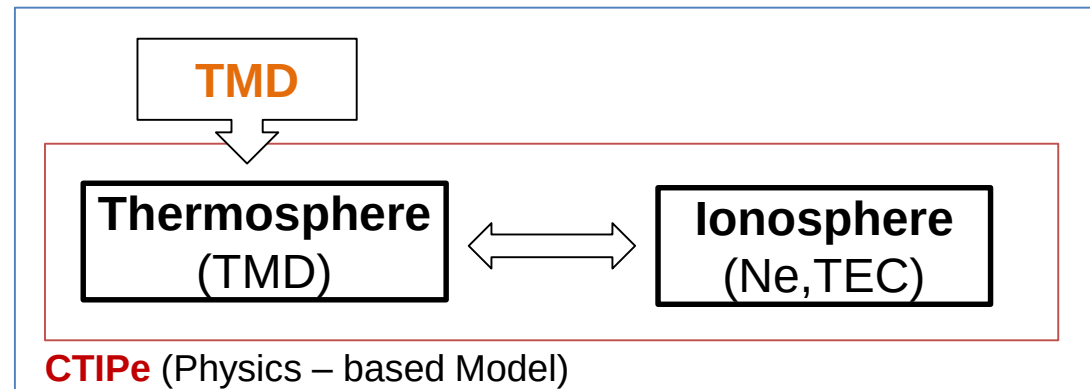
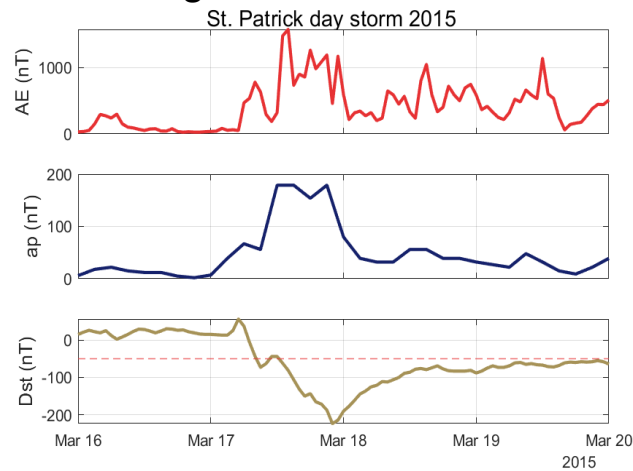


The impact of severe storms on forecasting the thermosphere – ionosphere system through the assimilation of SWARM-derived neutral mass density into physics-based models

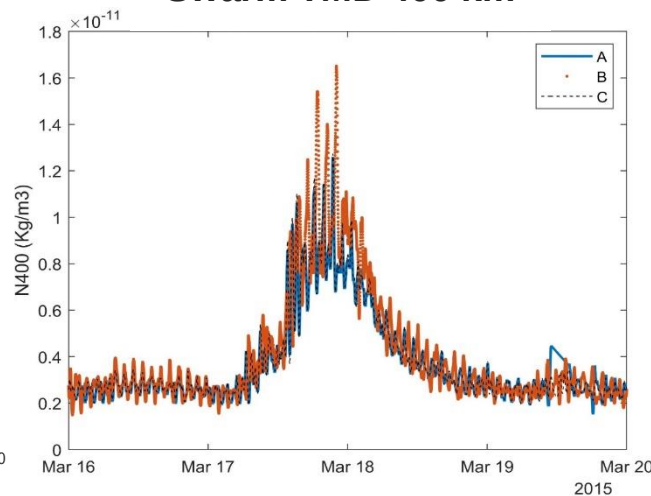


TIDA (Thermosphere Ionosphere Data Assimilation scheme)

