AGU Fall Meeting 2020

Hindcasting the ionosphere via assimilation of neutral mass density into physics-based models.

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Introduction

- The understanding of the **upper atmosphere coupling mechanisms** depends to a large extent on an accurate estimate of the true state of the Thermosphere – Ionosphere system.

- We **assimilate measurements into physics-based models** to provide a better estimate of the state of the system than the one obtained using the model alone. Some of the most important parameters that define the state of the thermosphere are **neutral composition and density**. Since their changes can modify the production-loss processes and impact the **plasma density**, in this study **we assimilate neutral mass density measurements to evaluate the impact that changes in the thermosphere produce in the ionosphere.**

- The analysis is done during a period of **quiet solar geomagnetic conditions** (4-8 March 2008) using the physics-based Coupled Thermosphere Ionosphere Plasmasphere electrodynamics model (**CTIPe**) coupled to an **ensemble Kalman filter** (EnKF) assimilation scheme, the Thermosphere-Ionosphere Data Assimilation (**TIDA**).

- The model results from assimilating accelerometer-derived **neutral mass density** from CHAMP and GRACE are compared with neutral mass density independent measurements to assess the **changes in the thermosphere**. **Total Electron Content** (TEC) observations from the International GNSS Service (IGS) as well as **ionosonde data** from the GIRO database are used to evaluate the **effect over the ionosphere**.

CTIPe 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.

