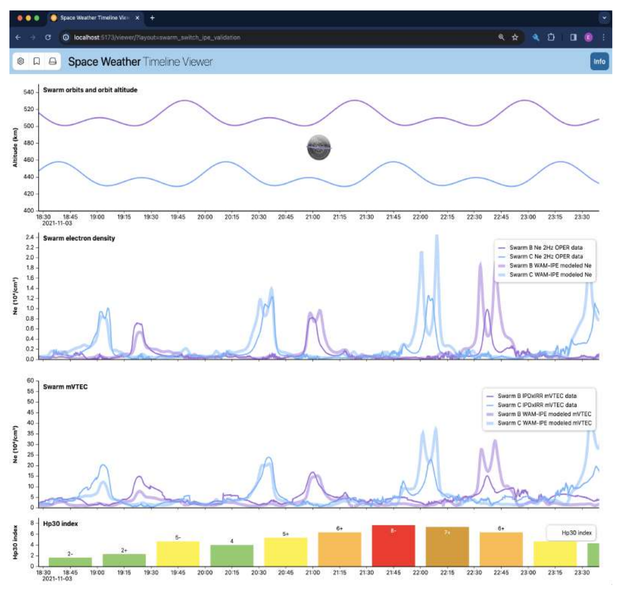

Figure 1: Sample display of ionospheric parameters relevant to the Nov2021 case study in the Space Weather timeline viewer.

TIE-GCM-DMD: A LINEARISED DYNAMIC MODEL

We describe a novel way to understand the ionosphere-thermosphere coupling via localized dynamic mode decomposition (DMD) based on the TIE-GCM (thermosphere-ionosphere-electrodynamics general circulation model) OTHITACS (open time-series of the high-resolution ionosphere-thermosphere aeronomic climate simulation; Kodikara, 2023). The possibility of inferring information from thermospheric neutral mass density measurements to ionospheric electron density and vice versa is studied in detail in the OSSEs.

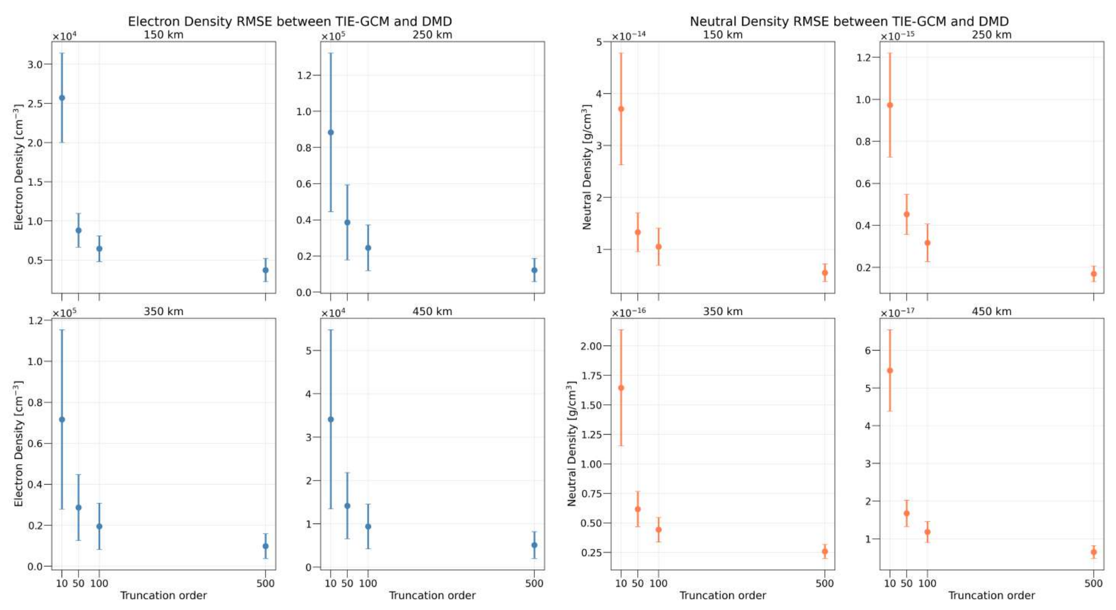

Figure 2: The root-mean-square error (RMSE) between the stand-alone TIE-GCM and the linearised coupled TIE-GCM-DMD constructed using different truncation order values for the (left) electron density and (right) neutral mass density states at the indicated height levels.

