Space Weather: Modelling the thermosphere ionosphere system during geomagnetic storms

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Outline

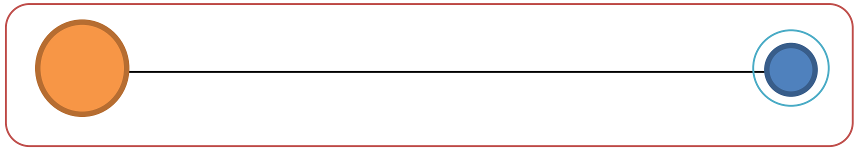
Space Weather
- Upper Atmosphere
- Geomagnetic storms

Objective
- Forecast the state of the upper atmosphere

Models and Methods
- Physics – based models : CTIPe
- Data Assimilation (DA)

Results
- Impact of magnetospheric drivers in near-real time
- Correcting the TI system state through data assimilation

Space Weather



- **Space Weather** (Solar – Terrestrial physics) → **Solar activity**
  - Sun and its atmosphere
  - Interplanetary space
  - Earth magnetosphere and upper atmosphere

} **Geospace**

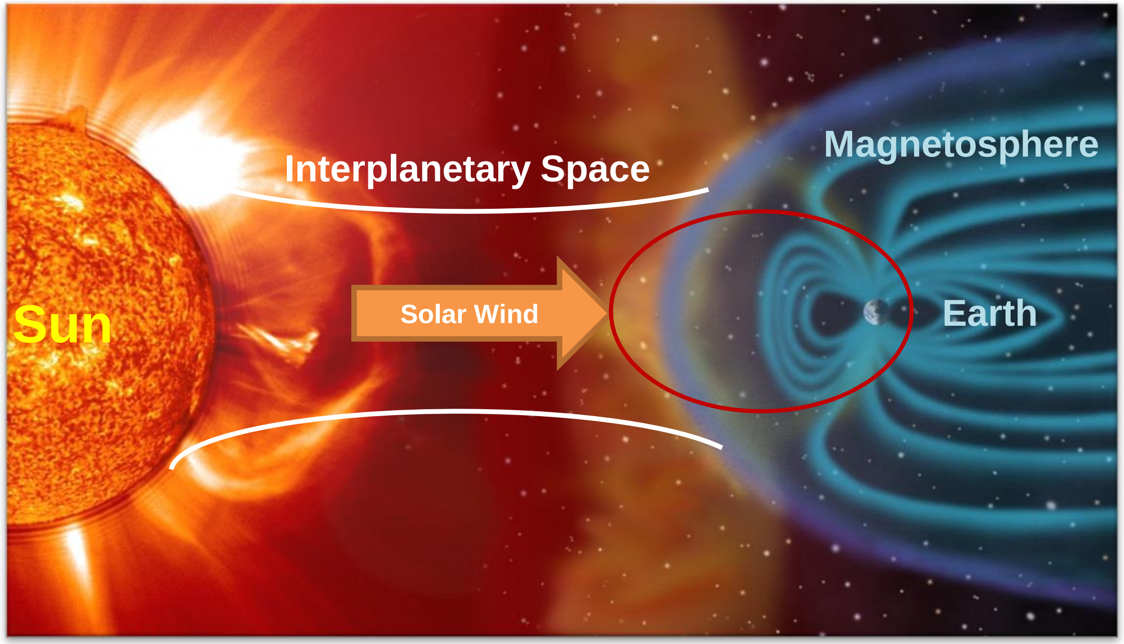


Image courtesy NASA

Solar Flares and Coronal Mass Ejections

Solar Flare

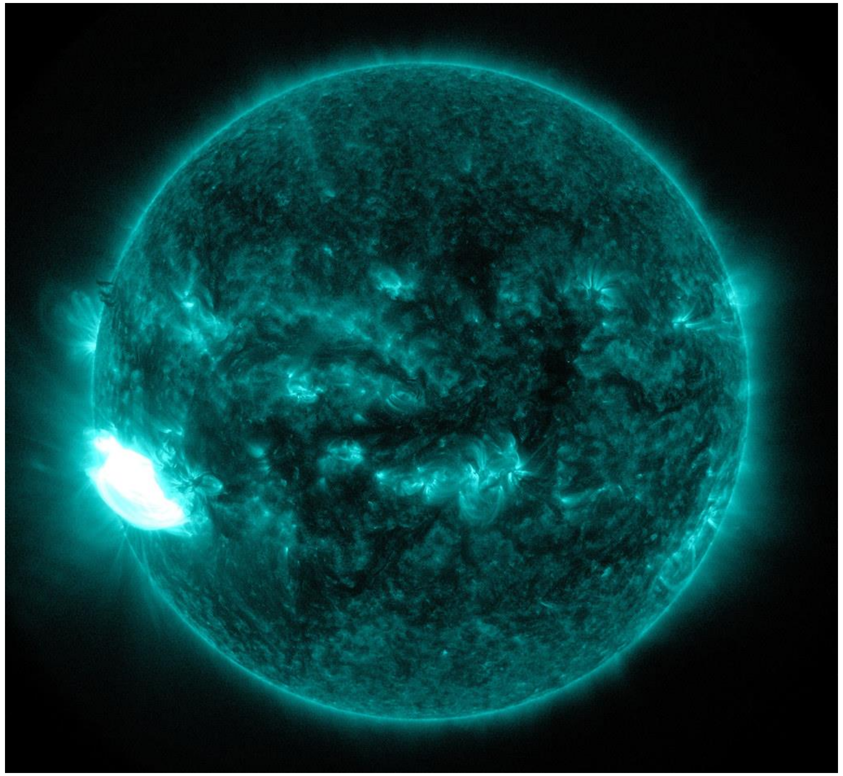


Image from NASA (SOHO mission)

Coronal Mass Ejection

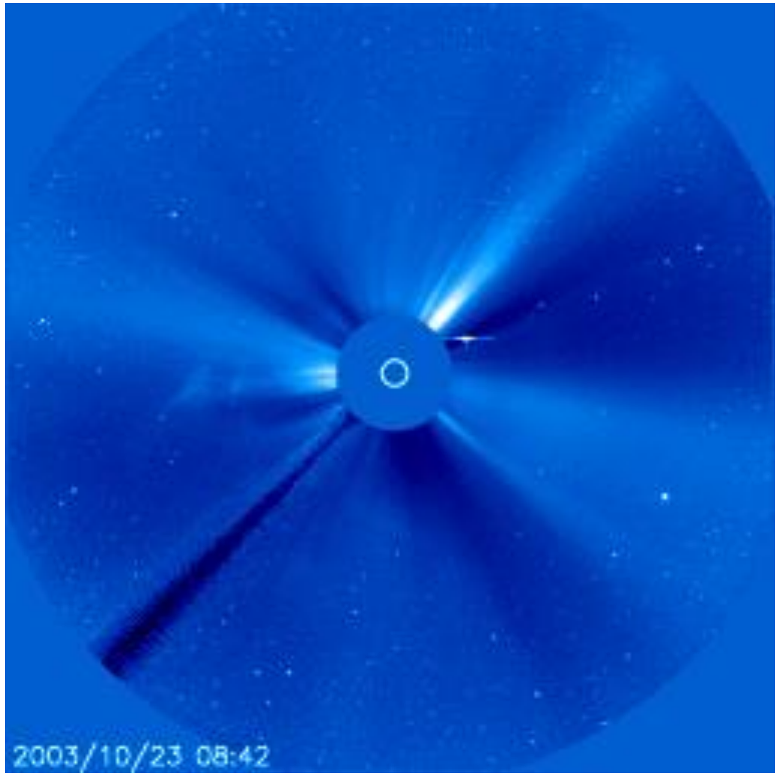


Image from NASA (SOHO mission)

Interplanetary Space and Magnetosphere

Interplanetary Space

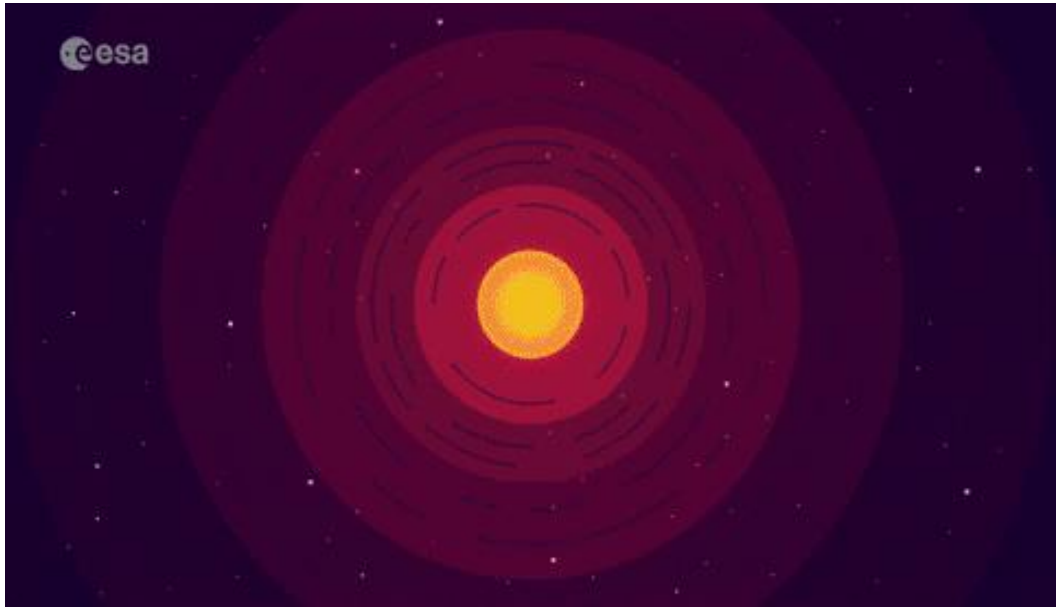


Image courtesy ESA

Magnetosphere

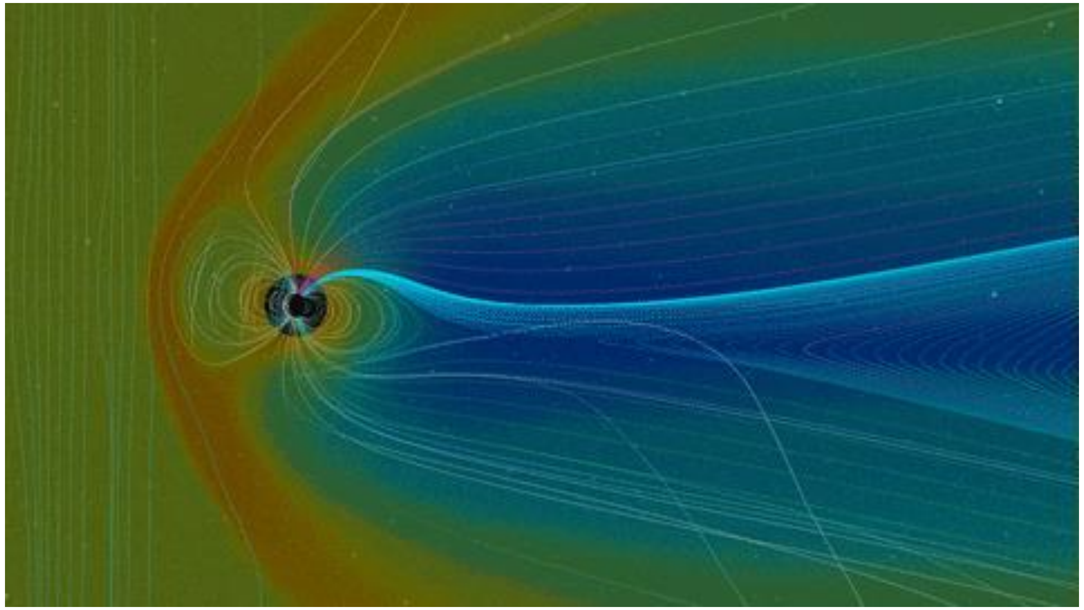
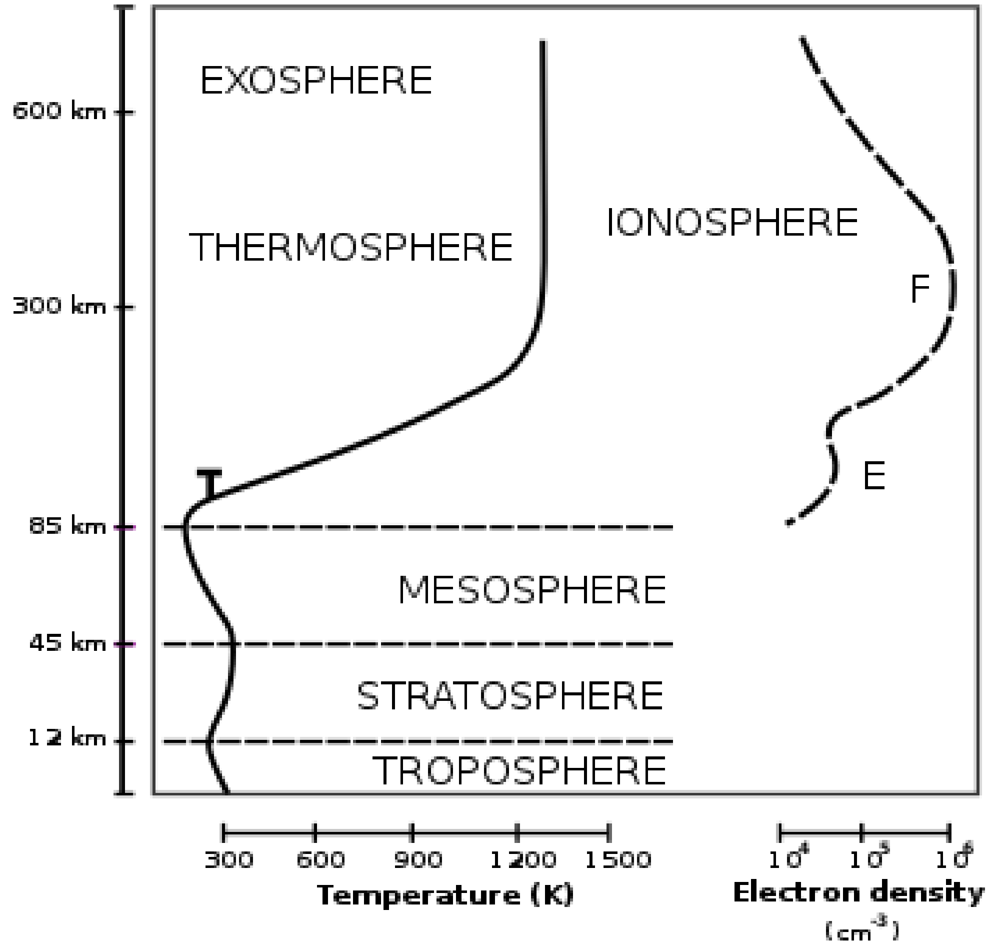


