Munawar

IAG-FA-GSWR-JSG1: Coupling processes between Magnetosphere, Thermosphere, and Ionosphere

Mid-Term Report 2019-2020

Chair: Andres Calabia (China, andres@calabia.com)
Vice-Chair: Munawar Shah (Pakistan, shahmunawar1@gmail.com)
Research Coordinator: Binod Adhikari (Nepal, binod.adhi@gmail.com)
Members: 16

IAG-FA-GSWR-JSG1

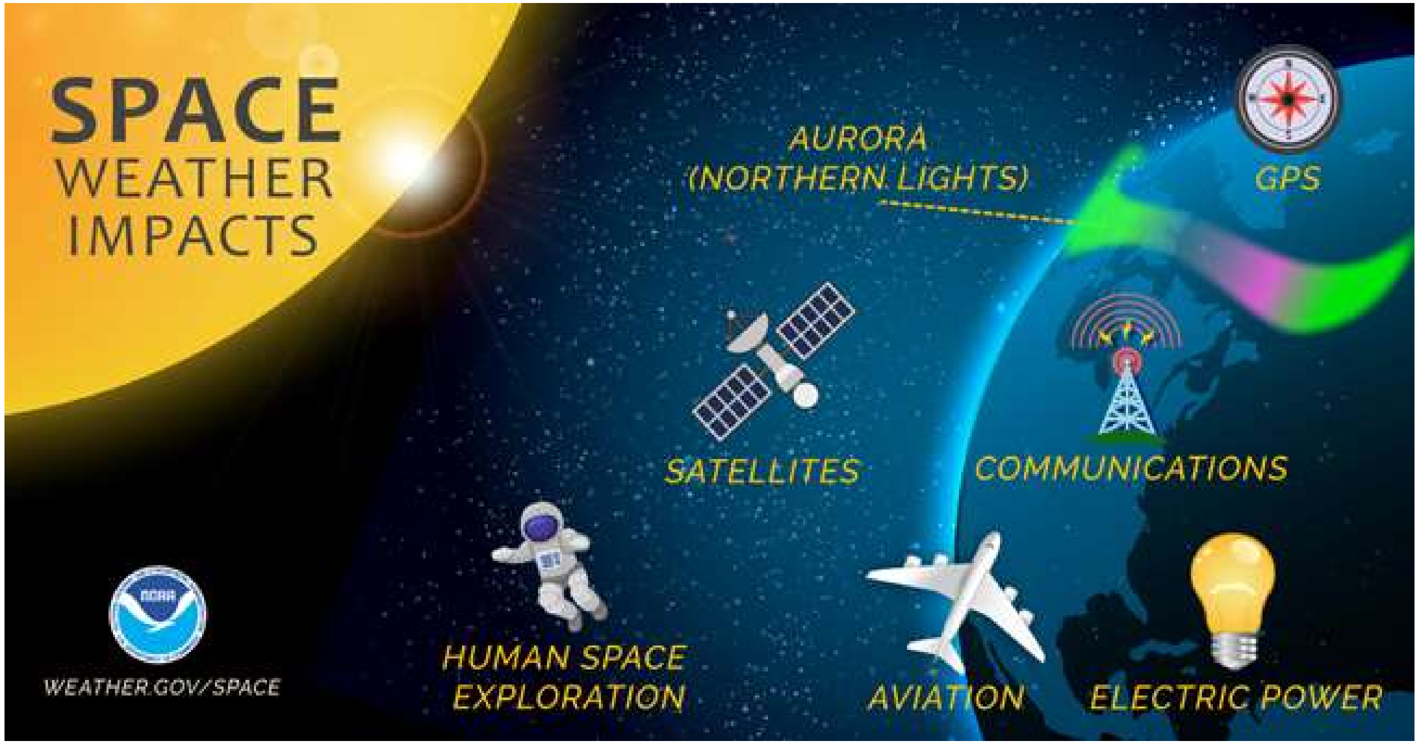
Implemented at International association of Geodesy (**IAG**) Inter-Commission Committee on Theory (**ICCT**); joint with IAG Global Geodetic Observing System (**GGOS**), Focus Area on Geodetic Space Weather Research (**FA-GSWR**); **IAG Commission 4 Positioning & Applications**; and **IAG Sub-Commission 4.3 Atmosphere Remote Sensing**.

Members:

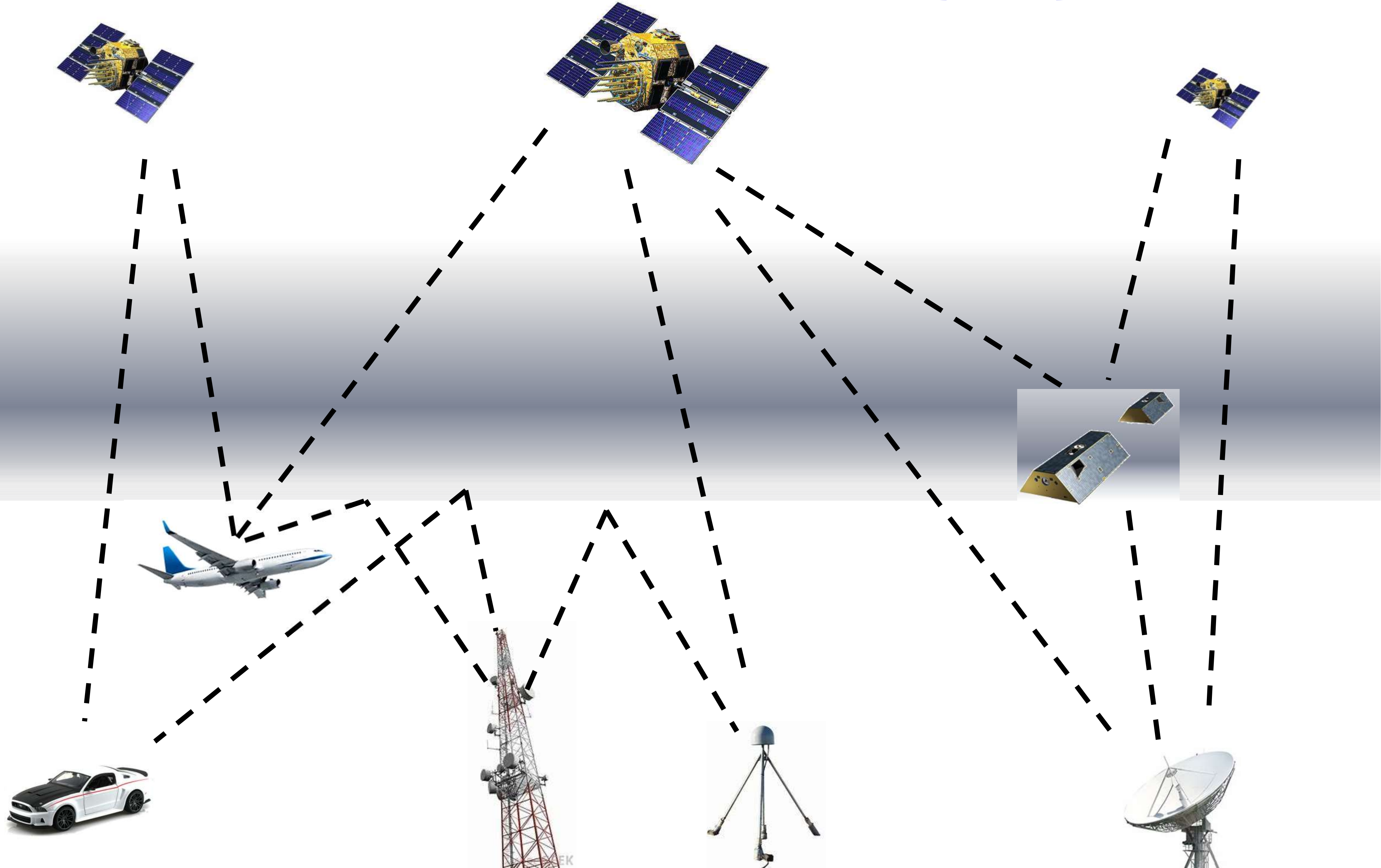
1. **Christine Amory-Mazaudier** (LPP, Observatoire de Paris, France; The Abdus Salam International Centre for Theoretical Physics (ICTP), Italy, christine.amory@lpp.polytechnique.fr).
2. **Astrid Maute** (High Altitude Observatory, USA, maute@ucar.edu).
3. **Yury Yasyukevich** (Russian Academy of Sciences, Russia, yu.yasyukevich@gnss-lab.org).
4. **Gang Lu** (High Altitude Observatory, USA, ganglu@ucar.edu)
5. **Olawale S. Bolaji** (University of Lagos, Nigeria, University of Tasmania, Australia, oloriebimpjch2002@yahoo.co.uk).
6. **Anoruo Chukwuma** (University of Nigeria, Nigeria, anoruochukwuma@gmail.com).
7. **Oluwaseyi Emmanuel Jimoh** (Adeleke University, Nigeria, oluwaseyi.jimoh@gmail.com).
8. **Munawar Shah** (Institute of Space Technology, Pakistan, shahmunawar1@gmail.com).
9. **Binod Adhikari** (St. Xavier's College, Nepal, binod.adhi@gmail.com).
10. **Andres Calabia** (Nanjing University Information Science Technology, China, andres@calabia.com)
11. **Piyush M. Mehta** (University of Minnesota, USA, piyushmukeshmehta@gmail.com).
12. **LiangLiang Yuan** (German Aerospace Center, Germany, liangliangyuan1994@gmail.com).
13. **Naomi Maruyama** (University of Colorado, USA, Naomi.Maruyama@noaa.gov)
14. **Toyese Tunde Ayorinde** (Brazilian Space Research Institute, Brazil, toye_tunde@yahoo.co.uk).
15. **Charles Owolabi** (Federal University of Technology Akure, Nigeria, talk2ocleen@yahoo.com)
16. **Emmanuel Abiodun Ariyibi** (Obafemi Awolowo University, Nigeria, ariyibi32@gmail.com).

Space Weather Impacts

- **Electromagnetic signal delay** in the ionosphere, affecting GNSS, communications, etc.;
- **Drag force** on **Low Earth Orbit** (LEO) satellites; and
- **Power and internet outages** due to intense **electric currents** induced during geomagnetic storms.

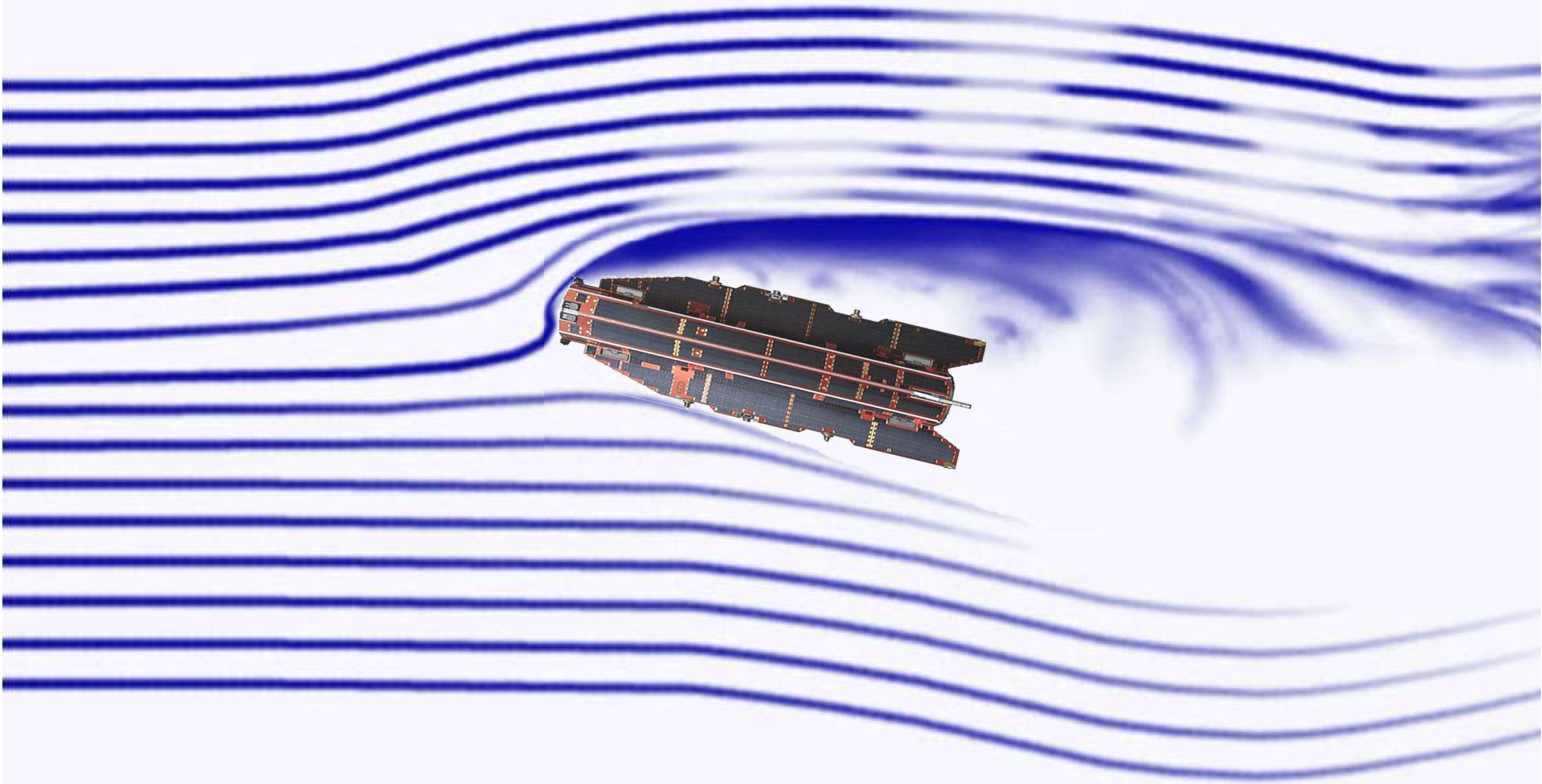


Total Electron Content (TEC)



Andres

Thermospheric Mass Density (TMD)



Existing Empirical Models

Thermospheric mass density:

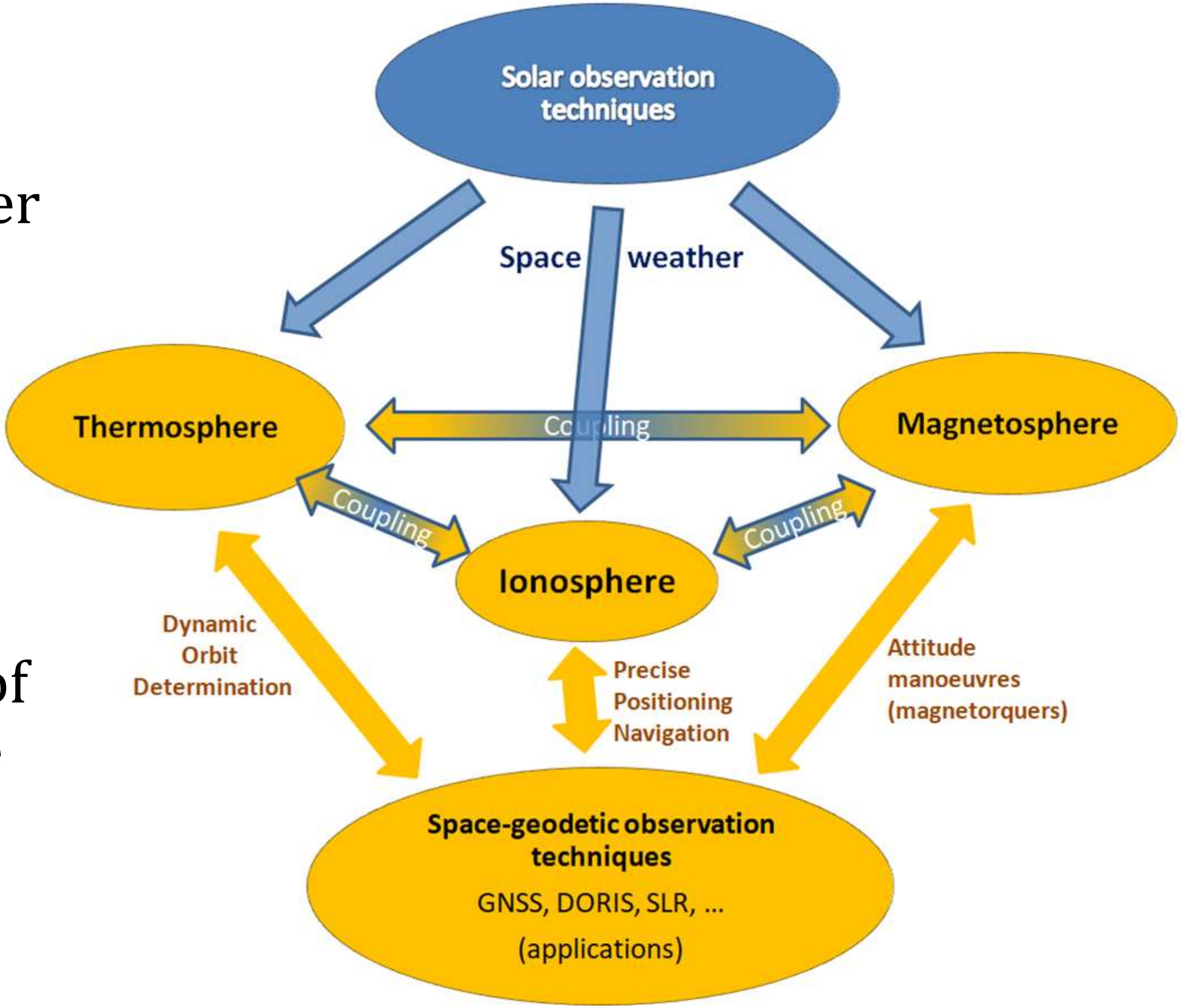
- **JB2008** [Bowman et al., 2008].
- Drag Temperature Model (**DTM**) [Bruinsma, 2015].
- US Naval Research Laboratory Mass Spectrometer and Incoherent Scatter-radar Extended 2000 model (**NRLMSISE-00**) [Picone et al., 2002].
- Parameterized PCA Mass GRACE (**PPMG-475**) [Calabia and jin, 2019].
- …

Plasma:

- **Klobuchar** model [Klobuchar, 1987].
- **Bent** Ionospheric Model [Bent and Llewellyn, 1973].
- Parameterized Ionospheric Model (**PIM**) [Daniell et al., 1995].
- **NeQuick** model [Radicella, 2009].
- International Reference Ionosphere (**IRI**) model [Bilitza et al., 2011].
- Parameterized PCA TEC GIMs (**PPTG**) [Calabia and jin, 2019].
- …

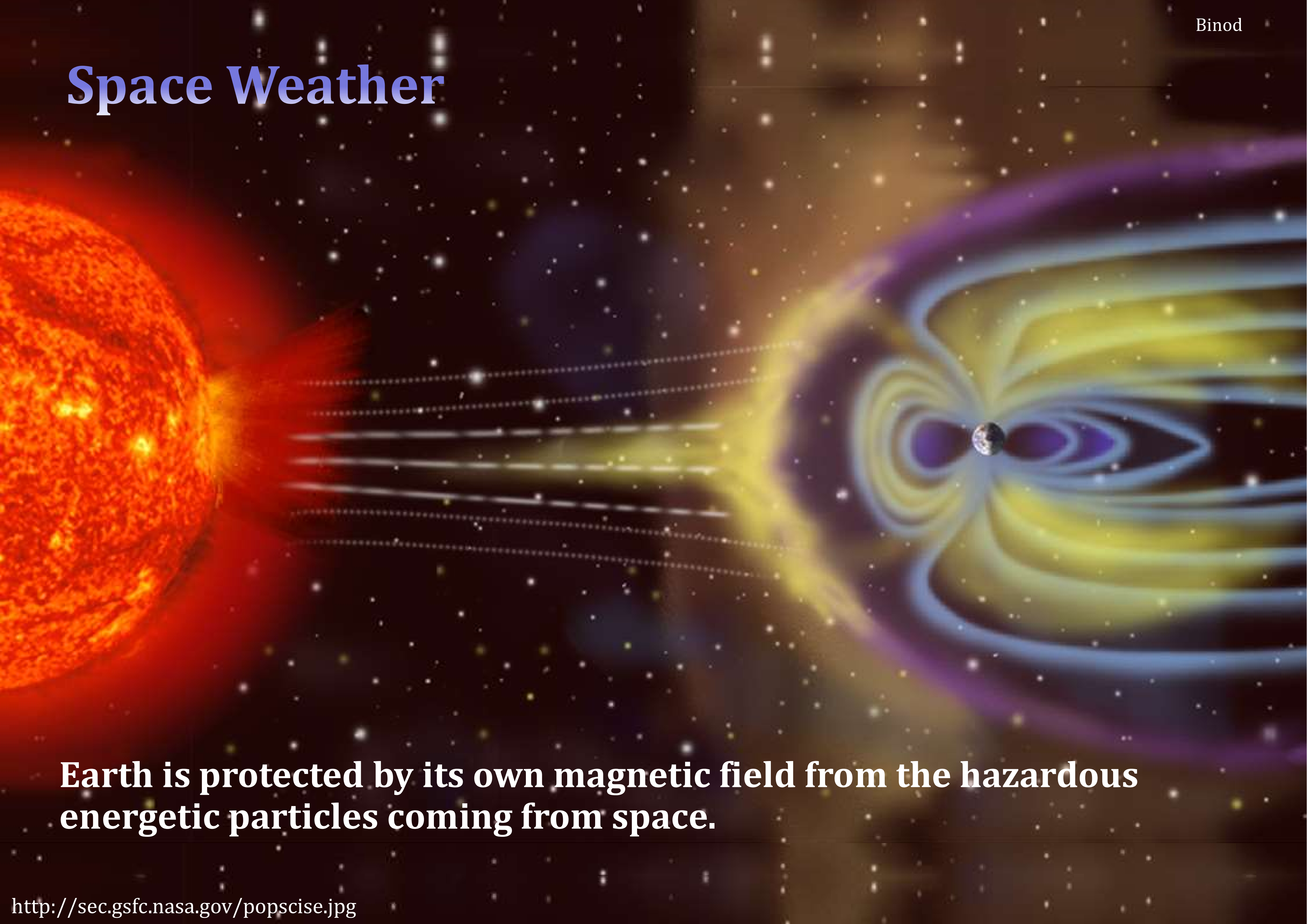
Geodetic Space Weather Research

Research on upper atmosphere aims to contribute for a better understanding of **Space Weather** phenomena within the coupled MIT system, and for the formulation of **predictive models** of the near-Earth space environment.