We relate the future state $\mathbf{x}_{k+1}$ of our dynamical system linearly via the operator $\mathbf{A}$ and current state $\mathbf{x}_k$ and time t_k as follows:

$$\mathbf{x}_{k+1} \approx \mathbf{A}\mathbf{x}_k + \mathbf{B}\mathbf{u}_k, \tag{1}$$

where $\mathbf{x} \in \mathbb{R}^n$, $\mathbf{A} \in \mathbb{R}^{n\times n}$, $\mathbf{B}$ is the control operator, and $\mathbf{u}_k$ is the control at time t_k. The dynamic mode decomposition aims to find the best linear approximation. Here $\mathbf{u} \in \mathbb{R}^l$ can be a staggered collection of length l with several drivers such as Kp index and $F_{10.7}$ solar flux. The focus is to find the best-fit solution to both $\mathbf{A}$ and $\mathbf{B}$. The nonexact relationship in 1 can be approximated computationally efficiently via the Singular Value Decomposition (SVD). Then the reduced-order form of equation 1 is given by the following:

$$\tilde{x}_{k+1} = \tilde{A}\tilde{x}_k + \tilde{B}u_k. \tag{2}$$

Figure 2 presents the error characteristics of the TIE-GCM-DMD. The figure shows that at a large truncation order of 500 the difference between the two models becomes significantly small. Interestingly, the standard deviation for the electron density is relatively larger than that for the neutral mass density. This may indicate that the variations in the electron density are controlled by much more nonlinear components in the physical model compared to the neutral mass density.

TWO CASE STUDIES. TWO OBSERVING SYSTEMS

We conduct several OSSEs for two case studies: the November 4, 2021 major geomagnetic storm (Nov2021), and the February 3, 2022 Starlink launch and loss of satellites in the subsequent weeks (Feb2022). The operational WAM-IPE model output from NOAA provides the nature run (NR). Synthetic observations are generated by adding a noise term to the estimates from the NR (a random percentage between 1 and 20% of the original NR).

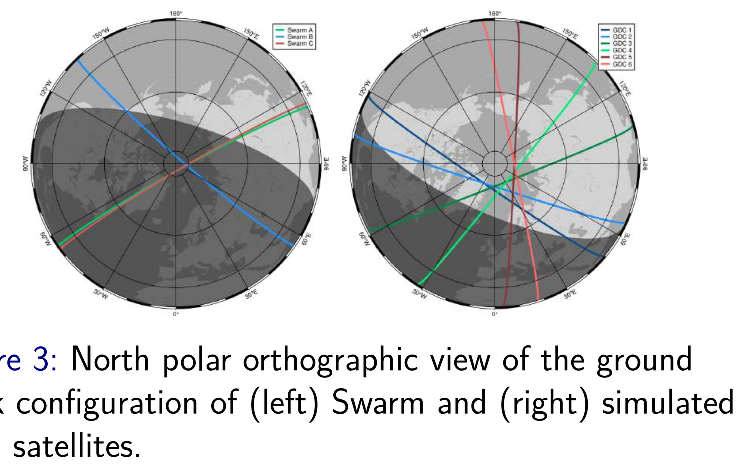

Figure 3: North polar orthographic view of the ground track configuration of (left) Swarm and (right) simulated GDC satellites.

Synthetic observations of both the electron density (Ne) and the neutral mass density (DEN) are assimilated into the new TIE-GCM-DMD using the Kalman filter technique. The observations are assimilated with no assumption of error and the assimilation window is 90 minutes.