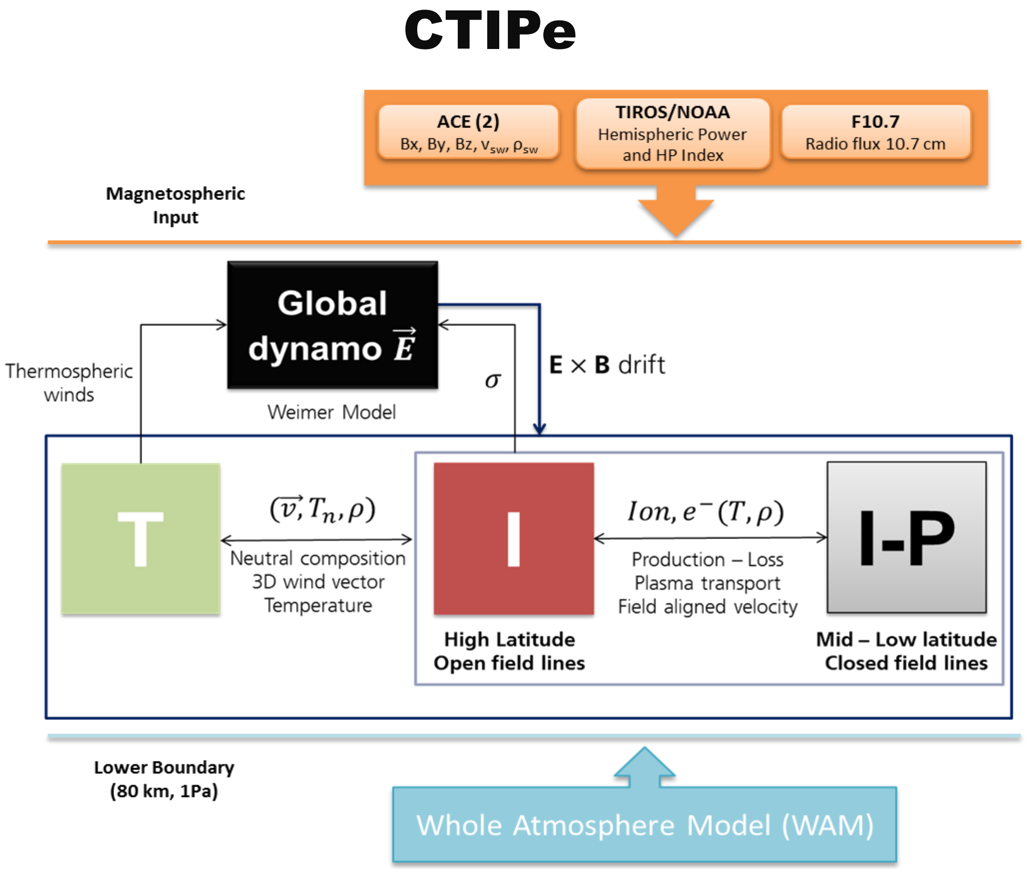


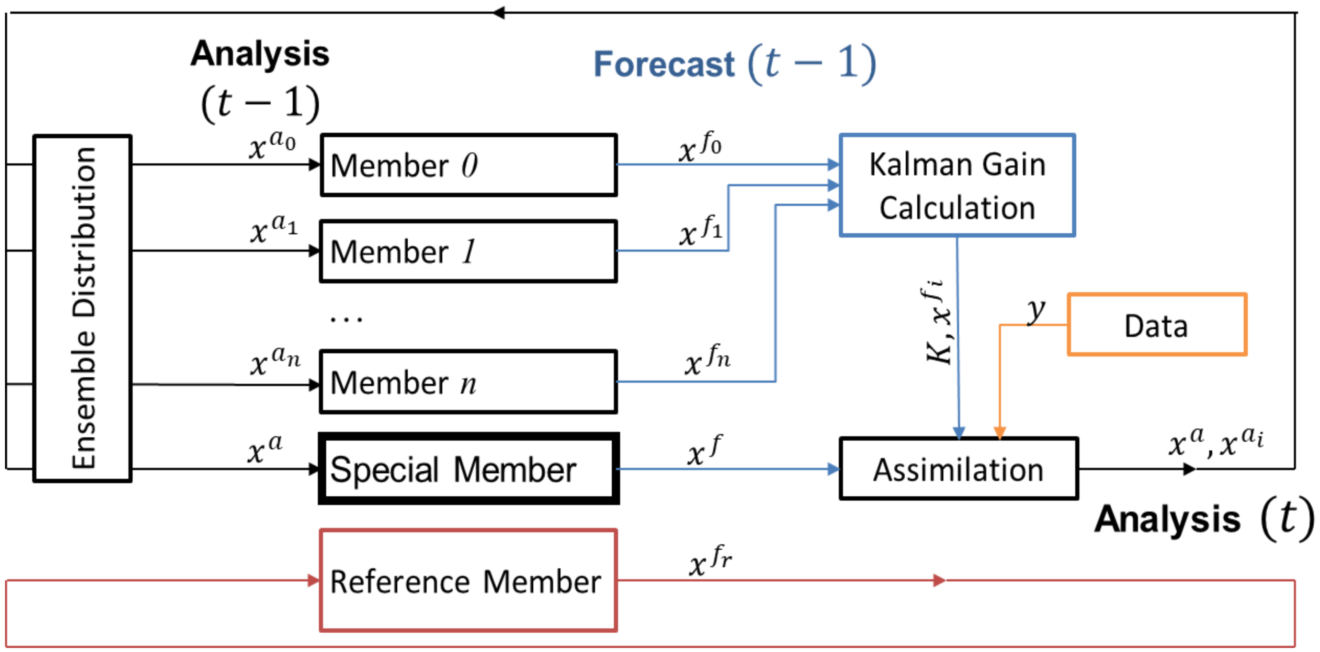
Fig.1 CTIPe model.

TIDA scheme

- The Thermosphere Ionosphere Data Assimilation scheme (TIDA) is a implementation of an ensemble Kalman filter (EnKF) that assimilates neutral mass density into the CTIPe model [Codrescu,2019].
- The ensemble (fig.2) is distributed by applying independent and identically distributed set of input forcing parameters to each member. The realizations are sampled from a normal distribution centred about the special member. As the ensemble mean approximates the true estate, the special member is a realization of the best estimate of the true state at any time.
- 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:
  - $\boldsymbol{x^f}$ is the **forecast** state estimate.
  - $\boldsymbol{x^a}$ is the **analysis** estimate of the state taking into account all **measurements**.
  - $\boldsymbol{K}$ is the Kalman gain.
  - $\boldsymbol{h(x)}$ is the function mapping from the state to the measurements.
- TIDA run conditions for this study are the following:
  - 75 members
  - Assimilation window of 10 minutes

TIDA Scheme

TIDA



State Vector $x = \begin{bmatrix} model\ forcing \\ model\ state \end{bmatrix}$ → $x^a = x^f + K(y - h(x^f))$, $y^f = h(x^f)$ **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.