Geomagnetic Storm conditions



Swarm TMD 400 km



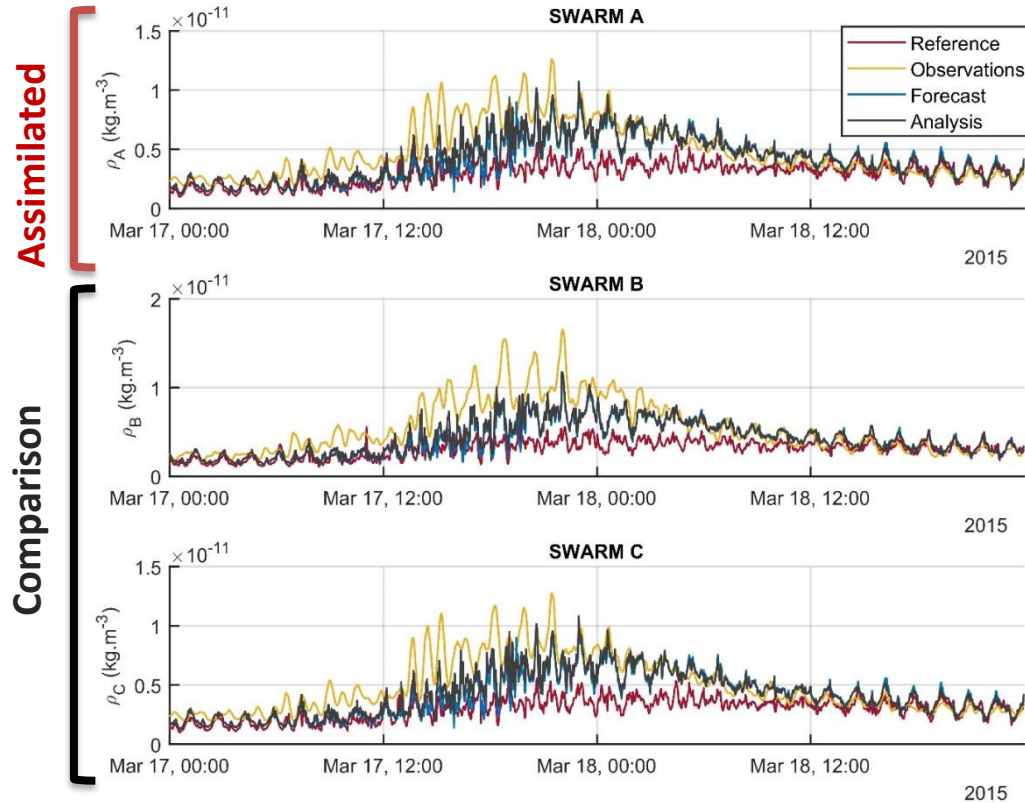
Objective

- Thermosphere – Ionosphere (TI) system response to **storm conditions**.
- **Assimilate Thermospheric Mass Density (TMD)** derived from SWARM satellites into **physics – based model CTIPe**.
- Assimilating thermospheric parameters will improve the thermosphere, but **what happens in the ionosphere?**

What did we found out?

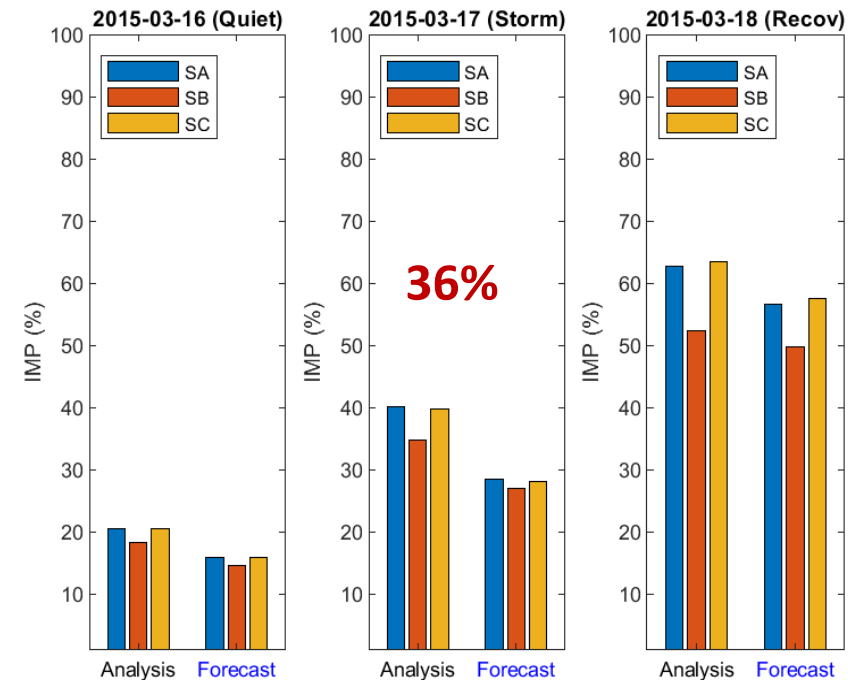
- TMD assimilation has a direct **impact on the thermosphere** with an average **improvement of a 36%** with respect to observations.
- The **effect on the Ionosphere** is more localized to the European – African sector, **improving the TEC estimation up to 50%.**

