中国科学院国家空间科学中心
National Space Science Center, CAS

Preliminary Application of a Global MHD Simulation Model of Earth's Magnetosphere on Space Weather Forecast

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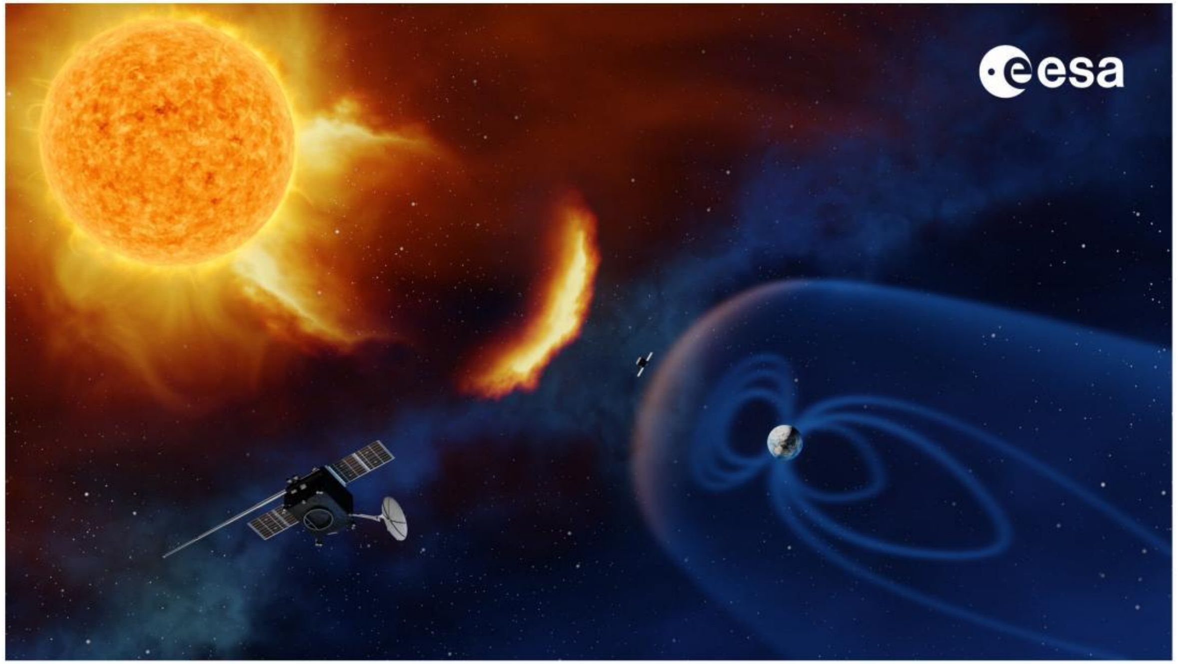
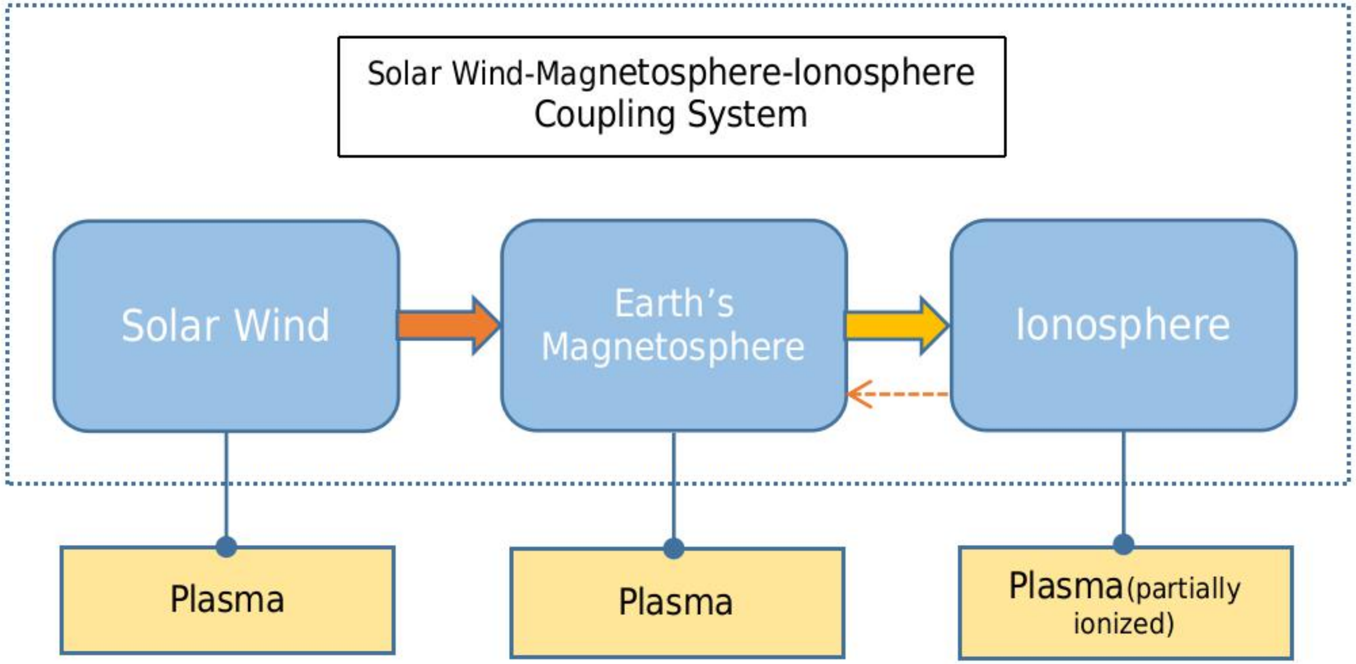
Space weather from Sun to Earth



Causal chain from Sun to Earth, and its geoeffects on ground.