Image courtesy NASA

Thermosphere – Ionosphere (TI) system



- **Thermosphere** (90,600)km: **Neutral composition**
  - Layer of the upper atmosphere between the mesosphere and exosphere.
  - Characterized by its **temperature** profile**.**
  - Increase of T with high at lower thermosphere and steady above 300 km

- **Ionosphere** (90, 2000)km: **Charged particles**
  - Characterized by high – densities of free charged particles – ions and electrons.
  - **Electron density** profile characterizes the changes of the ionosphere in altitude.
  - Coupling between transport heating, electrodynamics and chemistry.

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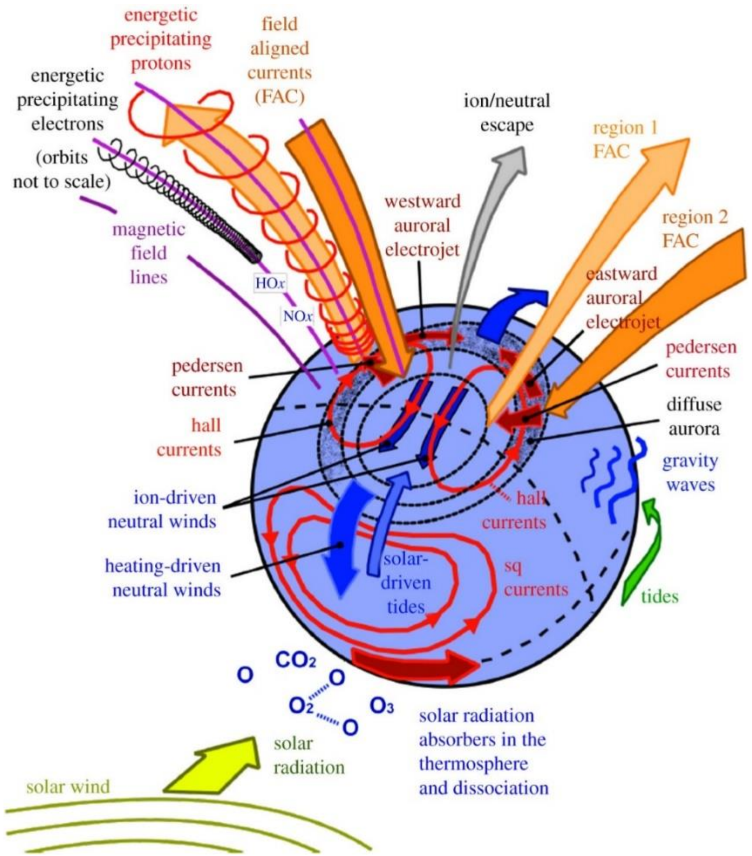
Causes of TI variability

- TI system varies with altitude, latitude, longitude, time, season, solar cycle and **geomagnetic activity**.

- Main **driving mechanism**:
  - Solar ultraviolet (**UV**) and extreme ultraviolet (**EUV**) radiation.
  - Sun **energetic particles.**
  - **Solar wind** and **magnetic field**.

- TI processes and their interaction with the magnetosphere and the solar wind



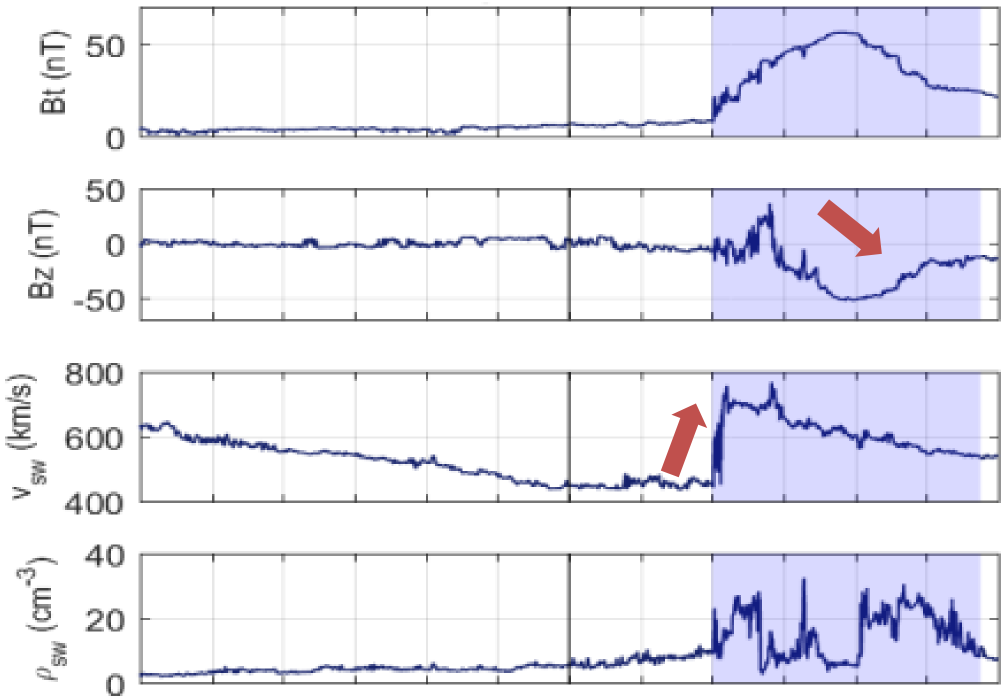
[Sarris, 2019]

Geomagnetic storms

- **Geomagnetic storm**: Major disturbance of Earth's magnetosphere that occurs when there is a energy exchange from solar wind into the space environment surrounding Earth. Caused by solar flares or **coronal mass ejections** (CMEs)

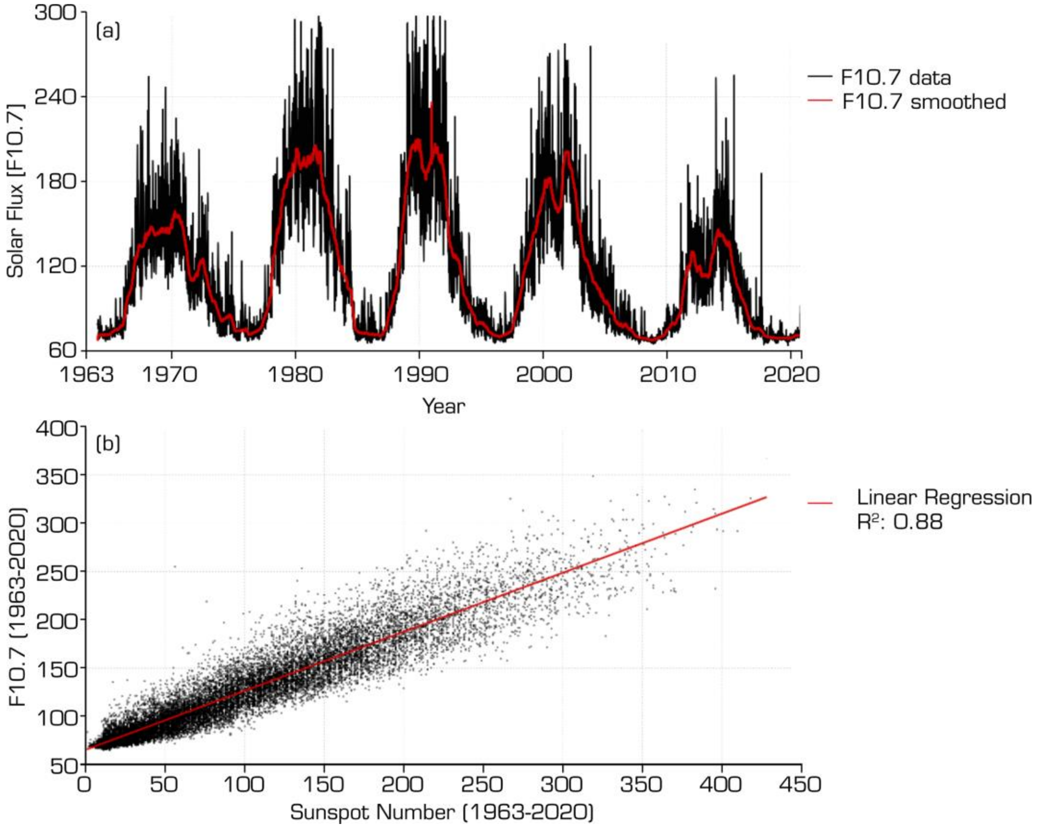
- **Conditions**: High speed solar wind and **Southward directed solar wind magnetic field** (Bz) opposing the Earth's magnetic field direction, at the dayside of the magnetosphere, sustained during several hours.

Solar wind parameters



Geomagnetic storms scales

- **F10.7**: Solar flux at **10.7 cm radio emission** is a good indicator of solar activity. It correlates well with the sunspot number, UV and visible solar irradiance.
- **AE**: Geomagnetic index of the **auroral electrojet**, characterizes the maximum range of divergence from quiet geomagnetic level.
- **Kp**: Index to indicate the severity of the **global magnetic disturbance** of the near-Earth space, based on the range of variation of the magnetic field.
- **Dst:** GS result in intense currents in the magnetosphere. Equatorial current around Earth produces magnetic disturbances on the ground. A measure of this current is the **Disturbance storm time** index.