Geomagnetic conditions

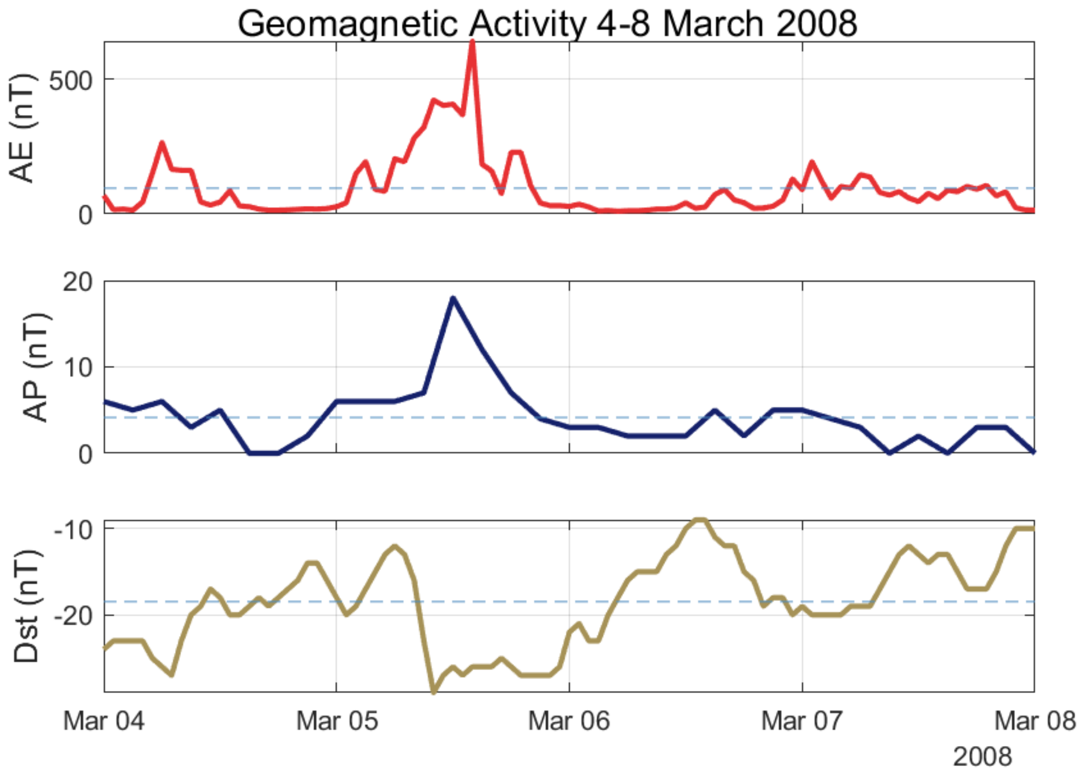


Fig.3 Geomagnetic indices for the period 4-8 March 2008

Quiet Geomagnetic Conditions

The study is done during quiet geomagnetic conditions during 4-8 March 2008. Geomagnetic indices are considered a proxy for the energy input or magnetic disturbances caused from solar activity. Dst, ap and AE indices can give us an idea of the activity level at different latitudes (fig.3).

