Current effort for a better understanding of the ionosphere through modelling, observations and new magnetic indices development

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Outline

Scientific context: the M-I-T system

Tools used and developed

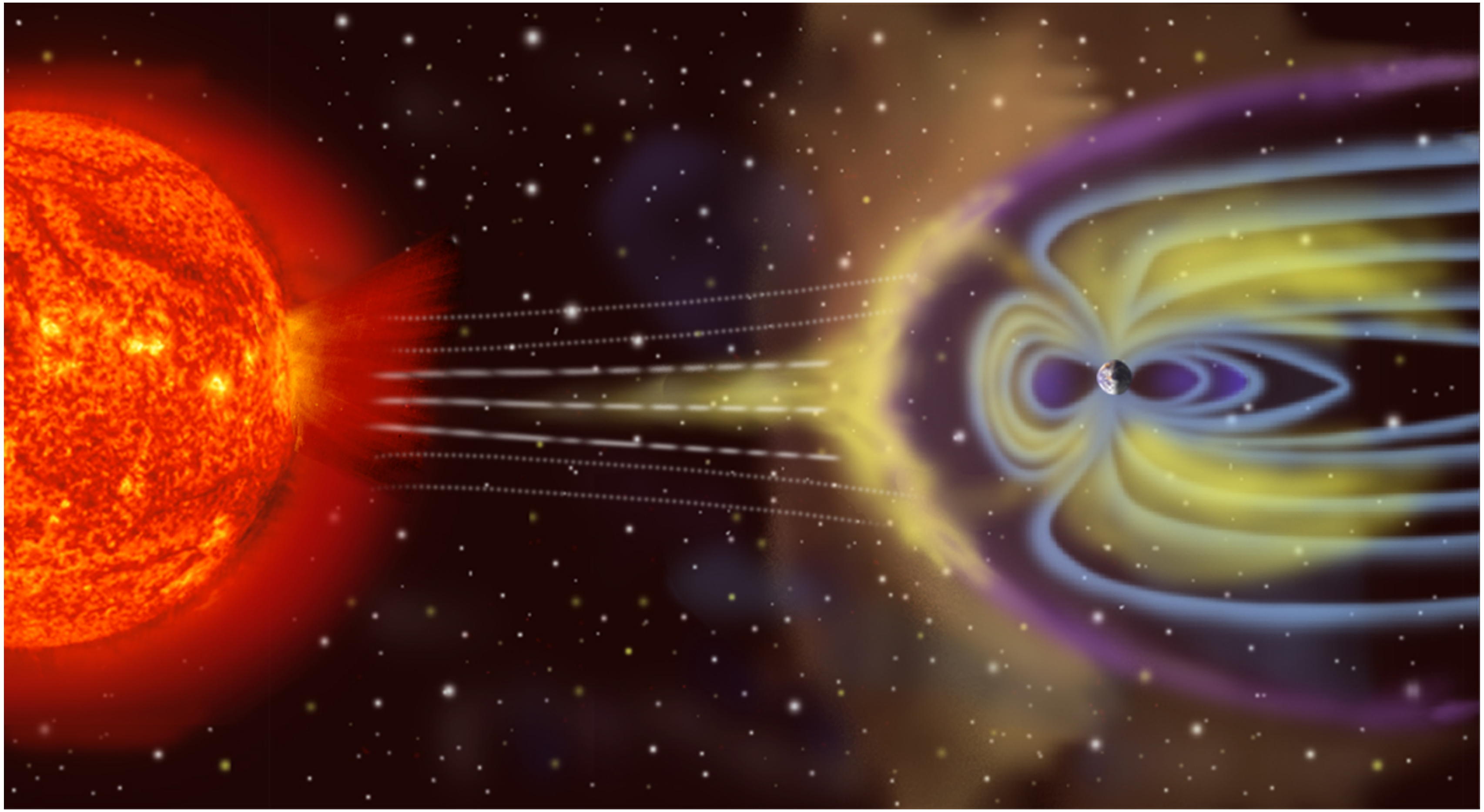
Major scientific questions about the M-I-T system

Example of results

Conclusions and perspectives

Indices development

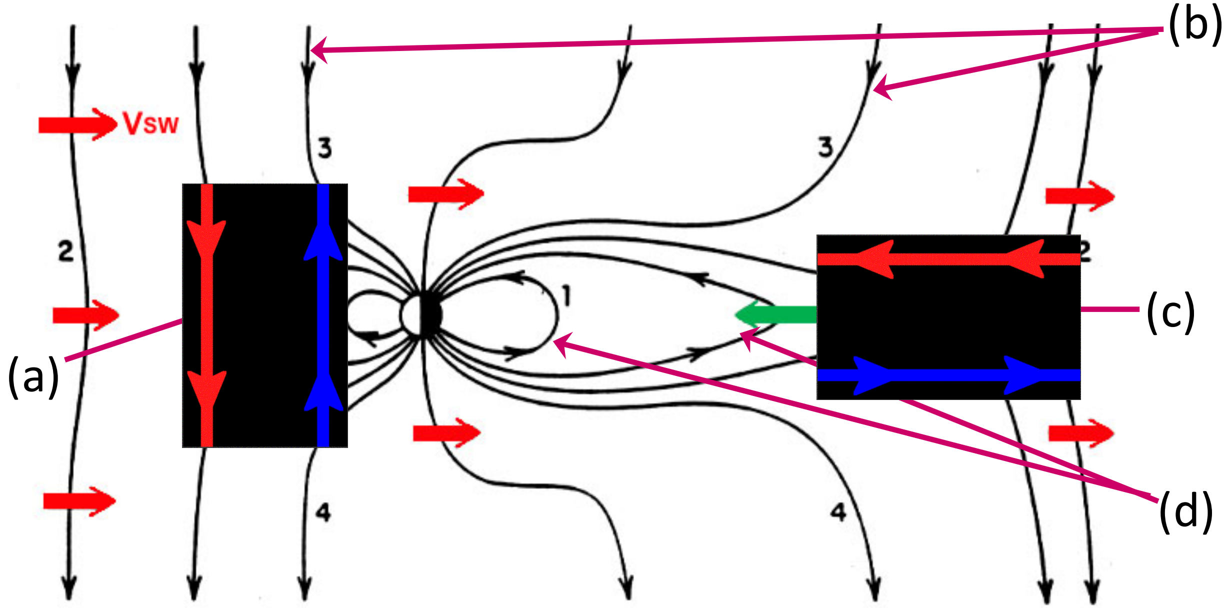
Sun-Earth Connection



- **Solar wind** flow: supersonic and superalfvénic (N_{SW} ~ 5 cm^{-3}, V_{SW} ~ 500 $km.s^{-1}$)
- Solar wind plasma and magnetic field move together → **"frozen-in"** conditions
- Shock must form upstream of the Earth's magnetic field → **Bow Shock**
- Solar wind plasma: heated and decelerated through bow shock and denser → **Magnetosheath**
- Magnetosheath plasma flows around the Earth's magnetic cavity → **Magnetosphere**

Dynamics of the outer magnetosphere

Magnetosphere in meridional plane



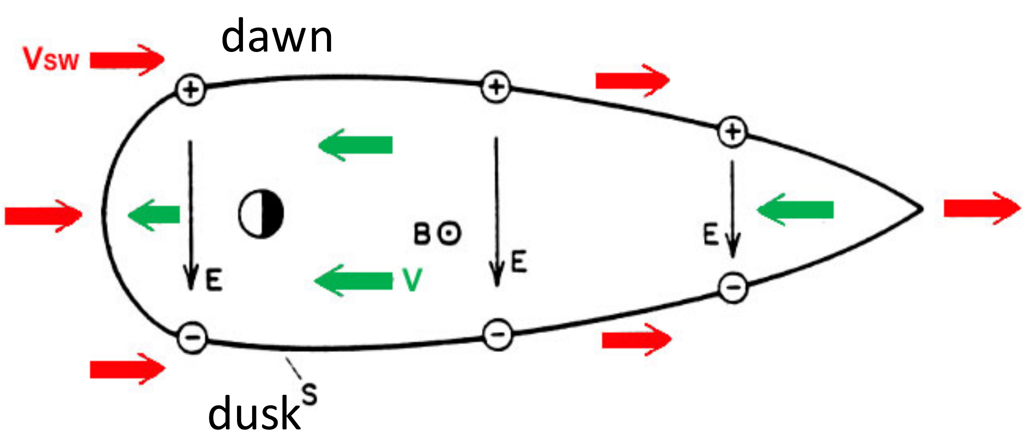
a) Reconnection between interplanetary FL (2) and closed Earth's FL

b) Reconnected opened FL (3 and 4) dragged antisunward (solar wind flow and magnetic tension)