[Sousasantos, 2021]

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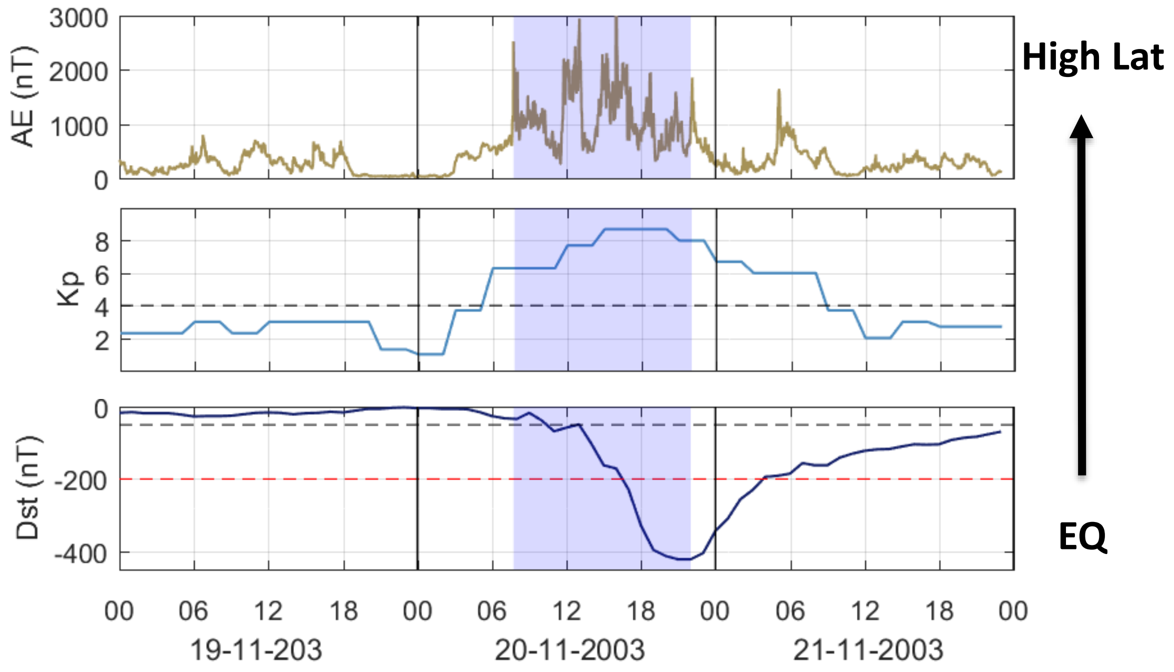
Geomagnetic conditions



Why is so important the TI system?

- **Free charged particles affect propagation of electromagnetic signals.**
- **Communication** systems that utilize the ionosphere to reflect radio signals over long distances can be disrupted.
- Effects on **navigation**, like the Global Positioning System (GPS). Free electrons induce group delays and phase acceleration of the signal resulting in a bias in position determination.
- **Electric power** may be affected during geomagnetic storms. The presence of magnetic fields in the vicinity of a conductor (wire) induce electric currents.
- The fluctuation geomagnetic fields can induce currents into **pipelines**.

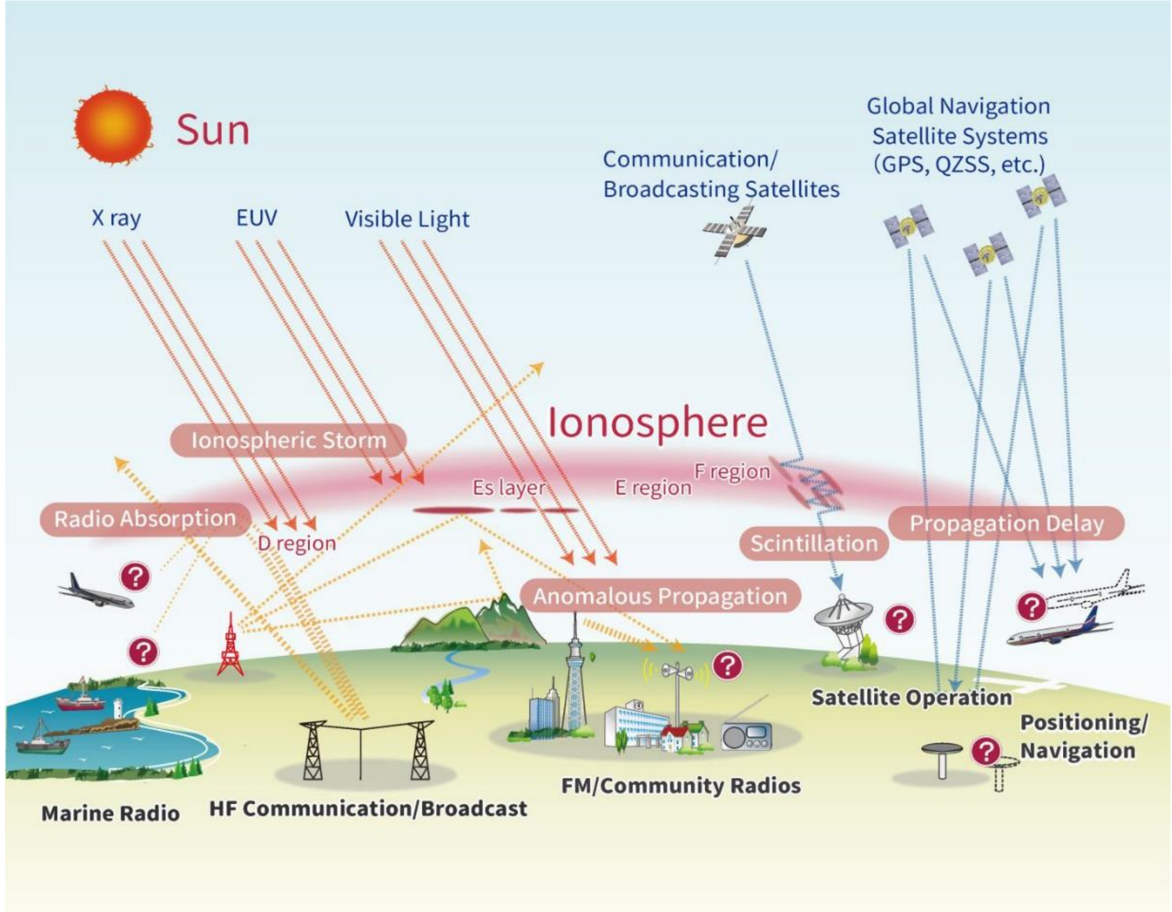


Image courtesy NIICT

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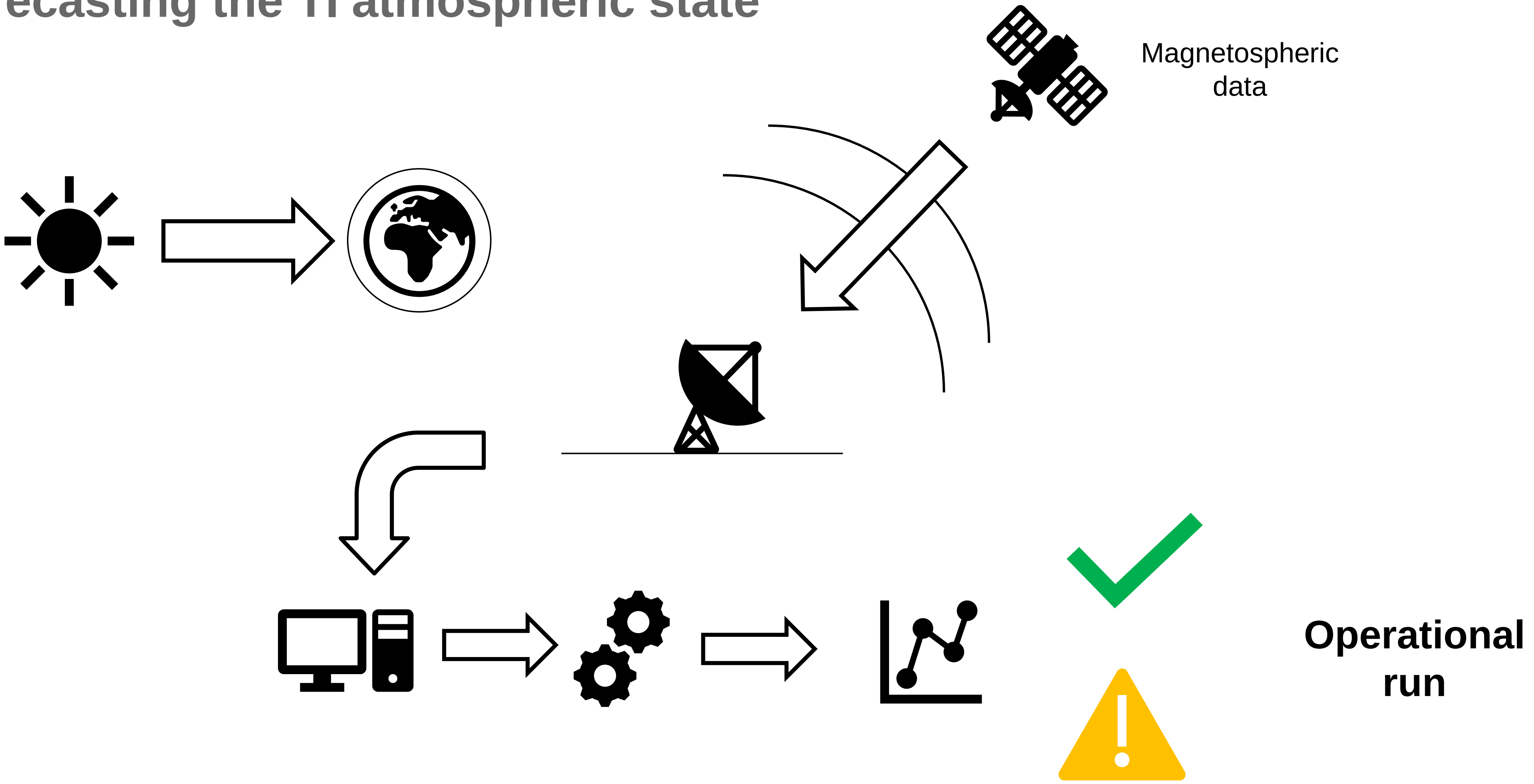
- Forecast the state of the upper atmosphere