Impact in the Thermosphere



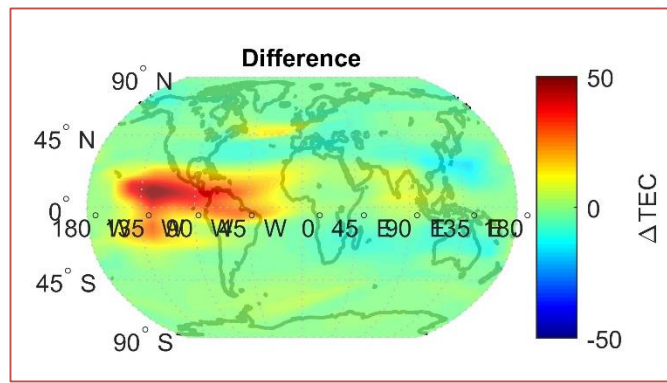
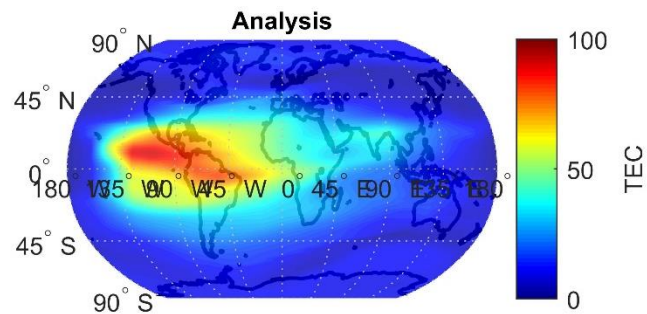
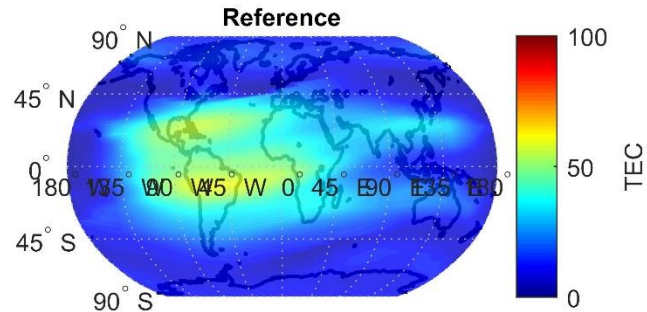
$$\text{IMP}(\%) = \frac{\text{RMSE}(\text{ref}) - \text{RMSE}(\text{analysis})}{\text{RMSE}(\text{ref})} \times 100$$

- In the experiment SwarmA-400km is assimilated, and compared to B and C satellites.
- TMD **observations** are compared to **reference**, **forecast** and **analysis** estimations, where:
 - **Reference** is the background model run with no assimilation
 - **Forecast** is the first guess or prior state estimate
 - **Analysis** is the estimation with all the observations
- Average TMD improvement of 36%