Measurements

- **Neutral Mass Density:** Neutral mass density products derived from the measurements of accelerometer on board of the CHAllenging Minisatellite Payload (CHAMP) and Gravity Recovery and Climate Experiment (GRACE) missions. The processing of the accelerometer data involves a calibration using GPS tracking data, removal of the acceleration induced by the thrusters as well as radiation pressure force and requires the modelling of the action for the aerodynamic force on the spacecraft [Sutton, 2007]. Neutral mass density observations from CHAMP and GRACE-A are assimilated into CTIPe model. The results are compared with GRACE-B neutral mass density measurements to determine the changes in the thermosphere.

- **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 ionosophere.

- **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.

DA impact on the thermosphere

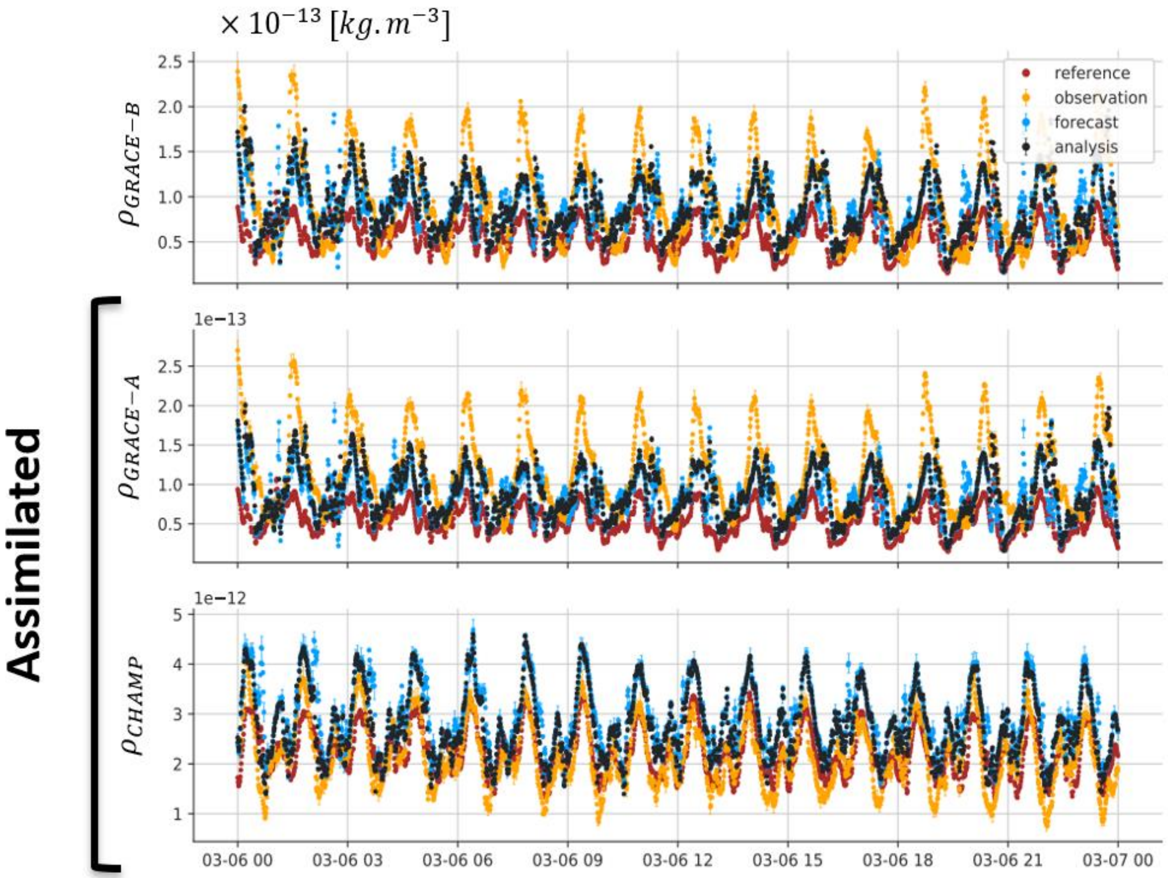


Fig.4 Neutral mass density observations of the 6 March 2008 compared to the reference (red), forecast (blue) and analysis (black) states.