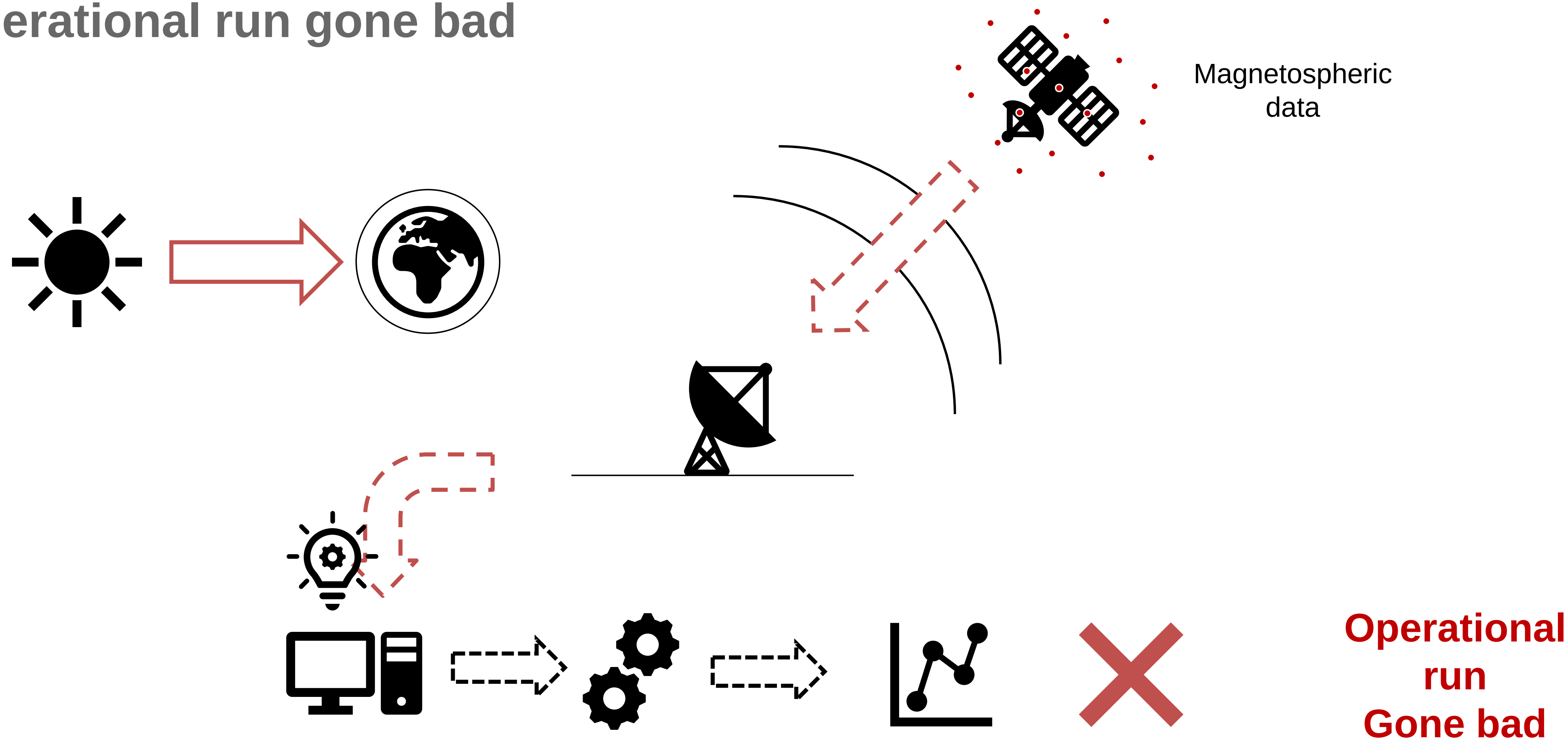
Models and Methods

Results

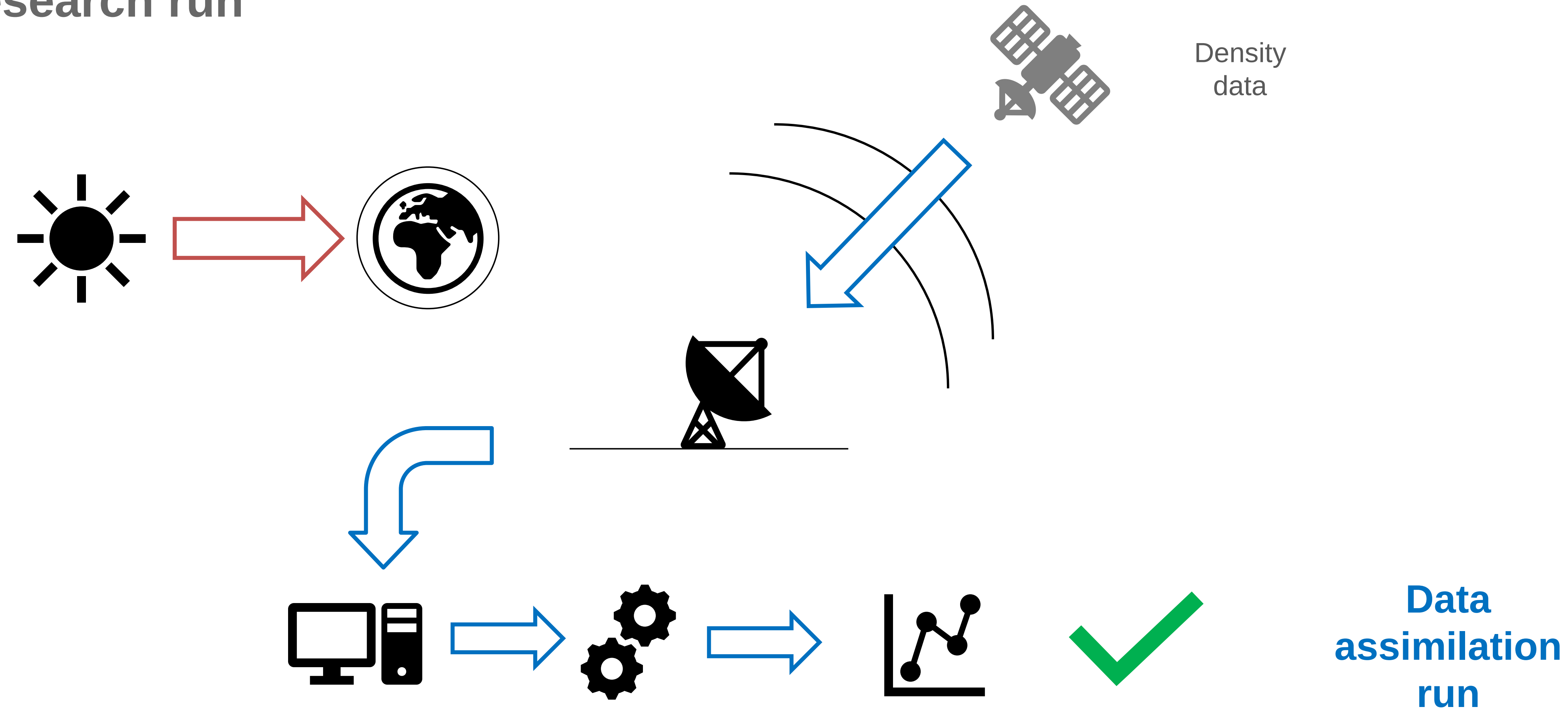
Forecasting the TI atmospheric state



Operational run gone bad

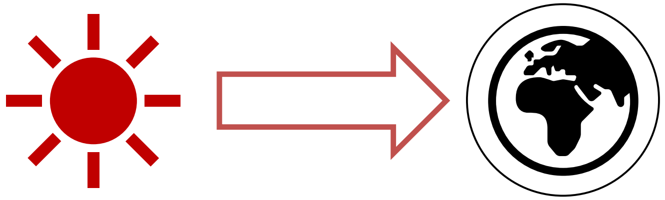


Research run



Objective: Operational vs. Research

Storm geomagnetic conditions



	Model run	Input data	Study during storm conditions
1	Operational	Magnetospheric real time data	Impact of magnetospheric drivers in real time simulations
2	Data Assimilation	TI Observations	Correcting the TI system state through data assimilation

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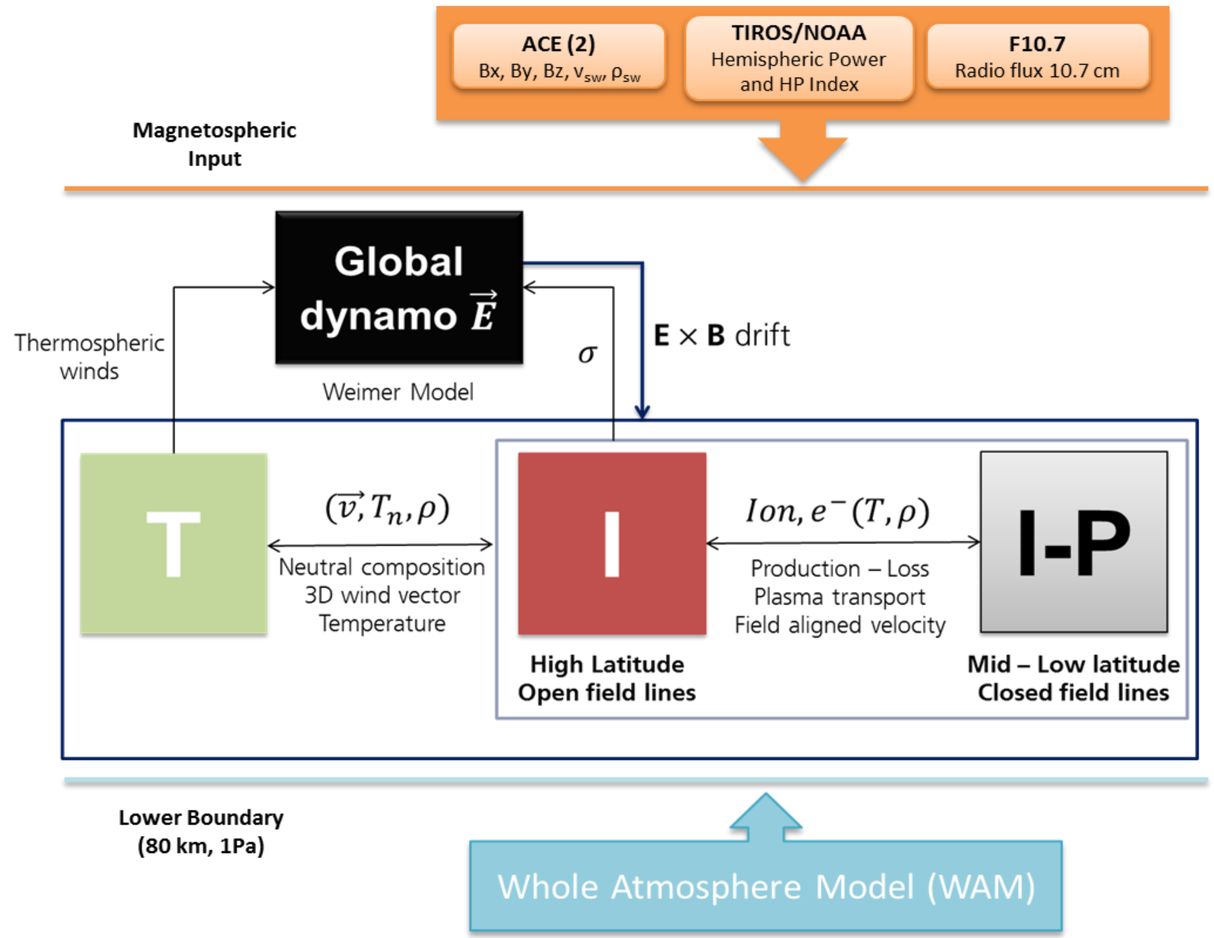
Physics – based model: CTIPe

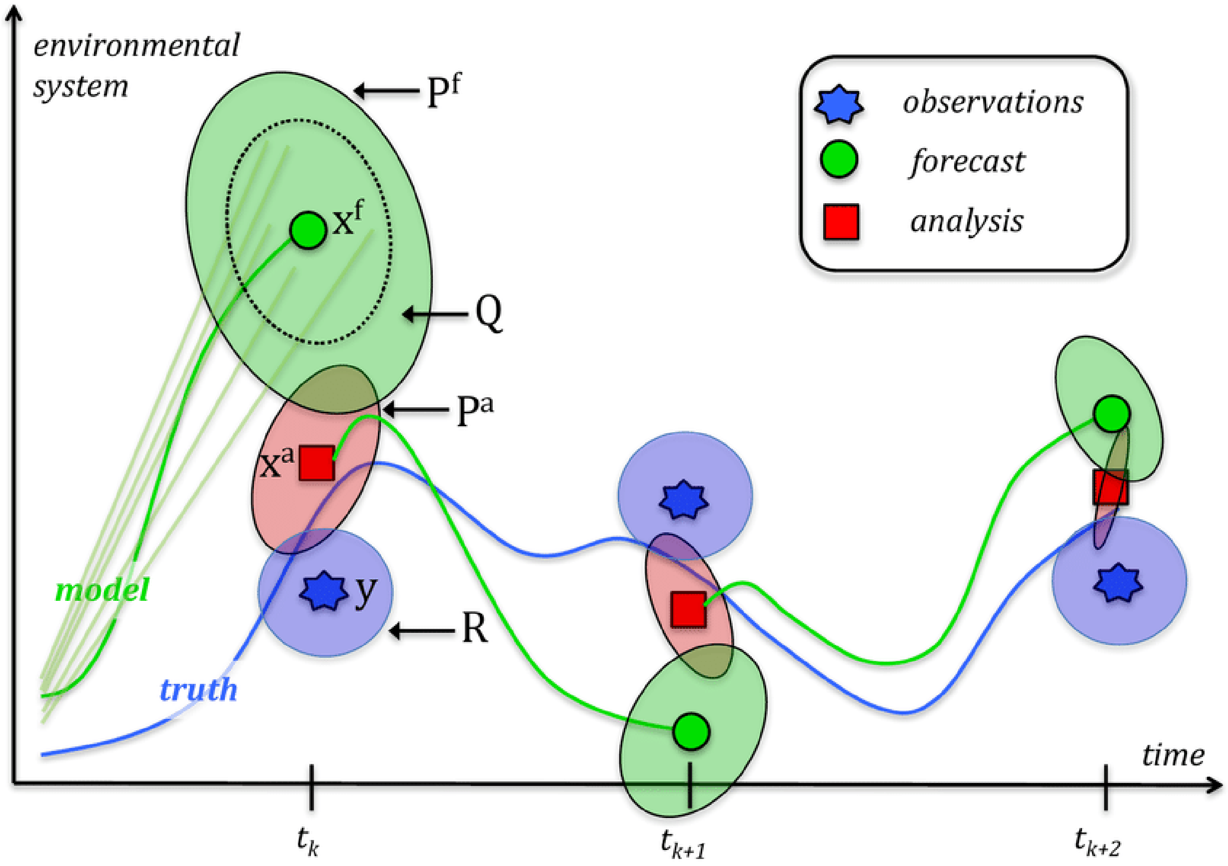


- Coupled Thermosphere Ionosphere Plasmasphere with Electrodynamics physics based model (SWPC-NOAA).
- Solves the equations of momentum, energy and composition for **neutral** (T) and **ionized** (I, I-P) **atmosphere.**
- **Global dynamo electric field**: Weimer Model
- **Magnetospheric input**: ACE measurements, TIROS/NOAA auroral precipitation and F10.7.
- **Lower boundary**: Simplified version of WAM at 80km

Data Assimilation (DA)

- **Data assimilation** combines different sources of information to estimate possible states of a system that evolves in time.