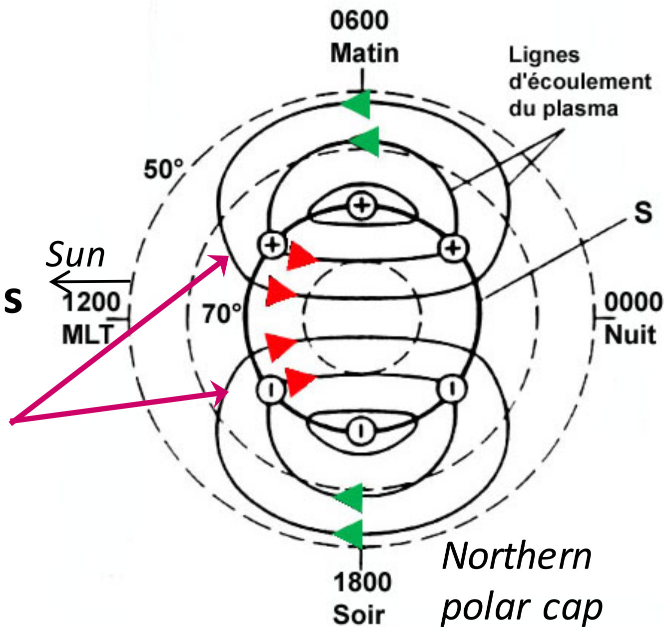
c) Inverse reconnection in the far tail

d) Solar flow of newly closed Earth's FL (1) (magnetic tension and **E x B** drift)

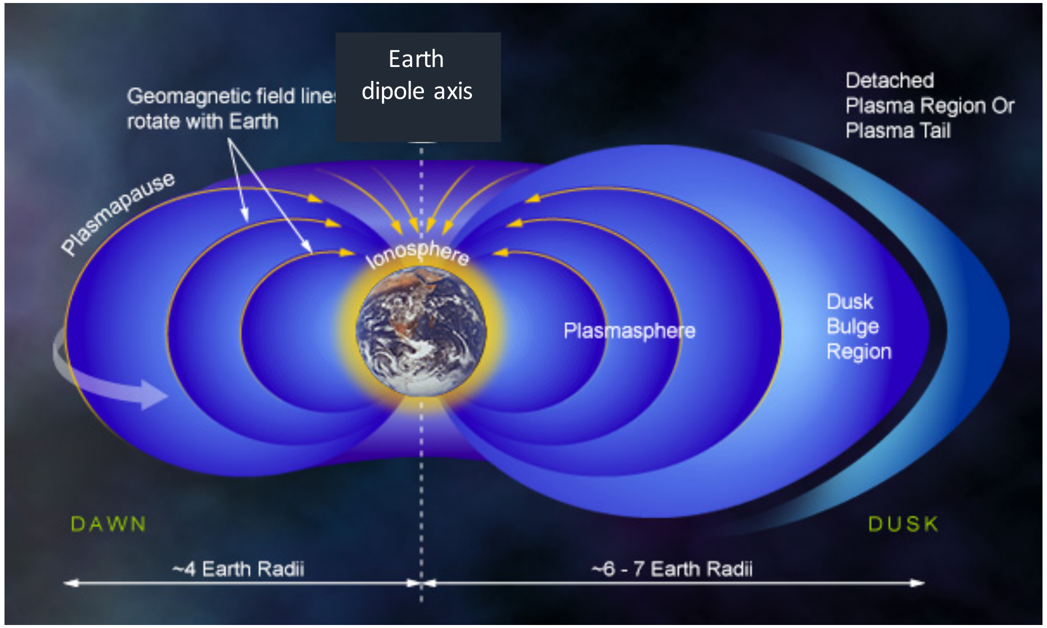
Magnetosphere in equatorial plane



2 ionospheric convection cells (intensity and orientation depending on IMF)



Dynamics of the inner magnetosphere



- **Plasmasphere** ($1 < R_{eq} < 6\ R_E$):

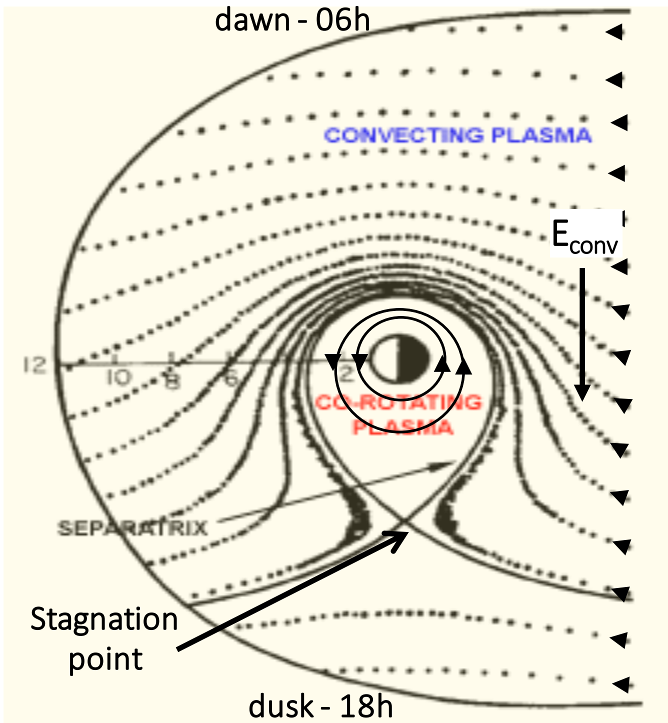
- Cold ($E \sim 1$ eV) and dense ($n \sim 10^3$ cm^{-3}) plasma

- Origin: ionized high atmosphere

- Corotating with Earth

- Asymmetric: extending further on the duskside

Magnetospheric equatorial plane



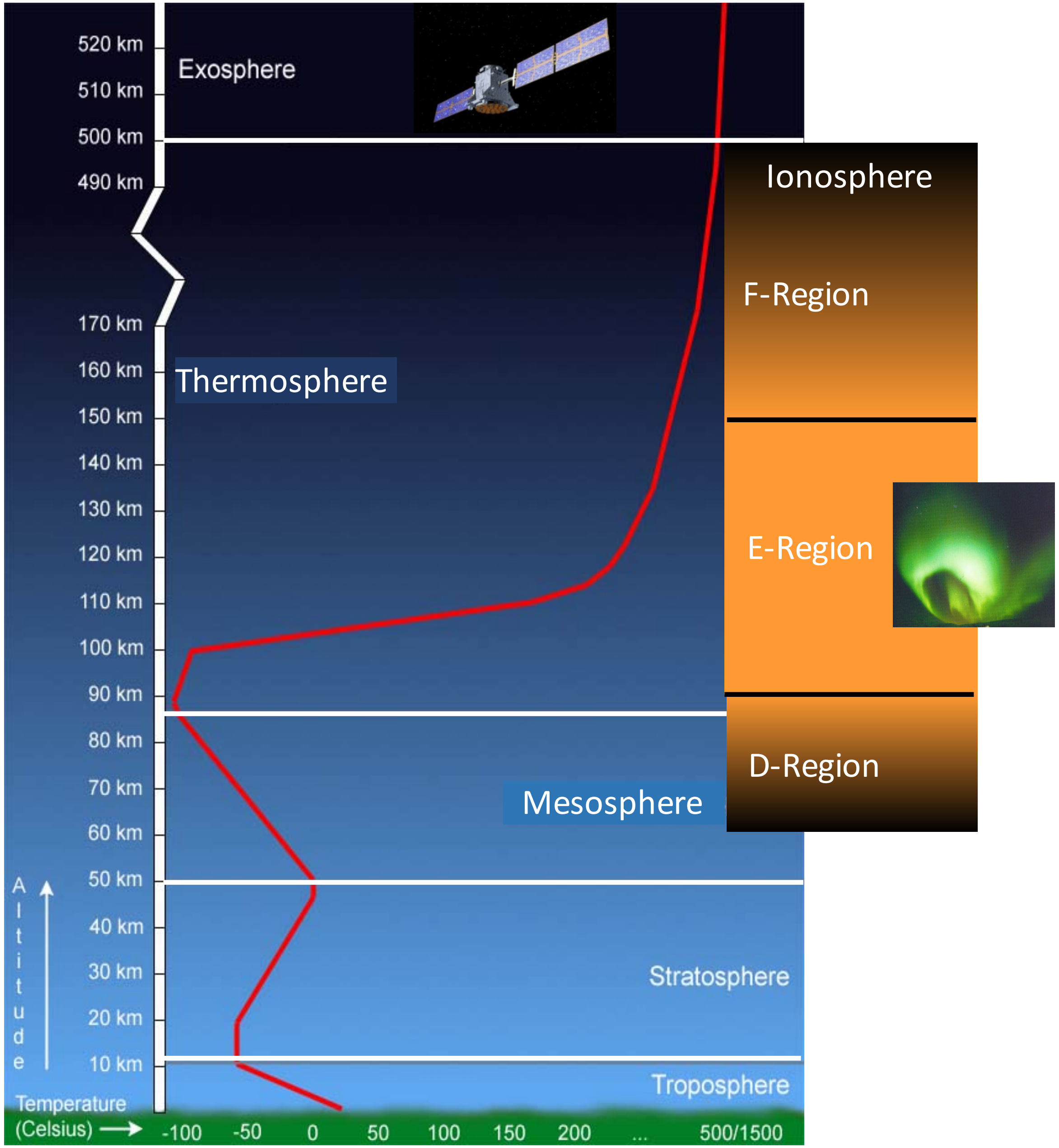
- Competition between **E x B drift** and **corotation** close to Earth