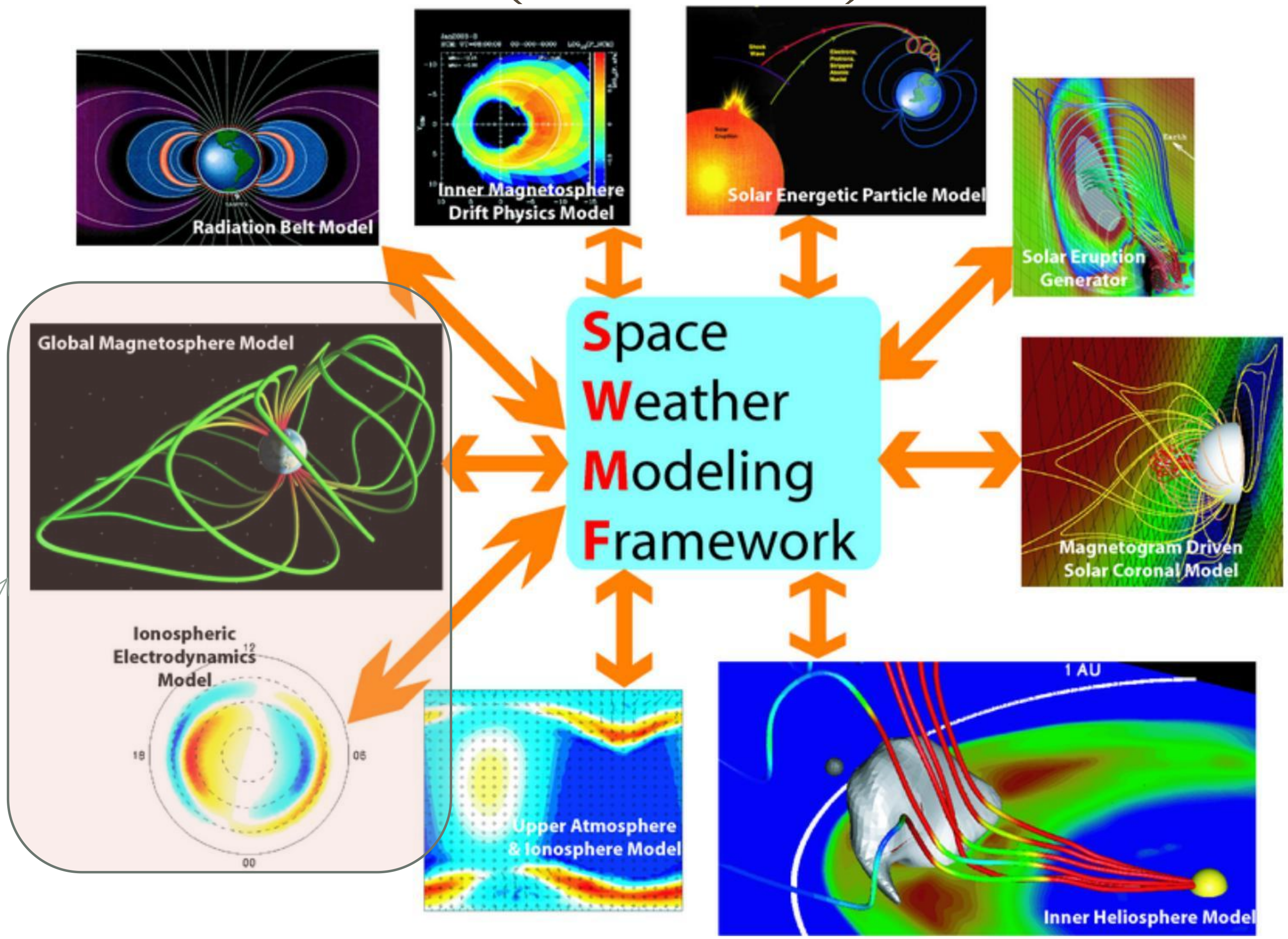
Physics of Space Weather



Physical discription:

- magnetohydrodynamics, for large- and meso- scale plasma in interplanetary space and magnetosphere;
- electrostatics, for ionosphere;

The Space Weather Modeling Framework (SWMF)

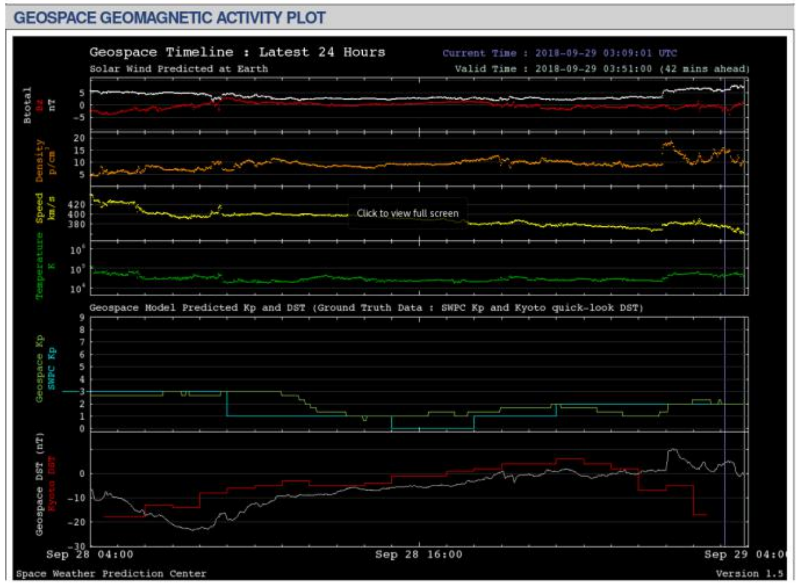


global MHD model

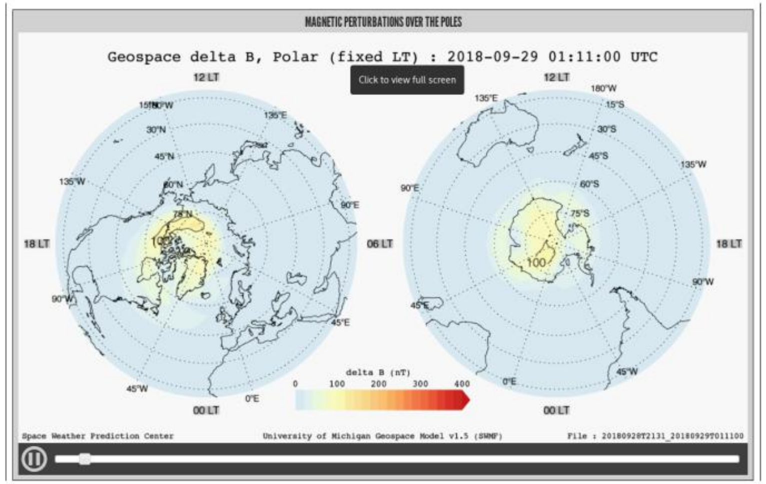
[Toth+, 2005]

Geospace Model Products

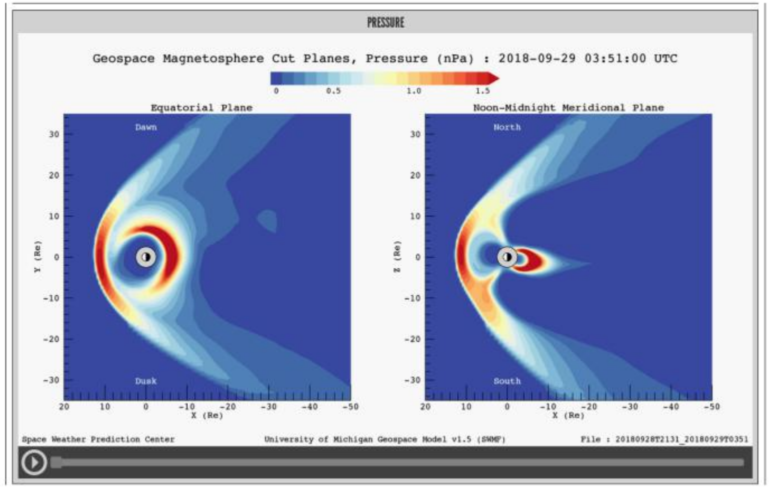
Geospace Global Geomagnetic Activity Plot



Geospace Ground Magnetic Perturbation Maps



Geospace Magnetosphere Movies



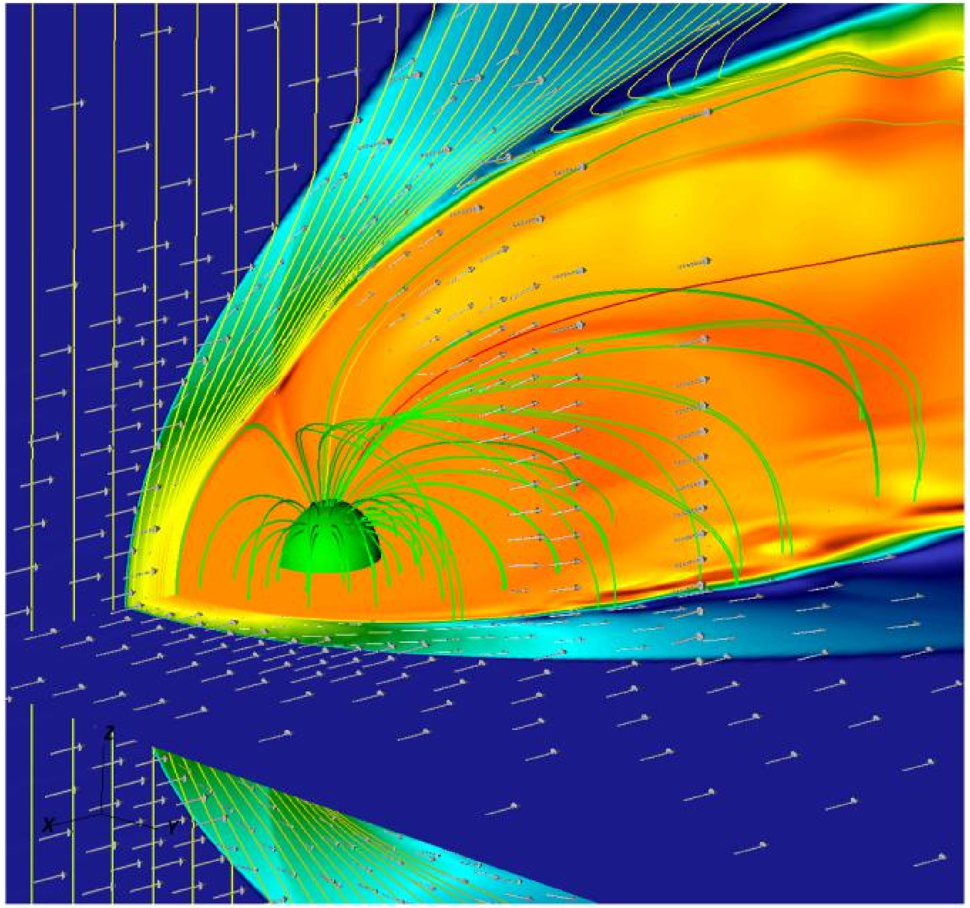
- Solar wind from ACE/DSCOVR, mapping to 32 earth radius ahead of the magnetosphere;
- 30 to 60 minutes advanced warning;