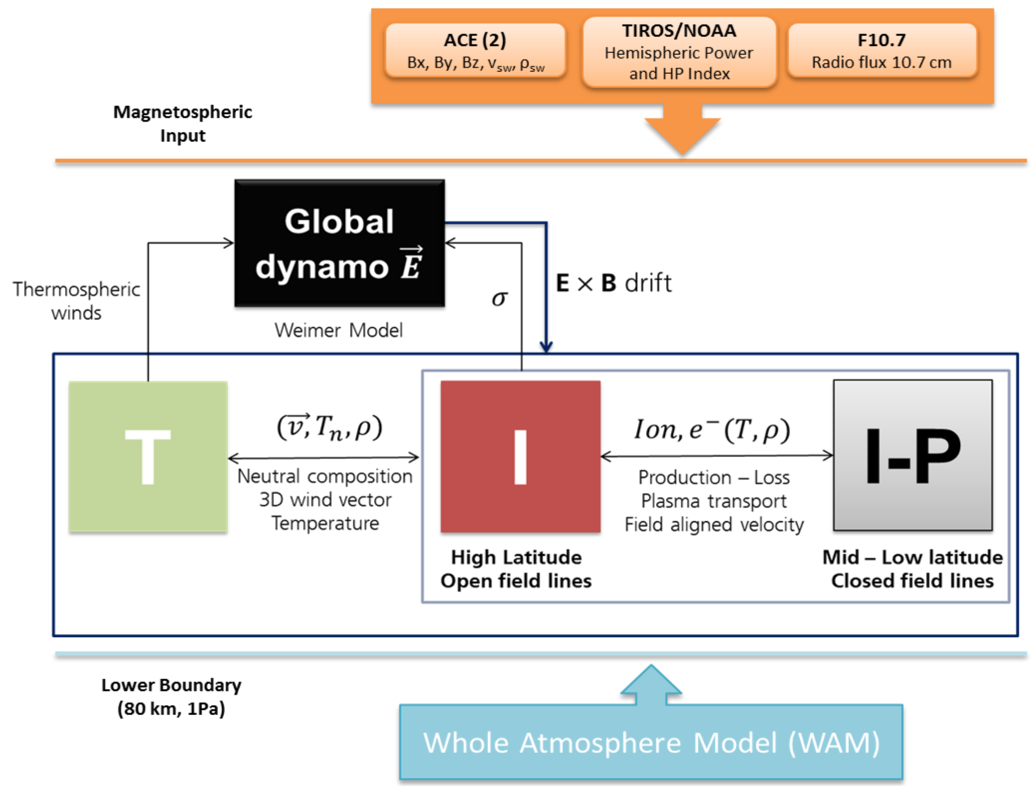
- Thermosphere – Ionosphere system is corrected by **combining density observations with models results** taking into account the **uncertainties** in each, while respecting certain constraints.



[Tandeo, 2018]

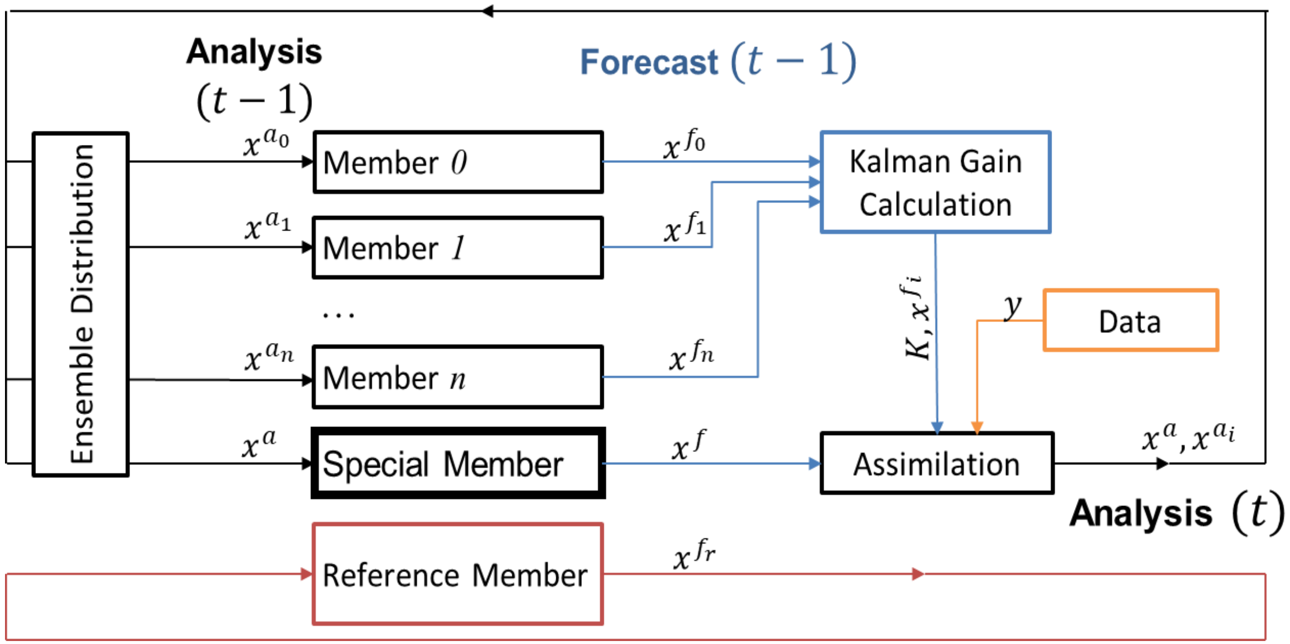
CTIPe – TIDA: Physics based model with neutral mass density DA

CTIPe



TIDA

[S. Codrescu, 2018]



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**

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

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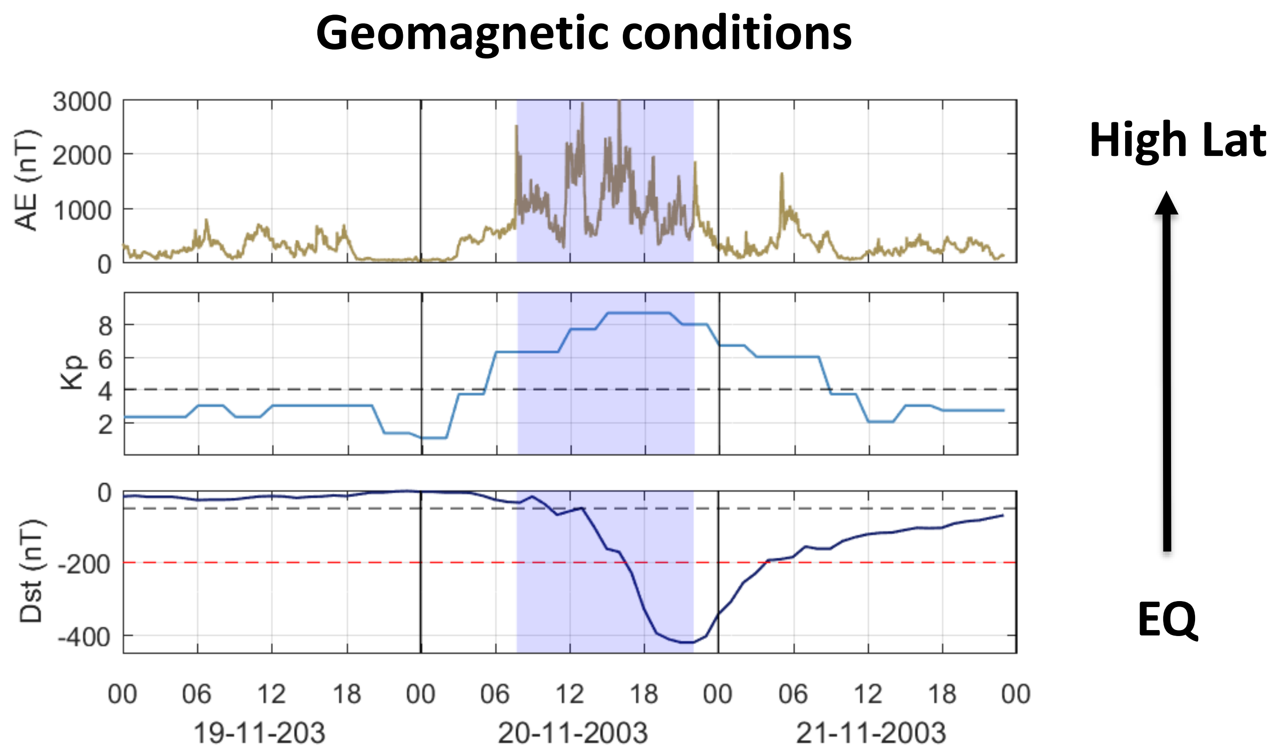
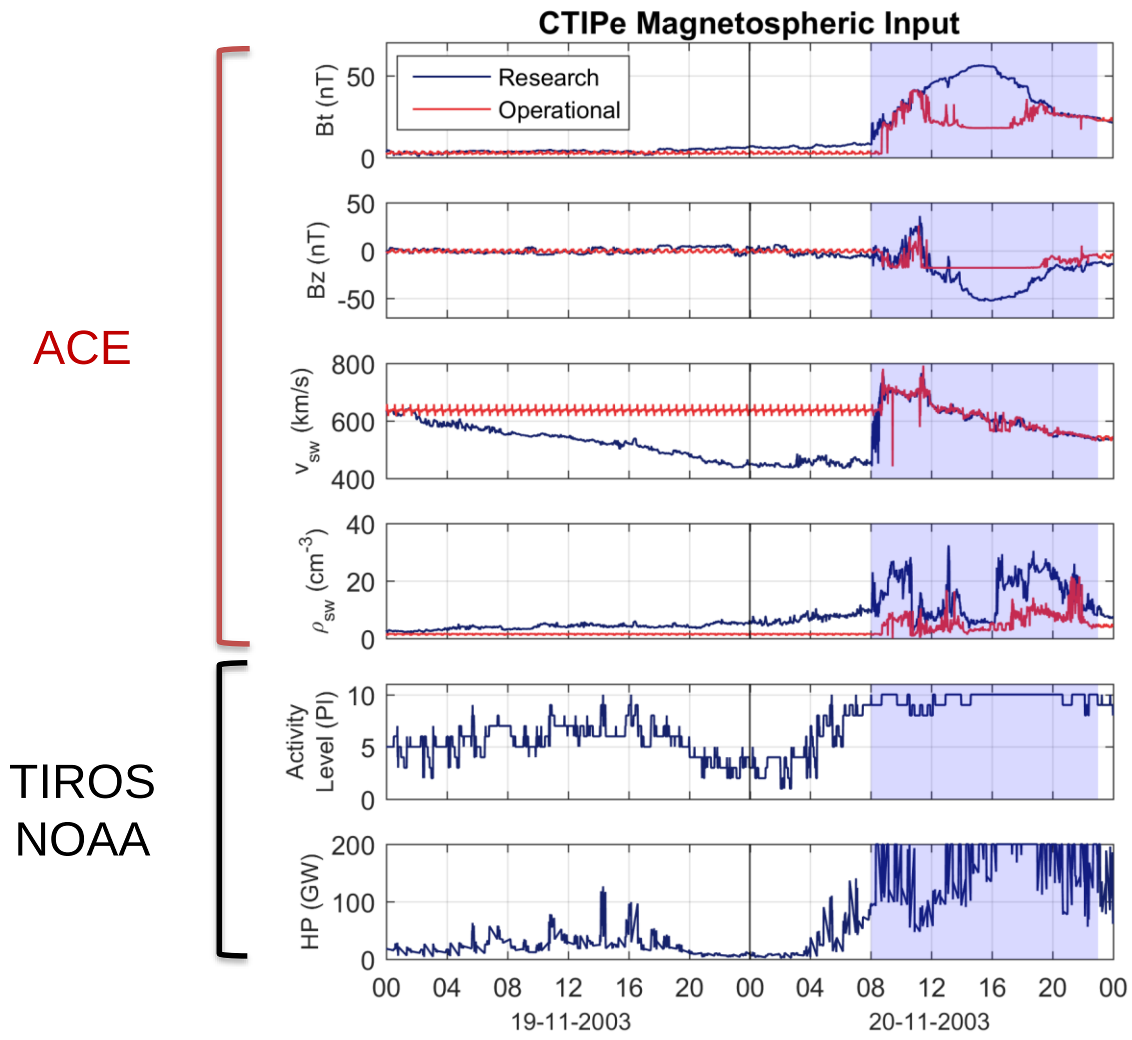
Case Study: 20th November 2003 Superstorm