OSSES WITH ELECTRON DENSITY ASSIMILATION

Table 1: *The mean percentage-deviation* $\Delta = \frac{1}{n}\sum_{i=1}^{n}\left(\left|\frac{\mathrm{NR}_i - \mathrm{Mod}_i}{\mathrm{NR}_i}\right| \cdot 100\right)$ *of the Ne assimilation experiments*

	Nov2021			Feb2022		
	Observation	Analysis	TIE-GCM	Observation	Analysis	TIE-GCM
GDC-01	10.0	13.9	40.8	10.0	15.4	57.4
GDC-02	10.0	11.5	40.3	10.0	16.3	56.6
GDC-03	10.0	32.8	157.3	10.0	109.4	733.9
GDC-04	10.0	10.7	49.3	10.0	42.3	181.7
GDC-05	10.0	10.4	46.4	10.0	18.0	83.2
GDC-06	10.0	10.3	44.1	10.0	19.9	92.3
Swarm-A	10.1	10.2	58.2	10.1	19.8	144.8
Swarm-C	10.0	9.8	55.4	10.0	20.4	143.7

Figures 4 and 5 show the improvement to the electron density state of TIE-GCM as a result of data assimilation (panel c: Analysis). The two figures highlight that the improvement is better along the GDC-06 satellite compared to GDC-03.