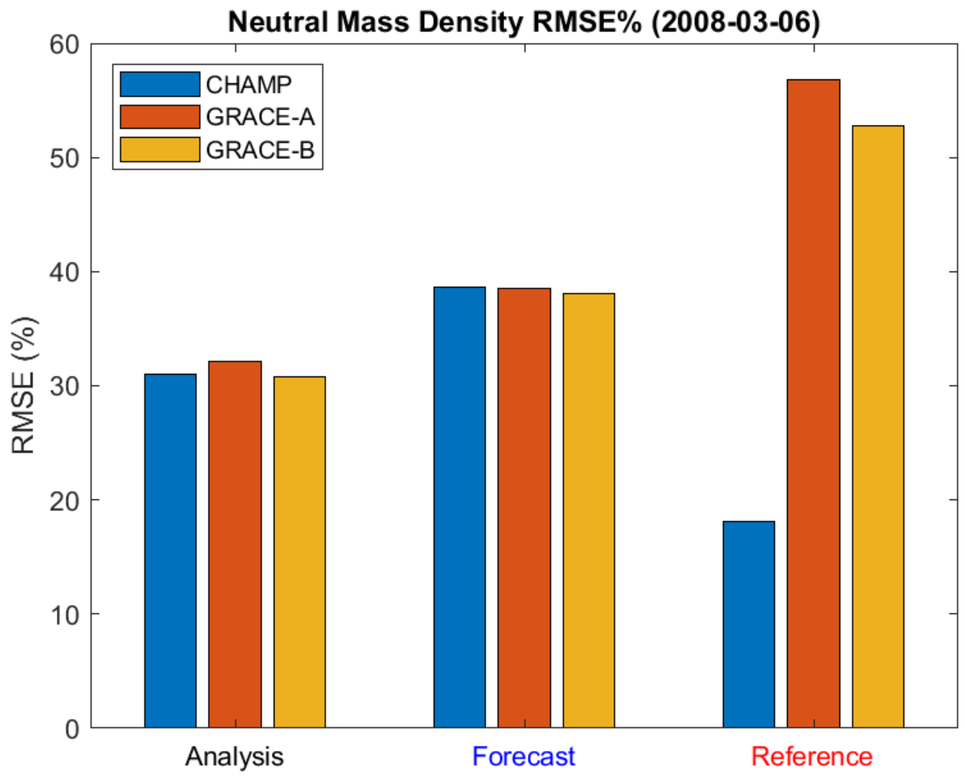
- The assimilation scheme is run for the 4-8 March 2008, a geomagnetically quiet period. In the experiment CHAMP and GRACE-A neutral mass density are assimilated, and compared with independent GRACE-B observations.

- Results of the run are shown in fig.4 where neutral mass density along the satellite orbit (**observations**) is 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

DA impact on the thermosphere

- RMSE (%) is calculated to evaluate the changes in the thermospheric state due to data assimilation (fig.5). **Analysis** and **forecast** estimations decrease the RMSE with respect to **reference** for both GRACE satellites. However, the opposite happens for CHAMP satellite in which it increases.

- These results show an **"on average" improvement of the thermospheric conditions due to DA** from two different satellites.



DA impact on the ionosphere

- To assess the changes in the ionosphere we evaluate the differences of the **analysis** with respect to the **reference**, shown in the TEC global map of the 6 March 2008 at 12:00UT (fig.6).

- Changes at high latitudes (temperature variations due to changes in the forcing estimate) and the equatorial region (composition changes due to neutral mass density DA) show the effects of data assimilation in the ionosphere.