  - Separatrix between the two circulations → **plasmapause**

  - Opposite direction of circulation on duskside → **stagnation point**

  - Separatrix moves wrt to convection strength (closer to Earth in case of storm)

Ionosphere and thermosphere



- Upper atmosphere composed of two coexisting media:

Neutral atmosphere → **Thermosphere**

Ionized atmosphere → **Ionosphere**

→ **partially ionized plasma**

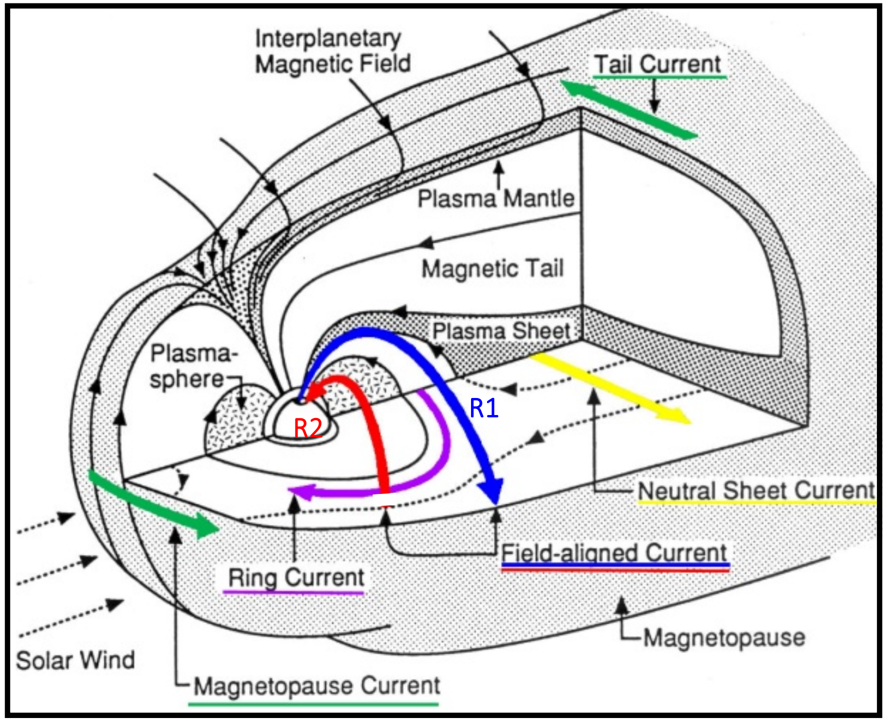
- Ionosphere at equilibrium (mostly) with balance between:
  - **Production** processes
  - **Loss** processes
  - **Transport** (horizontal and vertical)

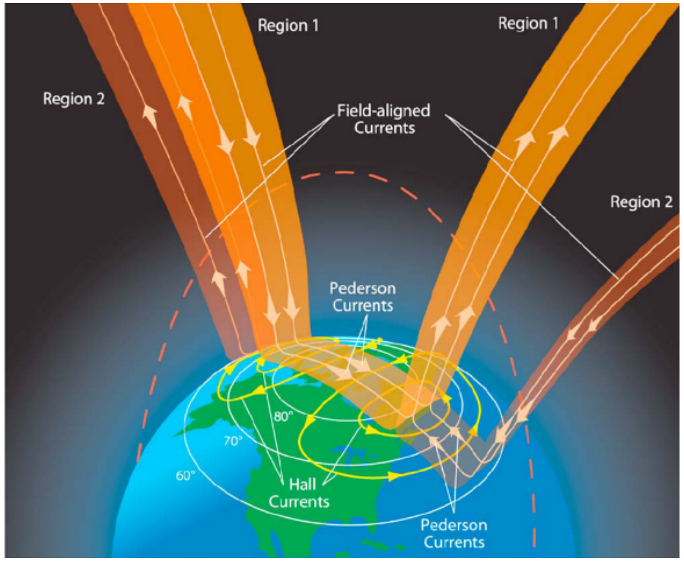
- Different processes:

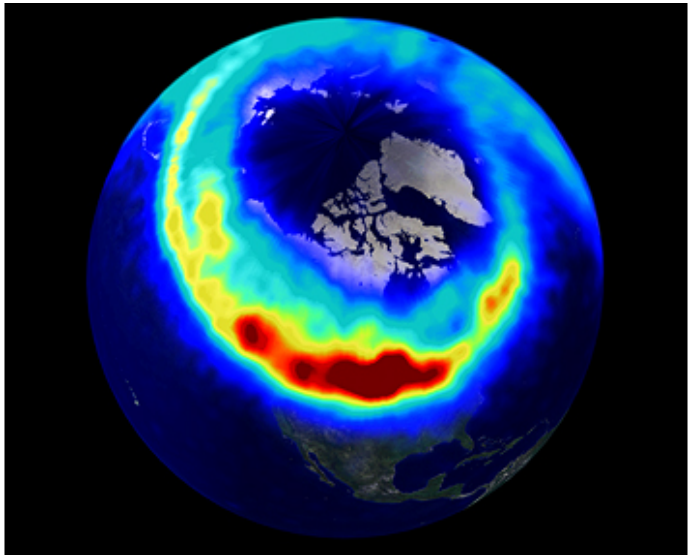
- dominant in different ionosphere regions (D-, E- and F-Region)

- **highly dependent on thermosphere** (composition, wind dynamics and thermodynamics)

Magnetospheric Electrodynamics and ionospheric closure







• 2 types of ionospheric horizontal currents due to anisotropic medium (magnetized):

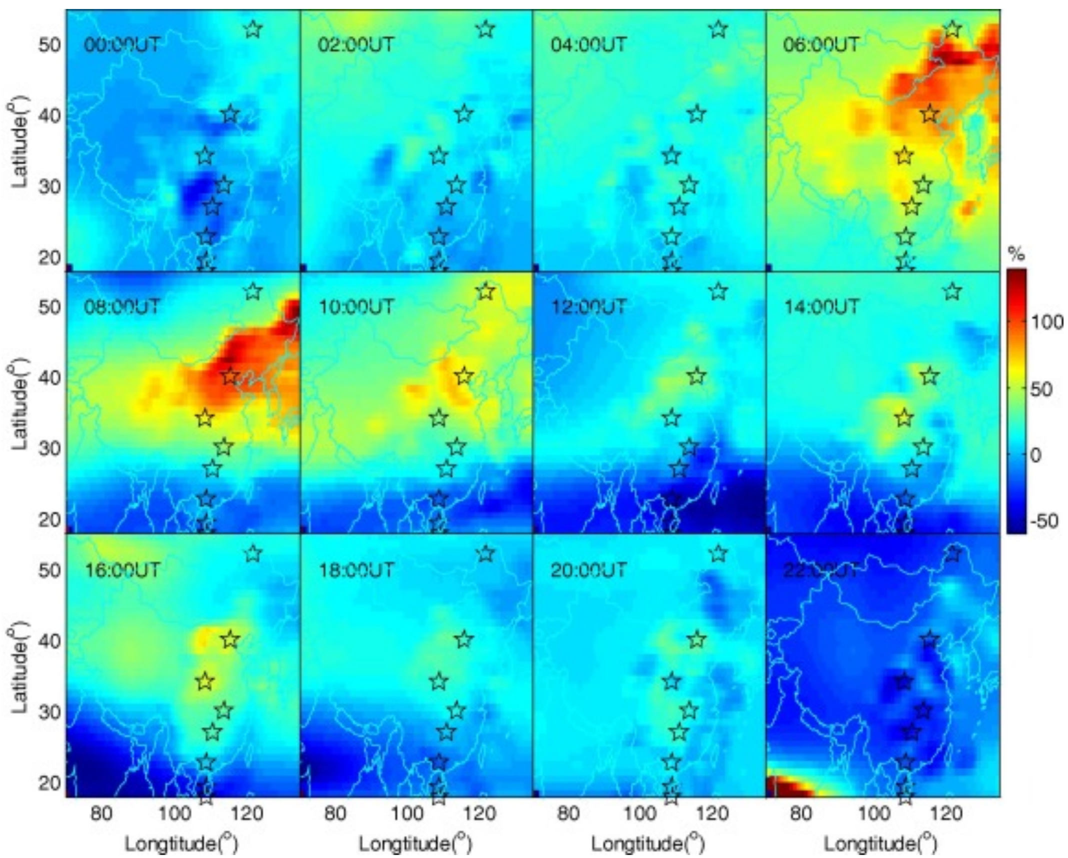
- **Pedersen currents** flow parallel to the convection electric field and close mainly the FACs in the low ionosphere

- **Hall currents** flow perpendicular to the convection electric field → **electrojets flowing antisunward on both auroral zones**

• Auroral precipitation are mainly localized at the FL footprint of dayside and nightside reconnection region → along the **auroral oval**

Impact of a strong perturbation on the ionosphere

After Mao et al. (2015)