Details, see: https://www.swpc.noaa.gov/products/

PPMLR-MHD Model

- 3D ideal MHD equations;
- Cartisian coordiante;
- MUSCL, or PPMLR numerical scheme;
- Up to third order in space;
- finite volume method (FVM);
- Rusanov+HLL type Riemann solvers, characteristic method;
- mixed GLM for divergence B cleaning;
- embeded with an electro-static ionosphere;
- fully MPI parallelization.

- original version [Hu, et al., 2007];
- Jovian magnetnosphere [Wang, et al., 2018];
- extended version for earth's magnetosphere [Guo+,2015; 2016]



magnetic field lines and plasma flows in magnetosphere from a simulation during a typical northward IMF condition.

Electrostatic ionosphere

- infinitely thin spherical shell;
- field-aligned currents near a radial distance of 3 earth radius

$$\mathbf{J}_{||} = \nabla \times \mathbf{B} \cdot \hat{\mathbf{b}}$$

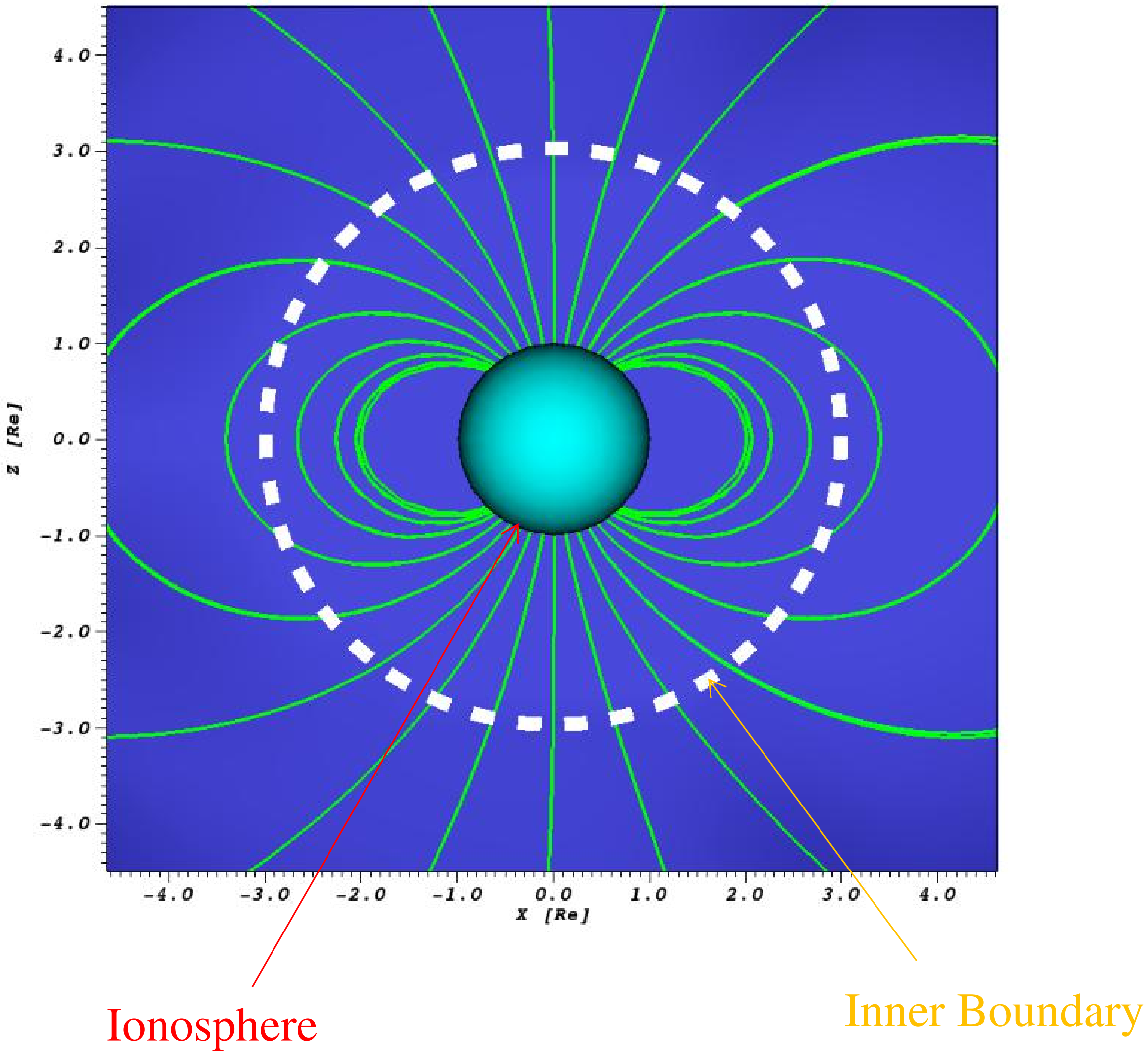
- FACs flow into ionosphere;
- Poisson equations

$$\nabla \cdot (\Sigma \cdot \nabla \Phi) = -j_{||} \sin I$$

- convection speed

$$\mathbf{u} = \mathbf{E} \times \mathbf{B} / B^2$$

- Perdeson and Hall conductivities;



Ionospheric Conductivities

Hall and Pedersen conductances [Robinson+, 1987]:

$$\Sigma_p = \frac{40E}{16 + E^2} F_E^{1/2}$$

$$\Sigma_H = 0.45 E^{0.85} \Sigma_p$$

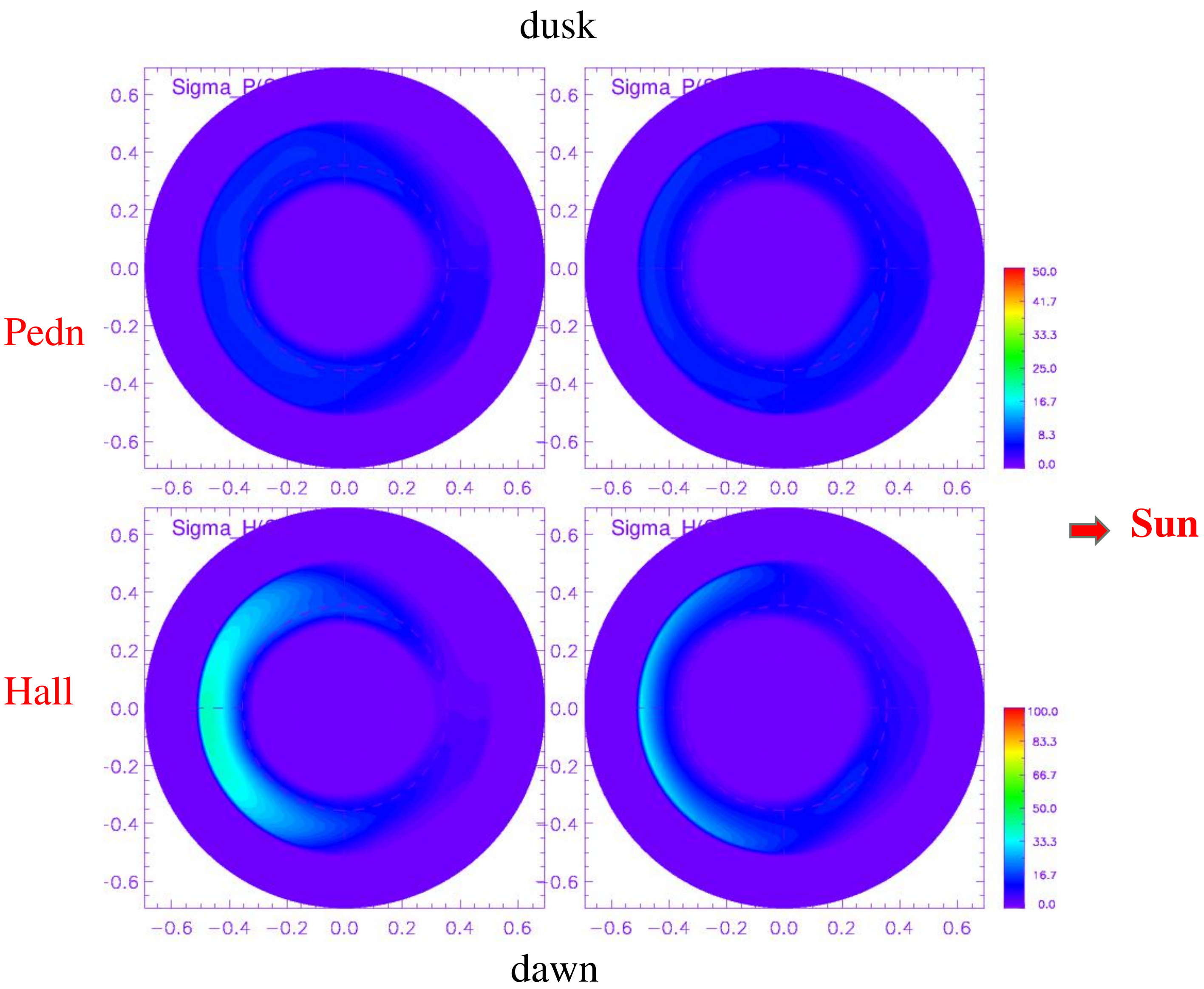
E is the average energy in keV and F is the energy flux in ergs/cm^2 s.

diffuse electron precipitation:

$$F = n_e \sqrt{E/m_e}, \quad E = kT_e$$

discrete electron precipitation[Knight, 1972]:

$$F = \Delta\Phi_{//} j_{//}, \quad E = e\Delta\Phi_{//}$$



Comparison with Other Models

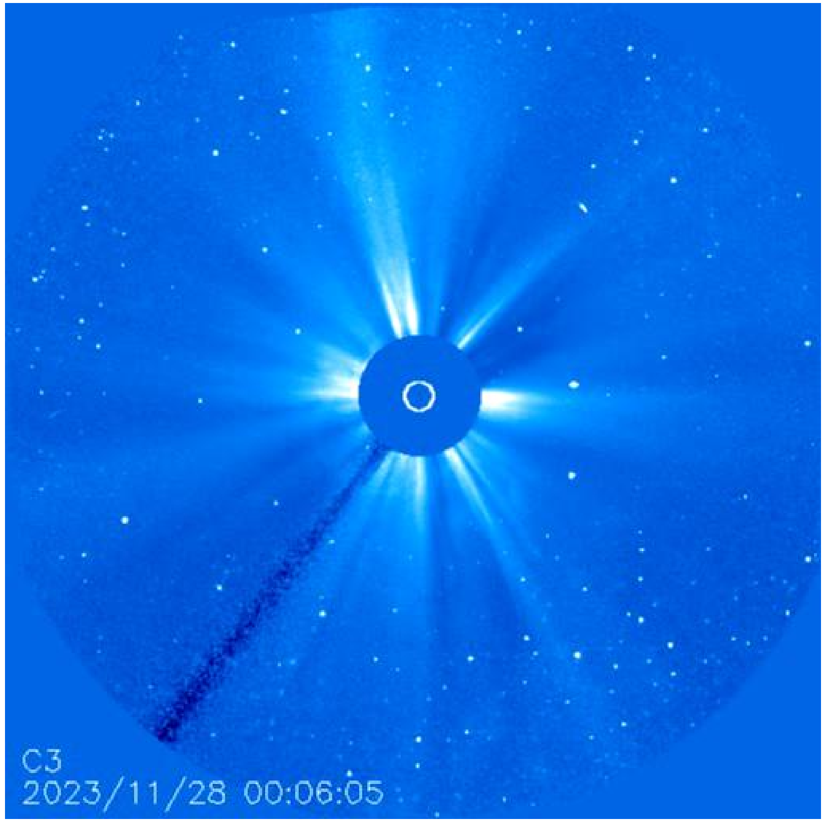
	BATS-R-US	GUMICS-4	LFM (GAMIRA)	OpenGGCM	PPMLR-MHD
MHD equations	ideal, con-servative, $B_0 + B_1$	ideal, con-servative, $B_0 + B_1$	ideal, resistivity, semi-conservative, $B_0 + B_1$	resistivity, non- and conserva-tive	ideal, con-servative, $B_0 + B_1$
Riemann Solver	Roe& HLLE	Roe& HLLE	Water-bag beam	Rusanov	HLLD, Characteristics
Spatial and time accuracy	2/2	1/1	8/2	4/2	2(3)/2
Grid	Cartesian, static, block-refined	Cartesian, dynamic, cell-refined	distorted, spherical, static, not refined	stretched Carte-sian, static, not refined	Cartesian, static, not refined
Coordiantes	GSM	GSE	SM	GSE	GSM