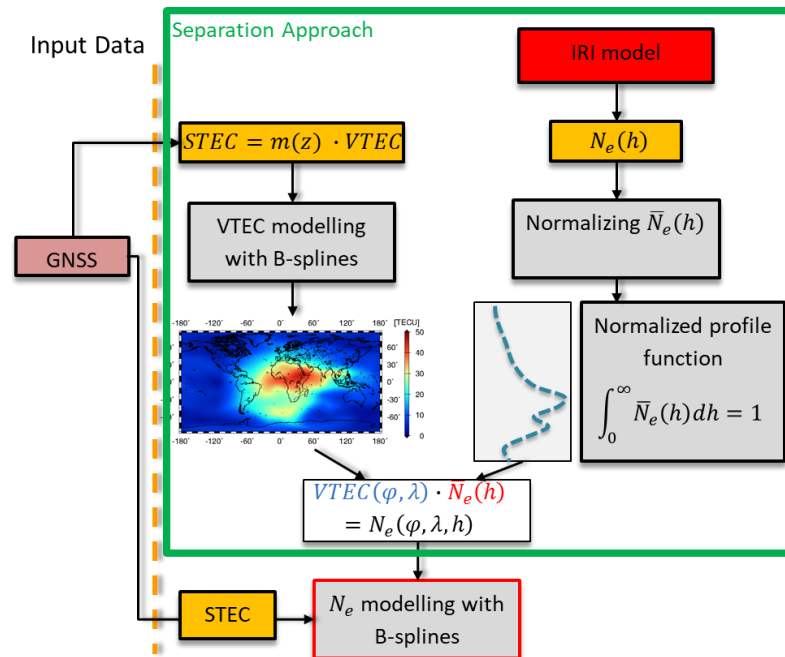


Impact in the Ionosphere

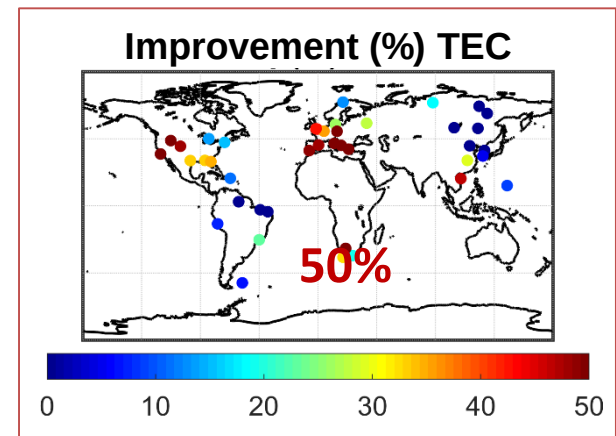
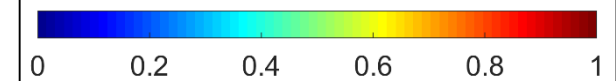
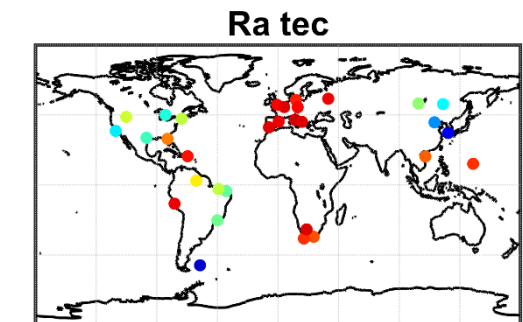
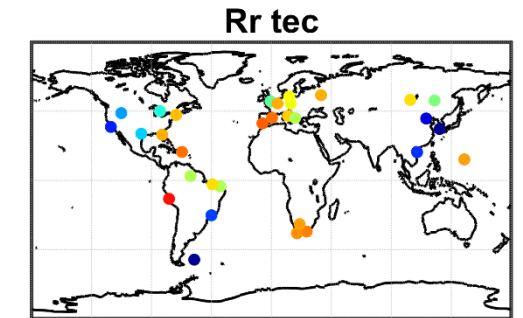
TEC 2015-03-17 17:00



- Differences between **reference** run and **analysis** state **Total Electron Content** (TEC) show the impact of TMD assimilation in the ionosphere.
- Comparison with TEC obtained from the **B-Spline Electron Density Model (TUM)** quantifies the improvement in the Ionosphere.
- European – African sector TEC **improvement of 50%**.