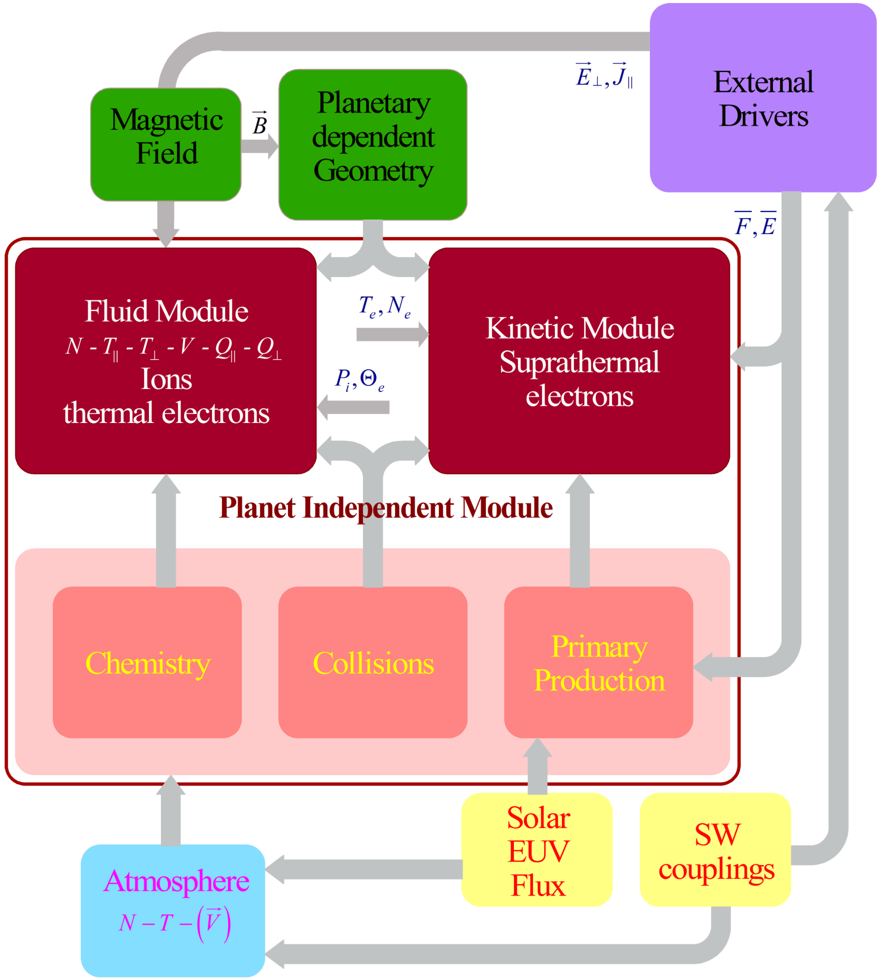
- **Change of atmospheric composition** → cause strong increase or strong decrease ionosphere density

- **Negative ionosphere storm**
→ decrease of the neutral density ratio O/N_2, leading to an ion loss rate enhancement

- **Positive ionosphere storm**
→ unpredictable feature especially at mid-latitudes
→ Cause(s) not fully elucidated

- Positive storm can occur before or after negative storm

TRANSCAR high-latitude ionosphere model
IPIM : *IRAP Plasmasphere Ionosphere Model*



New IPIM model for closed dipolar (excentric/tilted magnetic field lines)

→ based on the high-latitude TRANSCAR model

e.g. *Blelly et al.* (1996; 2005);

- **Motivation**

- to develop a new model to study the plasmasphere-ionosphere coupling

e.g. Marchaudon and Blelly (2015)

http://transplanet.irap.omp.eu/

- to uniformise the TRANSCAR and IPIM models

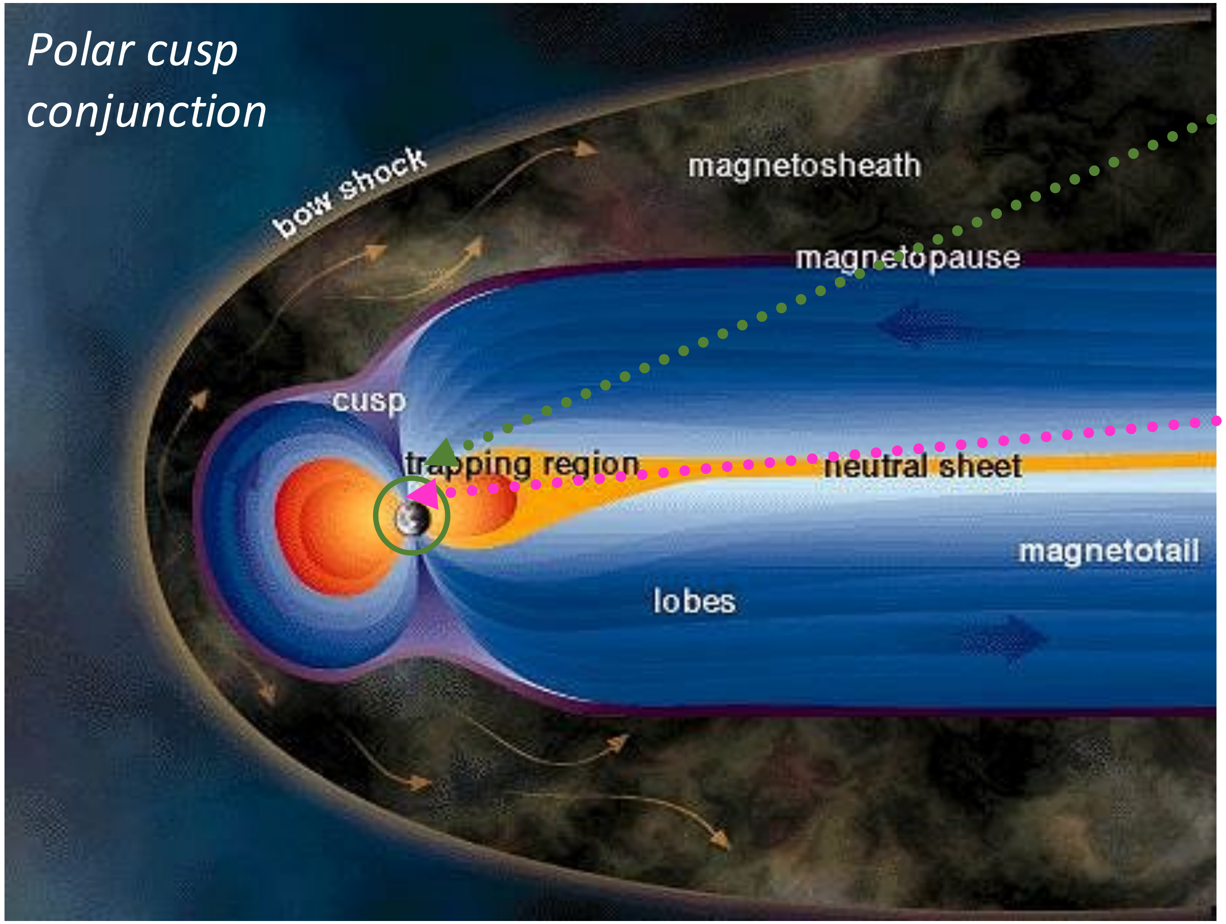
- to obtain a global ionosphere model

Conjugated ground-based and spacecraft measurement

- **Motivation**

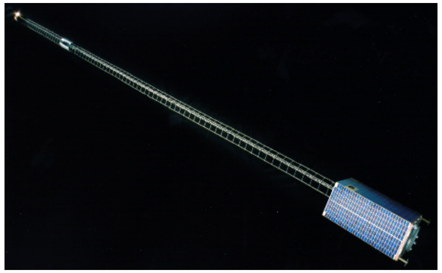
- Quantitative study of the M-I-T coupling