Binod

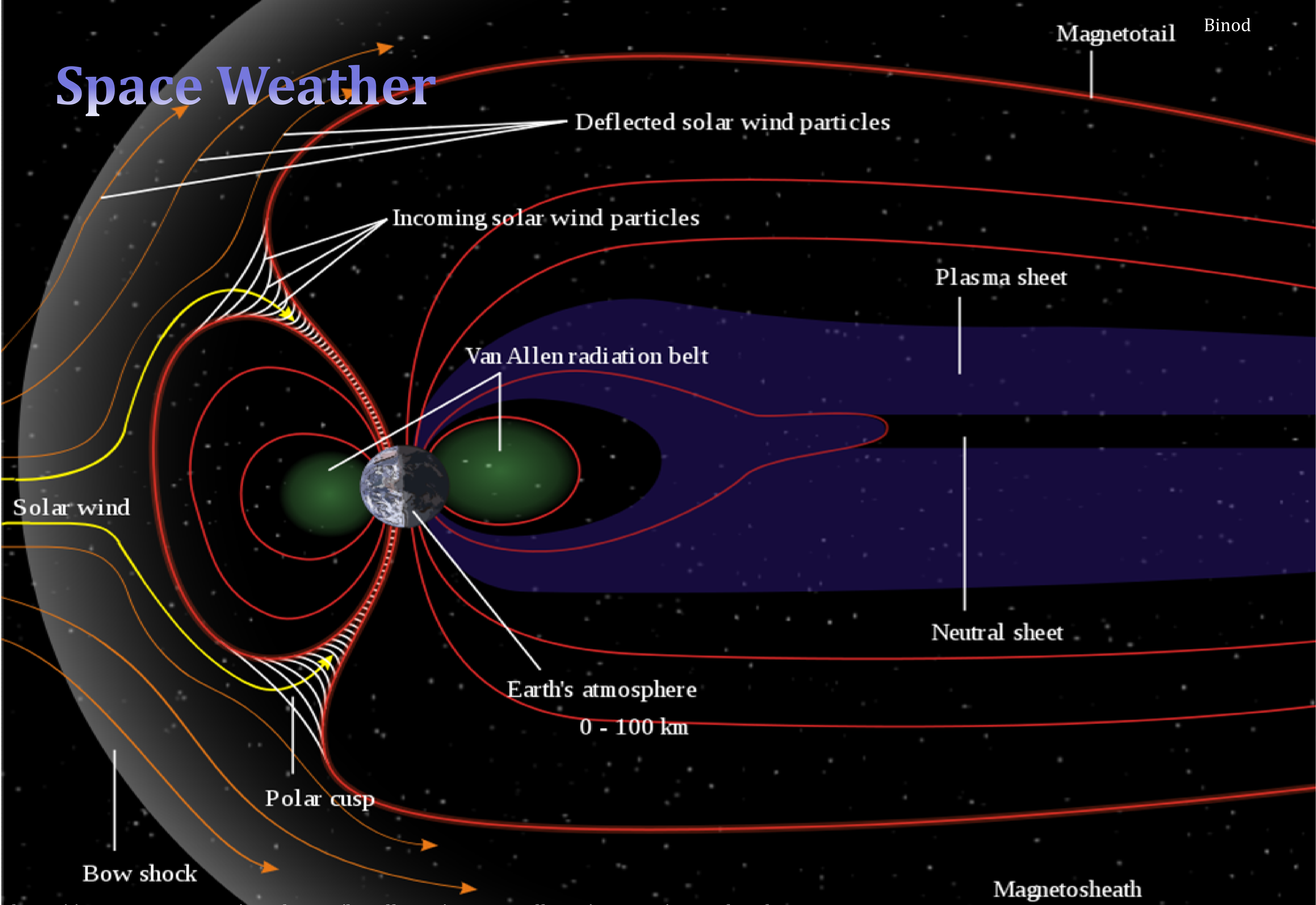
Space Weather



Earth is protected by its own magnetic field from the hazardous energetic particles coming from space.

http://sec.gsfc.nasa.gov/popscise.jpg

Space Weather



http://science.nasa.gov/newhome/headlines/guntersville98/images/mag_sketch_633.jpg

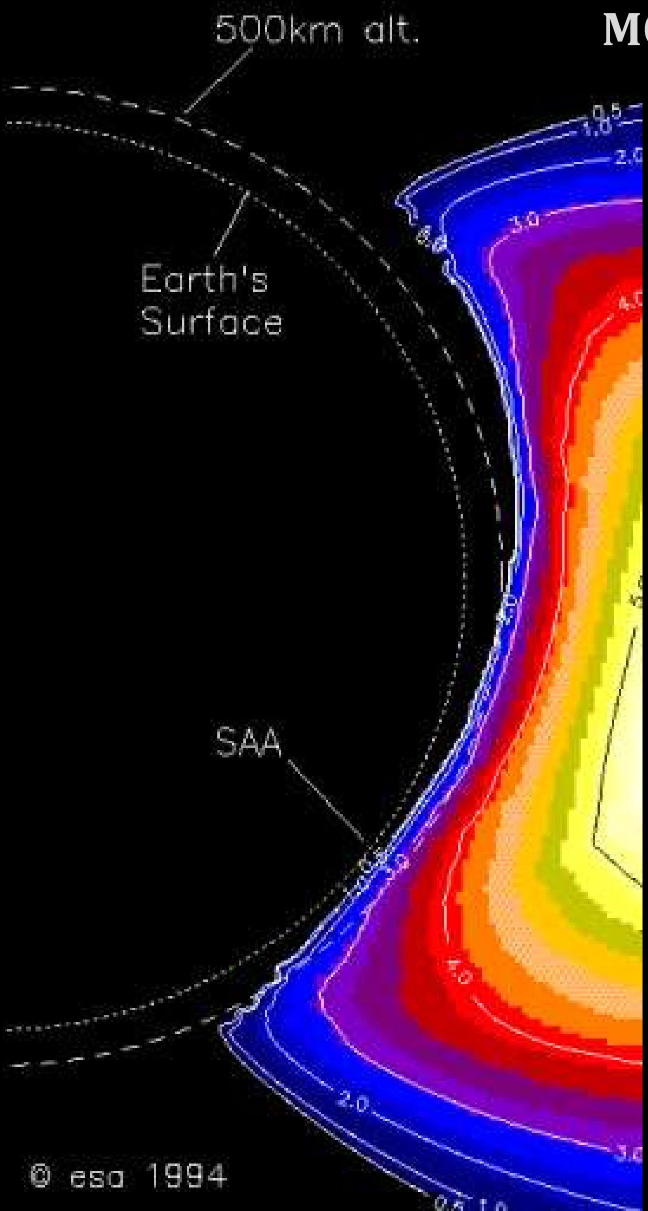
Space Weather

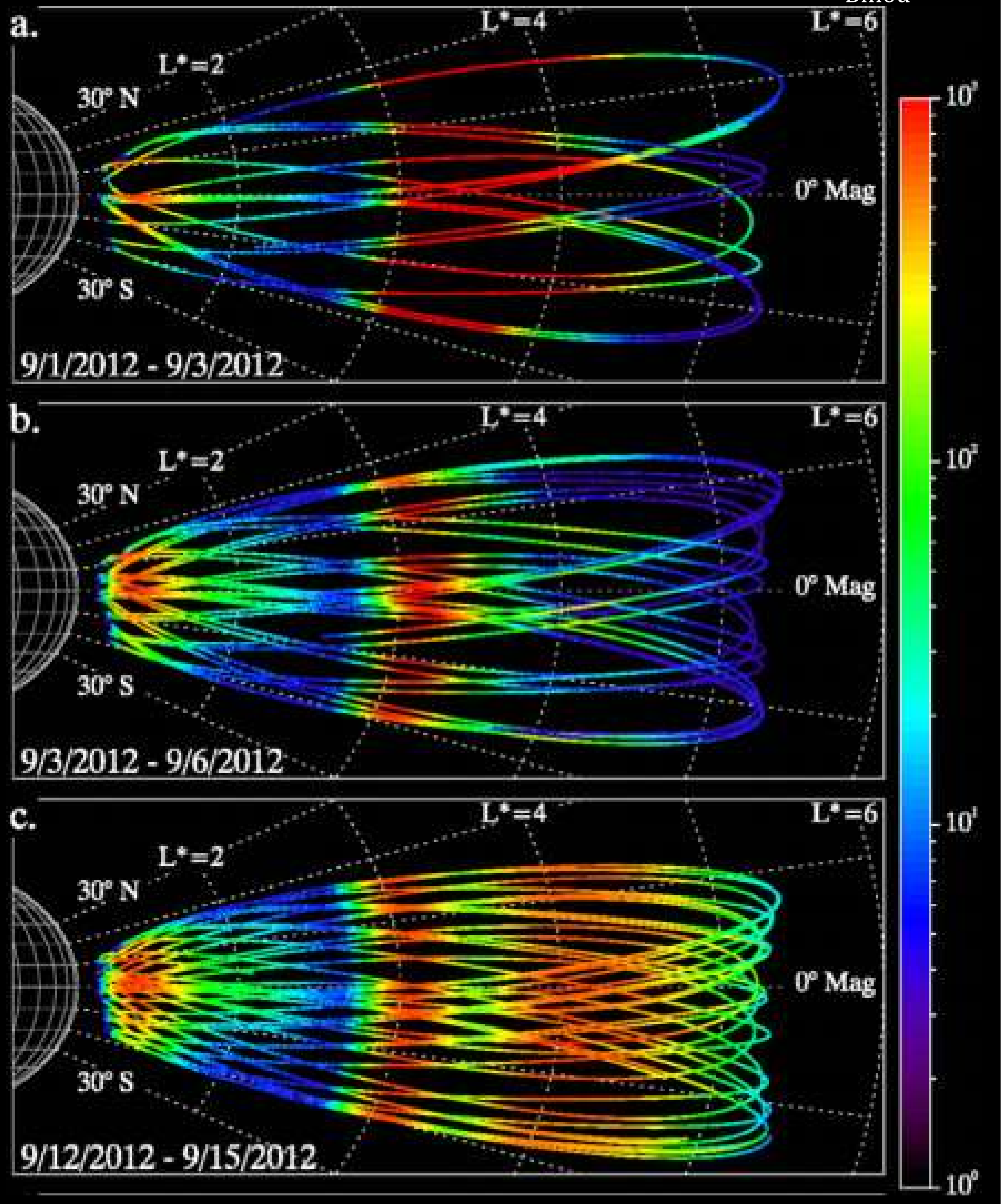
Van Allen Radiation Belt

MODEL

vs

DATA

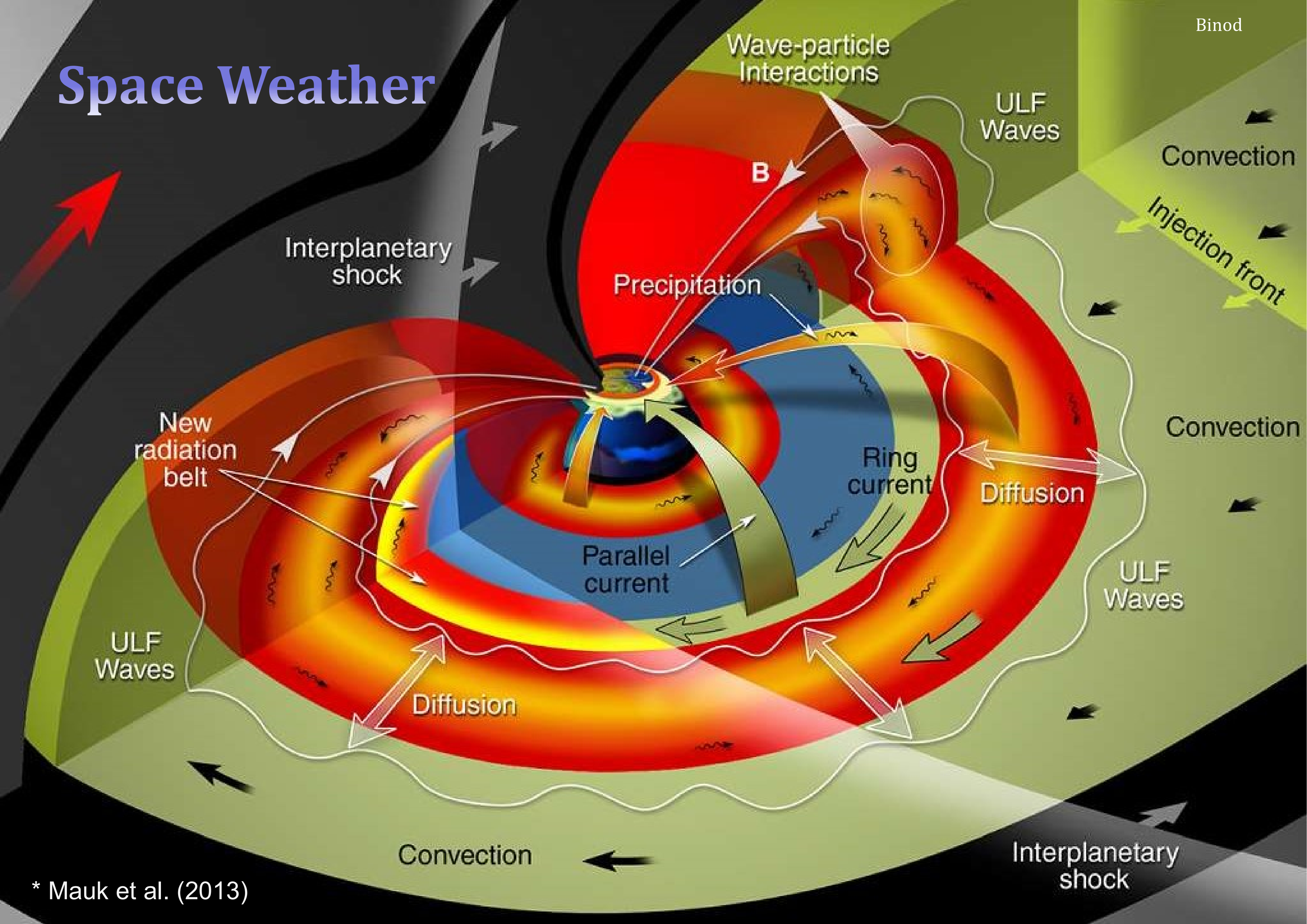




* Baker et al. (2013)