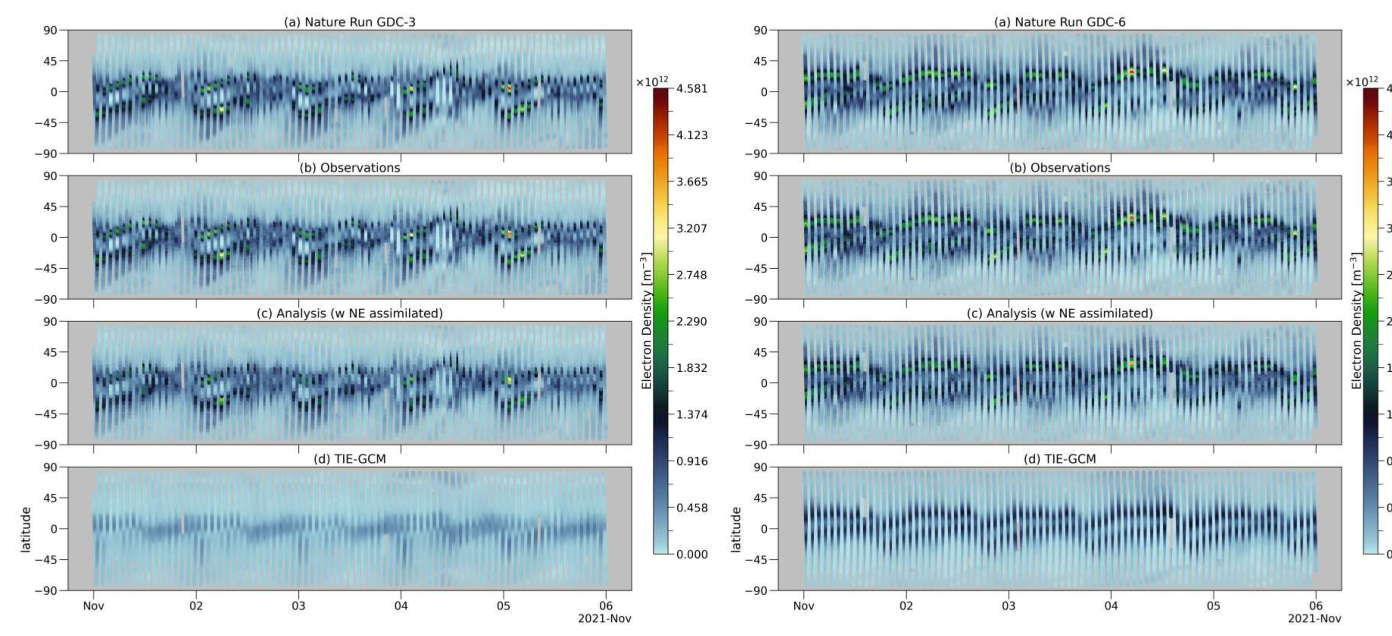

Figure 4: The Ne outputs along the orbits of (left) GDC-03 and (right) GDC-06 satellites for the Nov2021 case study. Analysis is the Ne state after assimilation of synthetic observations in panel b. TIEGCM is the control run.

In Figures 4 and 5, the background model (TIE-GCM control run) underestimates significantly more along the GDC-03 track compared to GDC-06. A plausible explanation for the poor performance along GDC-03 could be the extent to which the background model deviates from the NR.

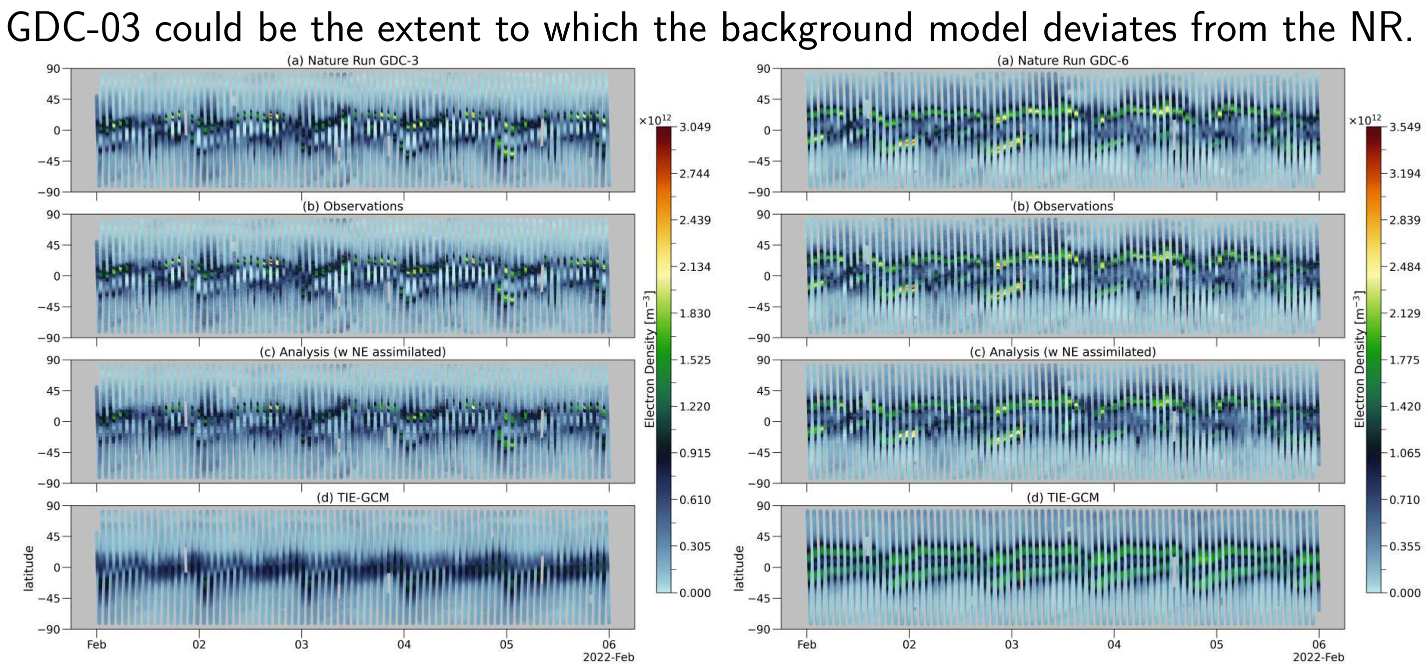

Figure 5: Same as Figure 4 except for the case study Feb2022.