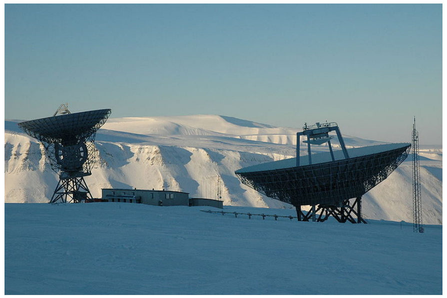
- Use as inputs for the IPIM model



Low-altitude satellites

CHAMP, Swarm, FAST, Ørsted…



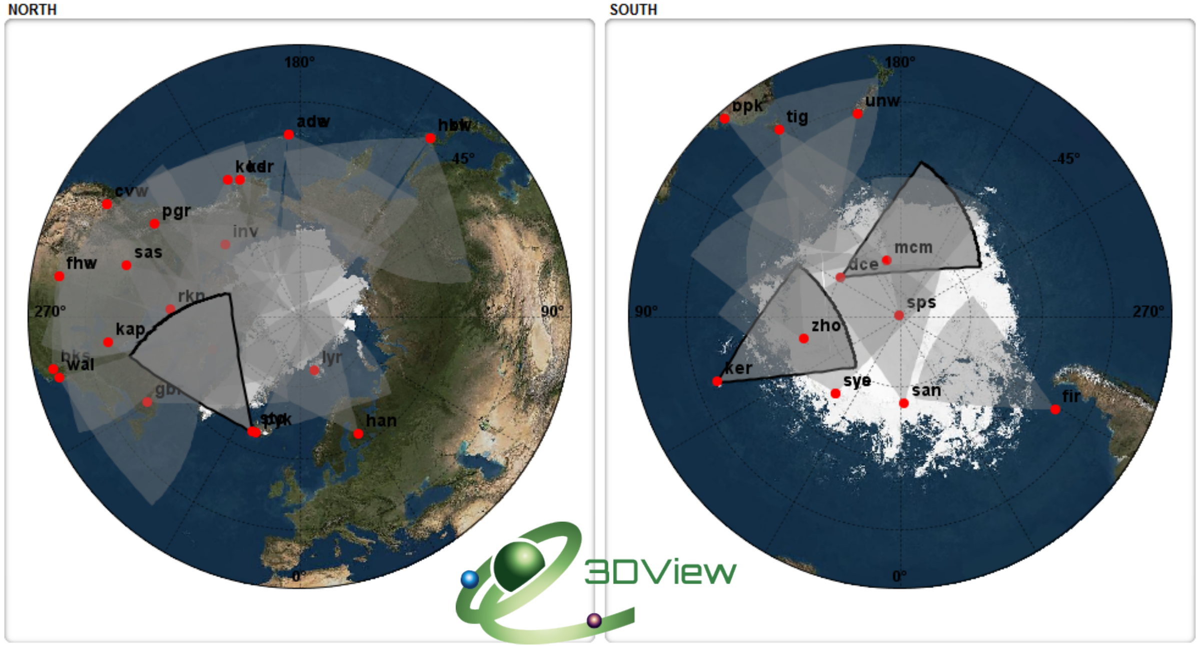


SuperDARN

Incoherent scatter radar ***(EISCAT)***

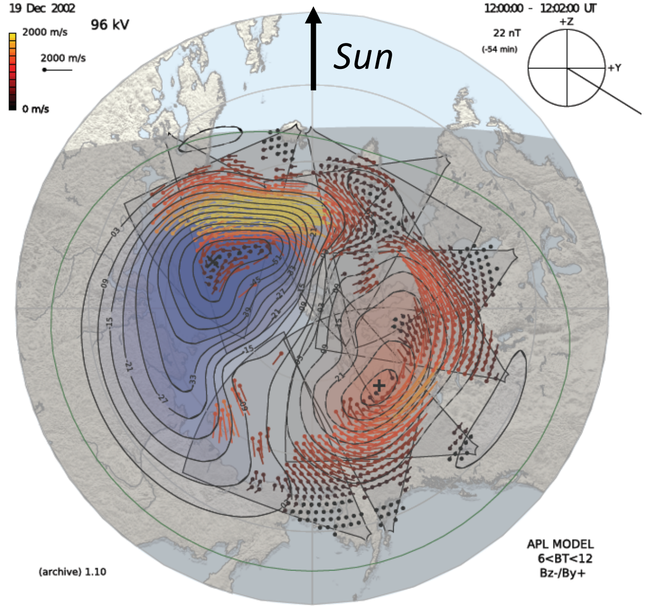
Ionosondes

SuperDARN : *Super Dual Auroral Radar Network*



International network of 35 over-the-horizon HF radars (1995)

Continuous monitoring of the ionosphere



Temporal tracking of ionospheric convection dynamics

Obtaining potential across the polar cap in each hemisphere

French PI of the Kerguelen radar since 2008

Major scientific questions: understand the global Magnetosphere-Ionosphere-Thermosphere (M-I-T) system

M-I-T system response to magnetic storms

Different types of disturbances: CME, CIR, flares

Different types of responses (even for the same type of disturbance!)

→ What is the history of the system?

→ What is the respective role of each region?

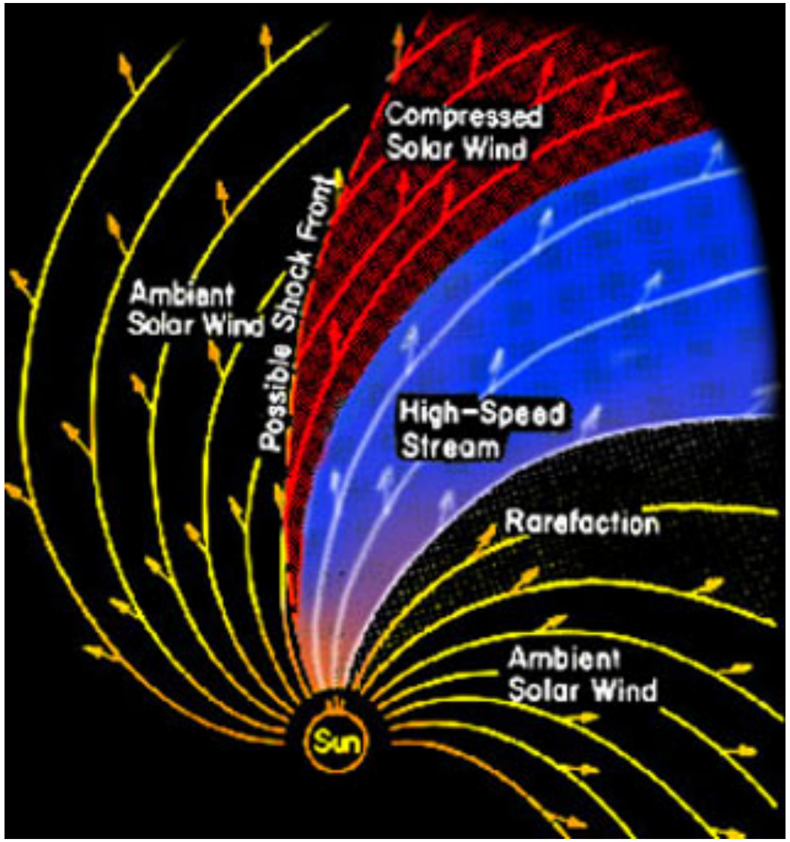
→ What are the response times of each region?

→ How is the perturbation propagating?

→ What external and / or internal parameters are involved?

→ What asymmetries of response between hemispheres to be expected?

Study of a magnetic storm caused by a Corotating Interaction Region (CIR)



- Fast solar wind overtaking ambient solar wind ambient → **Corotating Interaction Region**
- Compression zone: increase in IMF magnitude and solar wind speed
- Fast solar wind region located right after the Stream Interface (SI) → **High Speed Stream (HSS)**
- Capable of **generating a moderate magnetic storm** in the magnetosphere

→ Grandin et al. (2015) statistically studied the impact of High Speed Stream (HSS) on the high latitude ionosphere with ionosonde data

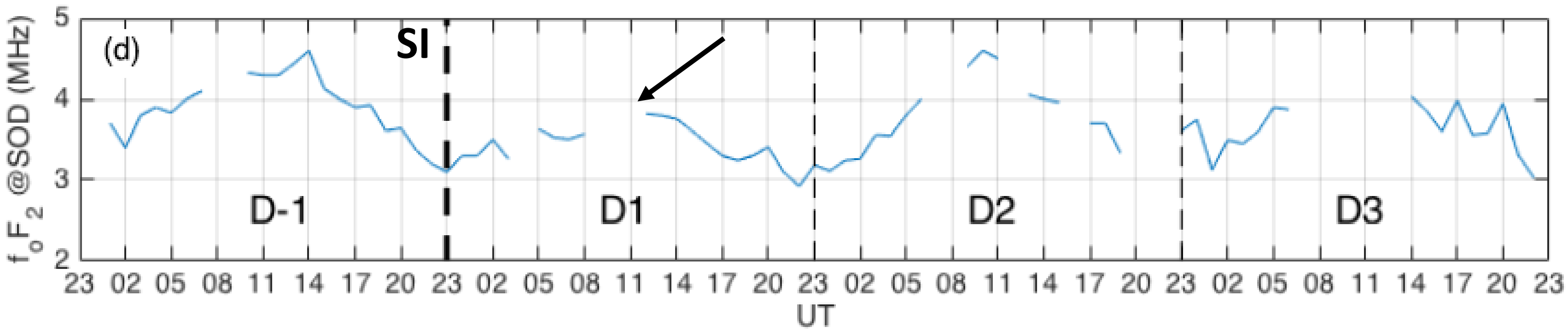
HSS effect on the ionosphere-thermosphere system

Ionospheric effect of a CIR / HSS on the ionosphere

Statistical study based on the Sodankylä ionosonde

→ decrease in the density of the F2 region at equinox and at Summer solstice between 12 and 23 MLT