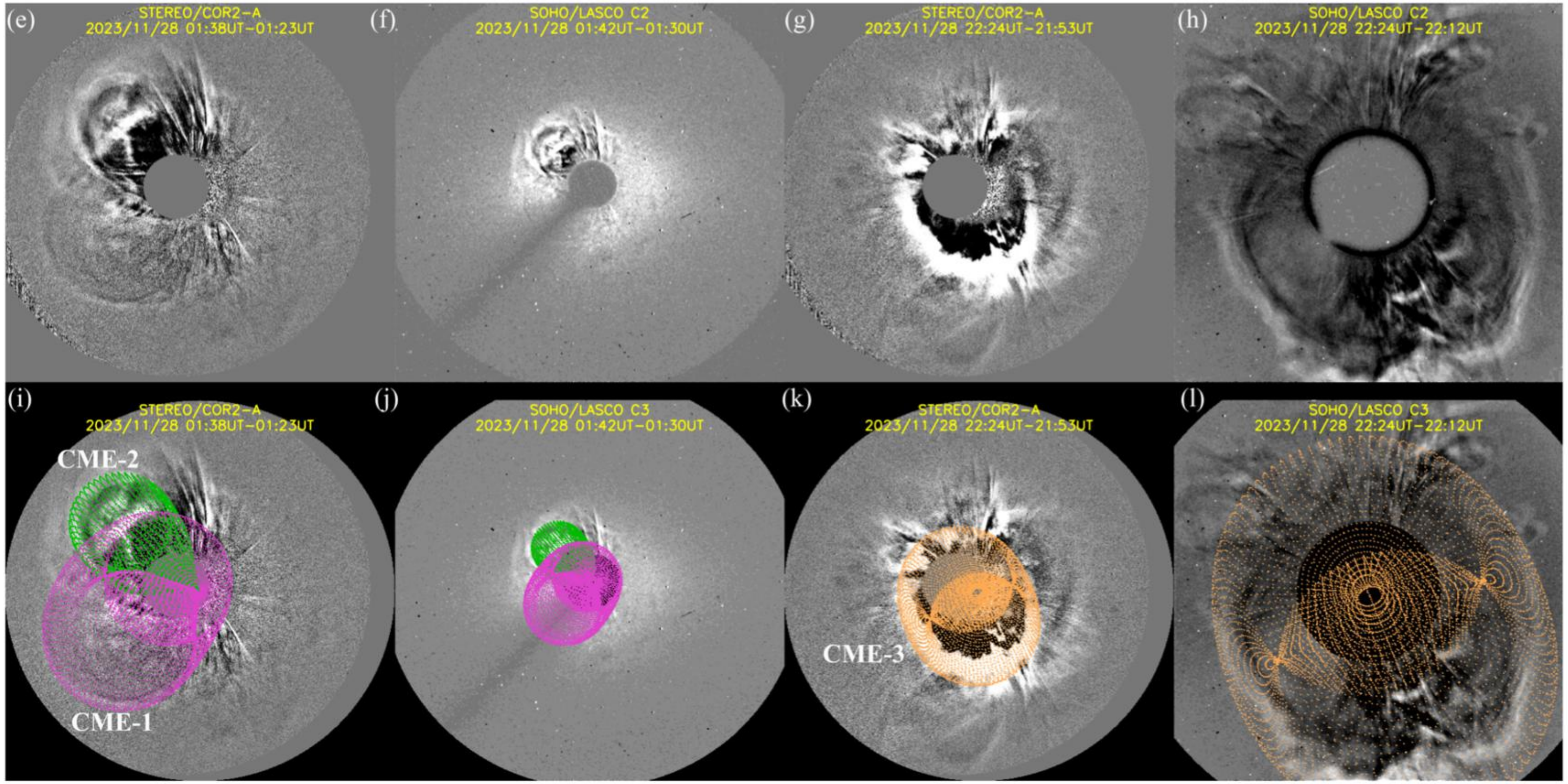
Products of Our Global MHD Model

- Large-scale structure of magnetosphere: bow shock, magnetopause, and other interested regions, virtual spacecrafts;
- Ground Magnetic Perturbation Maps: a global or local view of magnetic perturbation due to varitions of ionospheric current, field-aligned current, and magnetospheric current;
- Geomagnetic Index Plots: Kp, Dst, AE index.

CME events on 12-01-2024

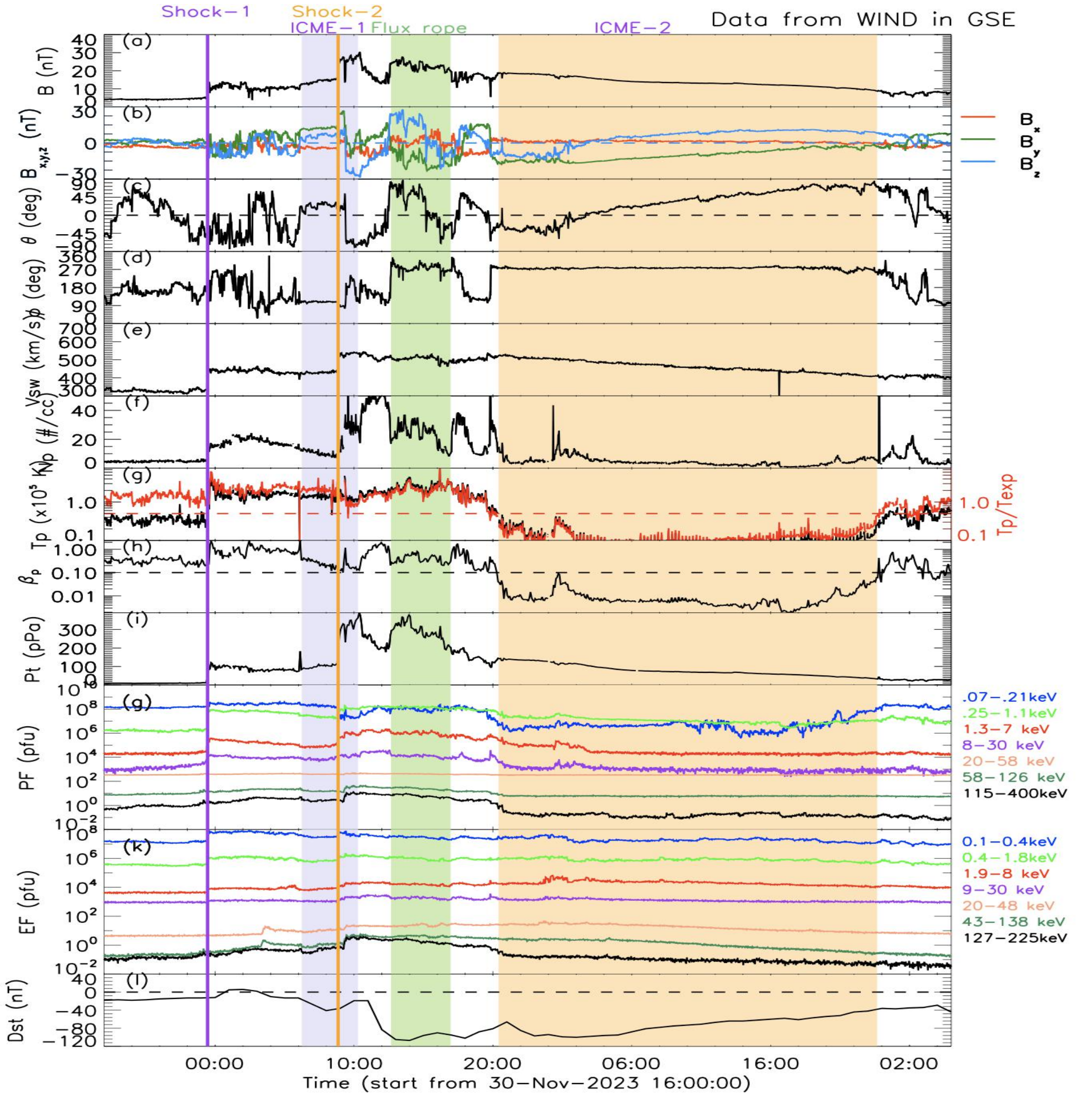
Courtesy of Shen Chenlong





No.Event	Initial Time (UT)	Longitude (°)	Latitude (°)	Half Width (°)	Height ($R_\odot$)	Initial Speed (km/s)	Tilt Angle (°)
CME-1	2023-11-27T20:53:30	-14.5(±5)	-3.2(±5)	30.48(±10)	6.13(±2)	901.57(±50)	48.0
CME-2	2023-11-28T00:38:30	-23.0(±5)	29.0(±5)	29.29(±10)	9.47(±2)	1184.15(±50)	-50.0
CME-3	2023-11-28T21:38:30	-2.0(±5)	-7.0(±5)	35.42(±10)	11.34(±2)	1374.25(±50)	-60.0