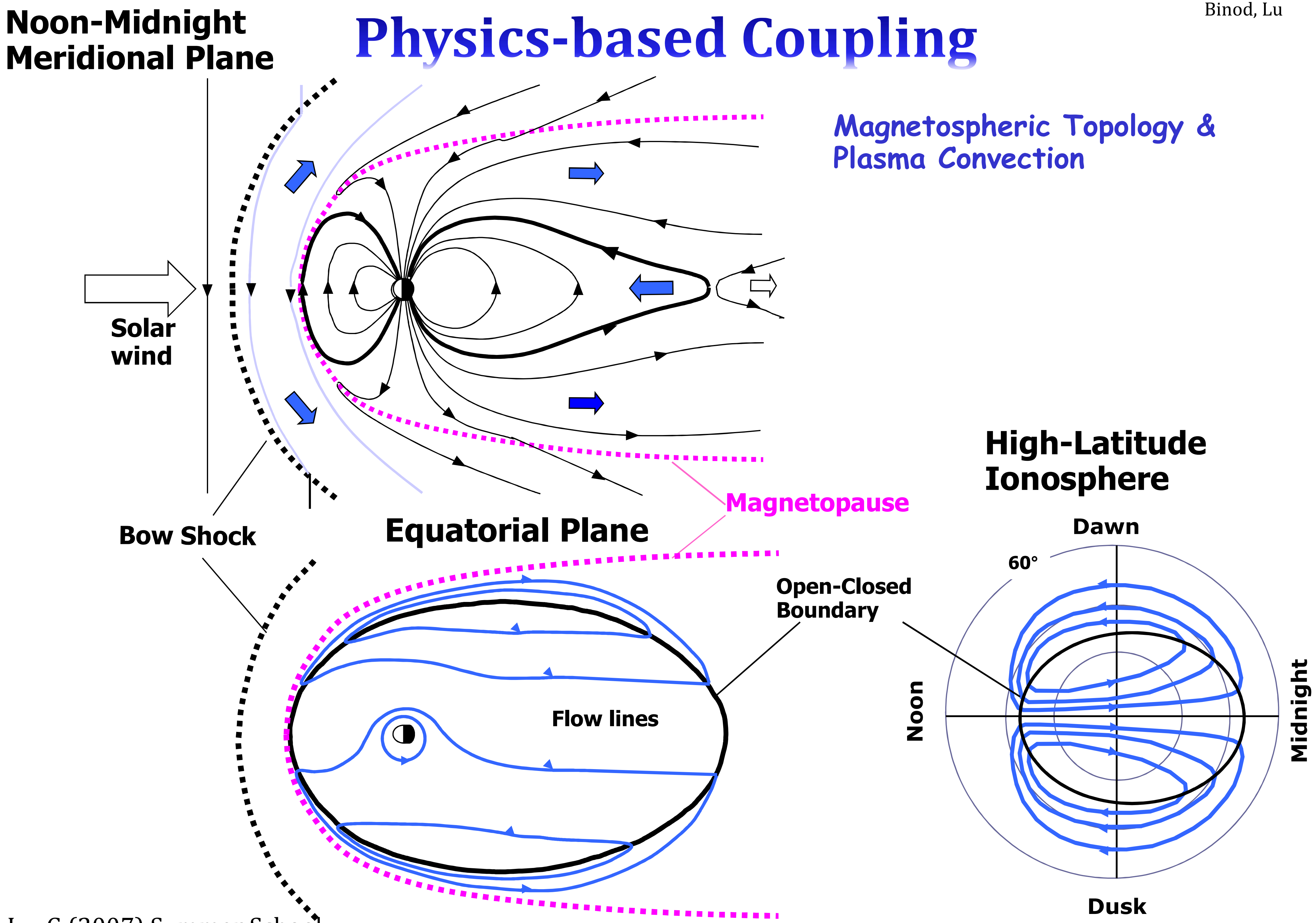
Binod

Space Weather

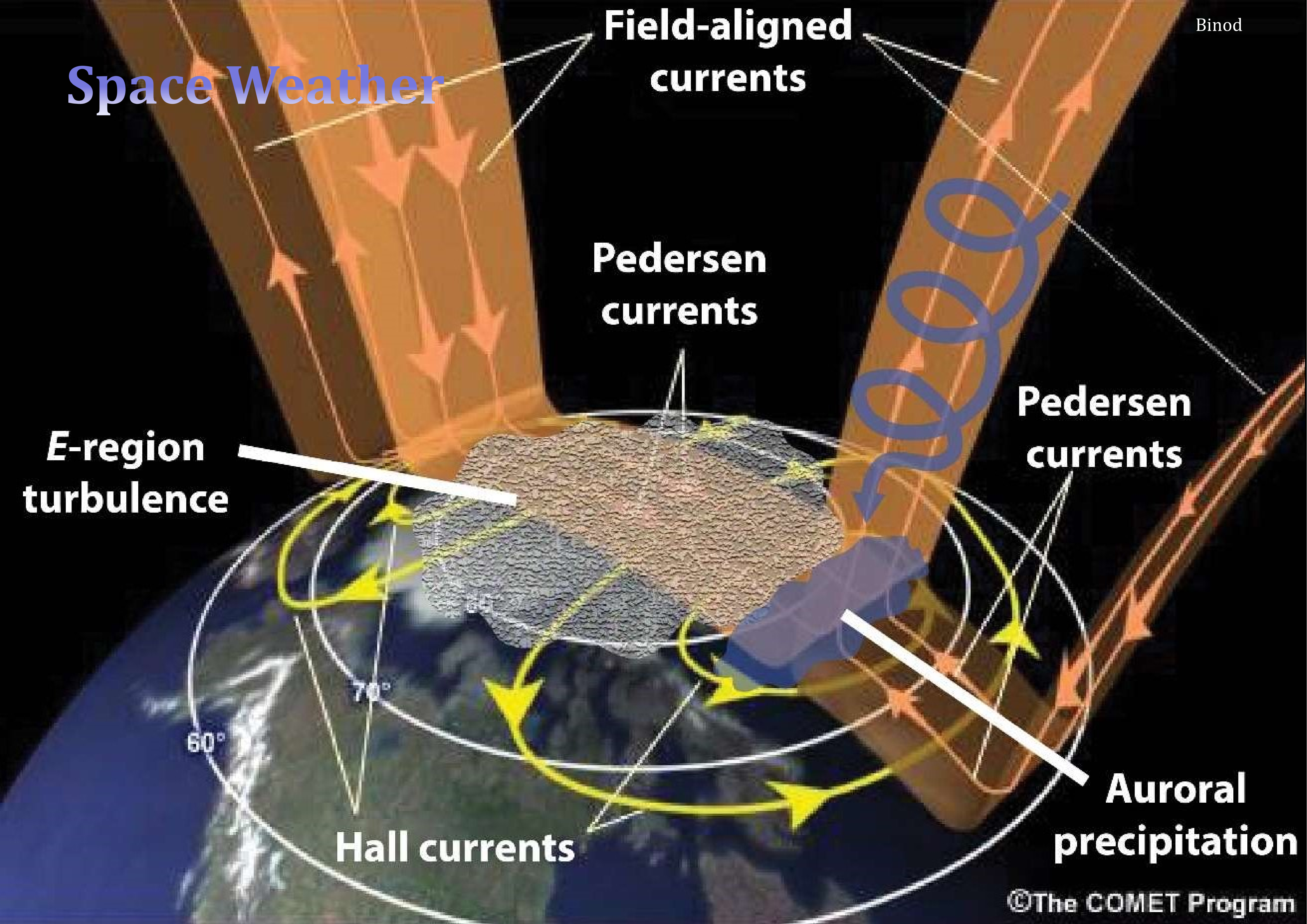


* Mauk et al. (2013)

Physics-based Coupling



* Lu, G (2007) Summer School


Binod
Space Weather
Field-aligned
currents
Pedersen
currents
Pedersen
currents
E-region
turbulence
70°
60°
Hall currents
Auroral
precipitation
©The COMET Program

Physics-based Coupling

Atmospheric Density column under Hydrostatic Equilibrium (above ~100 km):

$$N(z_0) = \int_{z_0}^{\infty} n(z_0) \exp\left[-\frac{z - z_0}{kT / m_i g} \right] dz = Hn(z_0)$$

z is altitude
g(z) is acceleration of gravity
r is mass density
k is Boltzmann's constant
m_i is molecular weight of species

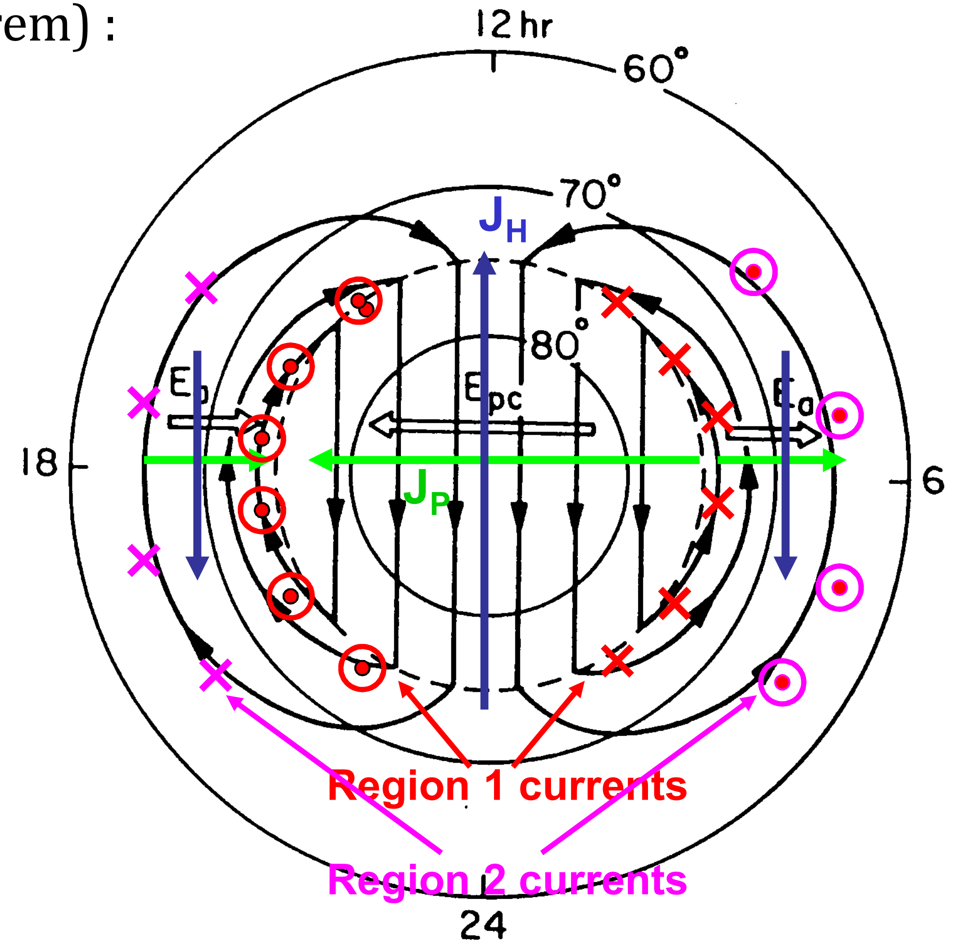
Electromagnetic Energy Dissipation (Poynting's theorem) :

$$\vec{J} \cdot \vec{E} = \underbrace{\left(\Sigma_P \vec{E} + \Sigma_H \vec{b} \times \vec{E} \right)}_{\text{Horizontal current}} \cdot \vec{E} = \underbrace{\Sigma_p E^2}_{\text{Joule heating}}$$

Field-aligned Current: $j_{||} = -\nabla \cdot \vec{J}$

E including neutral wind is:

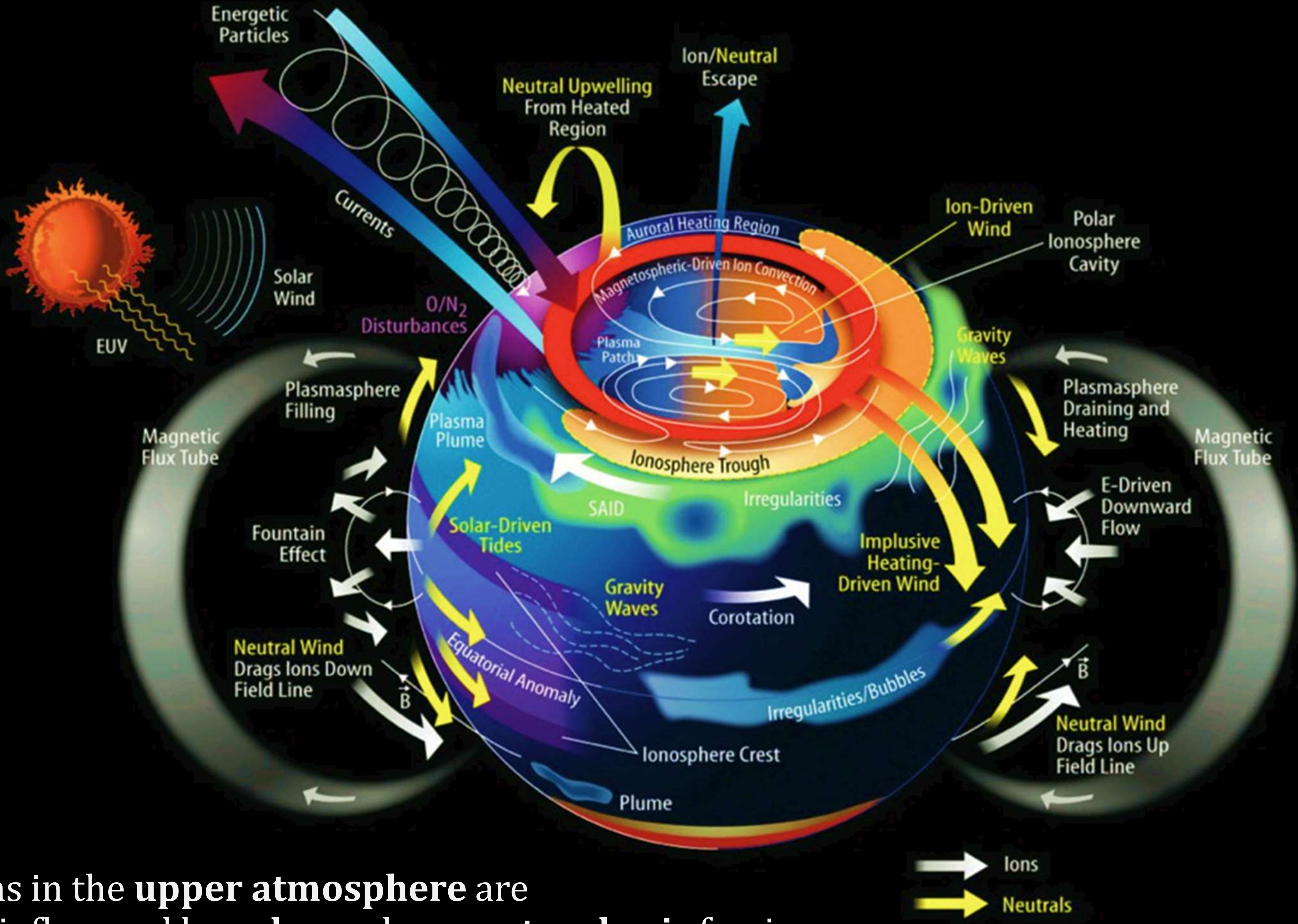
$$\vec{E} \rightarrow \vec{E}' = (\vec{E} + \vec{U} \times \vec{B}) = -(\underbrace{\vec{V}}_{\substack{\text{Plasma}\\ \text{drift}\\ \text{velocity}}} - \underbrace{\vec{U}}_{\substack{\text{Neutral}\\ \text{wind}\\ \text{velocity}}}) \times \vec{B}$$



* Lu, G (2007) Summer School

Space Weather

The understanding of coupled processes between **neutral gas** and **plasma** is still a challenge.

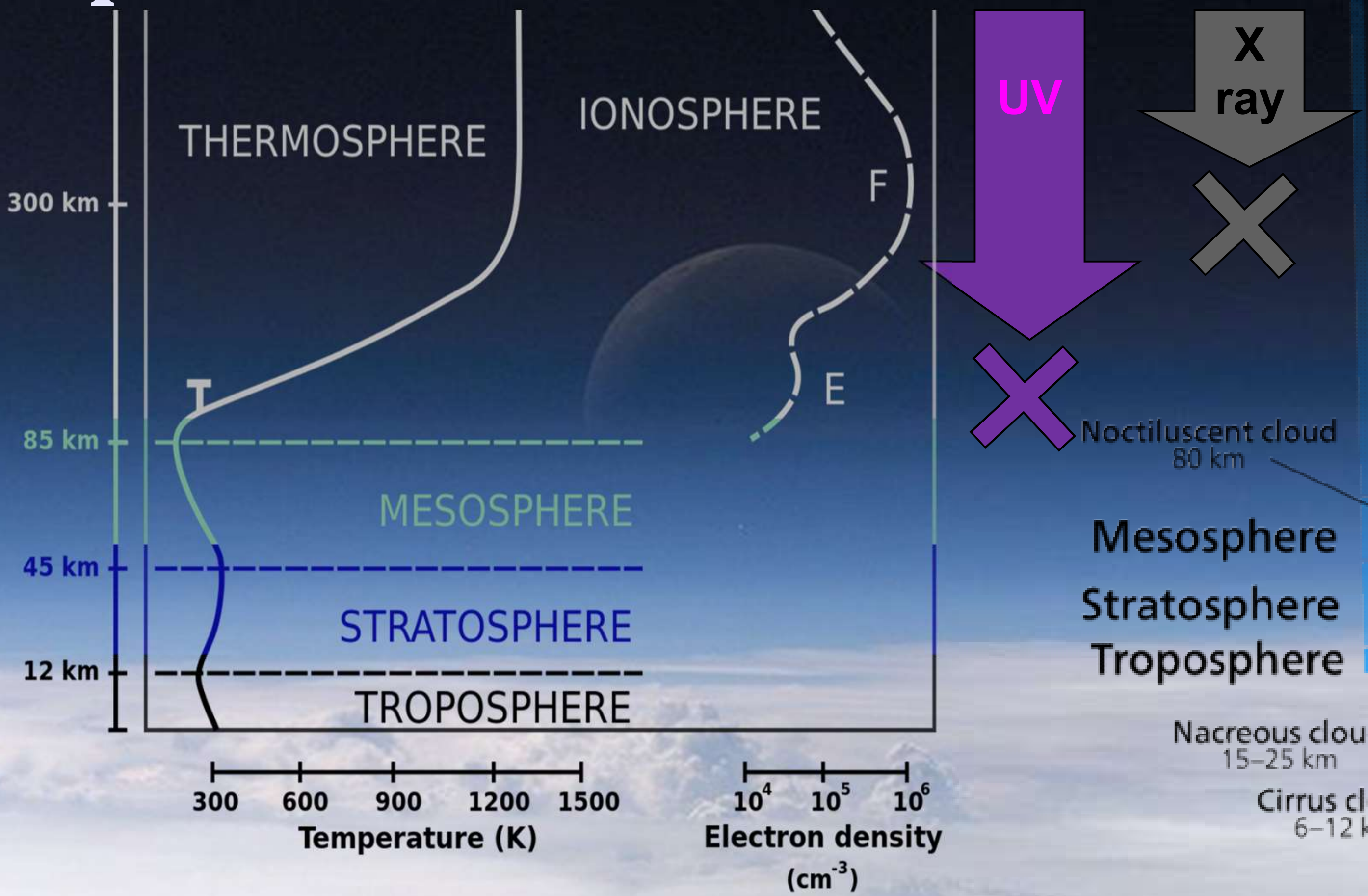


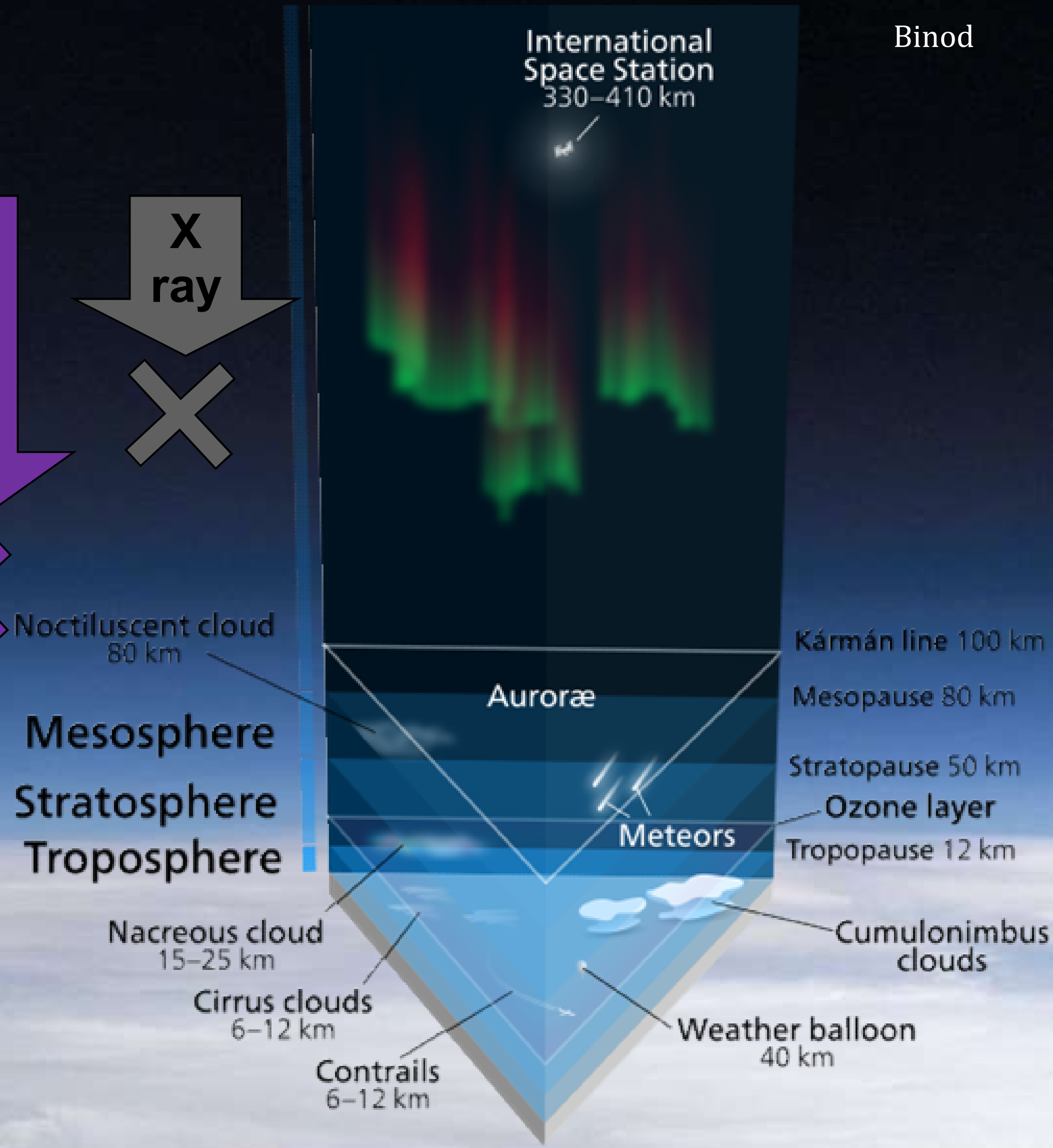
Variations in the **upper atmosphere** are strongly influenced by **solar** and **magnetospheric** forcing.

https://svs.gsfc.nasa.gov/4641

Binod

Space Weather





In addition, highly energetic **solar radiation is absorbed in the thermosphere**, through ionization/dissociation of molecules, and thus **creating the ionosphere**.