OSSES WITH NEUTRAL MASS DENSITY ASSIMILATION

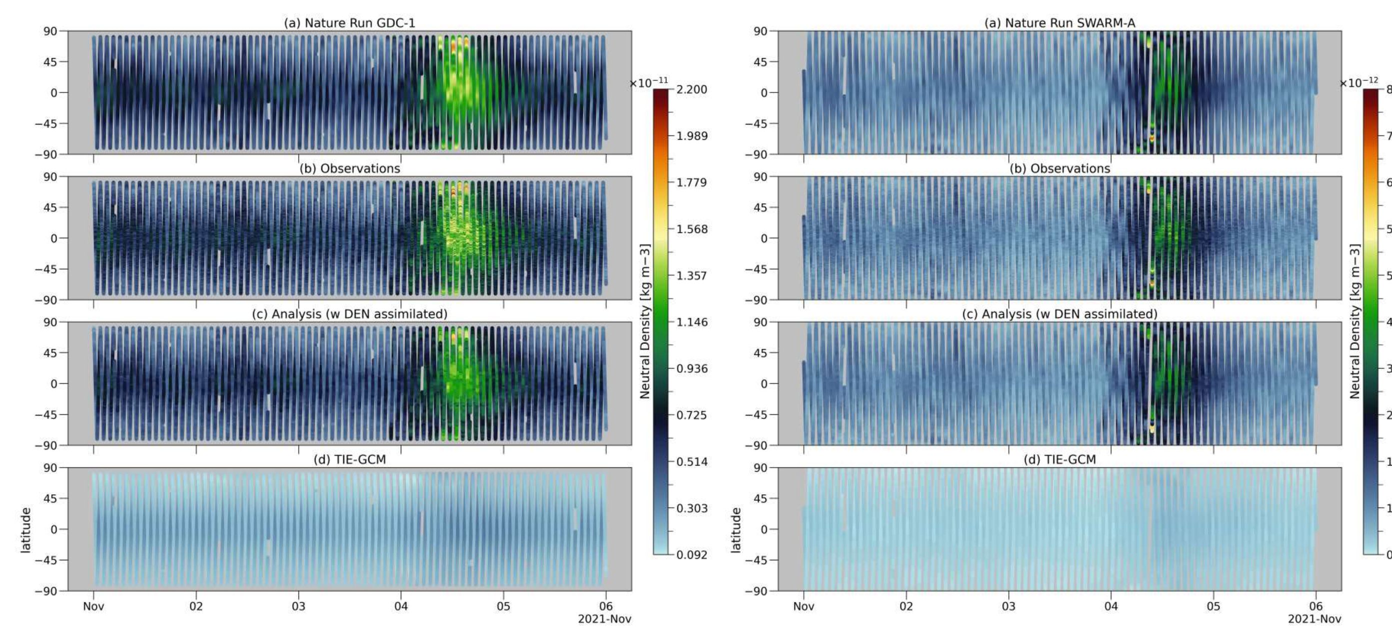

Figure 6: Same as Figure 4 except for the case study Feb2022.

Table 2: *The mean percentage-deviation Δ [%] of the DEN assimilation experiments relative to the NR*

	Nov2021			Feb2022		
	Observation	Analysis	TIE-GCM	Observation	Analysis	TIE-GCM
GDC-01	9.9	7.8	66.2	10.0	11.1	63.6
GDC-02	10.0	8.1	65.7	10.0	10.4	63.2
GDC-03	10.0	8.2	66.7	10.0	10.7	63.5
GDC-04	10.0	8.1	67.4	10.0	12.1	64.0
GDC-05	10.0	8.2	67.8	10.0	13.3	64.9
GDC-06	10.0	8.4	67.6	10.0	13.4	64.9
Swarm-A	10.0	5.0	65.8	10.0	14.6	62.7
Swarm-C	10.0	5.1	65.8	10.0	14.7	62.7