Solar wind near Earth



Events from multiple ICME

Dst = -107nT at the time：

2023-12-01T14:00:00

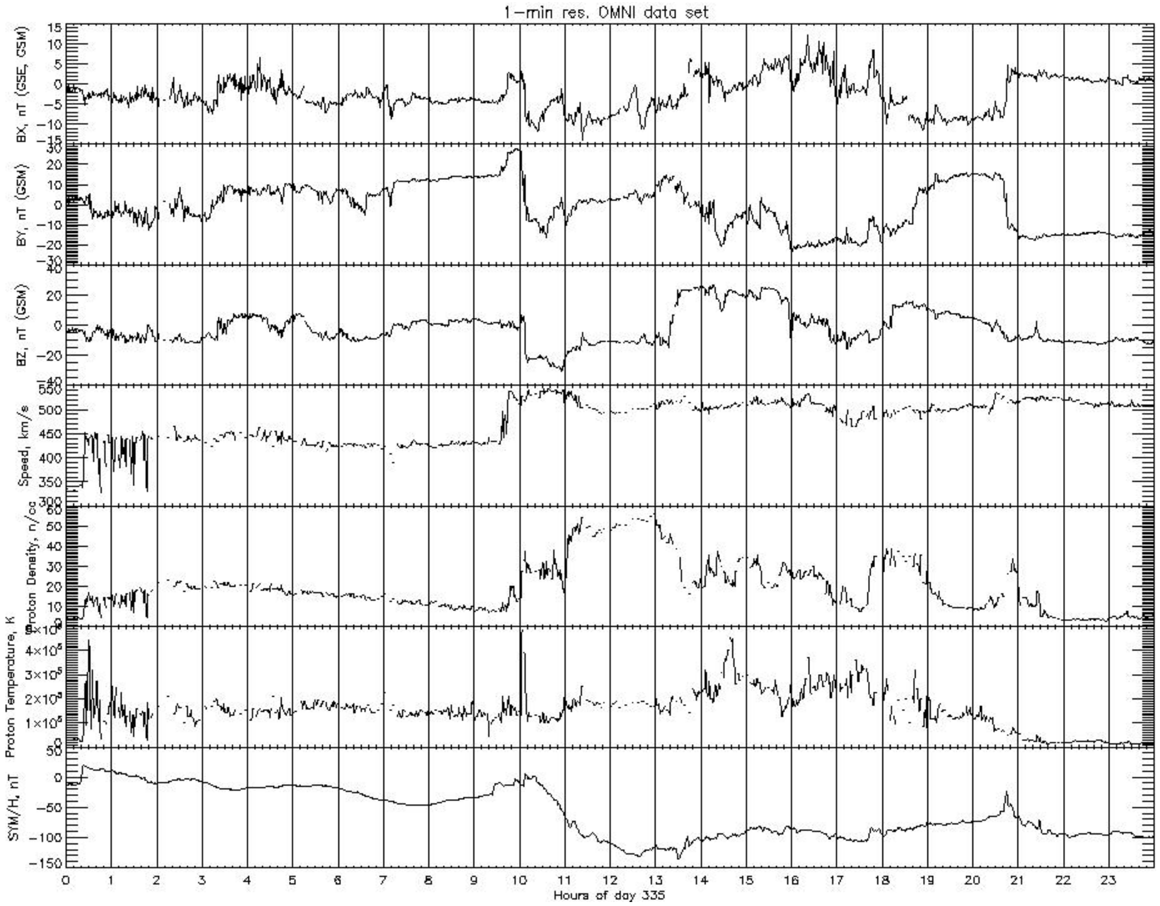
Courtesy of Shen Chenlong

Observed Auroras

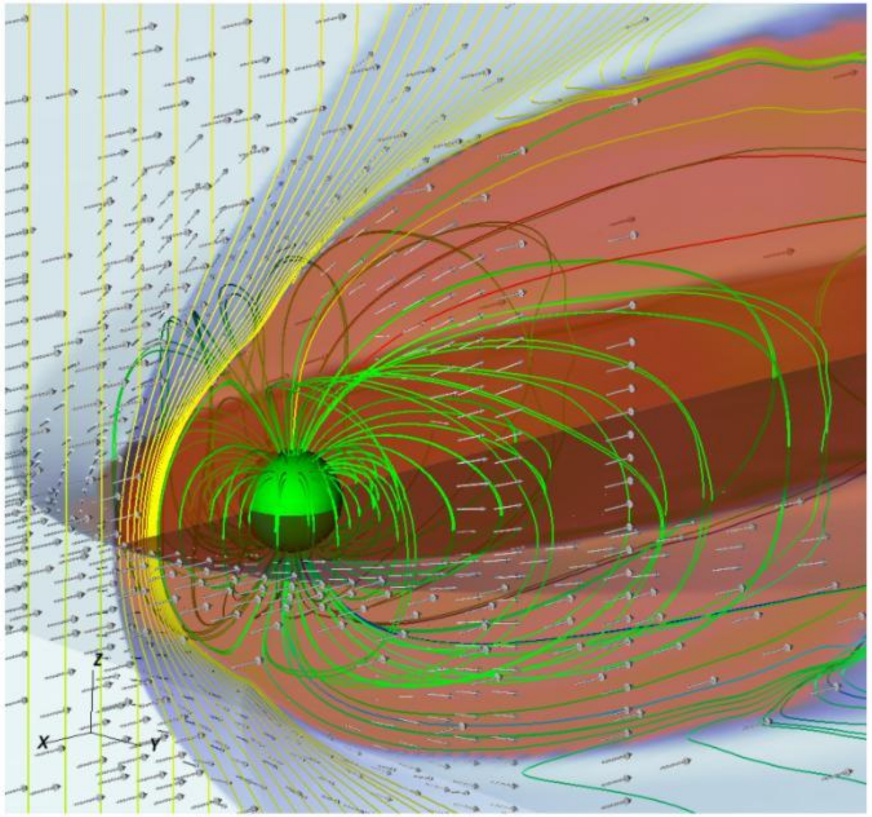
Beijing suburbs (~ 40° lat)

Mohe, Heilongjiang Province (~ 53° lat)