Correlation Coefficient



Summary

- Differences in thermospheric mass density and total electron content between the **reference** run and **analysis** estimates are an indicator of how the **Thermosphere - Ionosphere system is affected by the assimilation of thermospheric observations**, specially during storm conditions.
- Thermospheric mass density assimilation has a direct **impact on the thermosphere** with an average **improvement of a 36%** with respect to observations.
- The **effect on the Ionosphere** is more localize to the European – African sector, **improving the TEC estimation up to 50%.**



More Information...



CTIPe physics based model

- The **Coupled Thermosphere Ionosphere Plasmasphere Electrodynamic** physics based model (fig.1) is composed by four main modules: The thermosphere (T), the high-latitude ionosphere (I), the mid-low latitude ionosphere-plasmasphere (I-P) and the global dynamo electric field [\[Weimer, 2005\]](#). The four components run concurrently and fully coupled with respect to energy, momentum and continuity.

- **Magnetospheric input:** Advance Composition Explorer (ACE) solar wind and interplanetary magnetic field (IMF) data, TIROS/NOAA hemispheric power index, and F10.7 radio flux.
- **Lower boundary:** Simplified version of the Whole Atmosphere Model (WAM) at 80 km altitude.

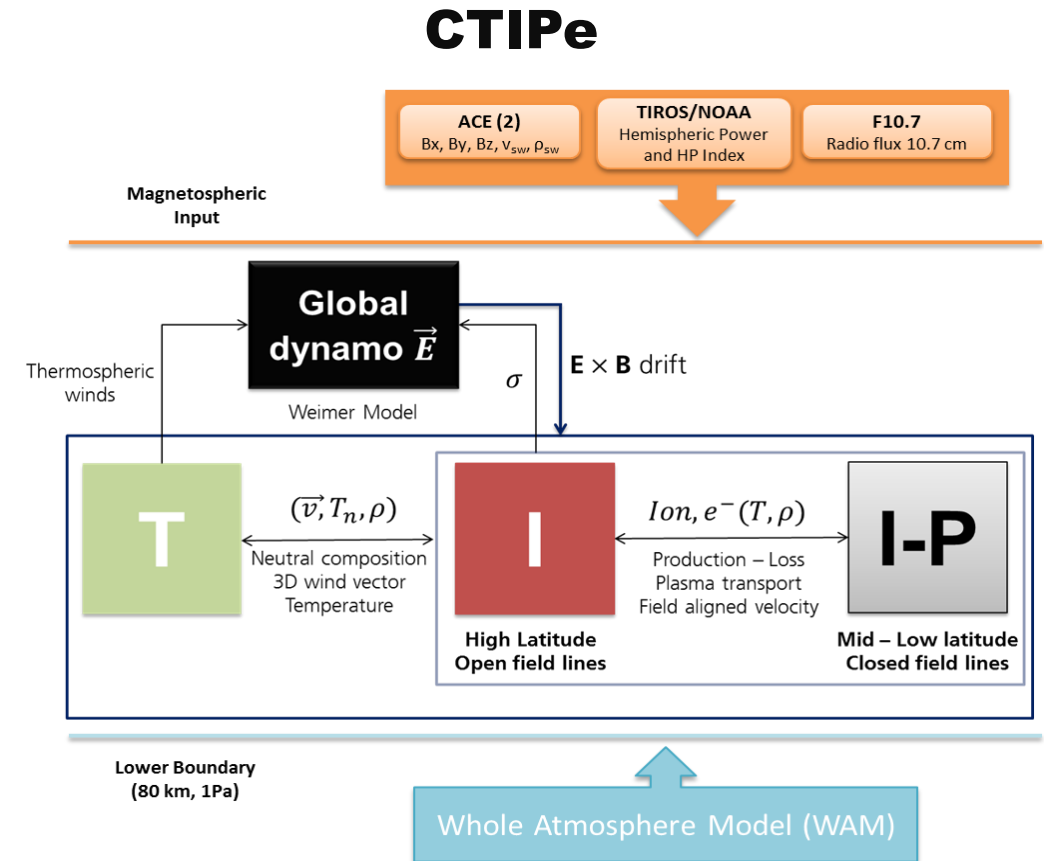
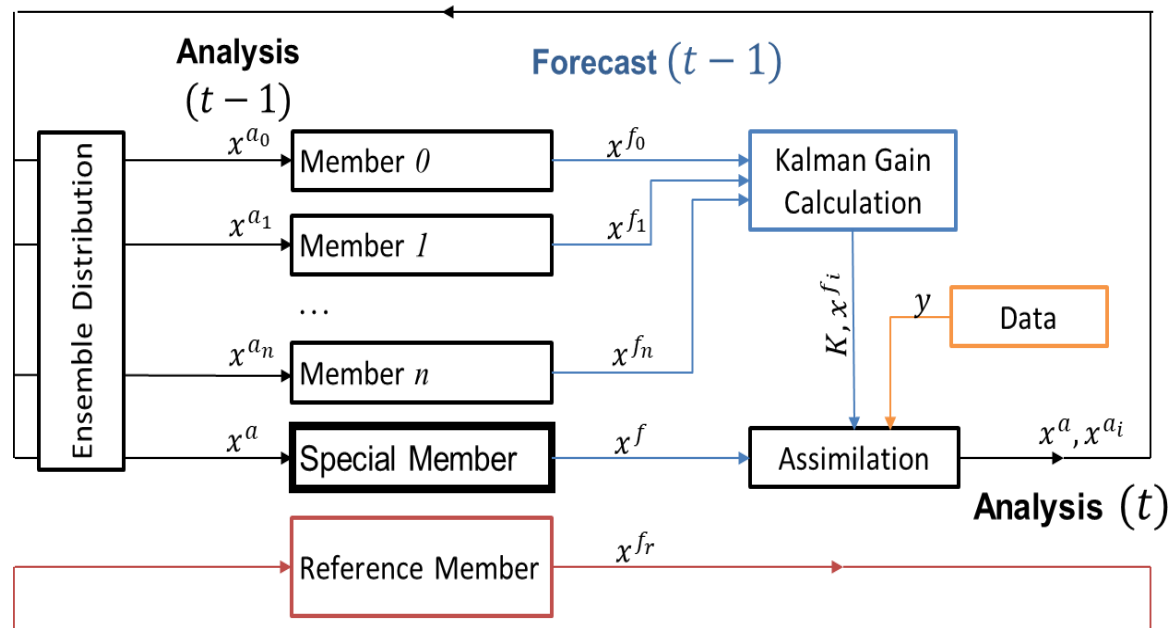