SUMMARY

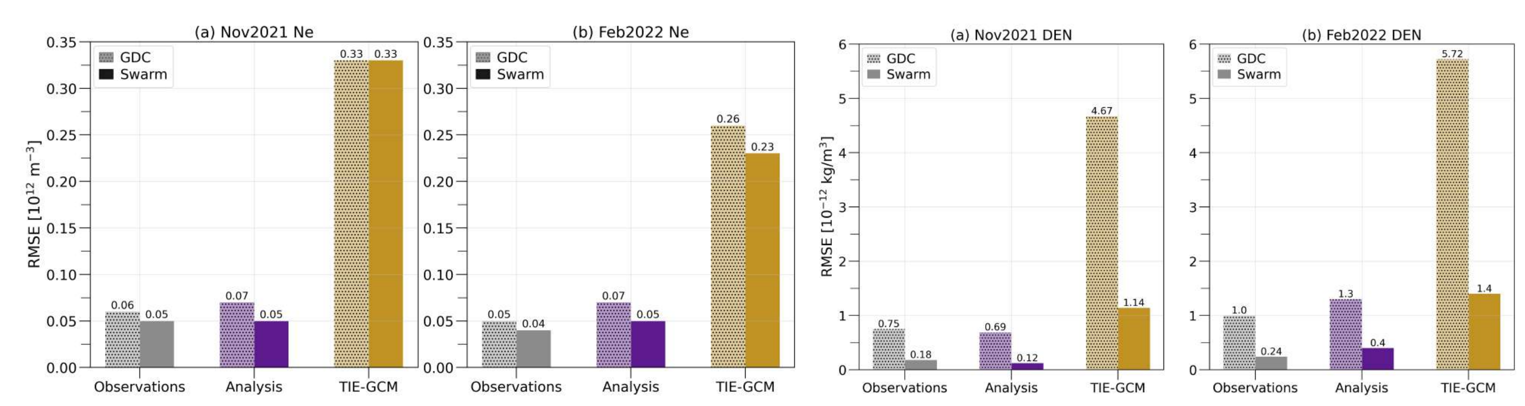

Figure 7: The RMSE of the (a-b; column-left) Ne (a-b; column-right) DEN assimilation experiments relative to the NR. The results correspond to the average RMSE considering all six satellites in the GDC (dotted-bar) constellation and Swarm-A and -B satellites (plain bar).

Tables 1 and 2 summarise the OSSE performance. We demonstrate the ability to perform OSSEs with the Swarm and GDC constellations. The results show that the use of both Ne and DEN synthetic observations can significantly improve the background model. The results highlight that the assimilation of DEN reduces the error in the background model more than that of Ne. The synthetic observations are assumed to be error free during the assimilation. The results show that the assimilation scheme performs equally well under quiet and storm conditions.

FUTURE WORK

The main advantage of TIE-GCM -DMD is the computation time compared to data assimilation with a large ensemble. The significant gain in computation time is important to extend the capability of the assimilation scheme to forecasting applications. The TIE-GCM-DMD is a linearised coupled model, and thus can be directly integrated into 4D-Var assimilation schemes with ease, which is a challenge for large nonlinear geophysical models. The effect of allowing for observation error in the assimilation must be investigated. Further work is required to investigate the stability of the coupled neutral and plasma states in TIE-GCM-DMD.

Reference:

Kodikara, Timothy (2023). The open time-series of the high-resolution ionosphere-thermosphere aeronomic climate simulation (OTHITACS). World Data Center for Climate (WDCC) at DKRZ. https://doi.org/10.26050/WDCC/OTHITACS_tiegcm

Acknowledgments: This work was funded by ESA via the Swarm DISC, Sub-Contract No. SW-CO-DTU-GS-132. https://earth.esa.int/eogateway/activities/swarm-switch