Binod, Astrid

Physics-based Coupling

Thermodynamic equation:

$$\frac{\partial T_n}{\partial t} = \underbrace{\frac{ge^z}{p_0 C_p}\frac{\partial}{\partial Z}\left\{\frac{K_T}{H}\frac{\partial T_n}{\partial Z} + K_E H^2 C_p \rho\left[\frac{g}{C_p} + \frac{1}{H}\frac{\partial T}{\partial Z}\right]\right\}}_{\substack{Molecular\\ conduction}} - \underbrace{\mathbf{v}_n \cdot \nabla T_n}_{Advection} - \underbrace{W\left(\frac{\partial T_n}{\partial Z} + \frac{R^* T_n}{C_p \bar{m}}\right)}_{Adiabatic} + \underbrace{\frac{Q^{\exp} - e^z L^{\exp}}{C_p}}_{Heating} - \underbrace{L^{imp} T_n}_{Radiation}$$

Momemtum equations:

Zonal velocity

$$\frac{\partial u_n}{\partial t} = \underbrace{\frac{ge^z}{p_0}\frac{\partial}{\partial Z}\left[\frac{\mu \partial u_n}{H \partial Z}\right]}_{\text{Viscosity}} + \underbrace{f^{corr} v_n}_{\text{Coriolis}} + \underbrace{\lambda_{xx}\left(v_{ExB,x} - u_n\right) + \lambda_{xy}\left(v_{ExB,y} - u_n\right)}_{\text{Ion drag}} - \underbrace{\mathbf{v}_n \cdot \nabla u_n}_{\substack{\text{Horizontal}\\ \text{advection}}} + \underbrace{\frac{u_n v_n}{R_E}\tan\lambda}_{\text{Mommentum}} - \underbrace{\frac{1}{R_E \cos\lambda}\frac{\partial \Phi}{\partial \phi}}_{\text{Pressure gradient}} - \underbrace{W\frac{\partial u_n}{\partial Z}}_{\substack{\text{Vertical}\\ \text{advection}}} - \underbrace{hd_u}_{\substack{\text{Horizontal}\\ \text{diffusion}}}$$

Meridional velocity

$$\frac{\partial v_n}{\partial t} = \underbrace{\frac{ge^z}{p_0}\frac{\partial}{\partial Z}\left[\frac{\mu \partial v_n}{H \partial Z}\right]}_{\text{Viscosity}} - \underbrace{f^{corr} v_n}_{\text{Coriolis}} + \underbrace{\lambda_{yy}\left(v_{ExB,x} - u_n\right) + \lambda_{xy}\left(v_{ExB,y} - u_n\right)}_{\text{Ion drag}} - \underbrace{\mathbf{v}_n \cdot \nabla v_n}_{\substack{\text{Horizontal}\\ \text{advection}}} + \underbrace{\frac{u_n v_n}{R_E}\tan\lambda}_{\text{Mommentum}} - \underbrace{\frac{1}{R_E}\frac{\partial \Phi}{\partial \lambda}}_{\text{Pressure gradient}} - \underbrace{W\frac{\partial v_n}{\partial Z}}_{\substack{\text{Vertical}\\ \text{advection}}} - \underbrace{hd_v}_{\substack{\text{Horizontal}\\ \text{diffusion}}}$$

Continuity equation:

$$\frac{d\Psi}{dt} = \underbrace{-e^z \tau^{-1}\frac{d}{dz}\left\{\frac{m}{m_{N_2}}\left(\frac{T_0}{T}\right)^{0.25}\alpha^{-1}L\Psi\right\}}_{\substack{Molecular\\ diffusion}} + \underbrace{e^z\frac{d}{dz}\left\{K(z)e^{-z}\frac{d\Psi}{dz}\right\}}_{\substack{Eddy\\ diffusion}} - \underbrace{V\cdot\nabla\Psi}_{\substack{Horizontal\\ advection}} - \underbrace{\omega\frac{d\Psi}{dz}}_{\substack{Vertical\\ advection}} + \underbrace{S - R}_{\substack{production\\ and\\ recombination}}$$

* Maute, A (2018) TIEGCM model description

Binod, Lu

Chemical Processes in the Physics-based Models

Photoionization:

$h\upsilon + O \Rightarrow O^+ + e^-$

$h\upsilon + O_2 \Rightarrow O_2^+ + e^-$

$h\upsilon + N_2 \Rightarrow N_2^+ + e^-$

Collisional Ionization:

$e^- + O \Rightarrow O^+ + 2e^-$

Charge Exchange:

$H + O^+ \Rightarrow H^+ + O$

$O_2 + O^+ \Rightarrow O_2^+ + O$

$N_2 + O^+ \Rightarrow N_2^+ + O$

Conversion:

$N_2^+ + O \Rightarrow NO^+ + O$

$N_2 + O^+ \Rightarrow NO^+ + O$

Recombination:

$O + O + N_2 \Rightarrow O_2 + N_2$

Dissociative Recombination:

$O_2^+ + e^- \Rightarrow O + O$

$N_2^+ + e^- \Rightarrow N + N$

$NO^+ + e^- \Rightarrow N + O$

Radiative Recombination:

$O^+ + e^- \Rightarrow h\upsilon + O$

Existing Physics-based Models

- Thermosphere-Ionosphere-Electrodynamics General Circulation Model (**TIEGCM**) [Richmond et al., 1992].
- Coupled Thermosphere Ionosphere Plasmasphere Electrodynamics (**CTIPe**) Model [Codrescu et al., 200].
- Global Ionosphere Thermosphere Model (**GITM**) [Ridley et al., 2006].
- Coupled Magnetosphere Ionosphere Thermosphere Model (**CMIT**) [Lyon et al., 2004].
- **SAMI** model [Huba et al., 2000].
- …

Usual Model Inputs: *solar wind, solar flux, magnetic field, etc.*

Usual Model Outputs: *neutral composition and densities, ion and electron densities, neutrals and plasma velocities, temperatures, electric fields, etc.*

5 min break !

Selected Scientific Outcomes

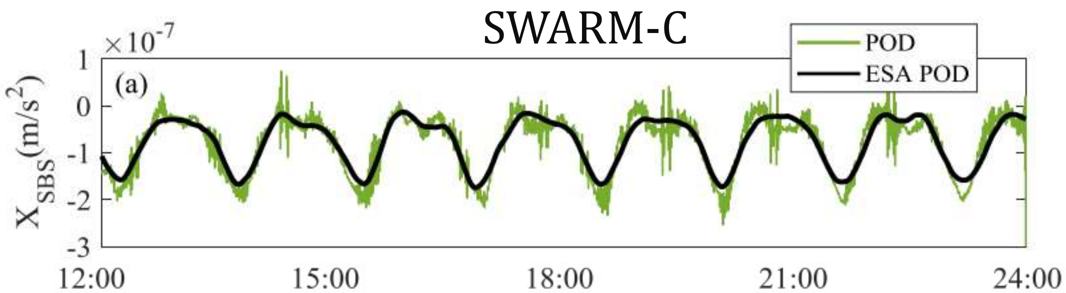
- This report focuses on some selected scientific outcomes of the IAG Joint Study Group 1 “Coupling processes between Magnetosphere, Thermosphere, and Ionosphere” along the term 2019–2020.

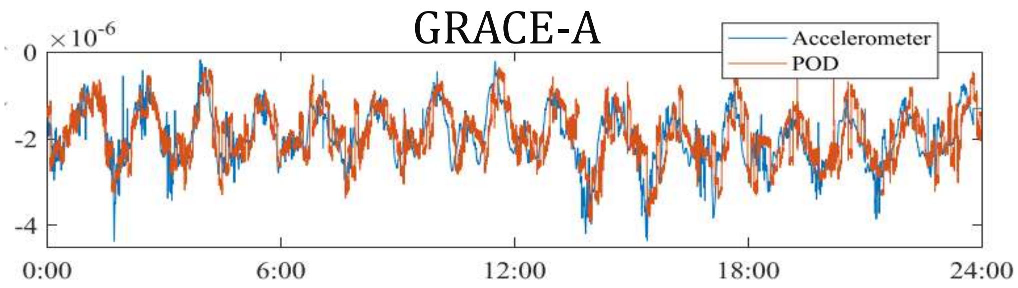
- It is based on its mid-term reports to
  IAG Inter-Commission Committee on Theory (ICCT) and
  IAG Global Geodetic Observing System (GGOS), Focus Area on Geodetic Space Weather Research (FA-GSWR).

LiangLiang, Andres

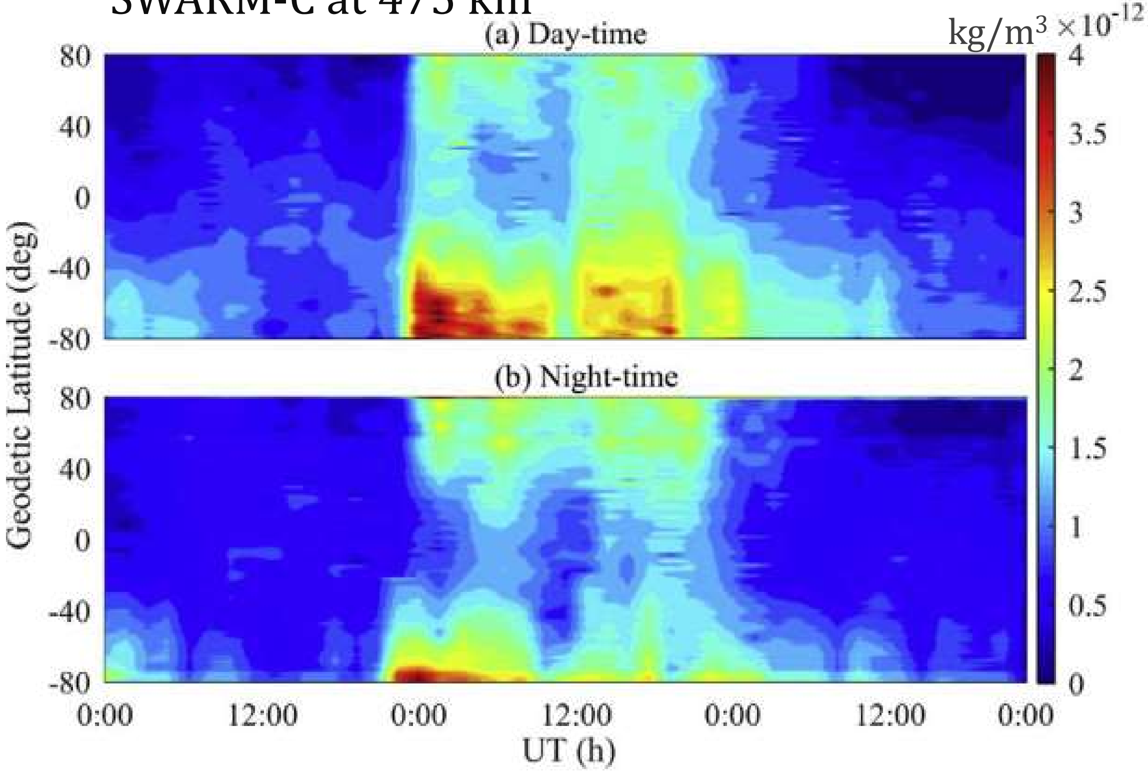
New GNSS-based TMD Observations during Geomagnetic Storms [joint JWG2]

GNSS-based TMD (TMD POD) is estimated from GRACE-A and SWARM-C to study density responses to geomagnetic storms **at different altitudes.**

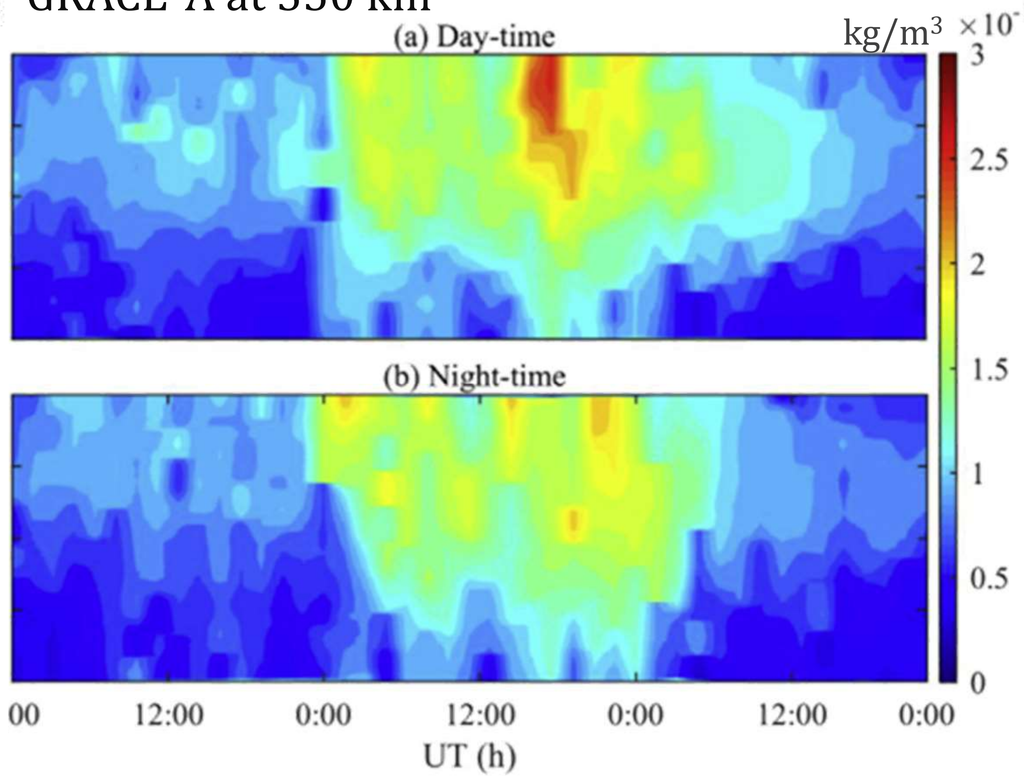




SWARM-C at 475 km



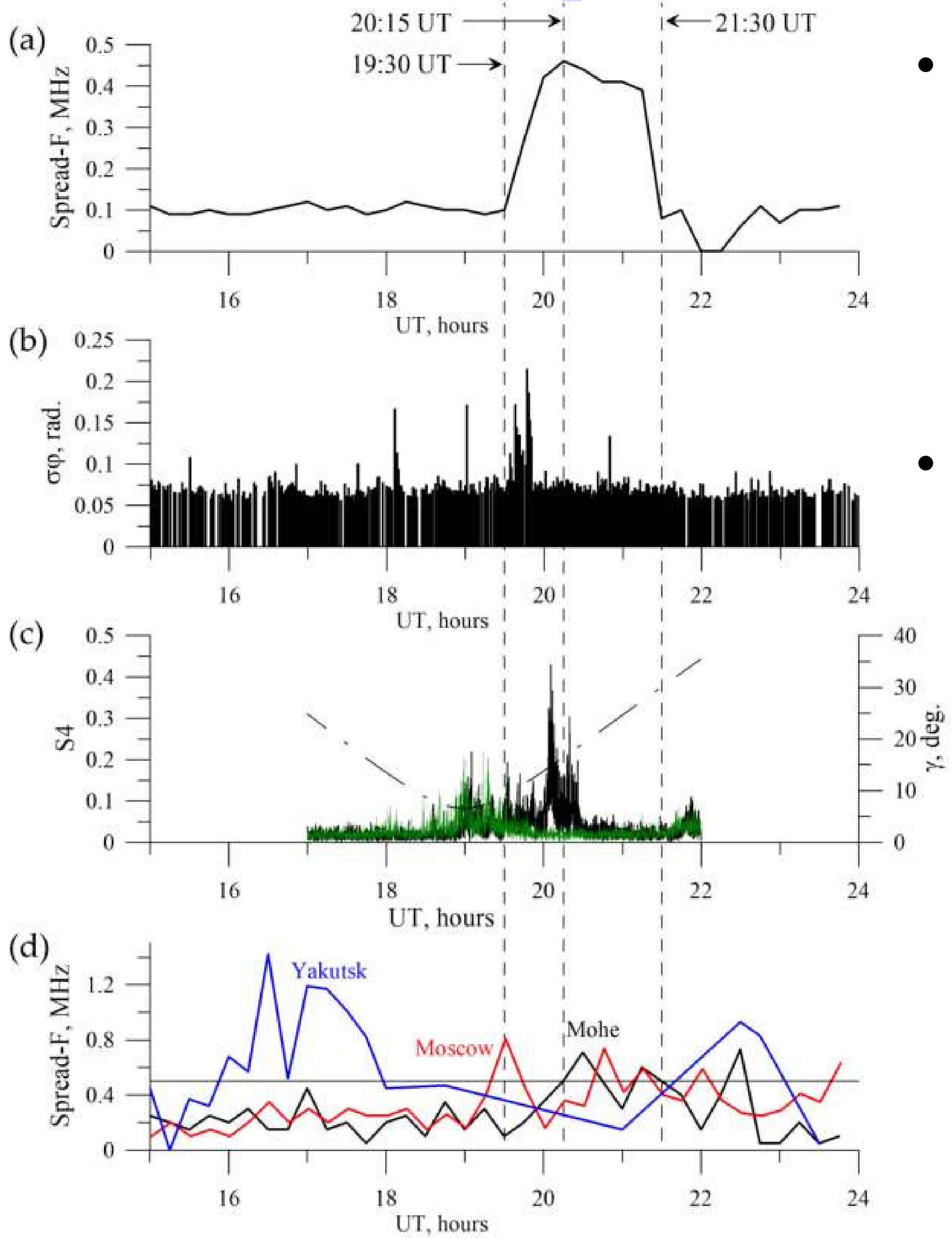
GRACE-A at 350 km



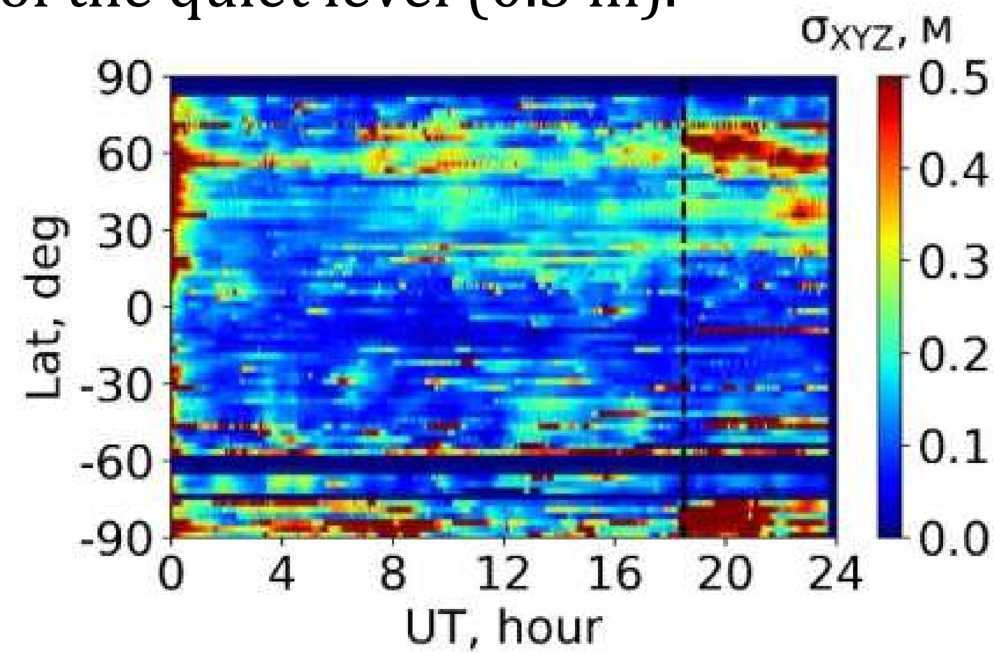
* Yuan et al (2019) doi:10.1016/j.jastp.2019.01.007

Yuri

Small-scale ionospheric irregularities caused by the Auroral oval expansion and GNSS PPP error [joint JWG1]



- Data from DPS-4 ionosonde, Irkutsk Incoherent Scatter Radar, and GPS/GLONASS show increased spread-F, Cygnus A signal amplitude scintillations, and GPS phase scintillations during geomagnetic storms.
- Mean PPP error is at least five times that of the quiet level (0.5 m).