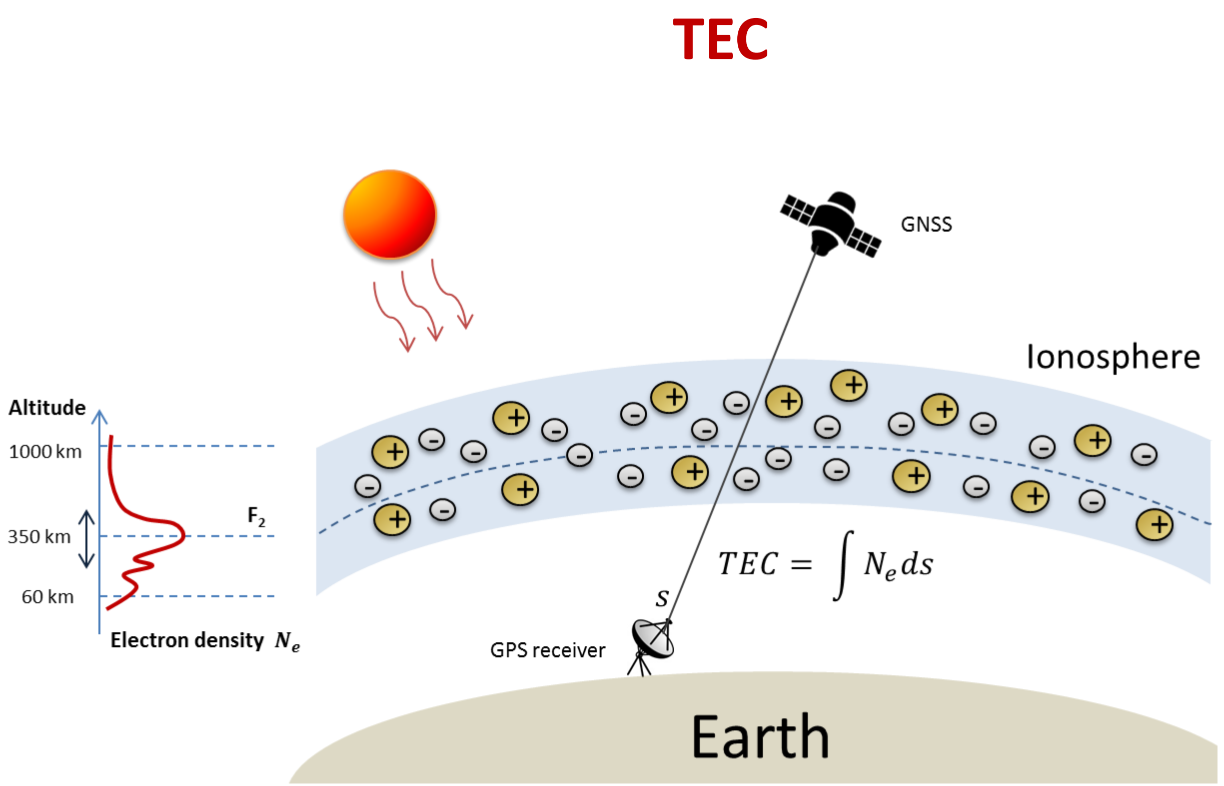
- **Dst** as indicator of storm phases with an Onset at 8UT and main phase 8-23UT with a minimum -470 nT.
- **AE** shows heating enhancement during the main phase
- **Kp** values increase up to 9 indicating very strong disturbance.

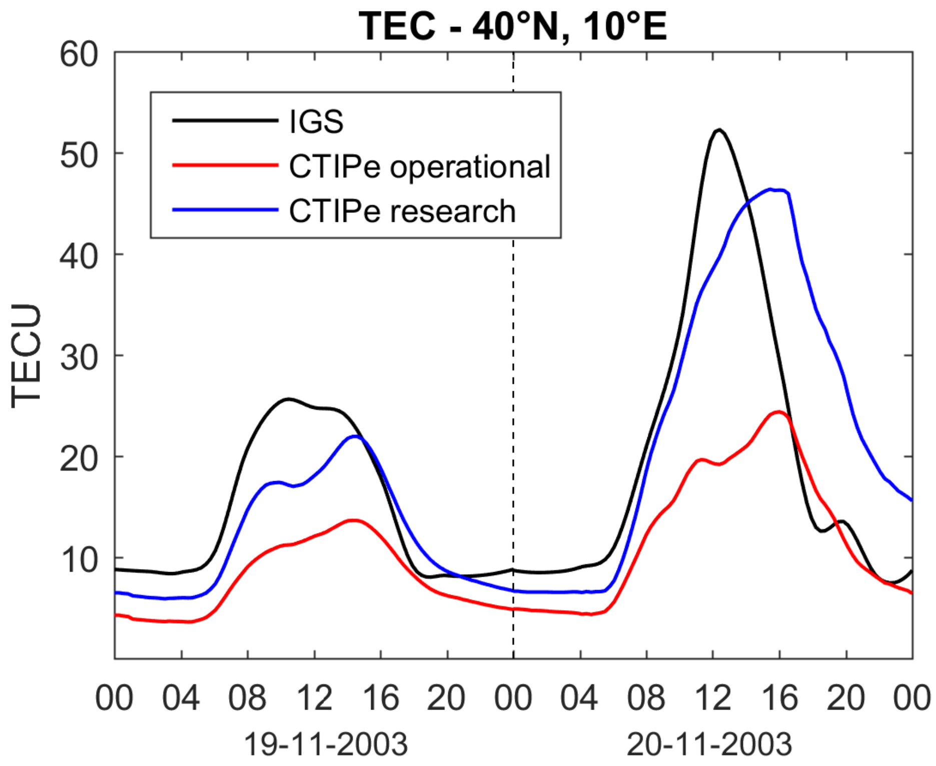
Operational vs. Research: Input data



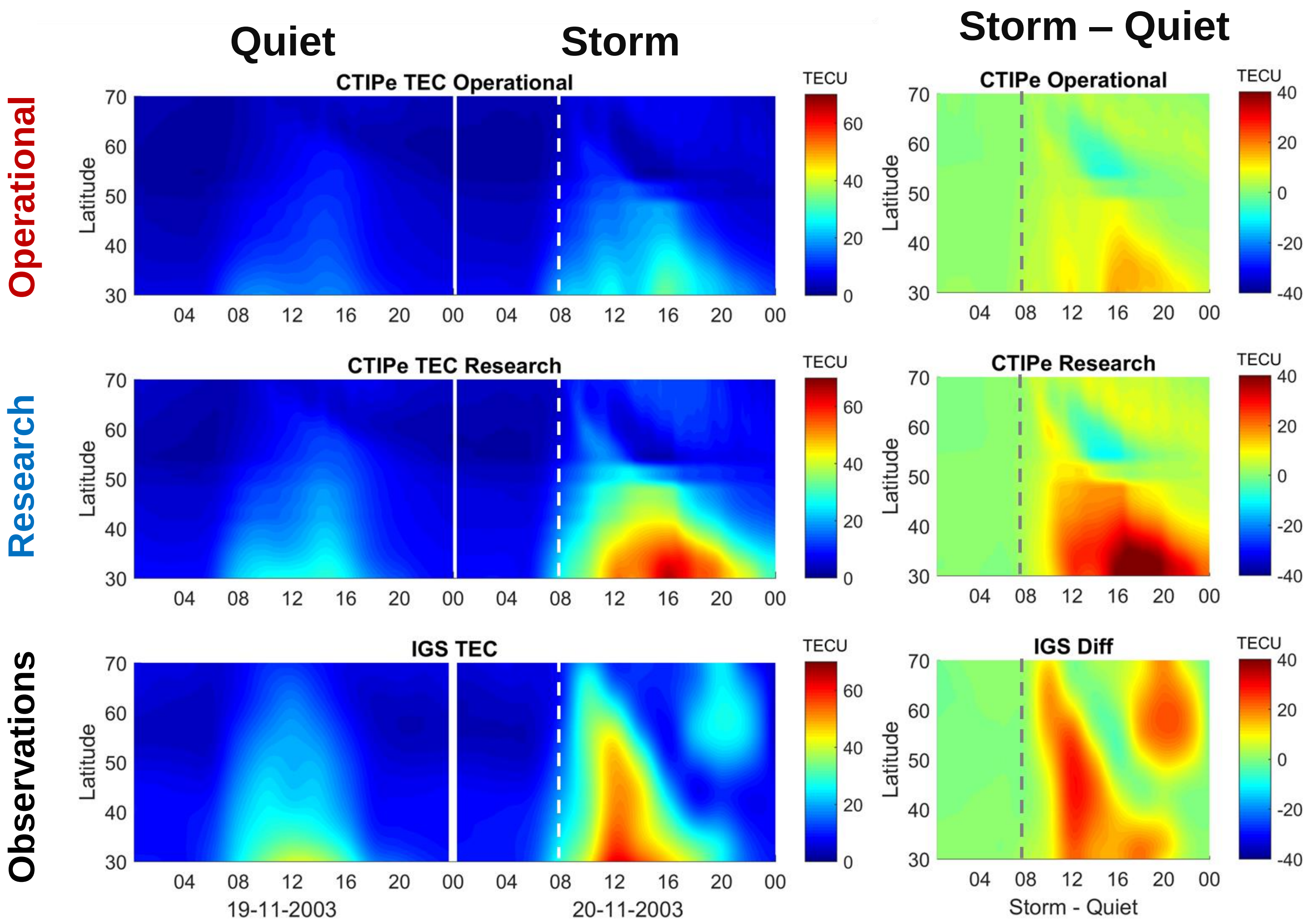
- CTIPe magnetospheric input
- Operational: Data available in real time
- Research: corrected with OMNI data.
- Clear discrepancies Operational vs Research.

Operational vs. Research: Ionospheric TEC





Operational vs. Research: Ionosphere (TEC) – Europe (10E lon)



- TEC change in lat vs. time (10E lon)
- Operational/Research runs and IGS TEC observations.
- Onset of the storm (dashed line)
- Enhancement starts high latitudes traveling equatorward with time.
- Discrepancies:
  - Operational underestimates and research overestimates it.
  - Depletion area travels faster for observations.
  - High latitude evening TEC enhancement.