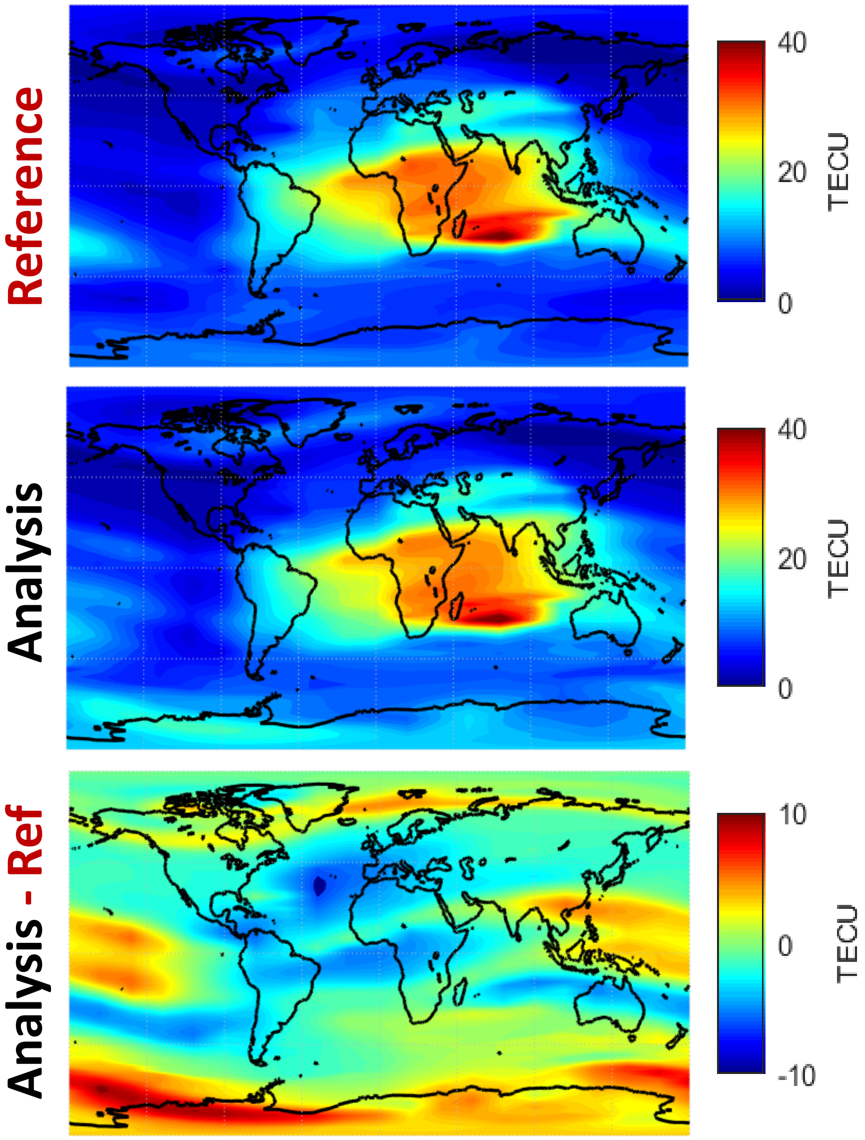


Fig.6 Reference, analysis and difference TEC global maps for the 6 March 2008 at 12:00 UT.

DA impact on the ionosphere

- Comparisons of IGS TEC and ionosonde (foF2, hmF2) data are shown for some of the ionosondes locations available at that time: For high-latitudes Gakona and Norislk, mid-latitudes Boulder and Athens and Kwajalein for the equatorial region.