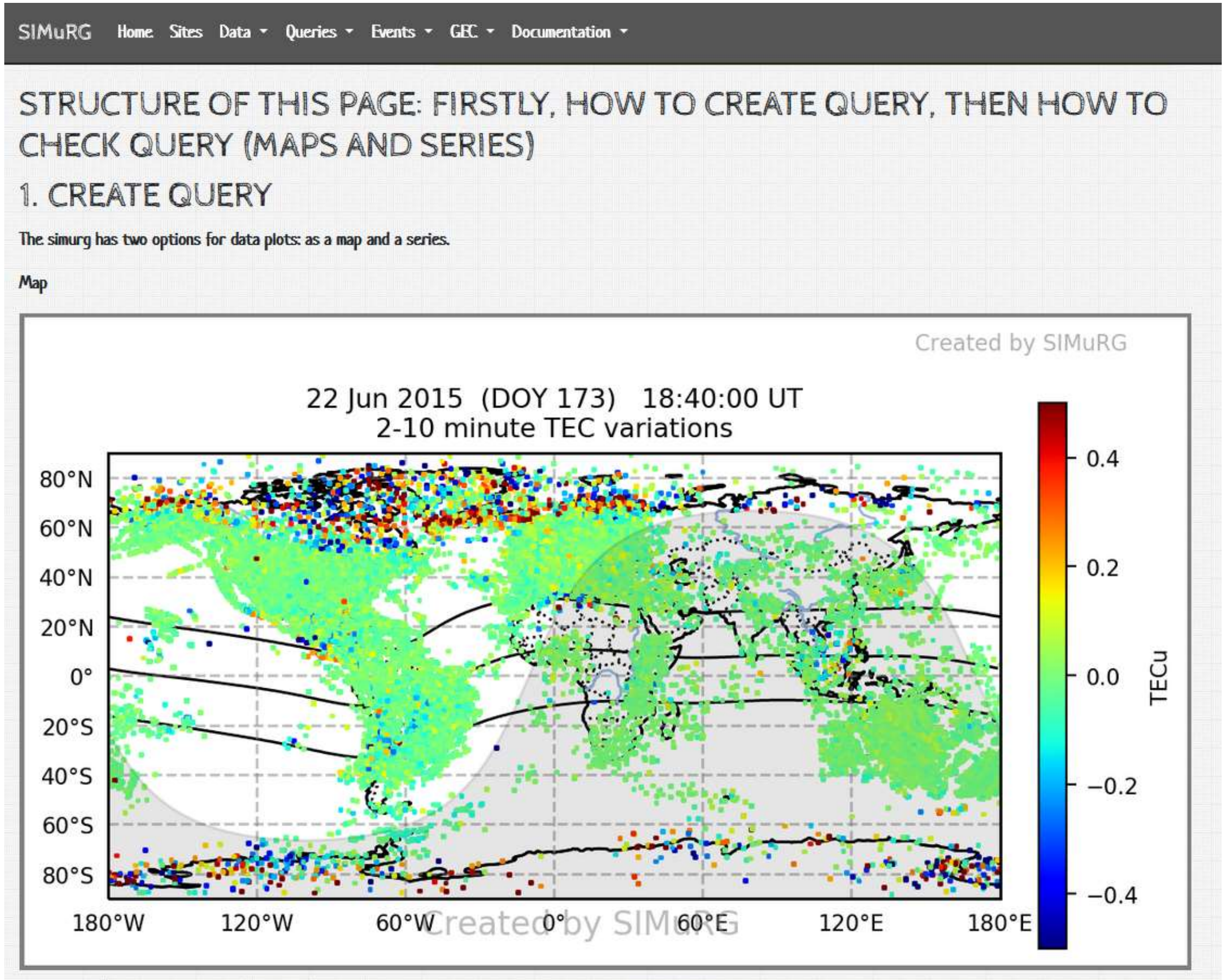


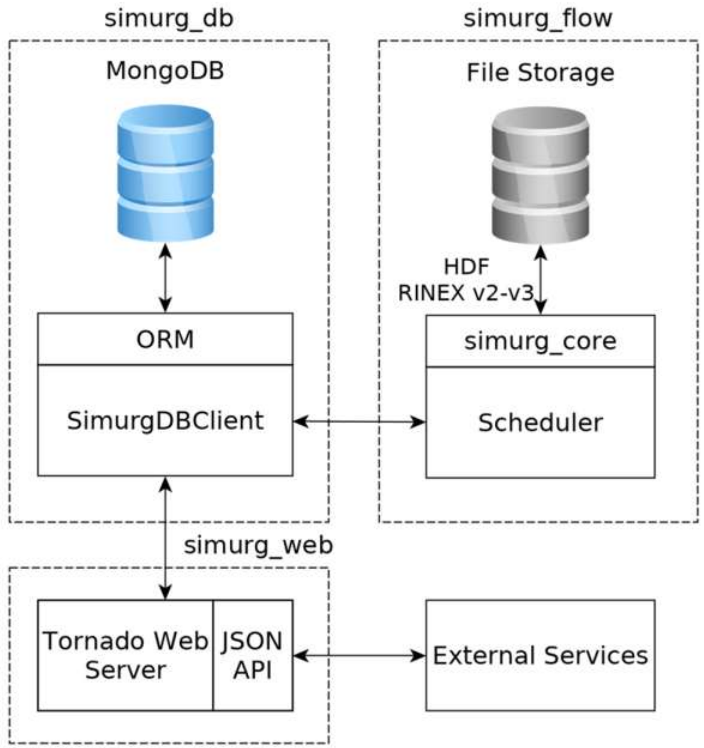
* Yasyukevich et al (2020b) doi:10.3390/rs12101579

Yuri

System for Ionosphere Monitoring and Research from GNSS [joint JWG1] (https://simurg.iszf.irk.ru)

SIMuRG is an **online service** that provides the TEC variations filtered within 2–10 min, 10–20 min, and 20–60 min, the Rate of the TEC Index (ROTI), the Along Arc TEC Rate index, and the vertical TEC.



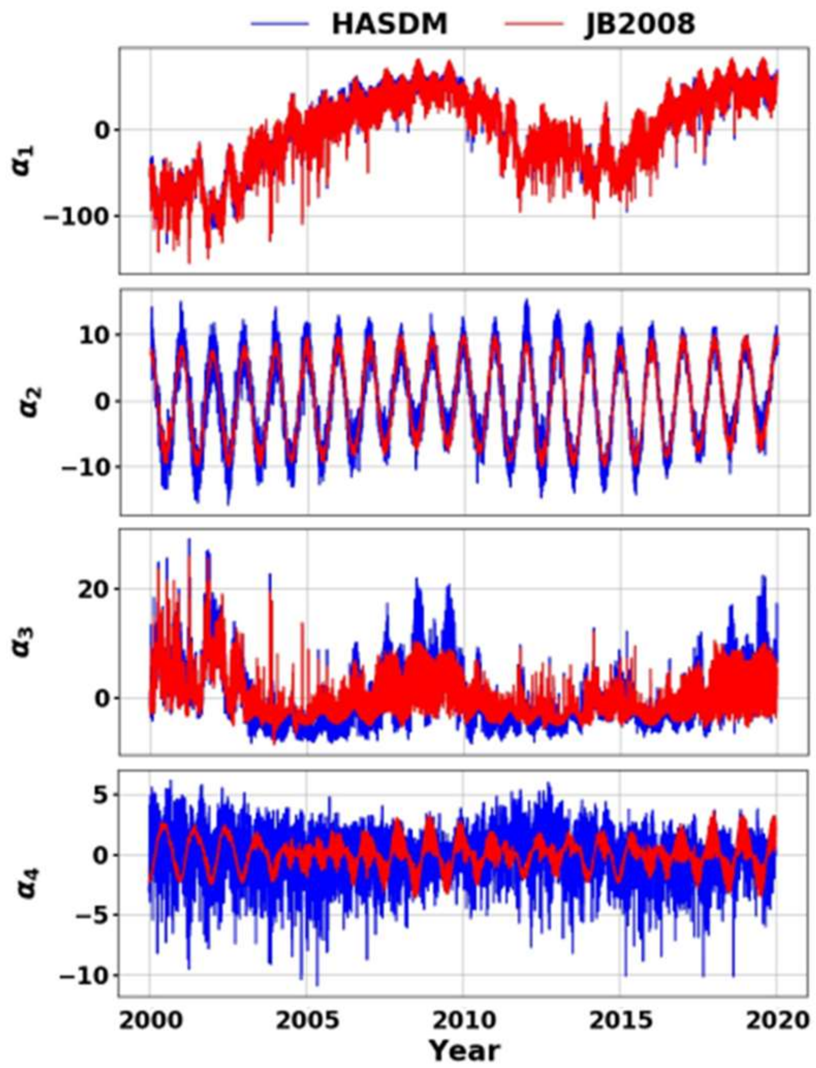


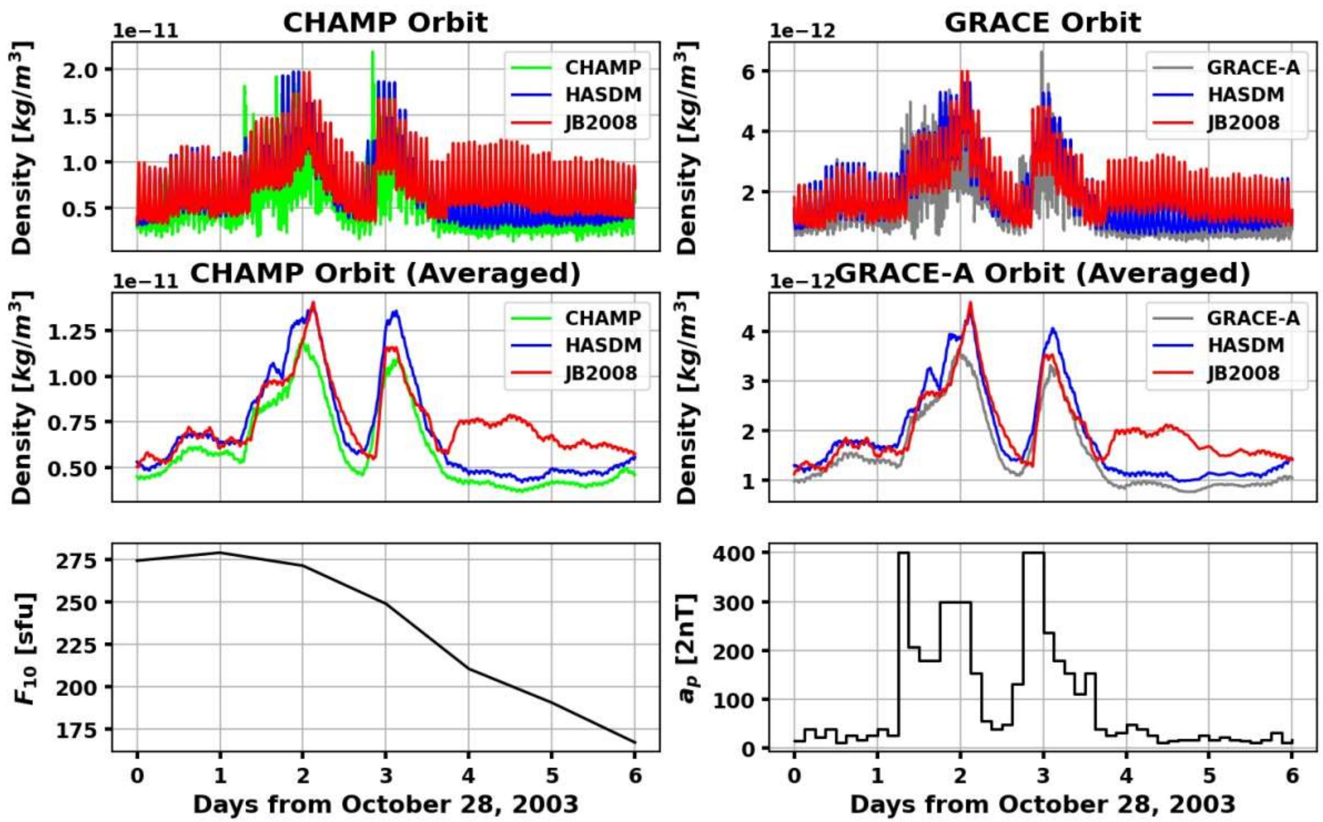
* Yasyukevich et al (2020a) doi:10.1007/s10291-020-00983-2

Piyush

Qualitative and Quantitative Assessment of the SET HASDM TMD Database [joint JWG2]

The new HASDM dataset is validated against the JB2008 using the Principal Component Analysis (PCA). Comparisons of HASDM to GRACE and CHAMP densities during geomagnetic storms show better agreement than JB2008.

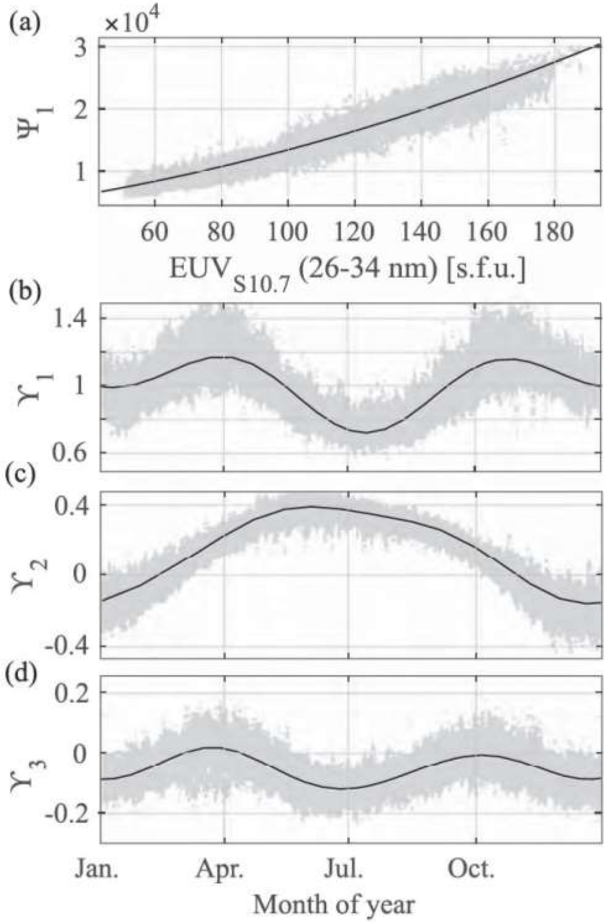


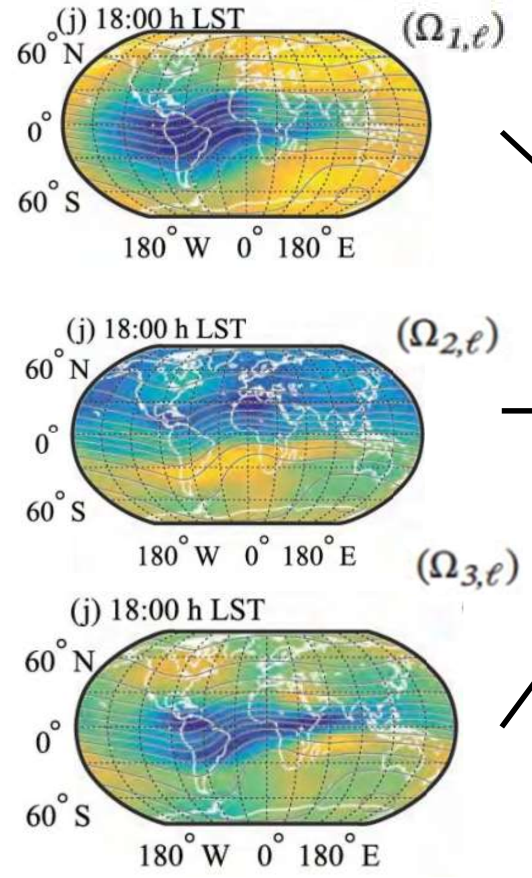


* Licata et al (2019) doi: 10.1002/essoar.10506516.1

Andres

New empirical TEC Model [joint JWG1]
(available at http://doi.org/10.5281/zenodo.3563463)





$$TEC(x_n, t_m) = \sum_{i=1}^{i=n} \left[\Gamma_{i,\ell}(t_m) \cdot \Omega_{i,\ell}(x_n)\right]$$

$$\Gamma_i = \Psi_i . \Upsilon_i + \varepsilon_i$$

$$\frac{\Gamma_1(t)}{\Upsilon_1(t)} \approx \Psi_1(t) = p_{00} + p_{10} \cdot FLUX(t+\tau_{FLUX}) + p_{01} \cdot MAG(t+\tau_{MAG}) + p_{20} \cdot [FLUX(t+\tau_{FLUX})]^2 + p_{11} \cdot FLUX(t+\tau_{FLUX}) \cdot MAG(t+\tau_{MAG})$$

$$\frac{\Gamma_i(t)}{\Psi_i(t)} \approx \Upsilon_i(t) = a_0 + a_{11} \cdot \cos(Sa(t)) + b_{11} \cdot \sin(Sa(t)) + a_{12} \cdot \cos(S1(t)) + b_{12} \cdot \sin(S1(t)) + a_{21} \cdot \cos(2 \cdot Sa(t)) + b_{21} \cdot \sin(2 \cdot Sa(t)) + a_{22} \cdot \cos(2 \cdot S1(t)) + b_{22} \cdot \sin(2 \cdot S1(t)) + a_{31} \cdot \cos(3 \cdot Sa(t)) + b_{31} \cdot \sin(3 \cdot Sa(t)) + a_{32} \cdot \cos(3 \cdot S1(t)) + b_{32} \cdot \sin(3 \cdot S1(t))$$

Variance Explained by each PCA Mode at each LST Epoch and Fitting Statistics. Values are Dimensionless

Mode	Variance explained (per LST)	Data versus model (66,894 samples)		
		Correlation	R^2	RMSE
PCA 1	75%	98%	0.97	902
PCA 2	15%	97%	0.98	454
PCA 3	2%	71%	0.73	413
PCA 4	1%	43%	0.43	534
PCA 5	1%	64%	0.51	528

* Calabia and Jin (2020) doi:10.1029/2019JA027703

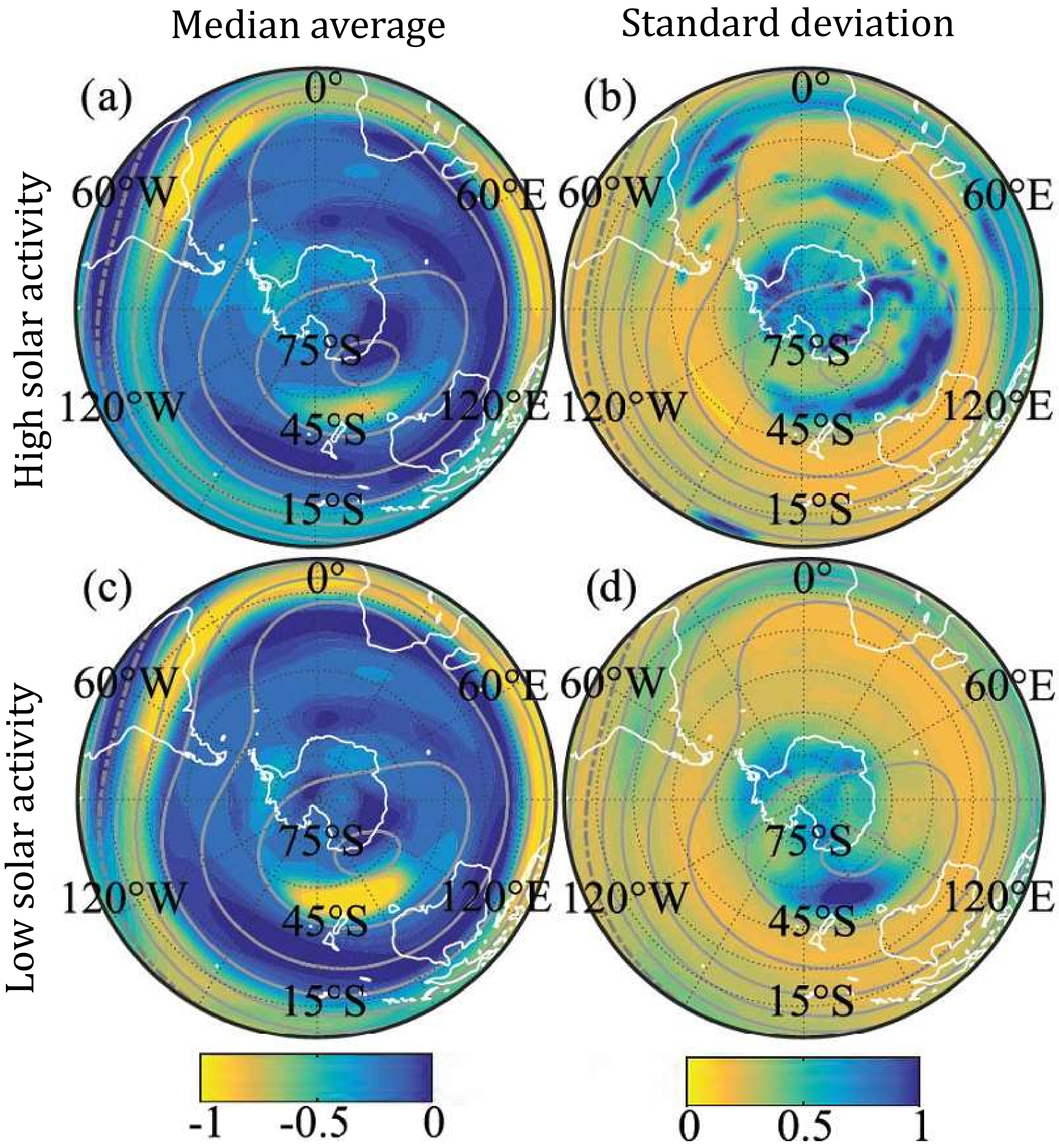
Andres

TEC features due to Magnetospheric Forcing

Relative residuals from TEC model

- Minimum values of the median average of relative residuals (a-c) show to decease at all the LST locations at about 15° from the South magnetic dip pole, and more prominent at 52°S 155°E.