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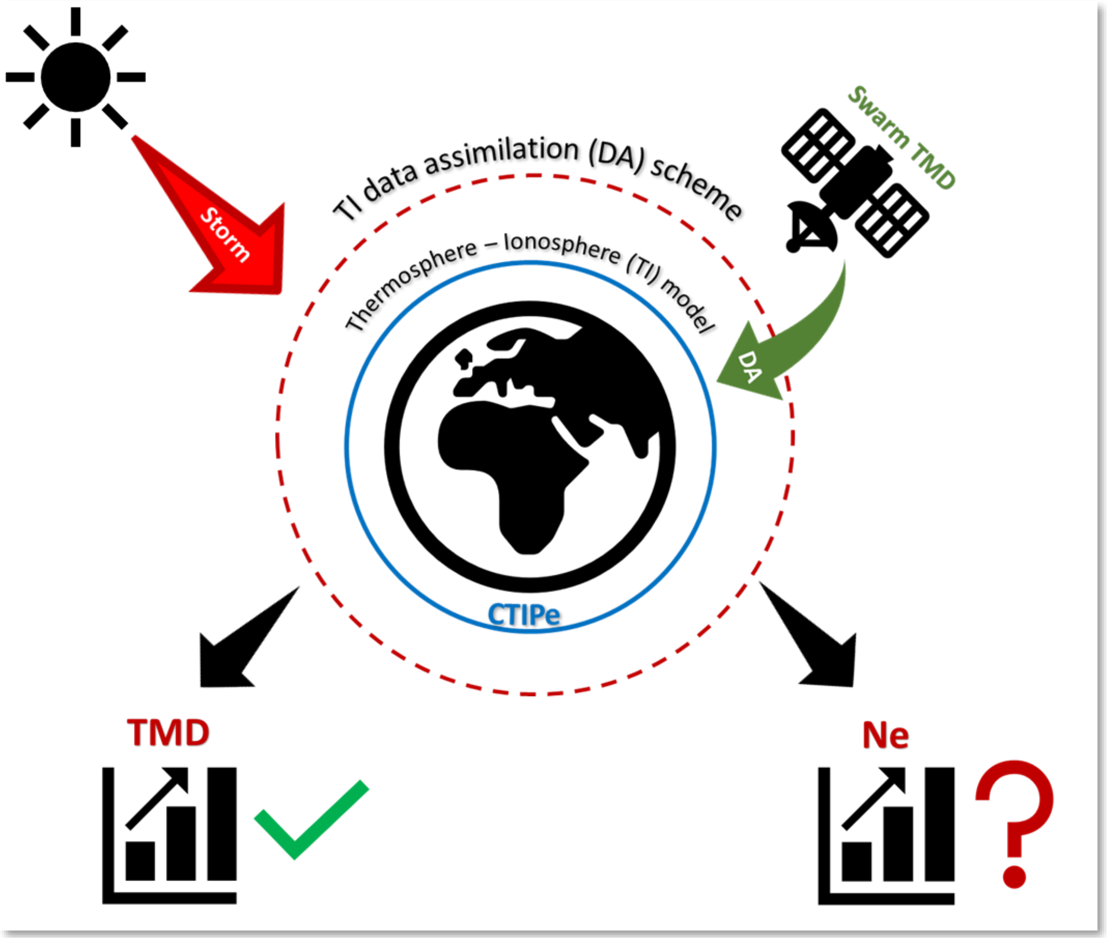
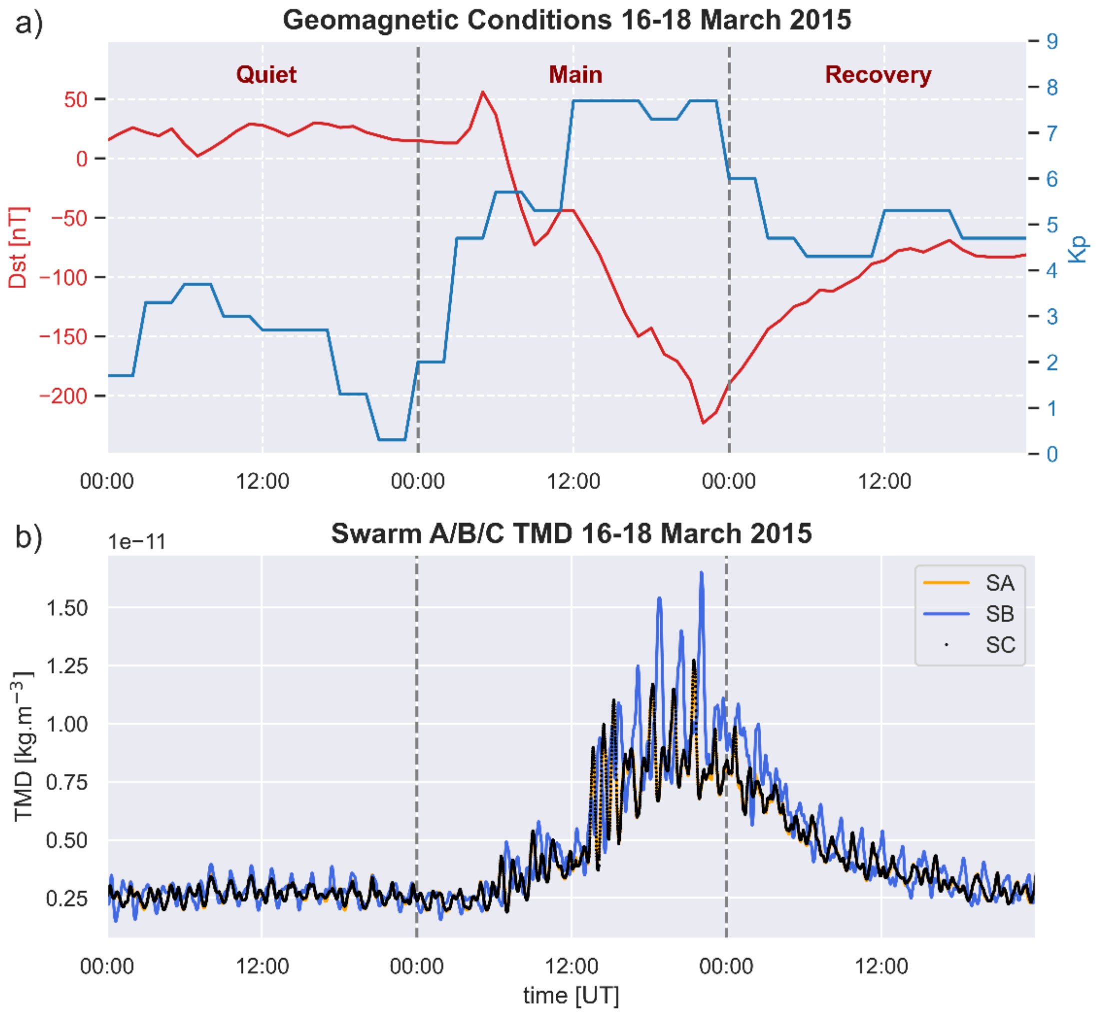
Correct the Thermosphere – Ionosphere (TI) System state with DA

Neutral density data assimilation effect on electron density

- Can we improve **ionosphere** by assimilating **thermospheric mass density** (TMD) during **geomagnetic storm conditions**?
  - St. Patrick's Day storm 2015
  - Assimilated Swarm TMD into CTIPe – TIDA
  - Evaluate the Thermosphere – Ionosphere effects



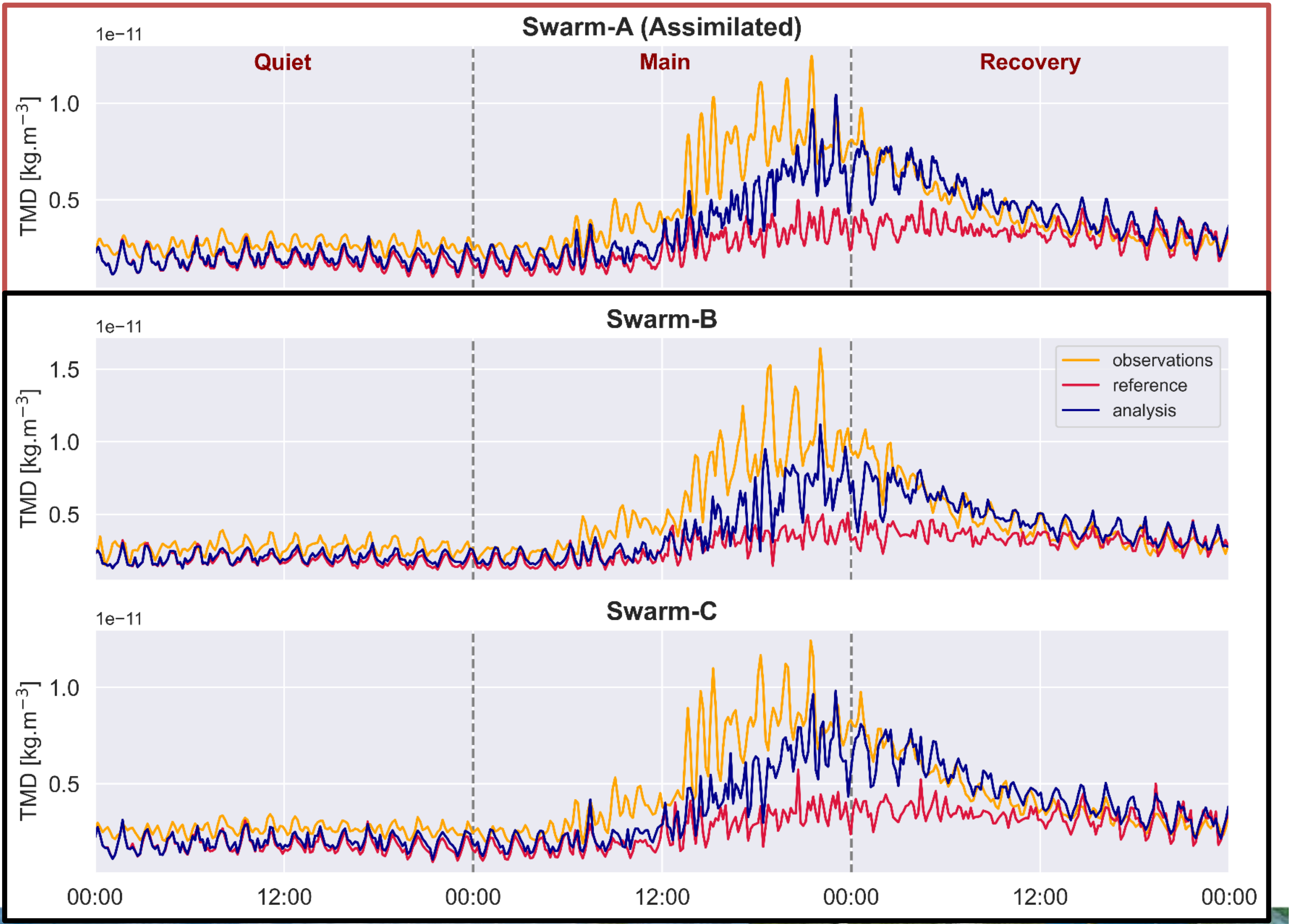
St. Patrick’s Day storm 2015 and DA conditions



- **Period:** 16-19 March 2015 containing St. Patrick’s Day storm
- Days are classified are quiet (16), main phase (17) and recovery (18)
- **TMD Data**: Swarm – A /B/C observations normalized to the common altitude of 400 km.
- **State vector**: Updates the forcing parameters and the necessary quantities to calculate neutral density.
- **Assimilation window**: 10 minutes
- TMD uncertainty is 10%

Swarm TMD assimilation into CTIPe – TIDA

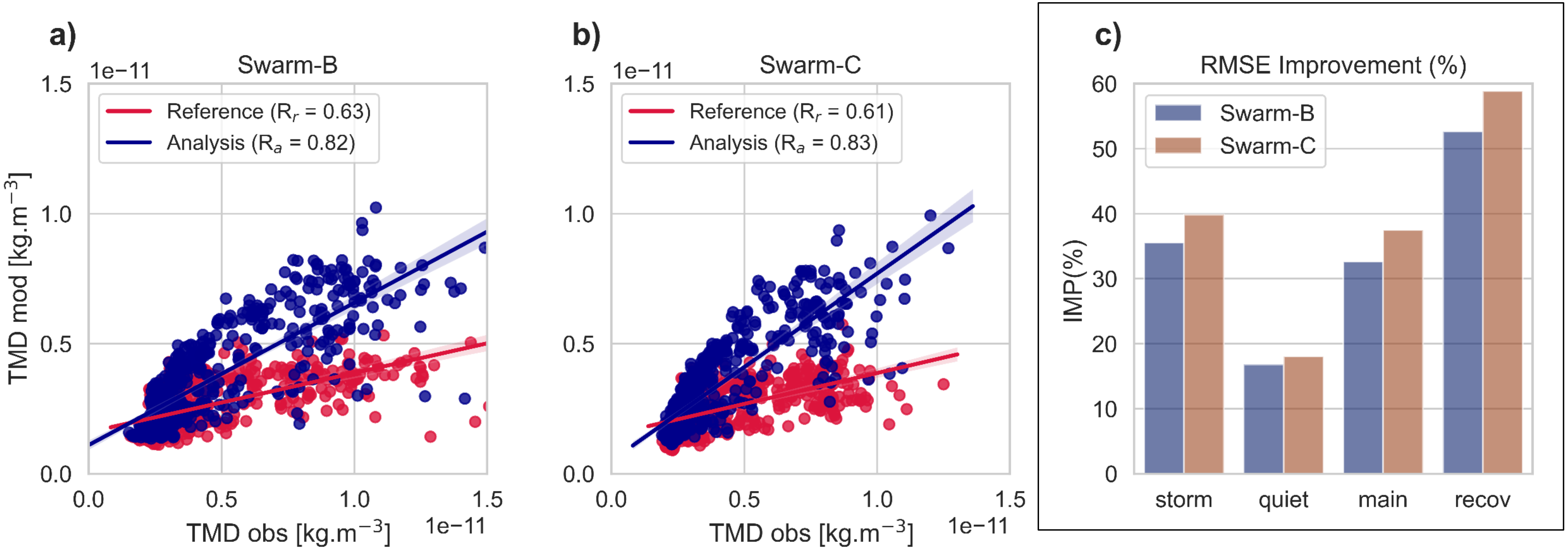
- **Assimilated data**: Swarm – A TMD observations normalized to the common altitude of 400 km.
- **Period:** 16-19 March 2015 containing St. Patrick's Day storm.
- Along the orbit neutral density
- **Observations**: Neutral density from Swarm A/B/C
- **Reference**: Background model results without assimilation
- **Analysis**: Assimilation estimate
- **Differences between Reference and Analysis** show the effect of data assimilation.