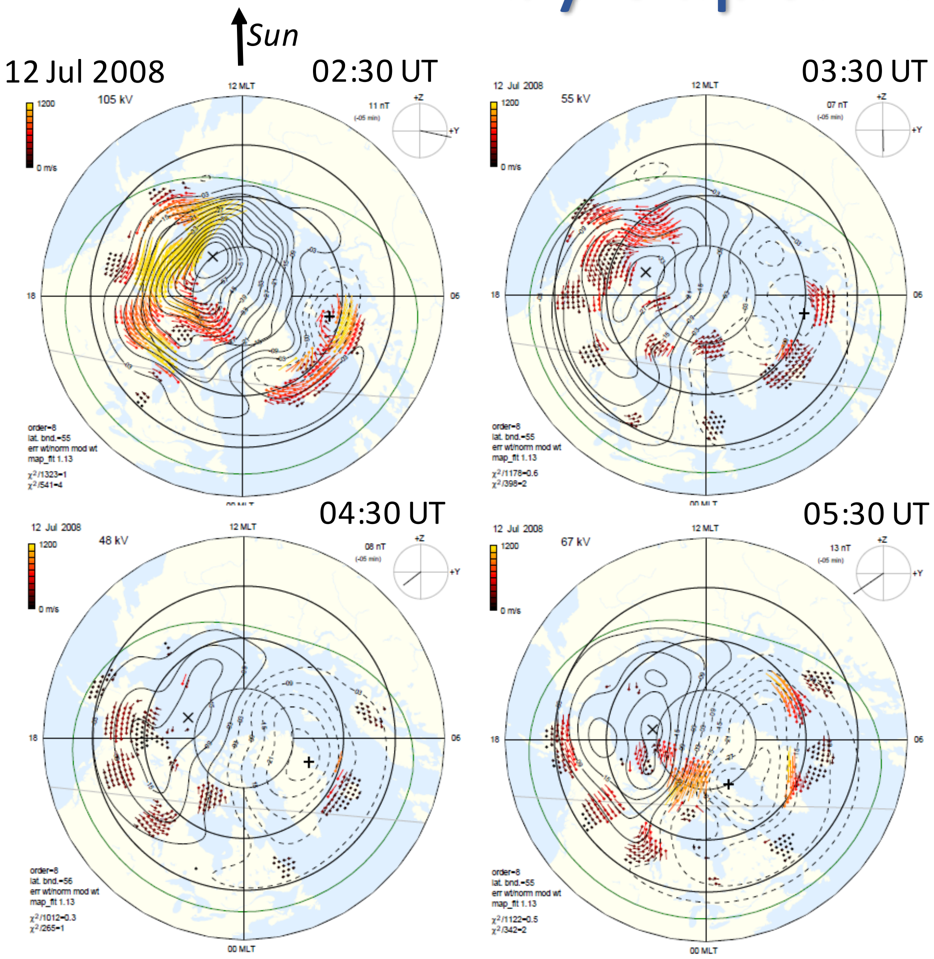
Region F2 peak as seen with Sodankylä ionosonde (Fi)



- **Motivation**

- to use the high latitude TRANSCAR model to understand the mechanism responsible for the decay of the F region in the high latitude ionosphere during an HSS event occurring in Summer solstice in NH (July 2008) → **Strong optimization of TRANSCAR inputs needed!**

TRANSCAR inputs optimization: convection as seen by SuperDARN and EISCAT

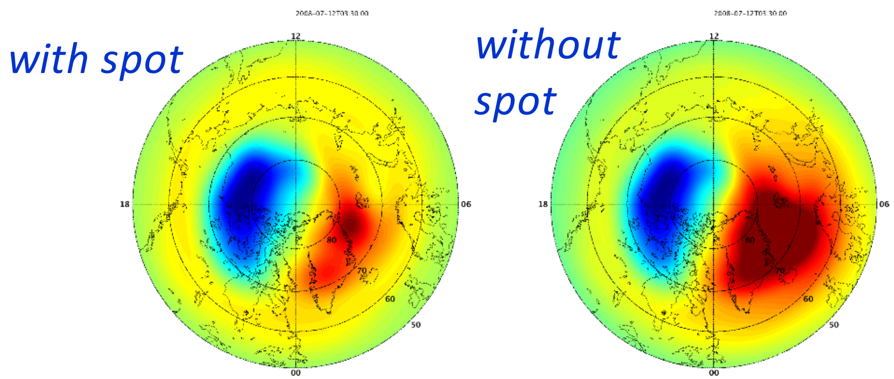


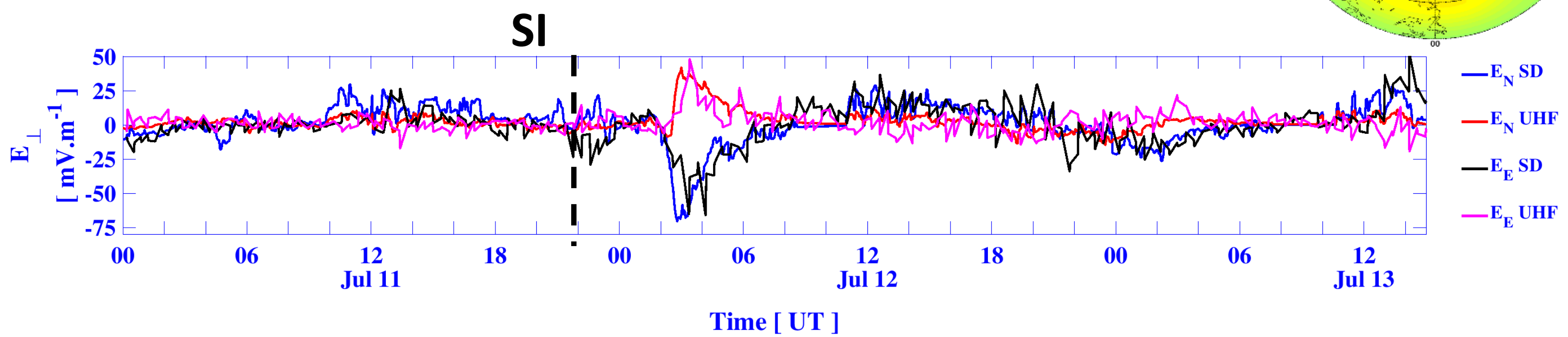
Use of SuperDARN convection maps as TRANSCAR input (Ruohoniemi and Baker, 1998)

Intensification of convection a few hours after SI

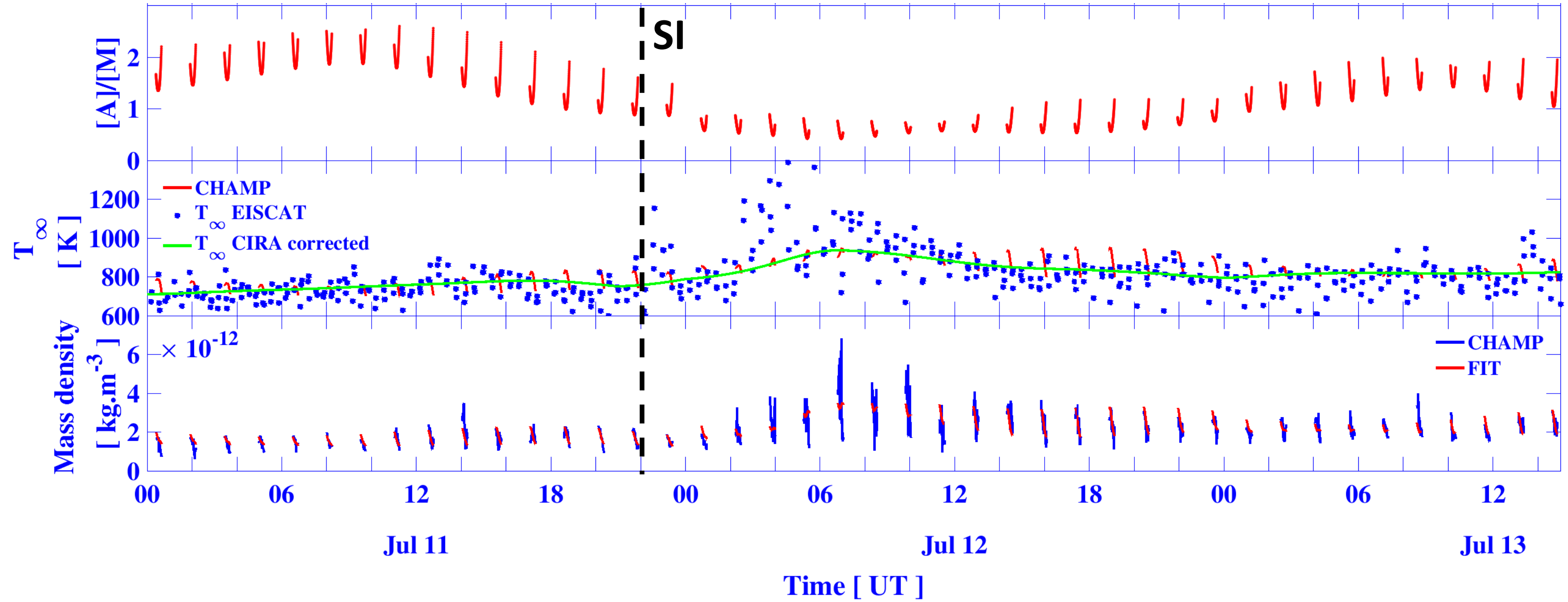
Good overall correspondence between SuperDARN and EISCAT measurements

→ necessity to add a supplementary convection spot around the maximum of the event (MLAT = 75 ° - MLT = 4)