- Only Southern hemisphere is shown. **The northern high-latitudes lack of such deviations.**

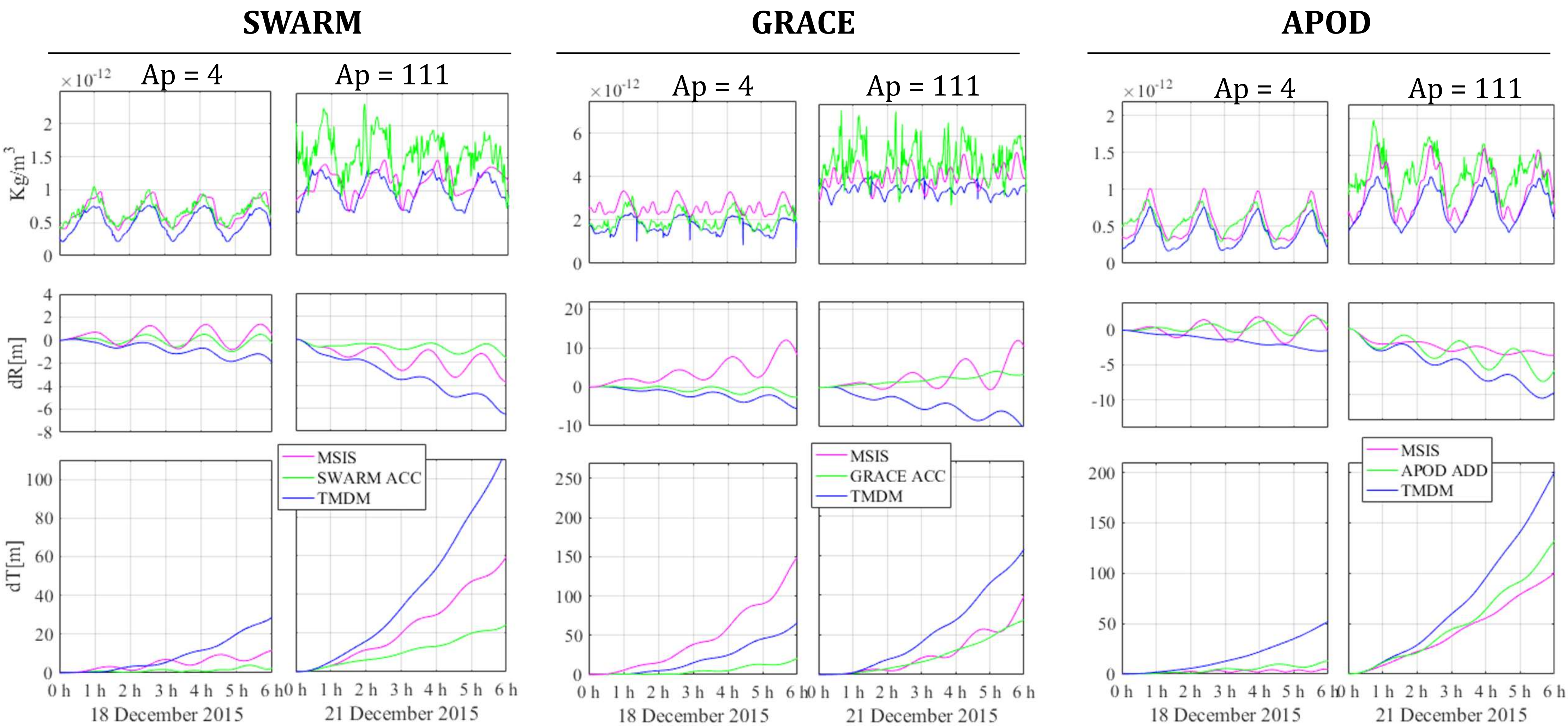


* Calabia and Jin (2020a) doi:10.1029/2019JA027703

Andres

New empirical TMD Model [joint JWG2]
(available at http://doi.org/10.5281/zenodo.3234582)

- Similar error range in Precise Orbit Determination.
- Good response under different magnetospheric conditions.

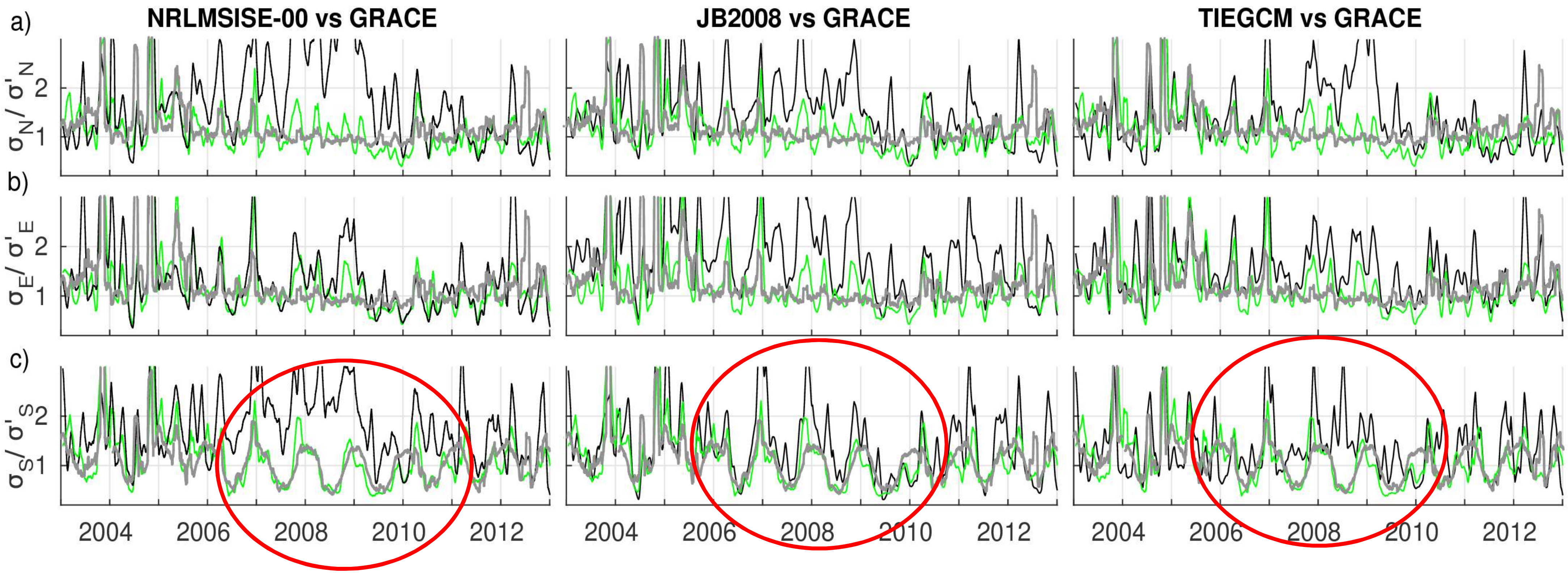


* Calabia et al (2020) doi: 10.1016/j.jastp.2020.105207

Andres

Modeling TMD variations due to Magnetospheric Forcing [joint JWG2]

- Seasonal dependence in amplitude of variability only in the southern high latitude.
- Only JB2008 agrees well with this seasonal variation.
- NRLMSISE-00 and TIEGCM overestimate the variability during low solar activity.

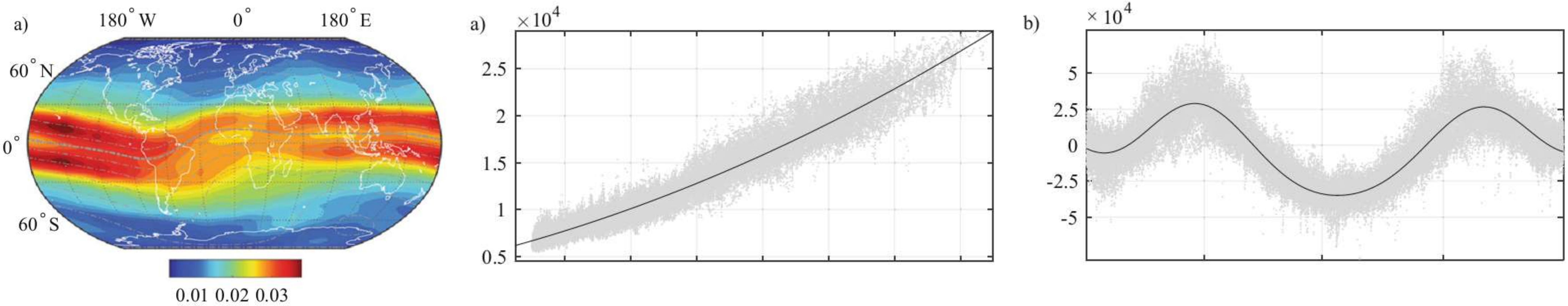


* Calabia and Jin (2019) doi: 10.5194/angeo-37-989-2019

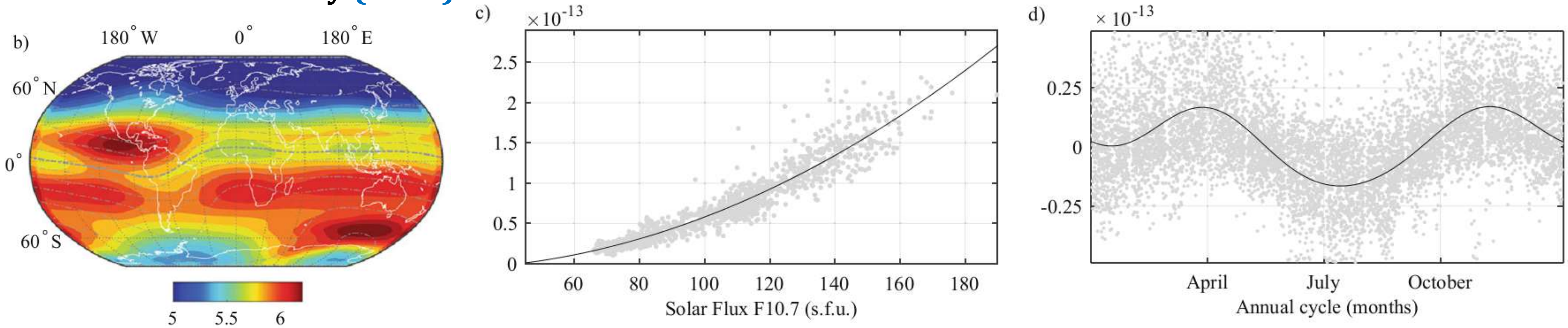
Andres

Coupling between TEC and TMD Observations

Total Electron Content (TEC)



Total Mass Density (TMD)

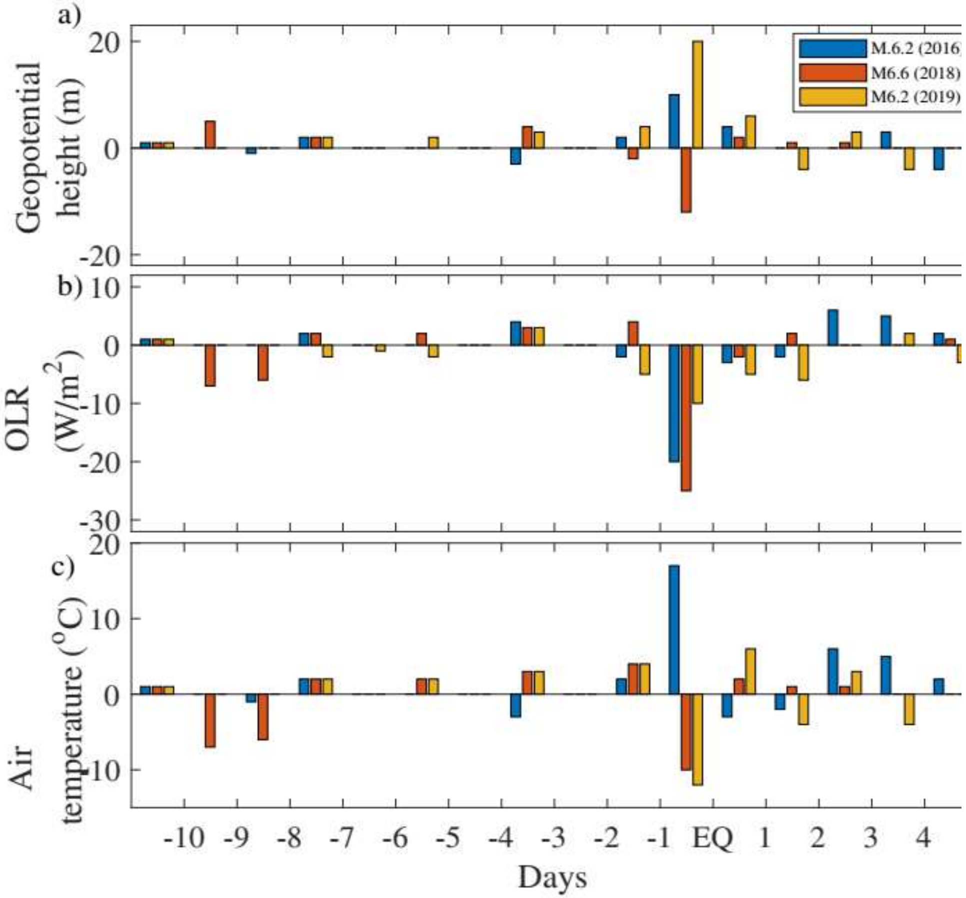


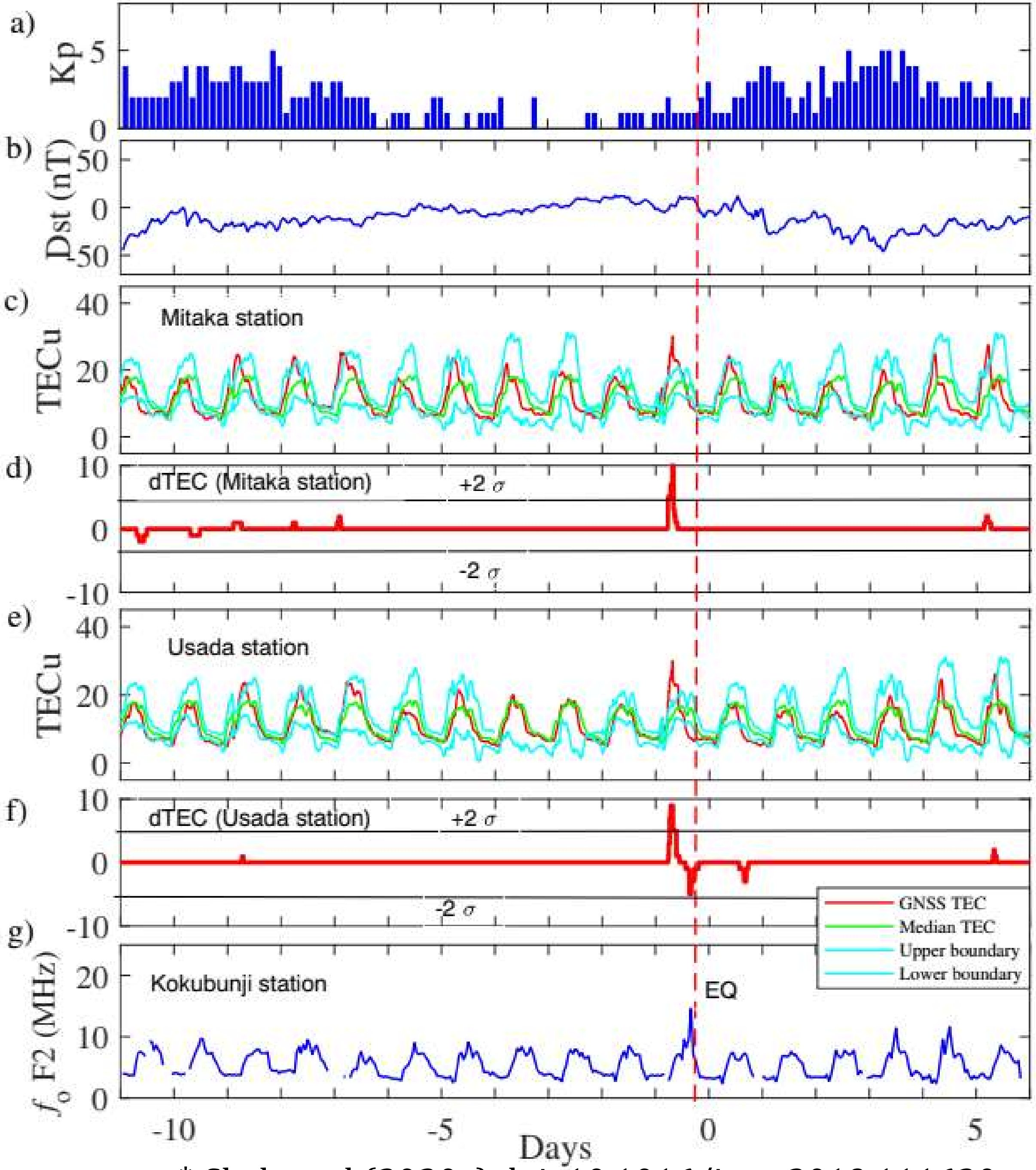
- Comparison of GNSS **TEC** and GRACE **TMD** shows a very similar response to solar flux at the **first PCA modes**. The annual cycle of **TEC** is approximately one order of magnitude larger.
- An hemispheric asymmetry is shown in **TMD**, with higher values in the southern hemisphere. The asymmetry is not visible in **TEC**.