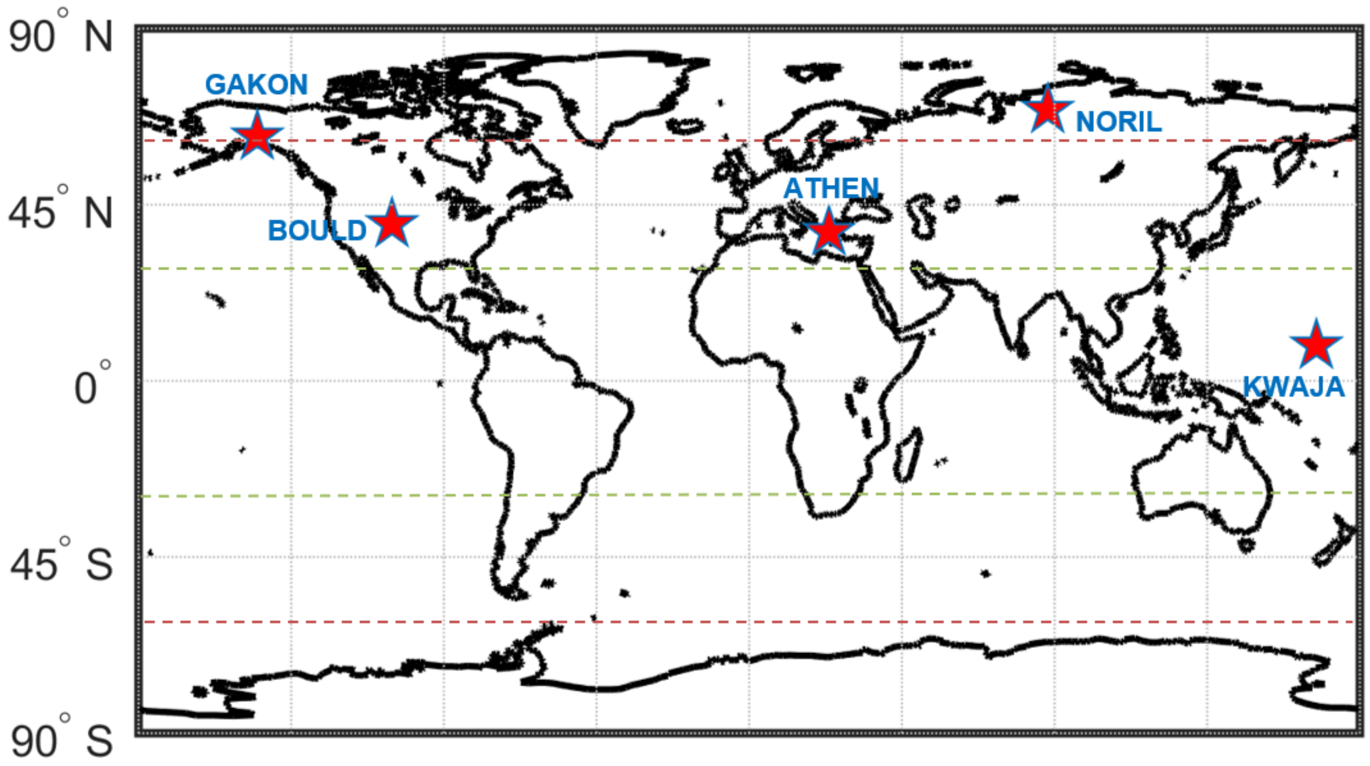
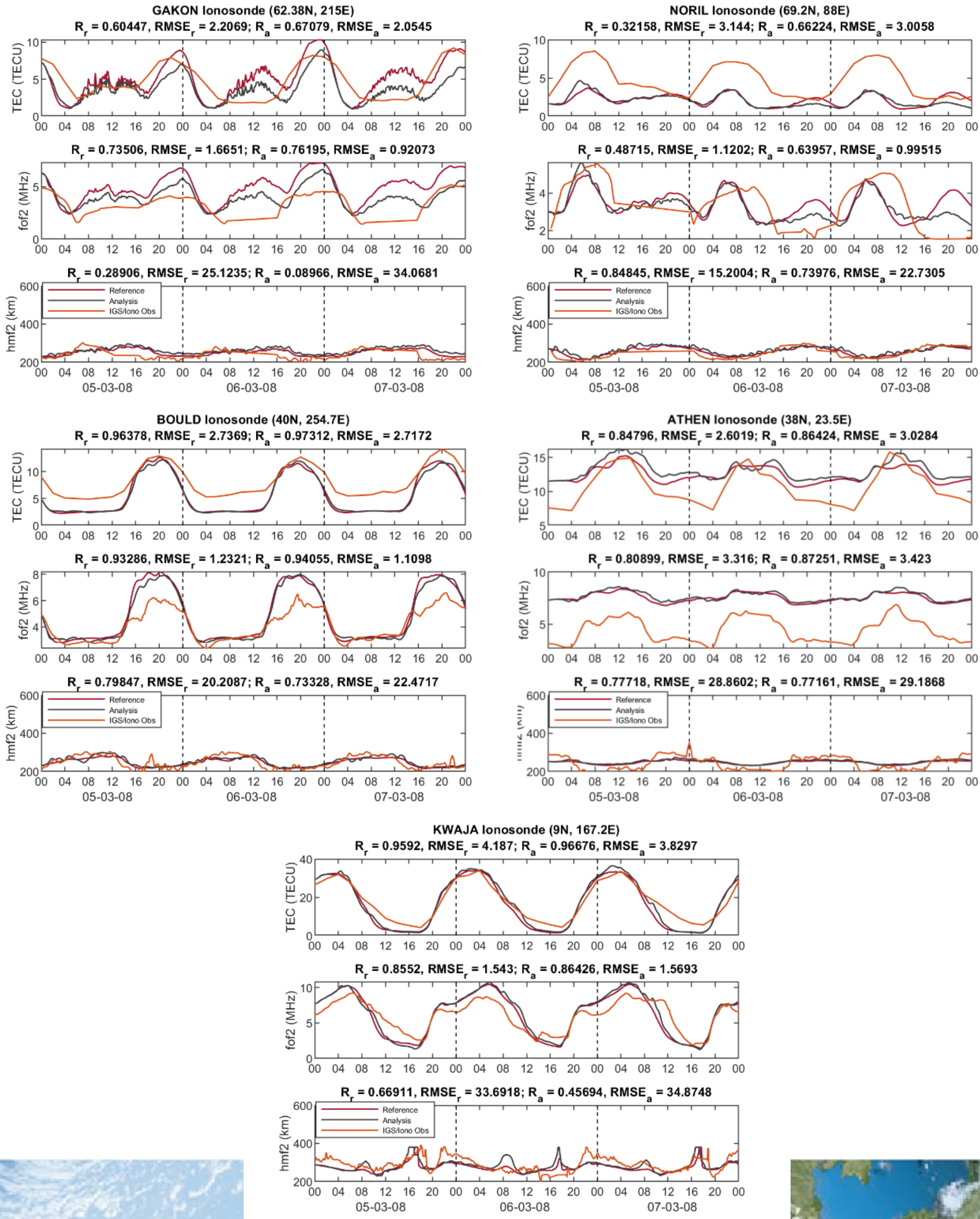