TMD DA impact on the Thermosphere

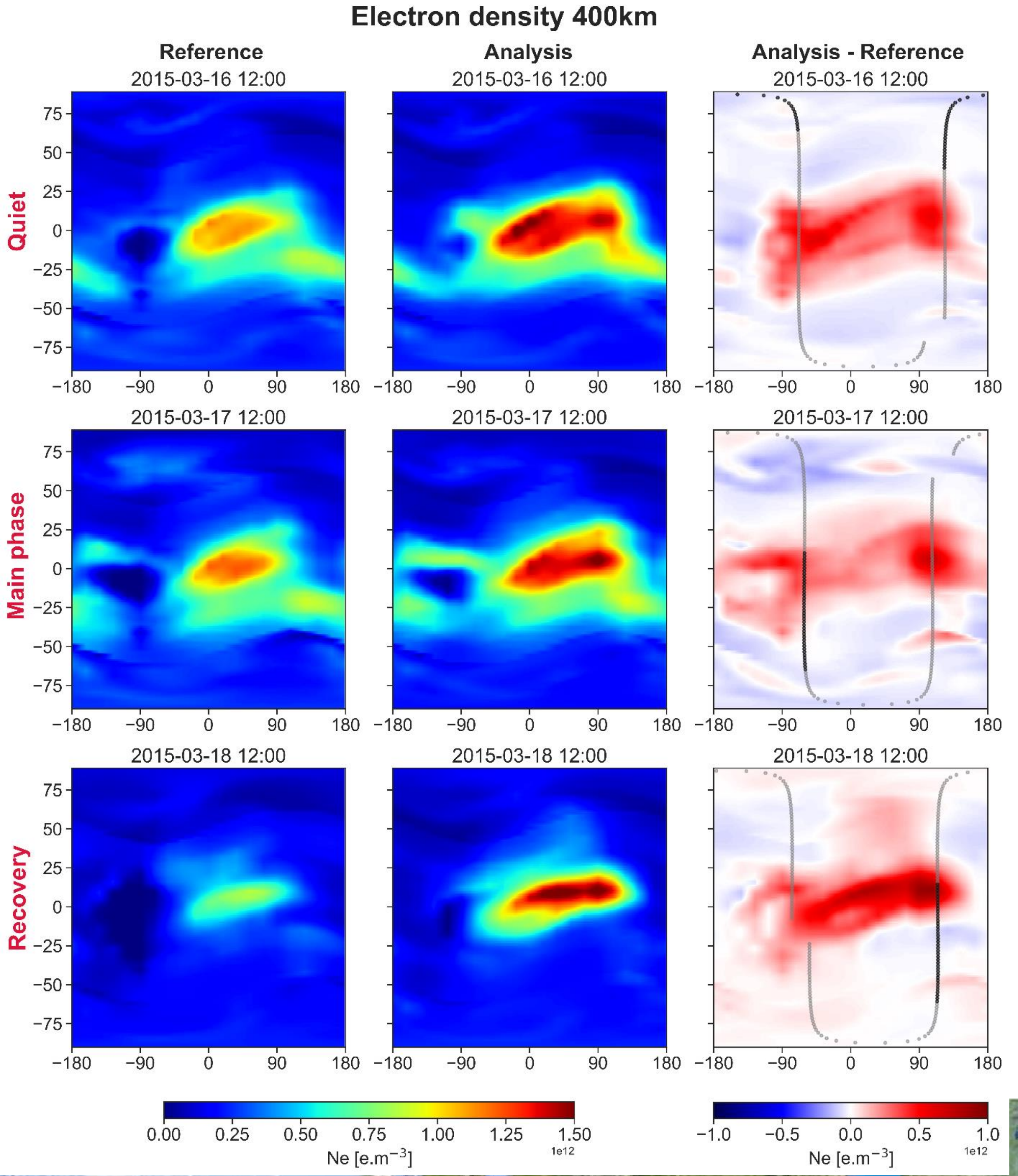
$$\mathrm{RMSE} = \sqrt{\frac{\sum(\mathrm{Obs} - \mathrm{Mod})^2}{\mathrm{N}}}$$

$$\mathrm{IMP}(\%) = \frac{(\mathrm{RMSE}_r - \mathrm{RMSE}_a)}{\mathrm{RMSE}_r} 100$$



TMD DA impact on the Ionosphere

- **Electron density** maps at 400 km altitude
- Reference, analysis and difference
- Quiet day, main and recovery phases at 12:00 UT
- Location of Swarm orbit is represented in the difference plot (grey line)
- Highlighted area of the last two assimilation intervals before 12:00 UT
- The **difference between analysis and reference** shows the **effect of TMD DA in electron density**
- The effect in altitude extends from 200 km to 800 km



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TMD DA impact on the Ionosphere: B-Spline Electron density model

$$\mathrm{RMSE} = \sqrt{\frac{\sum(\mathrm{Obs} - \mathrm{Mod})^2}{\mathrm{N}}}$$

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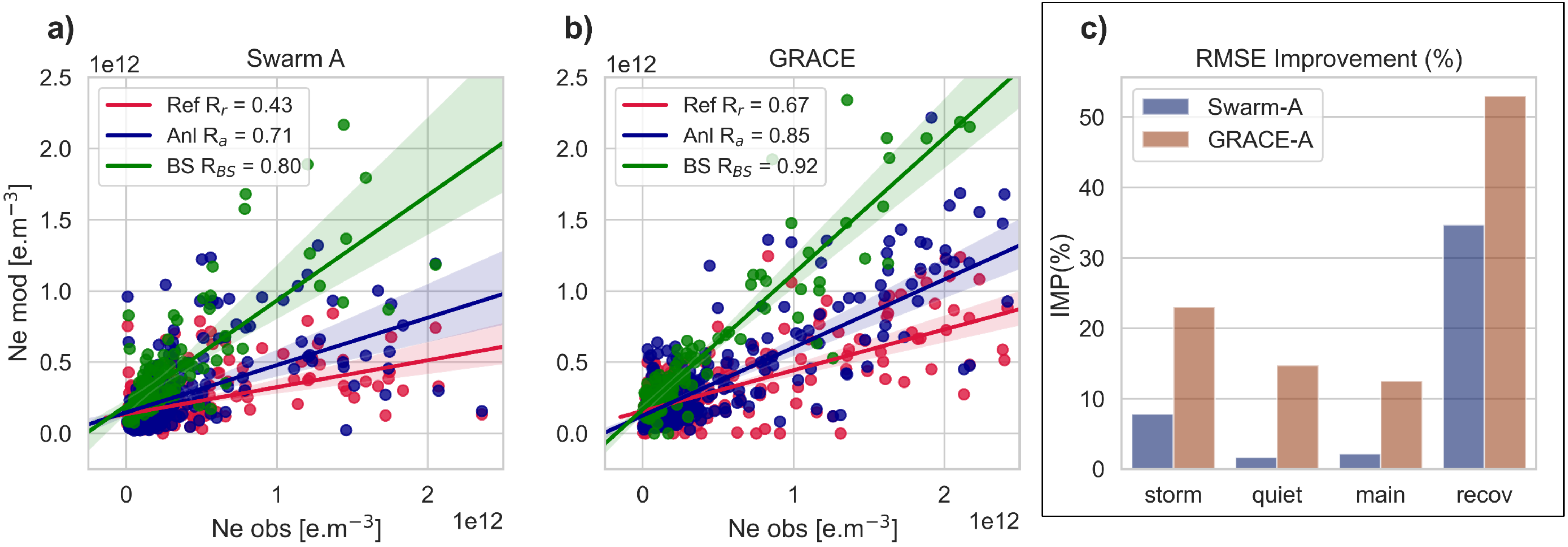
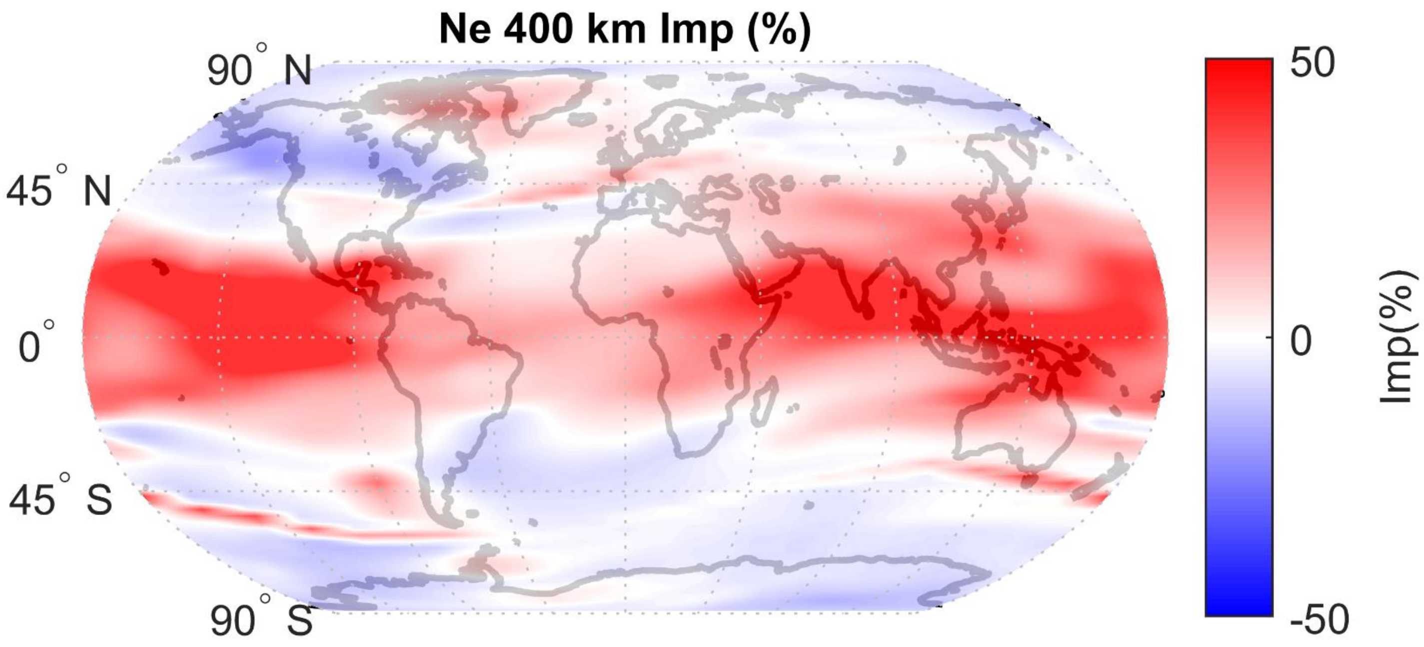


TMD DA effect on the Ionosphere: B-Spline Electron density model

- **Electron density global improvement at 400 km** between analysis and reference with respect to the B-Spline electron density model
- For the three days of the storm
- Lower RMSE → Better fit of the model to observations
- Improvement (%) of RMSE of the analysis and reference differences.
- **Positive values** are areas of improvement
- The **main area of improvement (red) is around the equatorial region** (-45, 45) deg latitude.
- In altitude the improvement extends from 200 km up to 600 km.

$$\text{IMP}(\%) = \frac{(\text{RMSE}_r - \text{RMSE}_a)}{\text{RMSE}_r}100$$



Summary

- Discrepancies between model and measurements increase with the increase in **uncertainties of the magnetospheric input data**.

"On the difference between real-time and research simulations with CTIPe"

I. Fernandez-Gomez, M. Fedrizzi, M. Codrescu, C. Borries, M. Fillion and T. J. Fuller-Rowell.
https://doi.org/10.1016/j.asr.2019.02.028

- **Assimilation of neutral density** measurements into a physics-based model **during storm conditions** in capable of **correcting the thermosphere and the ionosphere** (with limitations).

"Improving estimates of the ionosphere during geomagnetic storm conditions through assimilation of thermospheric mass density"

I. Fernandez-Gomez, T. Kodikara, C. Borries, E. Forootan, A. Goss, M. Schmidt and M. Codrescu
https://doi.org/10.21203/rs.3.rs-1342228/v1

Thanks for you attention!