Fig.1 CTIPe model.

TIDA data assimilation scheme

TIDA



State Vector $x = \begin{bmatrix} \text{model forcing} \\ \text{model state} \end{bmatrix} \longrightarrow \begin{matrix} x^a = x^f + K(y - h(x^f)) \\ y^f = h(x^f) \end{matrix} \text{ KF update equation}$

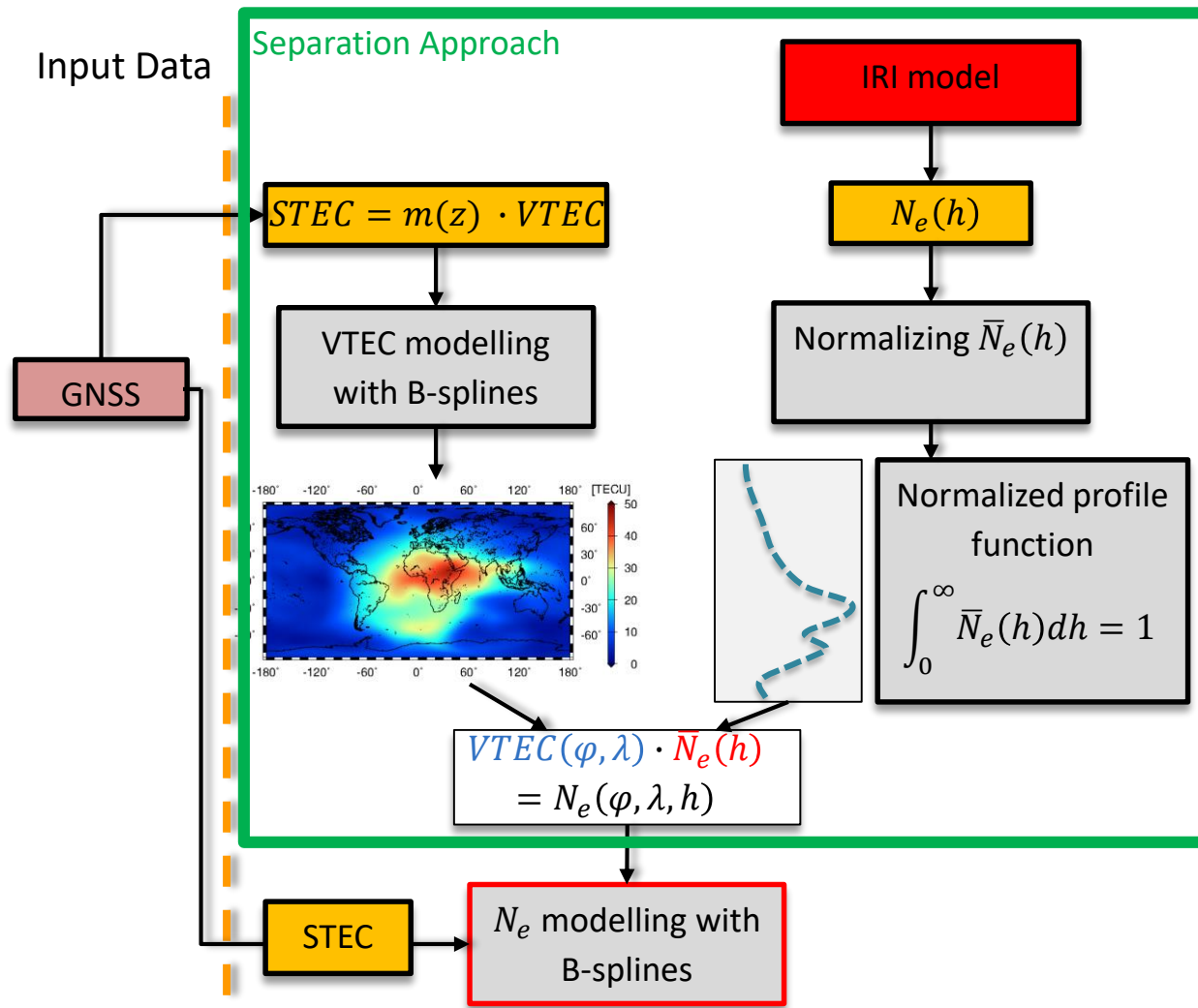
$$x = \{F_{10.7}, |v_{sw}|, \rho_{sw}, B_N, B_\theta, T_n, \gamma_O, \gamma_{O_2}, \gamma_{N_2}, M, U, V\}$$

Fig.2. TIDA assimilation scheme.

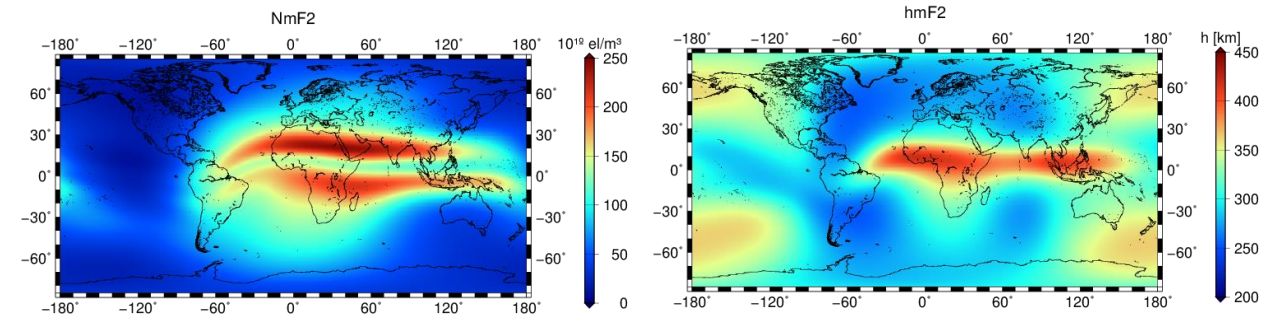
- A **reference** member is run in parallel with no assimilation, using the initial conditions and inputs that would have been available in operational real time. This is used as a reference to compare and measure improvement due to DA.
- The EnKF state vector consists of the model forcing parameters appended to the model state. The system updates following the Kalman filter (KF) equations:
 - x^f is the **forecast** state estimate.
 - x^a is the **analysis** estimate of the state taking into account all **measurements**.
 - K is the Kalman gain.
 - $h(x)$ is the function mapping from the state to the measurements.
- TIDA run conditions for this study are the following:
 - 75 members
 - Assimilation window of 60 minutes