Fig.7. Geographical location of ionosondes used in the study classified as high-latitudes (Gakona, Norilsk), mid-latitudes (Boulder, Athens) and Equatorial region (Kwajalein).

DA impact on the ionosphere

- A small improvement of the correlation coefficient (R) and RMSE of the **analysis** with respect to the **reference** for TEC and foF2 is found at mid-latitudes locations (fig.8), although the differences between them are very small.
- Very similar situation is found at the equatorial region (fig.9).
- The differences between **reference** and **analysis** are more visible at high latitudes (fig.10).
- The results show that **the ionosphere is much more difficult to improve with DA than the thermosphere**. This may be because the electron density is not only dependent on neutral temperature and composition, which are globally coherent but also on local neutral winds and electric field conditions.



Conclusions

- The results of neutral mass density assimilation into CTIPe physics based model with TIDA scheme show an **"on average" improvement of the model thermosphere through neutral mass density assimilation**.
- Differences in TEC between the **reference** and **analysis** estimates are found at high latitudes and the equatorial region.
- These TEC differences could be an indicator of how **the ionosphere is affected by the assimilation of thermospheric observations**.
- A small improvement of the correlation coefficient and RMSE of TEC and foF2 time series is found for different ionosondes locations.
- These results show that **the ionosphere is much more difficult to improve with DA than the thermosphere**.