Simulation of 2023-12-01 event

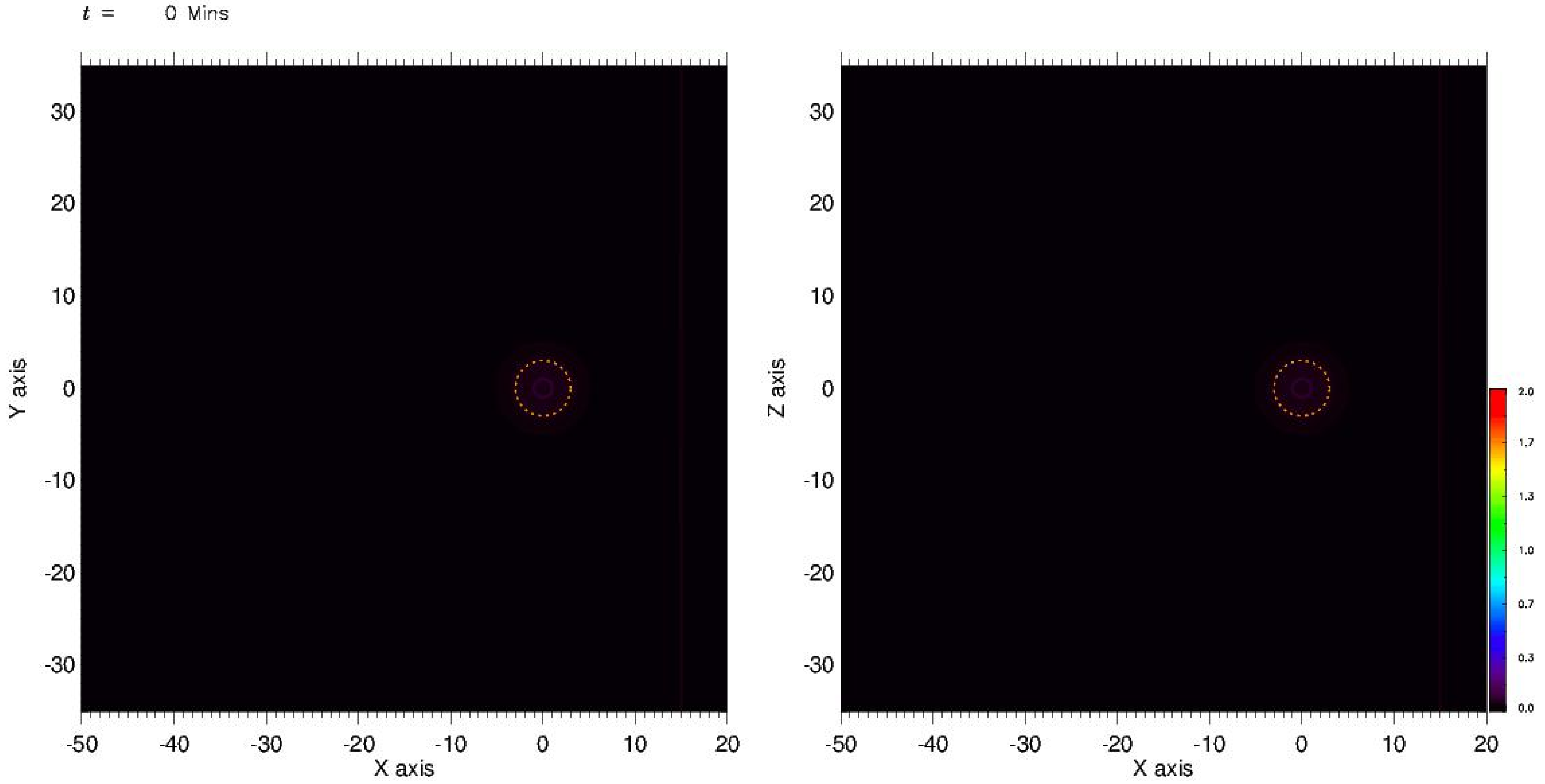


solar wind from OMNI database



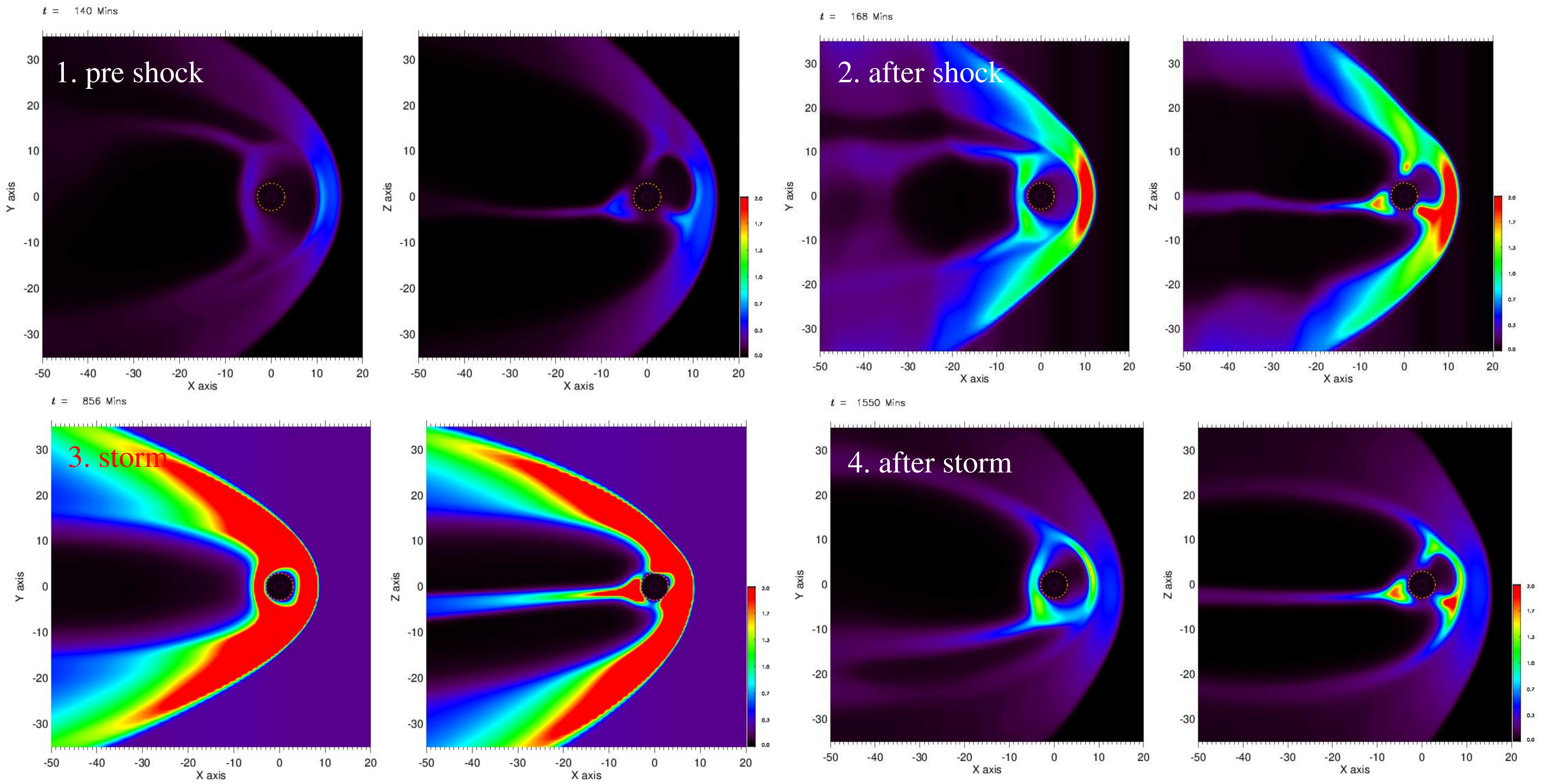
global MHD simulation

MHD Evolution of magnetosphere

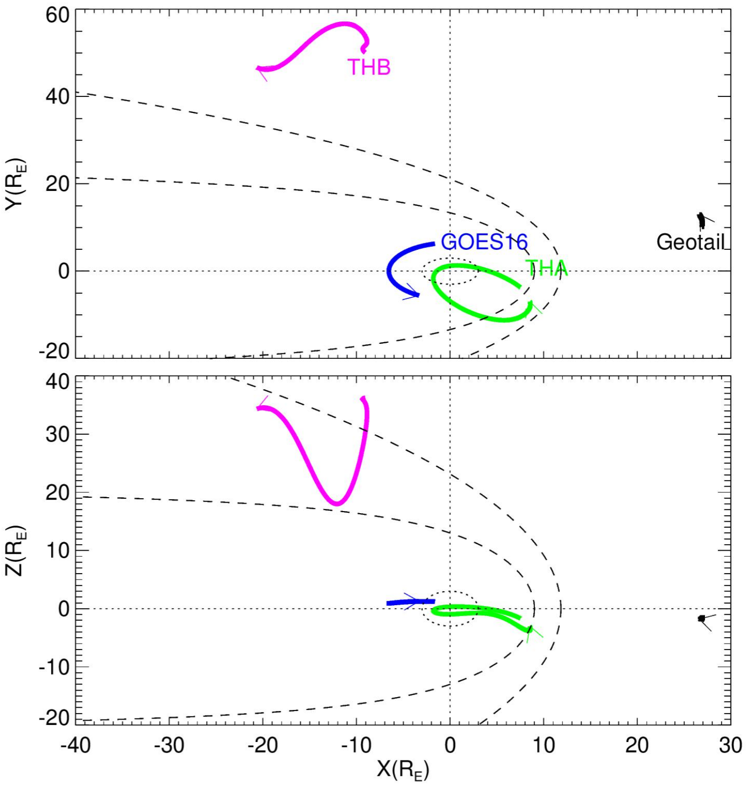


simulation with an interval from 2023-11-30-22:00 to 2024-12-2-00:00

P1. Large-scale structure - magnetosphere



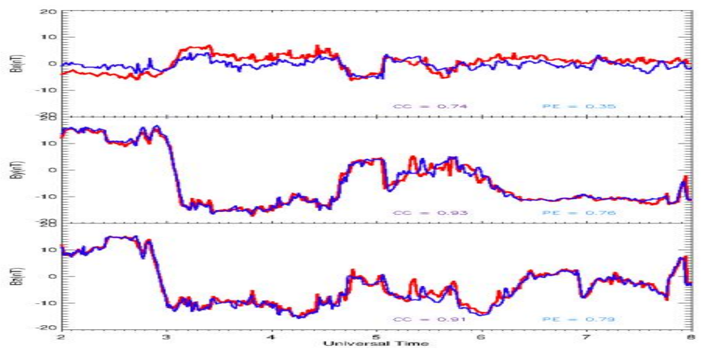
P1. Large-scale structure - virtual spacecrafts



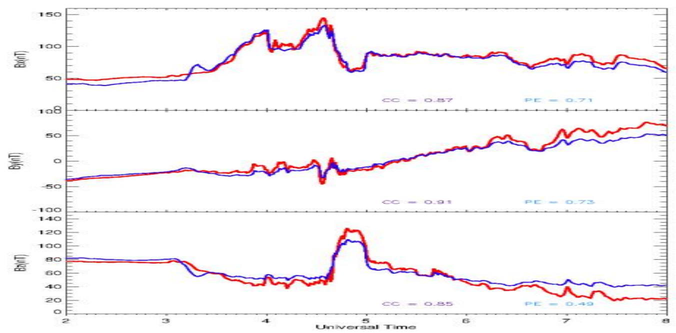
Trajectories of Geotail, GOES 16 and THEMIS A/B in GSM coordinate during the time.