B-Spline Electron Density Model (TUM)



- The **separation approach** provides the division of the three-dimensional function $N_e(\varphi, \lambda, h)$ into a horizontal $VTEC(\varphi, \lambda)$ and a **vertical** $\bar{N}_e(h)$ fraction at each position $P(\varphi, \lambda)$ on the Earth's surface.
- The $N_e(\varphi, \lambda, h)$ generated by means of the separation approach and additional observations from GNSS (GPS and GLONASS) have been used to estimate the Chapman parameters of the **F_2 -layer**.
- The **F_2 -layer is described in the literature as most important** and thus the parameters $N_m^{F_2}$ and $h_m^{F_2}$ are described by B-splines. The scale height of the F_2 -layer can be obtained by a relation between $N_m^{F_2}(\varphi, \lambda)$ and $VTEC(\varphi, \lambda)$.

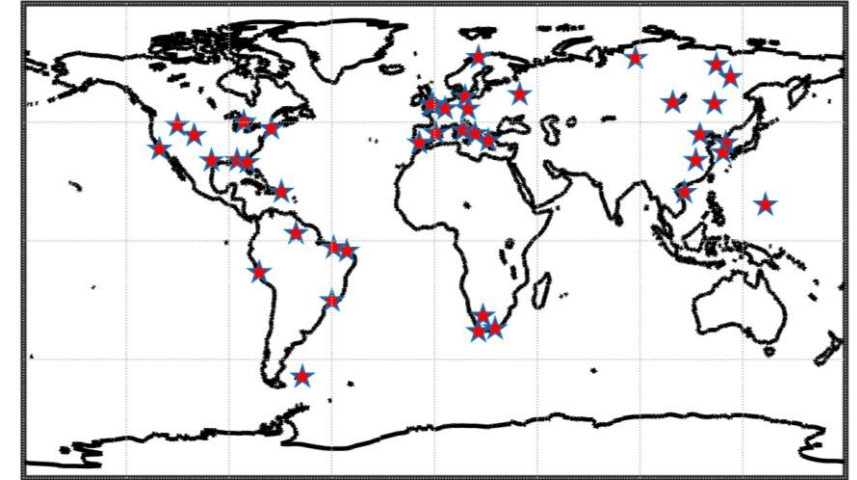


Examples show the estimated horizontal variations of $N_m^{F_2}$ and $h_m^{F_2}$ as global maps

- For estimating the unknown B-spline series coefficients for $N_m^{F_2}$ and $h_m^{F_2}$ a Kalman filter with a **temporal step size of 5 min** is applied.
- At each step of the Kalman filter these observations which have been observed within an interval of 5 minutes are used.

Validation with measurements (IGS TEC and Ionosonde fof2)

- **Total Electron Content (TEC):** Global Navigation Satellite Systems (GNSS) measurements are used to determine the total number of electrons along a path between the receiver and radio transmitter and generate Total Electron Contents (TEC) maps. As TEC maps effectively describe the average behaviour of the ionosphere, in this study, GNSS based TEC data provided by the International GNSS Service ([IGS](#)) is used to evaluate the effects in the ionosphere.
- **Ionosonde foF2 and hmF2:** Another source of validation data is ionosonde stations that provide electron density measurements in the Earth's ionosphere. We will use F2 layer parameters like the foF2 (critical frequency) and hmF2 (peak height) from the [GIRO](#) database to assess the state of the ionosphere.



The geographical locations of the **stations available** during the St. Patrick day Storm 2015.

Validation with measurements (IGS TEC and Ionosonde fof2)