TRANSCAR inputs optimization: thermospheric density as seen by CHAMP and EISCAT

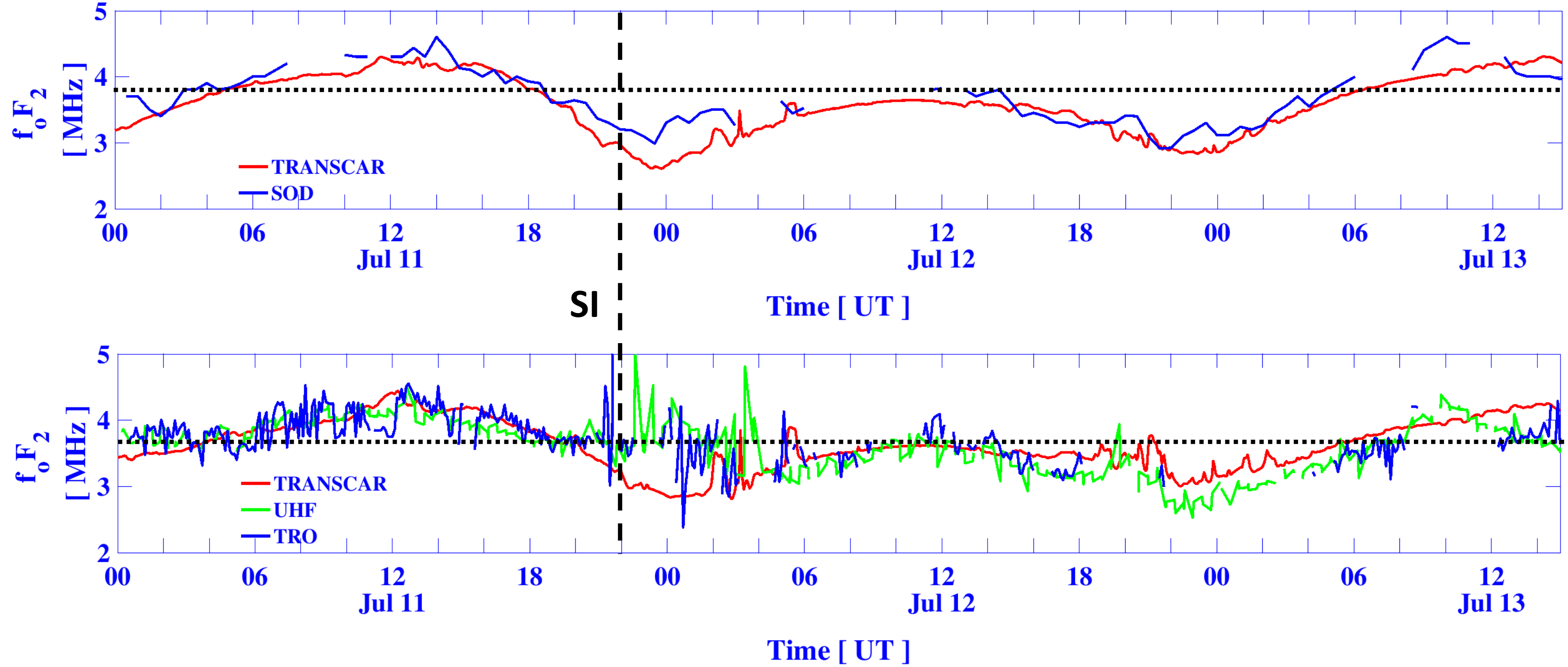


Use of the empirical thermosphere model NRLMSISE-00 (Picone et al., 2000)

Exospheric temperature deduced from EISCAT and thermospheric density deduced from CHAMP → large increases centered on maximum disturbance (a few hours after the SI)

Adjustment of the NRLMSISE-00 model to reproduce these observations
→ addition of an exospheric temperature perturbation of almost 200 K and a very important decay (factor 3) of the atomic oxygen density

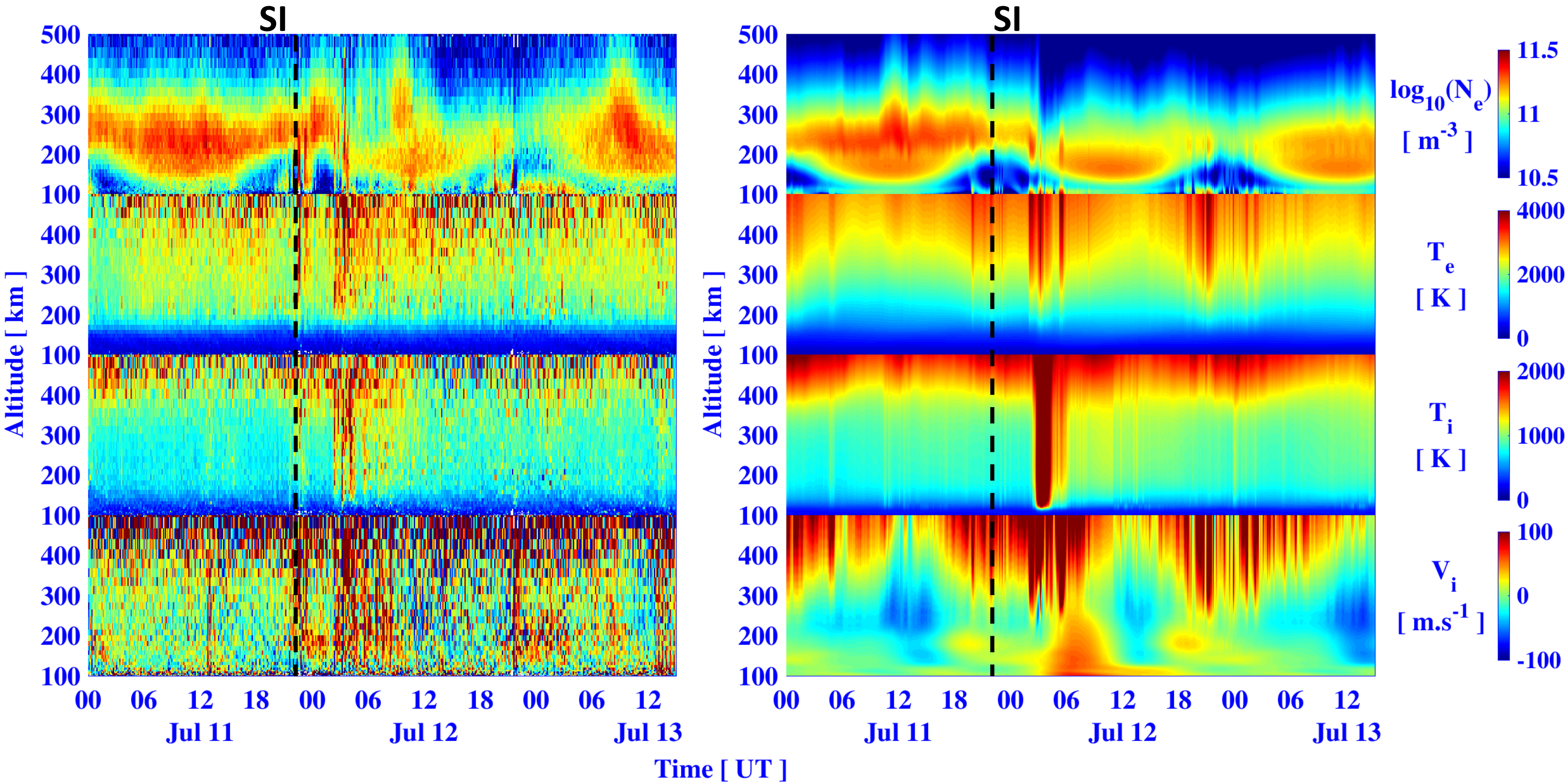
TRANSCAR Runs at Tromsø and Sodankylä during 3 days around the HSS



Excellent agreement between modeling and observations (ionosondes Sodankylä and Tromsø and EISCAT-Tromsø) for foF2 (electron density max in Region F) and foE (density max in Region E)

→ only made possible with convection and thermosphere optimization previously exposed

TRANSCAR Run at Tromsø : detailed comparison with EISCAT measurements



Again: excellent agreement between modeling and observation

Decrease of the ionospheric electron density due to the decay of the F2 region (dominated by O^+) in favor of a F1 region (dominated by NO^+) → **negative storm**

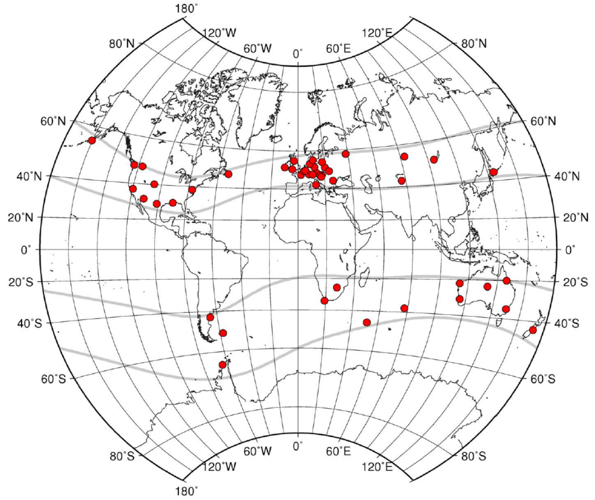
Conclusions

- TRANSCAR made it possible to understand the cause of the decay of F2 region after the HSS impact → **transition from F2 region to F1 region**
- **Change F2 → F1** due to a sharp and rapid decrease in the atomic oxygen density of the thermosphere related to the impact of HSS (E-field increase)
- Counter-intuitive: thermosphere essential and rapid cause of the ionosphere modification
- Statistical thermosphere model (NRLMSIS-00) not adapted to the simulation of a magnetic storm