* Calabia and Jin (2020b) doi:10.1007/1345_2020_123

TEC variations during Earthquakes [joint FA-Geohazards]

- **Lithosphere-ionosphere coupling** is investigated from TEC, geopotential height, air temperature, and outgoing longwave radiation during earthquake events.

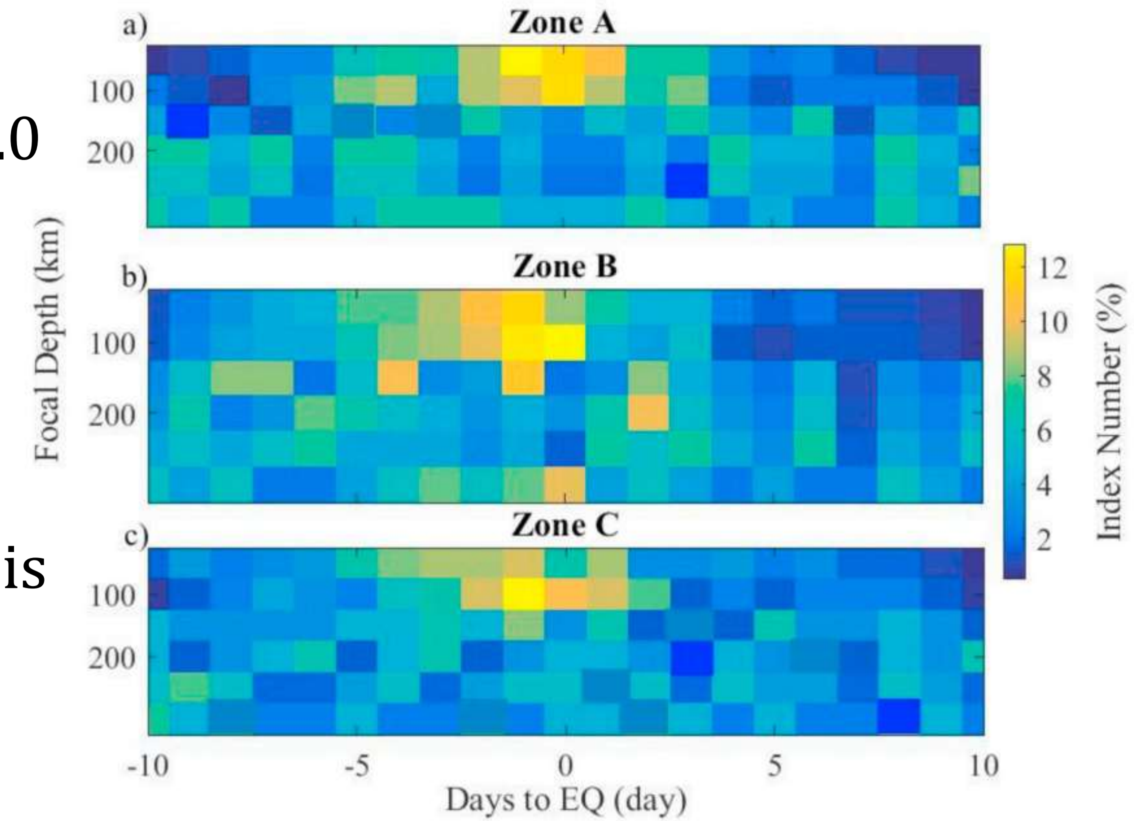


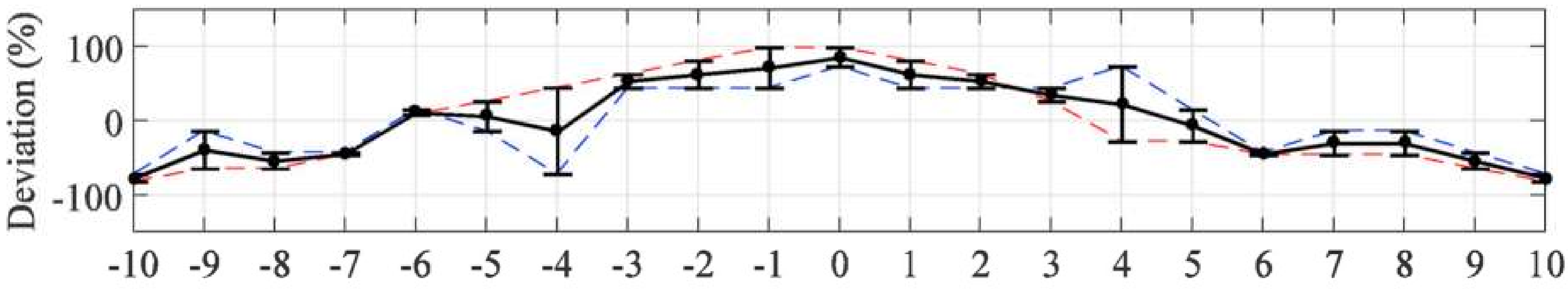


* Shah et al (2020a) doi: 10.1016/j.rse.2019.111620

TEC variations during Earthquakes [joint FA-Geohazards]

- **Statistical analysis of 1182 earthquakes** of magnitude Mw > 5.0 during 1998–2019 produce TEC anomalies within 5 days before the main shock.
- The probability of TEC anomalies occurred before Mw ≥ 6.0 and focal depth of less than 220 km (Zone B) is about 0.8.

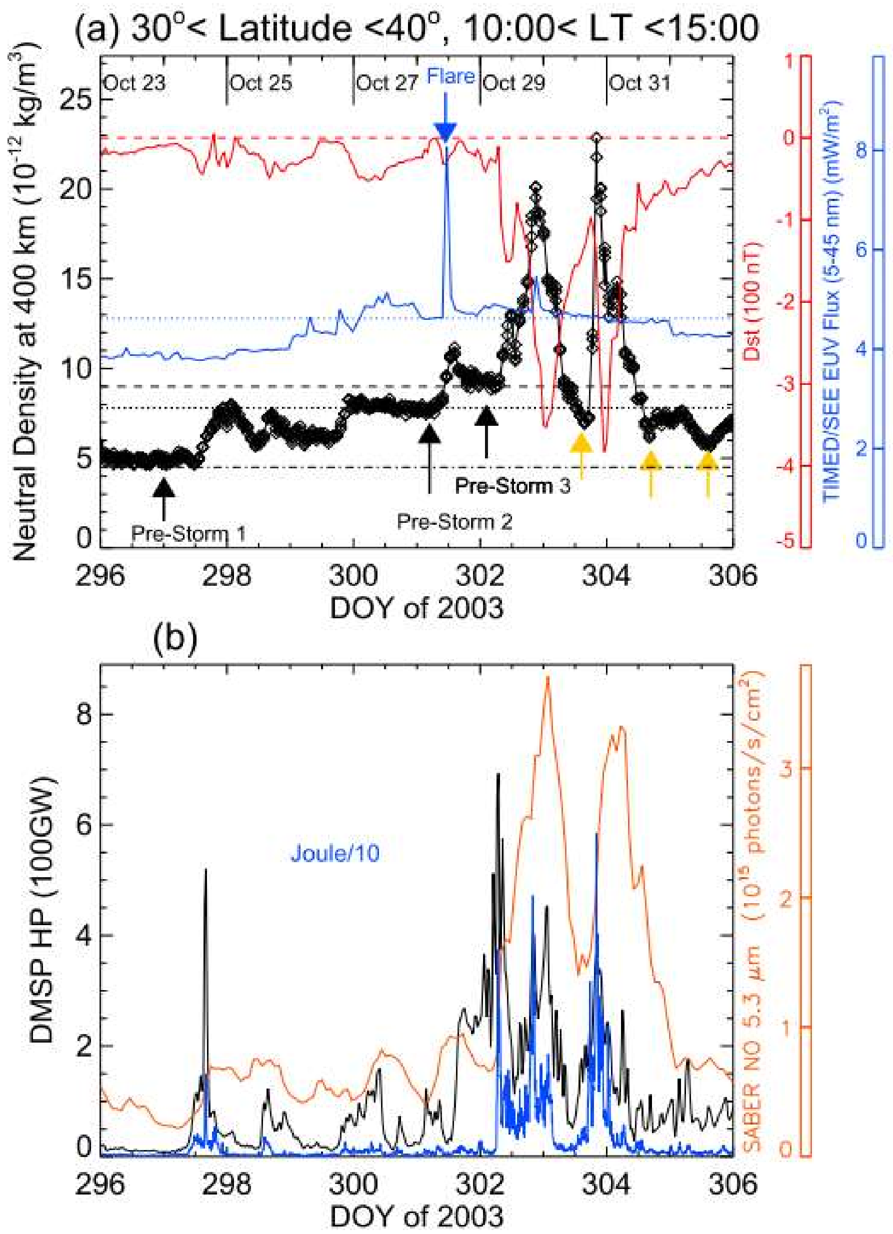


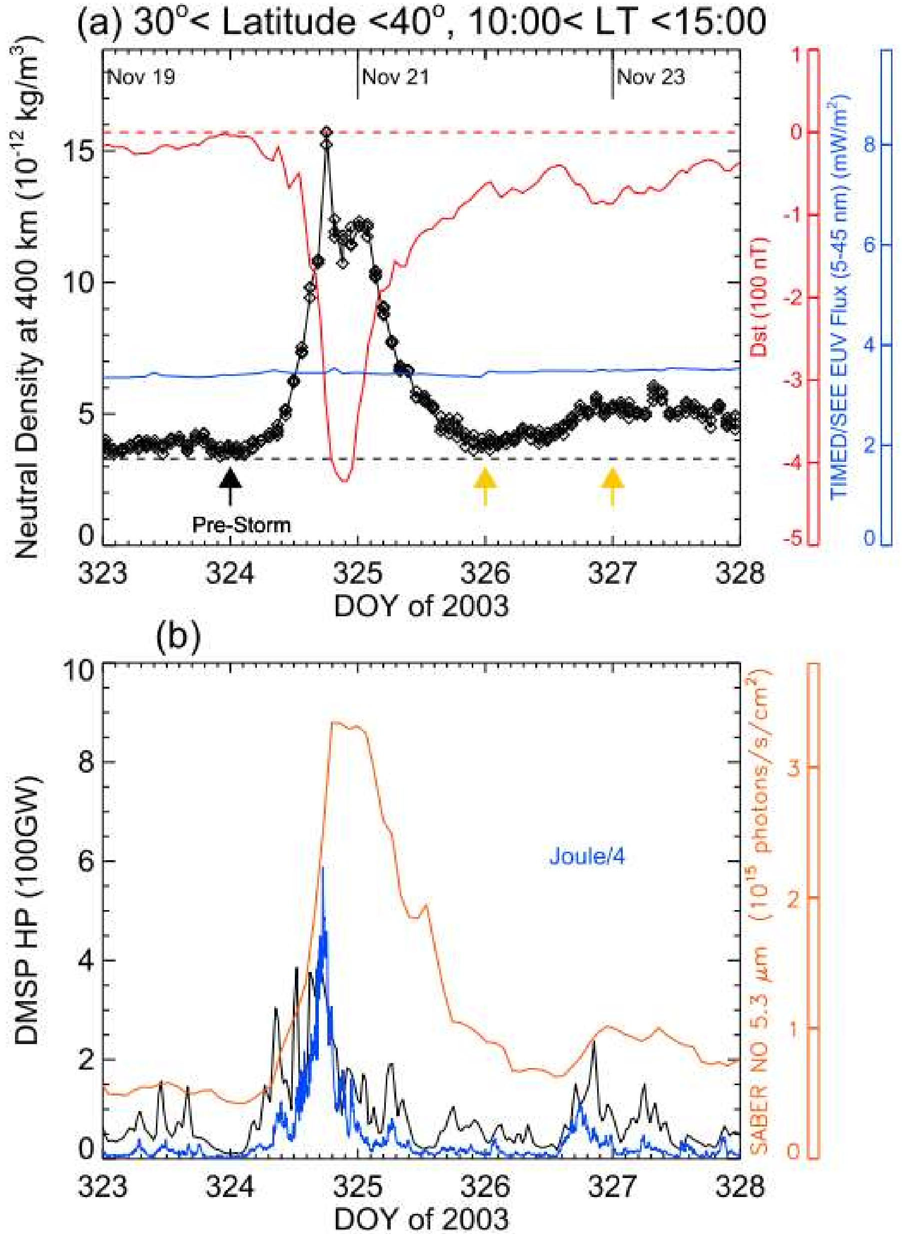


The deviation percentage of the positive and negative TEC anomalies related to EQs in the three different zones of the world.

* Shah et al (2020b) doi: 10.1016/j.actaastro.2020.06.005

TMD cooling due to only NO may not be sufficient

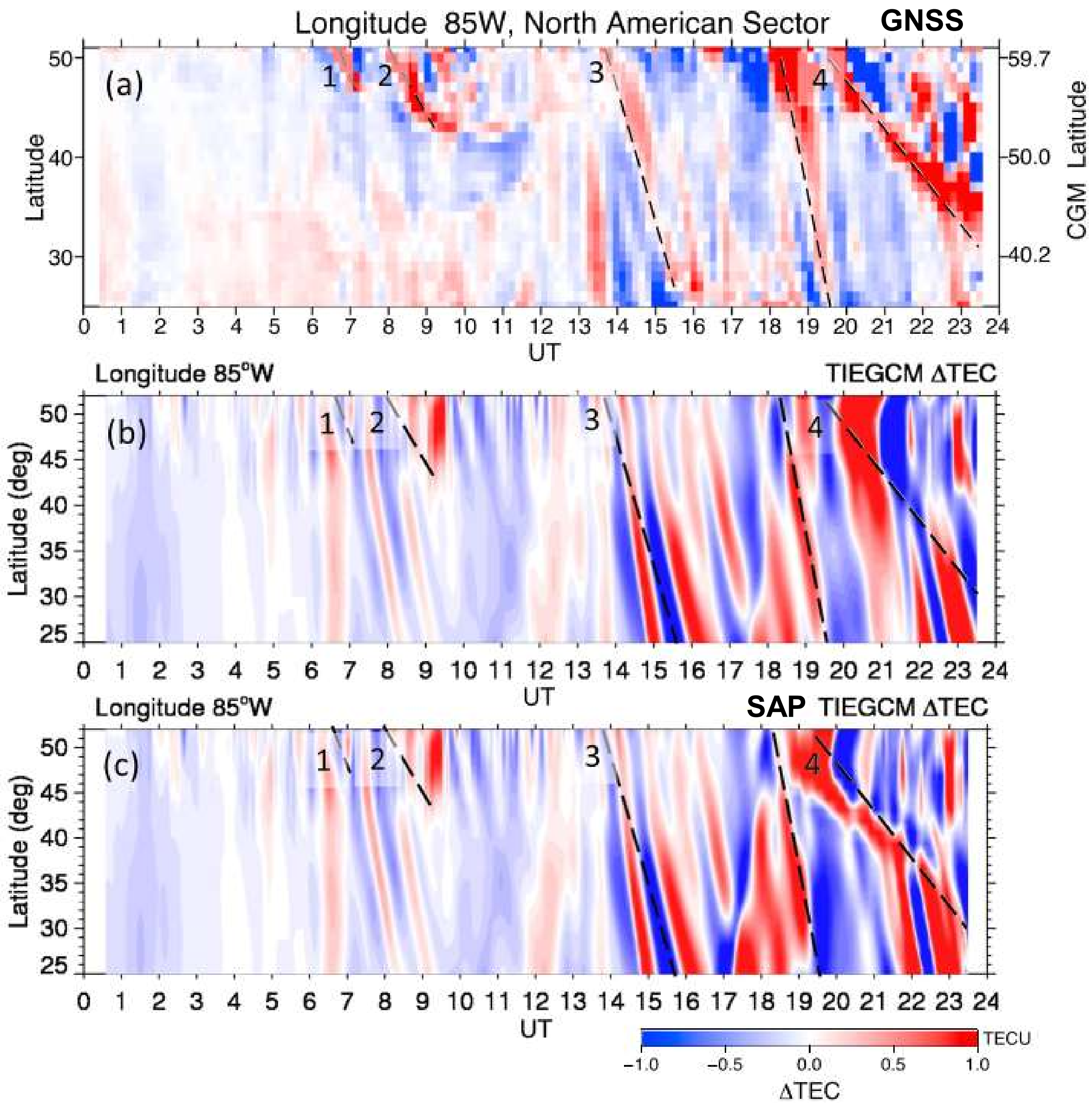


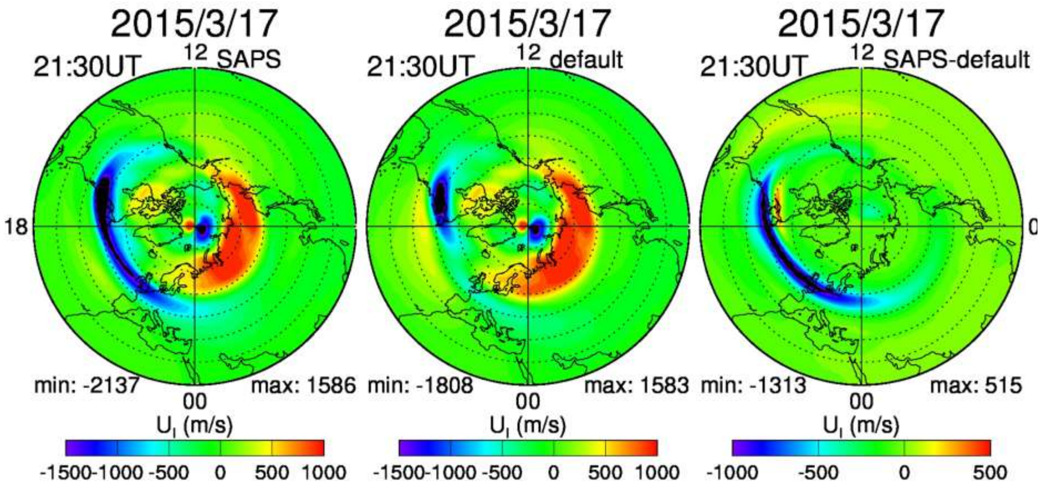


* Zhang et al (2020) doi: 10.1016/j.jastp.2018.11.016

Physics-based Models vs TEC Observations

- TIEGCM and GNSS TEC show storm phenomena driven by **ionospheric convection**, **auroral precipitation**, and **SubAuroral Plasma Stream (SAP)** field.
- Results indicate **further improvements to TIEGCM are required** (such as a more realistic, self-consistent electrodynamic coupling of the ionosphere and magnetosphere).