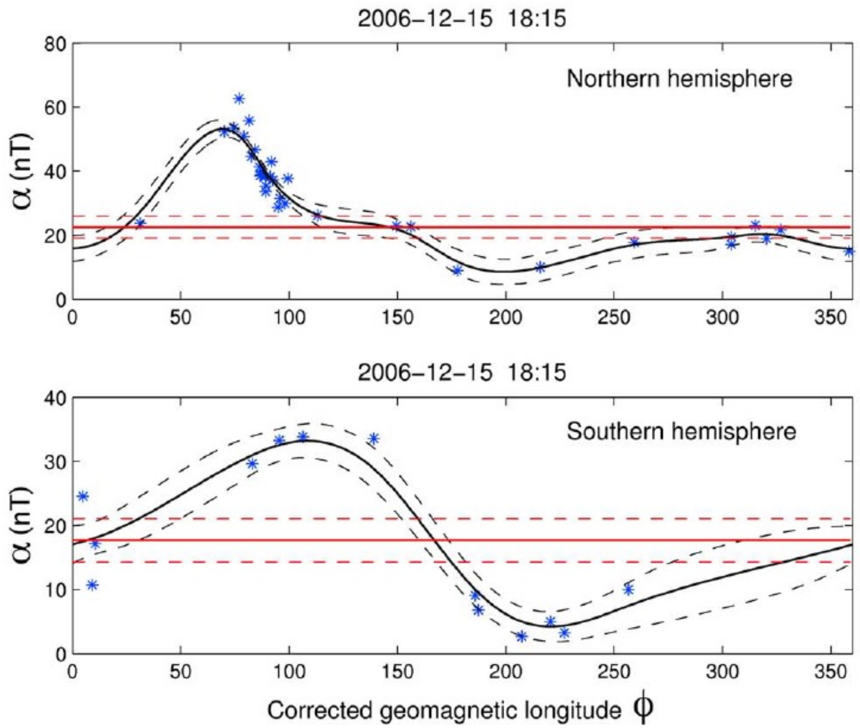
Perspectives

- Mid-latitude and southern hemisphere modeling of the same event
- Spatial propagation of this event remains unclear → use of indices α (see next slides)
- Development of a dynamical thermosphere model (internship started in January 2018)
- Systematize this type of study for different solar perturbations

Developments of new magnetic indices: α



Network of α stations in 2000



- **Motivation**

- to develop new indices with better spatio-temporal resolution

- Network as dense as possible (subauroral zones) and variable with time (Intermagnet)
→ follow activity wrt magnetic longitudes

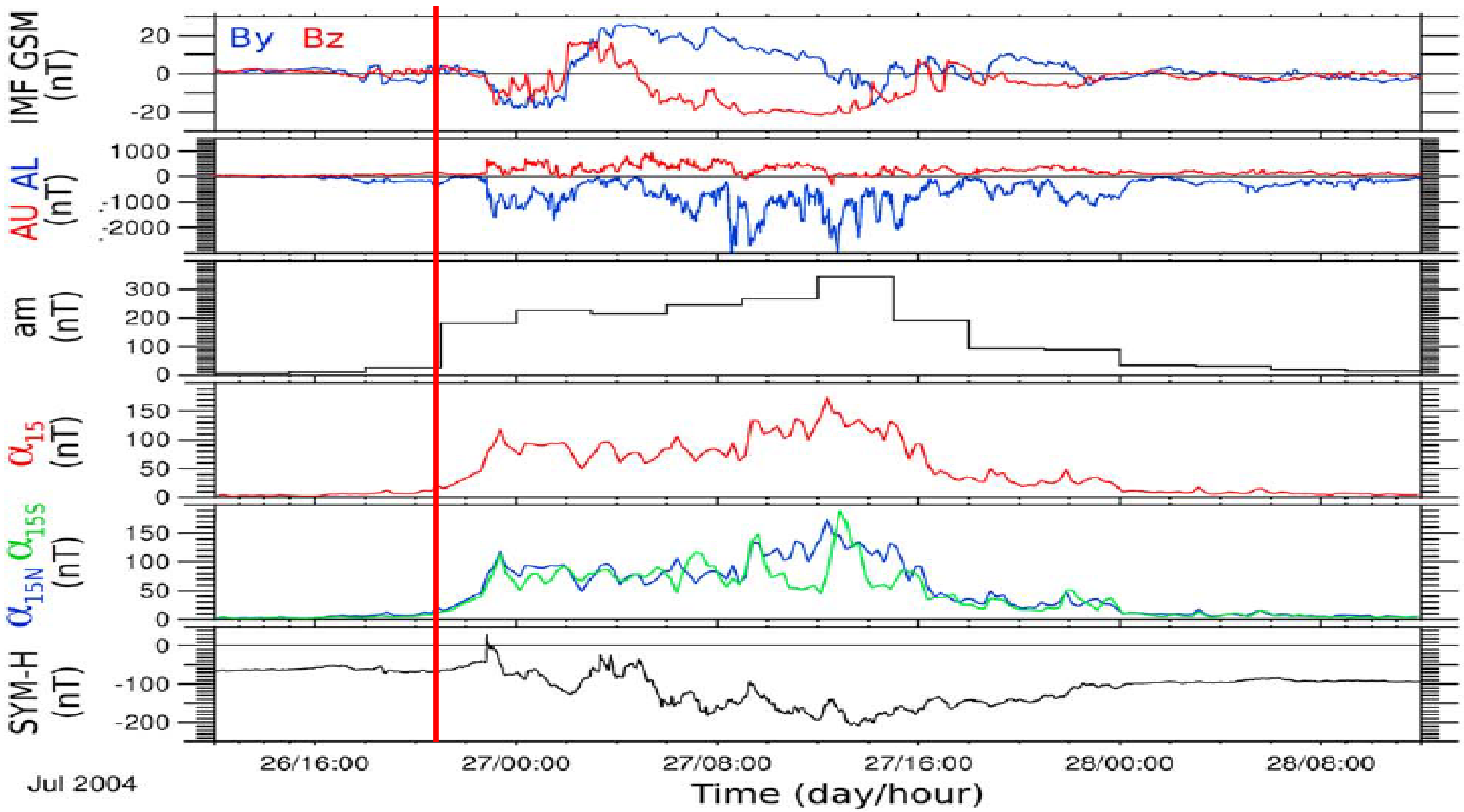
- time resolution: 15 min
→ but adaptable to user needs → 30, 60, 90 min ...

- simpler, more reliable algorithm and physical scale (in nT) → ideal for real-time and prediction

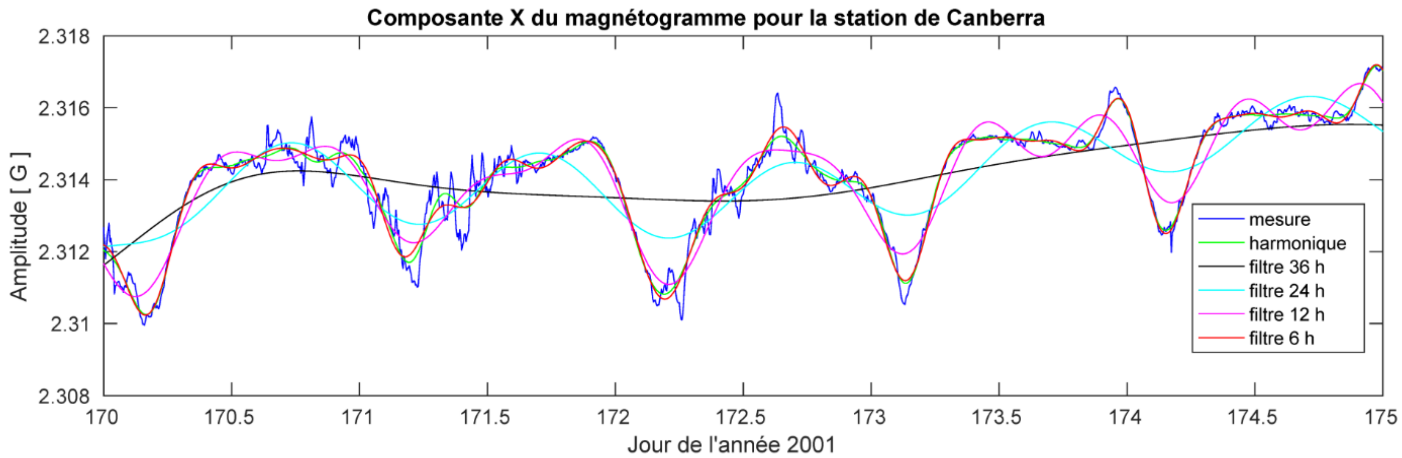
e.g. Chambodut et al. (2015)

Interests of α magnetic indices

- to follow rapid temporal variations of magnetic activity
- to detect the onset of a magnetic storm
- to compare the activity between hemispheres
- to discriminate activity in Magnetic Local Time (MLT)



Improvement and sectorization of α indices



New data temporal filtering at each station

→ new definition of the baseline

→ easily automatable method

Statistical studies of α magnetic indices for different types of events (quiet, CIR, CME), taking into account tilt of magnetic dipole, local time

→ variability according to MLT

→ deducing MLT sectorization of α magnetic indices