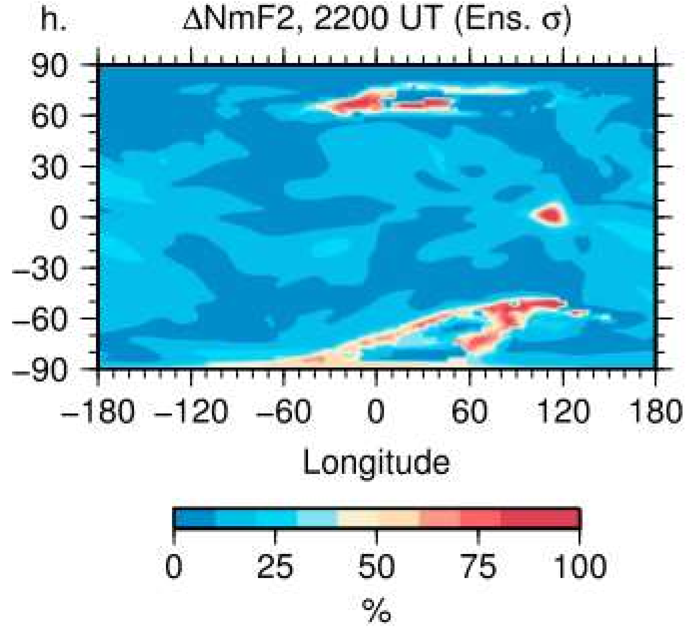


* Lu et al (2020) doi:10.1029/2019JA027726

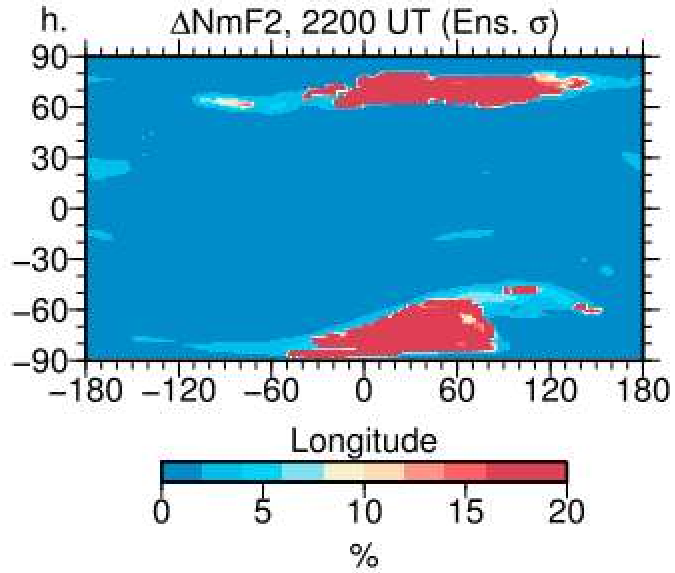
Uncertainties in Physics-based Models

- TIEGCM uncertainties are investigated by perturbing high-latitude electric potential or auroral energy flux in the Assimilative Mapping for Ionosphere Electrodynamics (AMIE).
- There is a large variability when perturbing high-latitude electric potential, in comparison to perturbing the auroral energy flux.
- The effects of the forcing uncertainty are primarily confined to high latitudes.
- Specification of high-latitude electric fields is an important source of uncertainty when modeling the low-latitude and midlatitude ionosphere response to geomagnetic storms.

Perturbing high-latitude electric potential



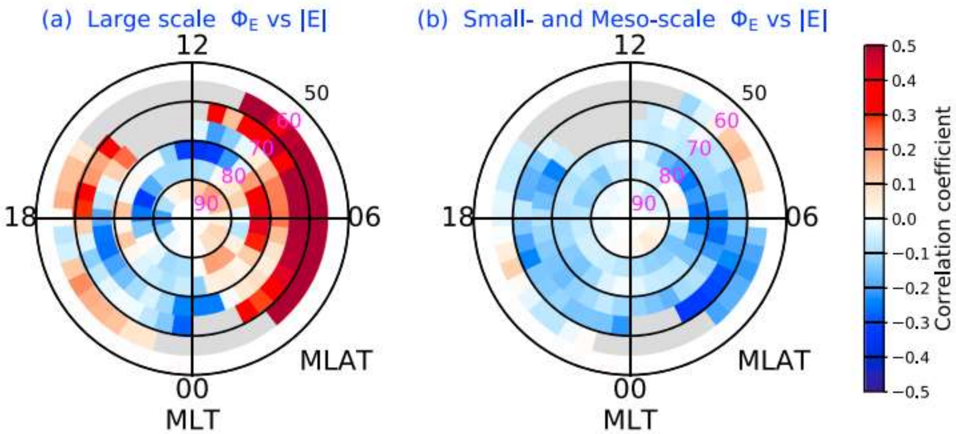
Perturbing auroral energy flux



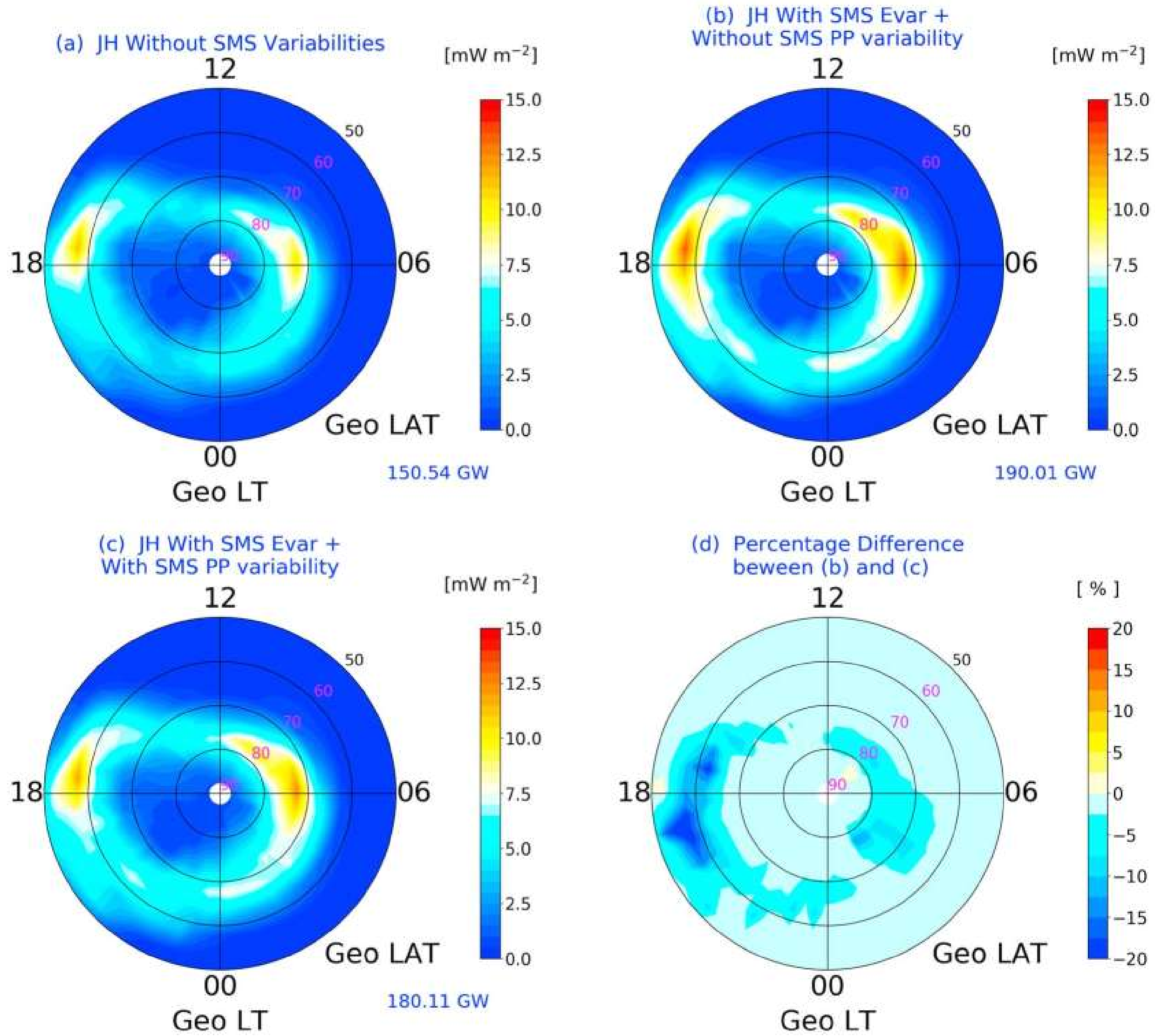
* Petadella et al. (2020) doi:10.1002/2017JA024683

Impact of Electric Field and Particle Precipitation on Joule Heating

- **Electric field** and **particle precipitation** from DE-2 satellite correlate well on small and meso scales.



- **GITM** simulations show **Joule heating** is 27**% globally enhanced by electric field variation**, and particle precipitation reduce this enhancement in 5% globally, and up to 18% locally.



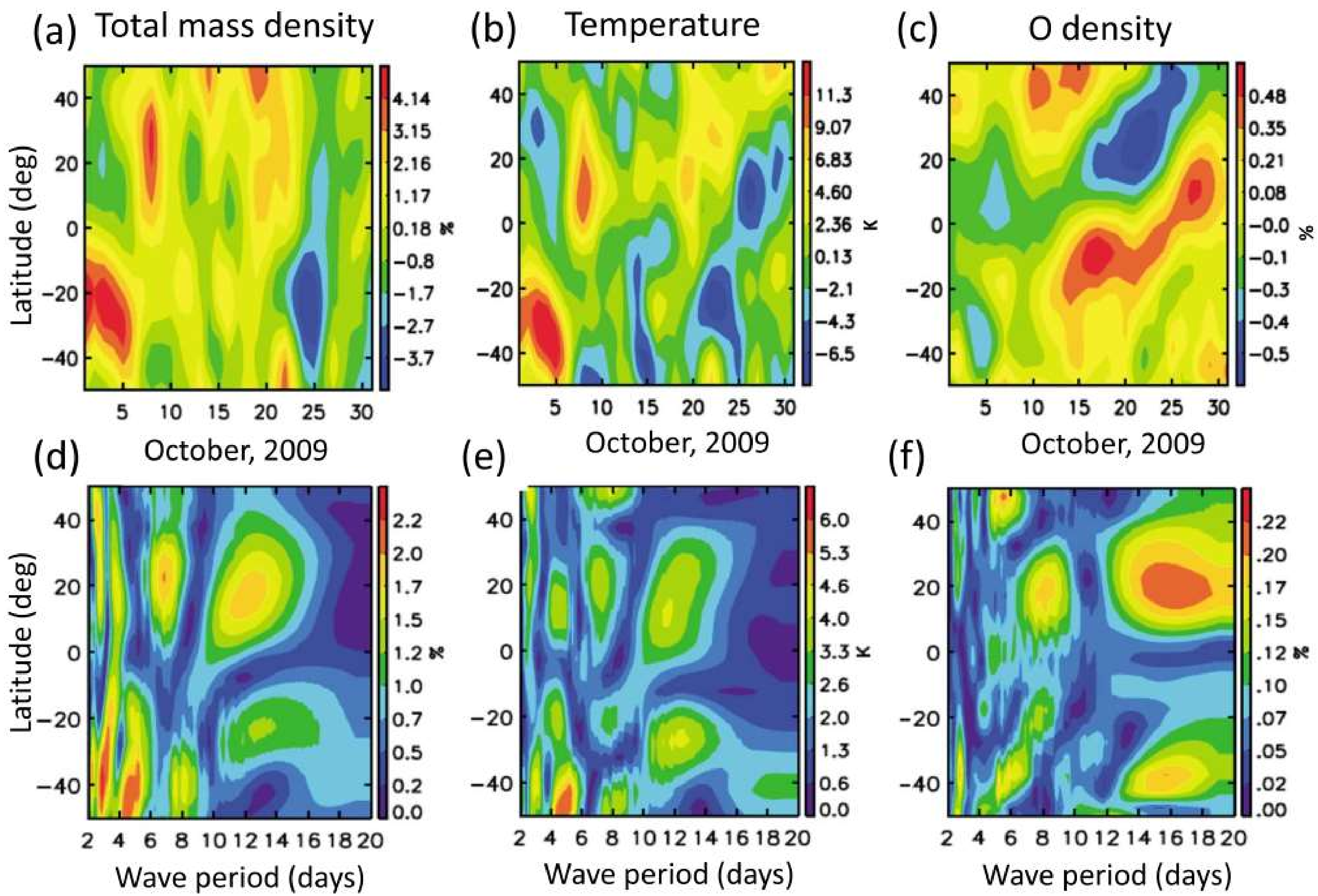
* Zhu et al. (2019) doi:10.1029/2018JA025771

Understanding Physics-based Models

- TIEGCM simulations show the tide contributions to S0 TMD response at 325 km consists of planetary wave fluctuations of order ±4%, roughly equivalent to the day-to-day variability associated with low-level geomagnetic activity.

- The short periods **TMD variability (< 9 days) correlates with temperature changes** (hydrostatic origin).

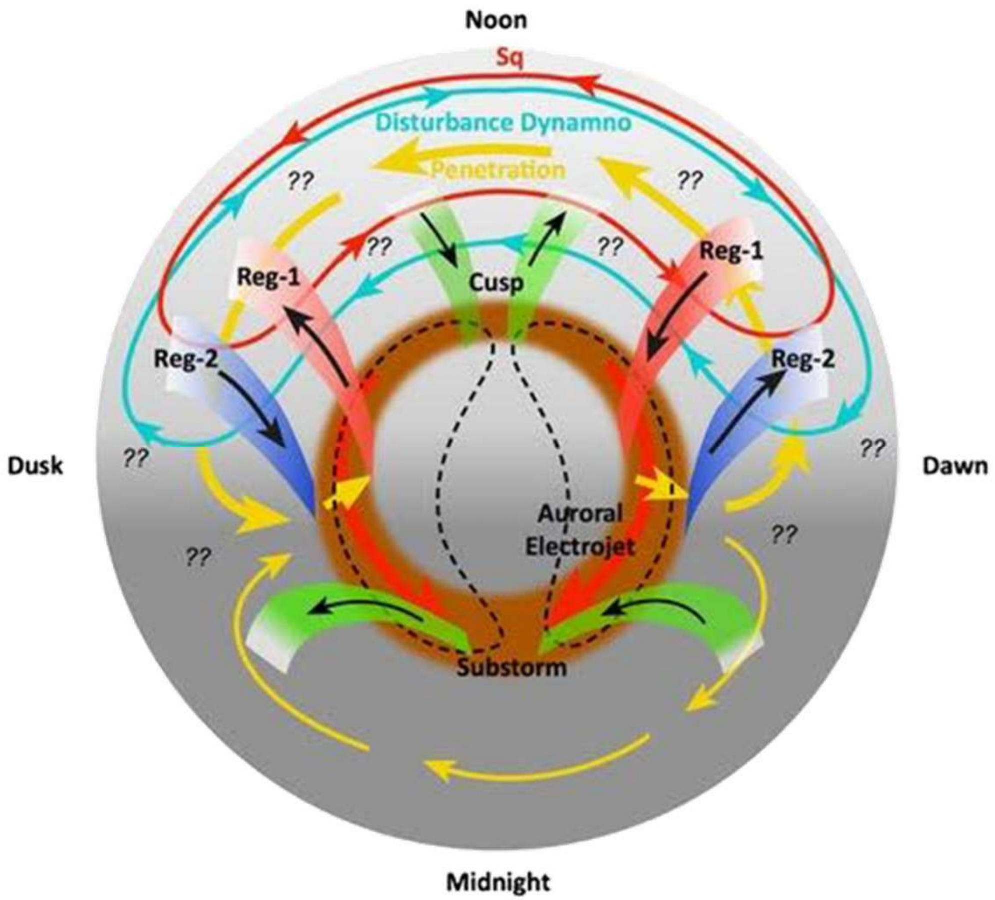
- Over longer periods TMD is also controlled by composition and mean molecular mass.

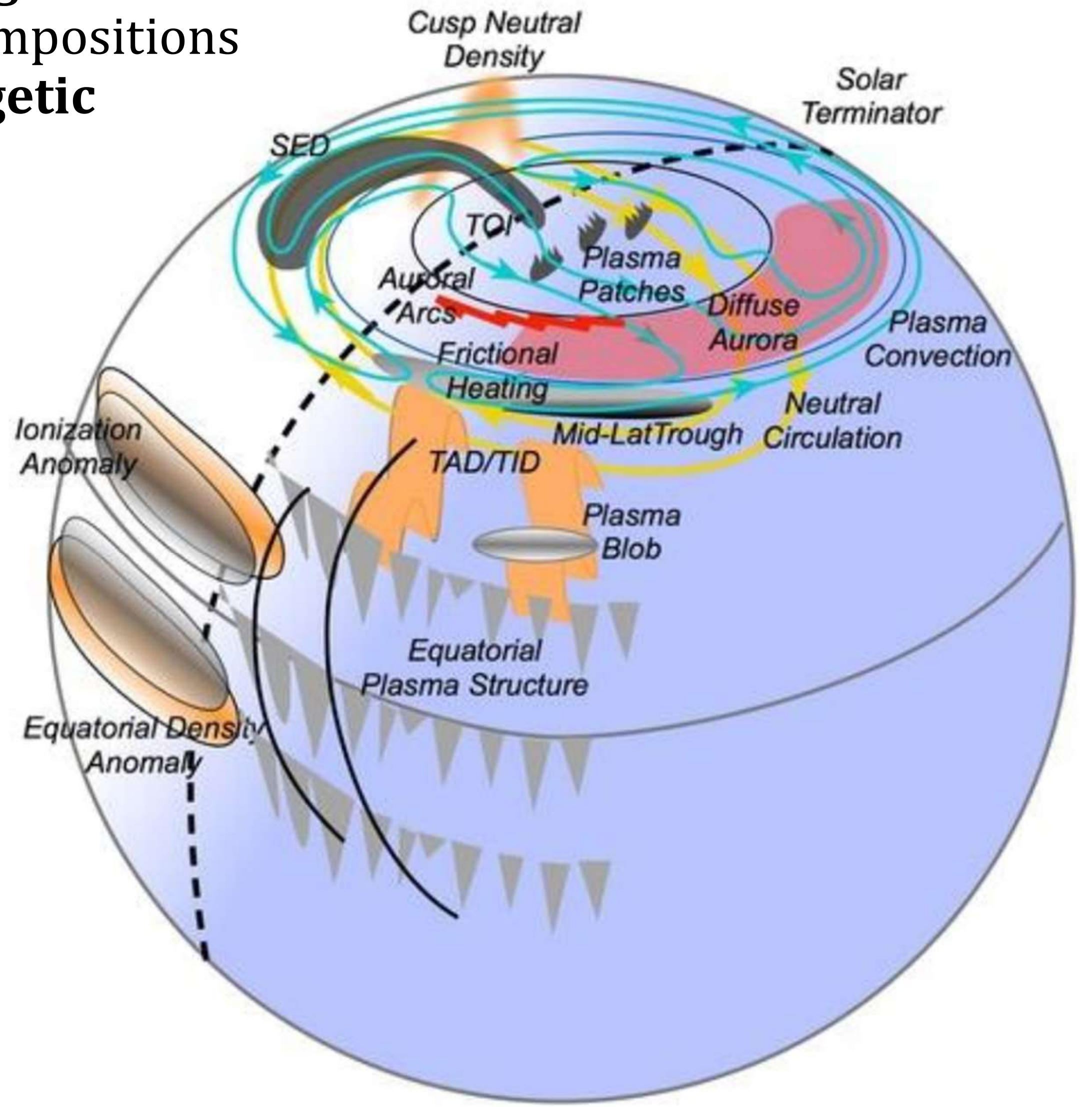


* Forbes et al. (2020)
doi: 10.1002/2018JA025258

A Challenge to Understand the MTI System

- MTI is strongly influenced by wave motions from the lower atmosphere, and is coupled through energetic particle precipitation and field-aligned currents.
- Addressing the challenge requires advances in **geodetic observations** of **plasma** and **mass density** compositions and velocities, as well as the dynamics of **energetic particles** and field-aligned **currents** from magnetospheric energy inputs.





* Heelis and Maute (2020) doi:10.1029/2019JA027497

Summary

Recent activities:

1. Enhancement of international cooperation with developing countries by sharing knowledge and research tools, co-supervising thesis and helping to improve manuscripts, etc.
2. Elaboration and submission of scientific manuscripts co-authored by JSG1 members.
3. Elaboration and submission of a project at the *International Space Intelligent Innovation and Entrepreneurship Competition*, Nanjing, China. (funds not granted)

Present work:

1. Working effectively within the group members, creating a common platform to increase communication. Prepare spreadsheet to know the interests of each group member.
2. Increase international cooperation to break the existing isolation.
3. Participation in a blended mode of international conference at Nepal Physical Society.
4. Elaboration of proposal for *International Workshop on MTI Coupling (IWMTIC2021): Prospects, Challenges, and Opportunities*. Kathmandu, Nepal. June 2022?

Future plans:

1. Advancement of MTI science in developing countries by organizing workshops, etc.
2. Organizing a session at the 2022 Hotine-Marussi symposium.
3. Improvement and submission of the existing project draft to request funds for publications fees, etc.

Munawar

Thank you !