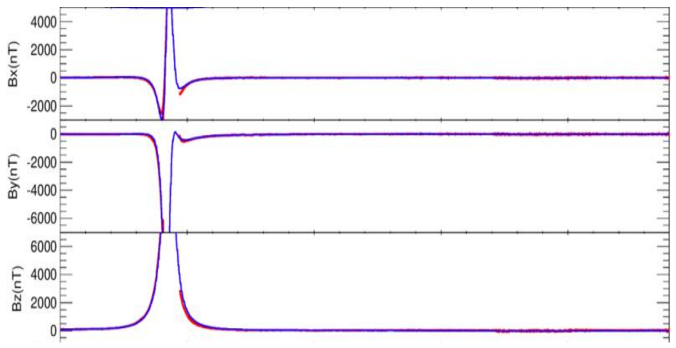
* 2022-04-10 case

Geotail

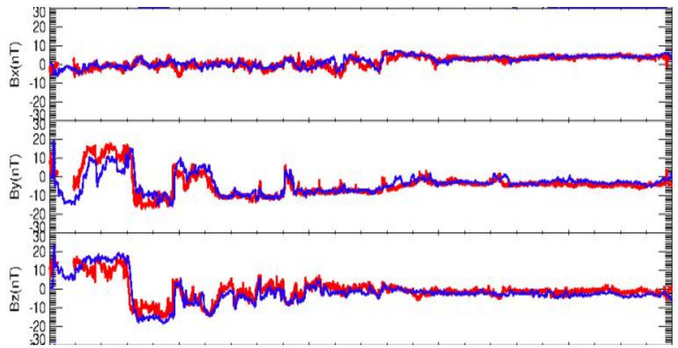


GOES16





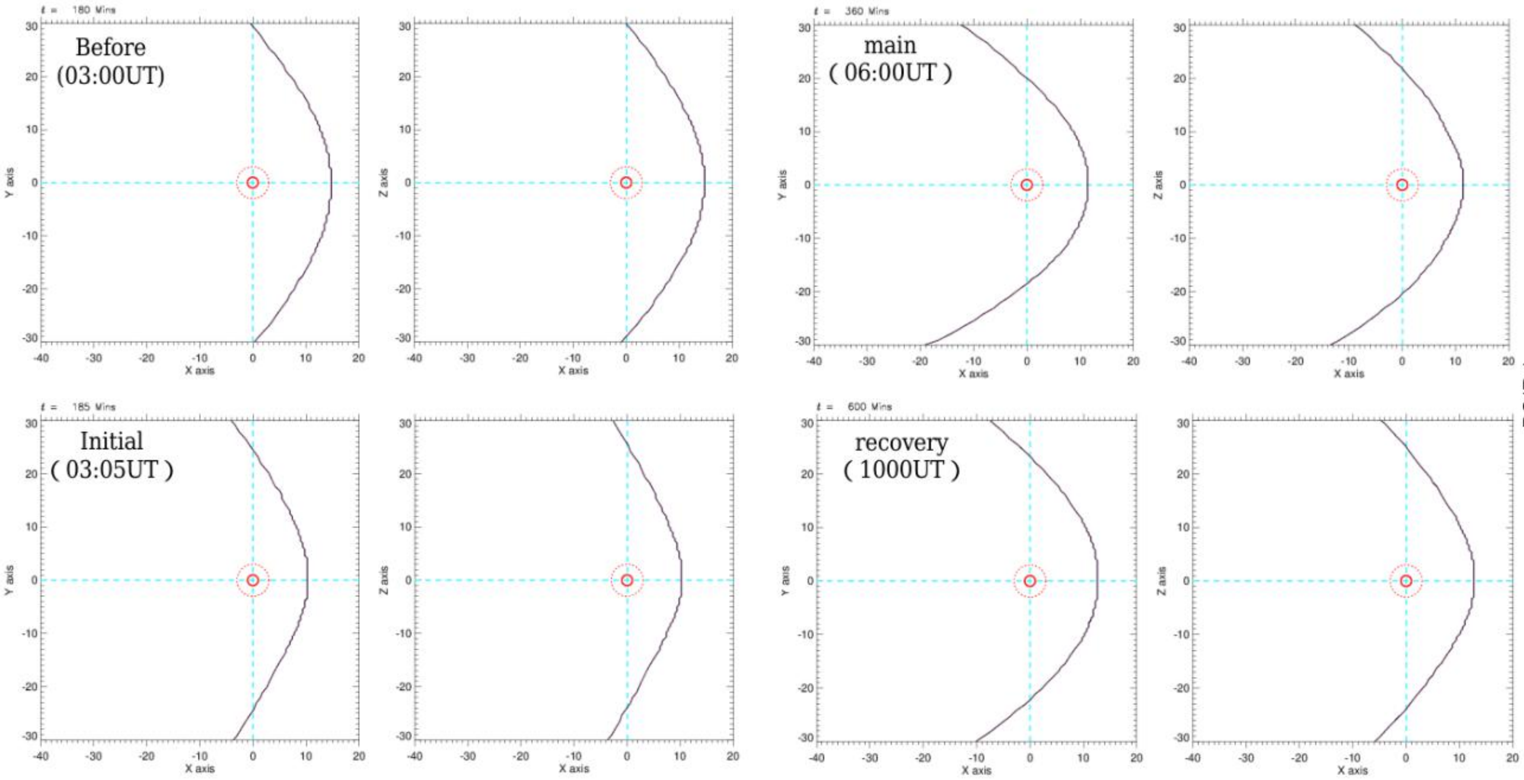
THA

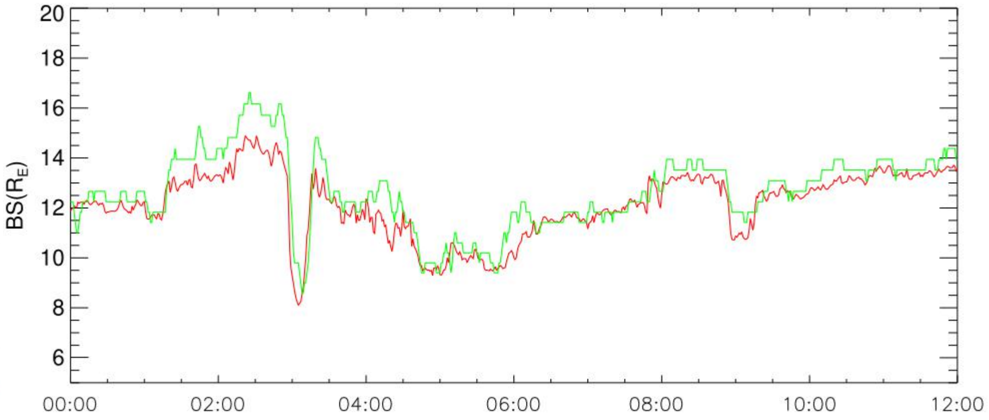


THB

red: observation; blue: simulation

P1. Large-scale structure - bow shock position

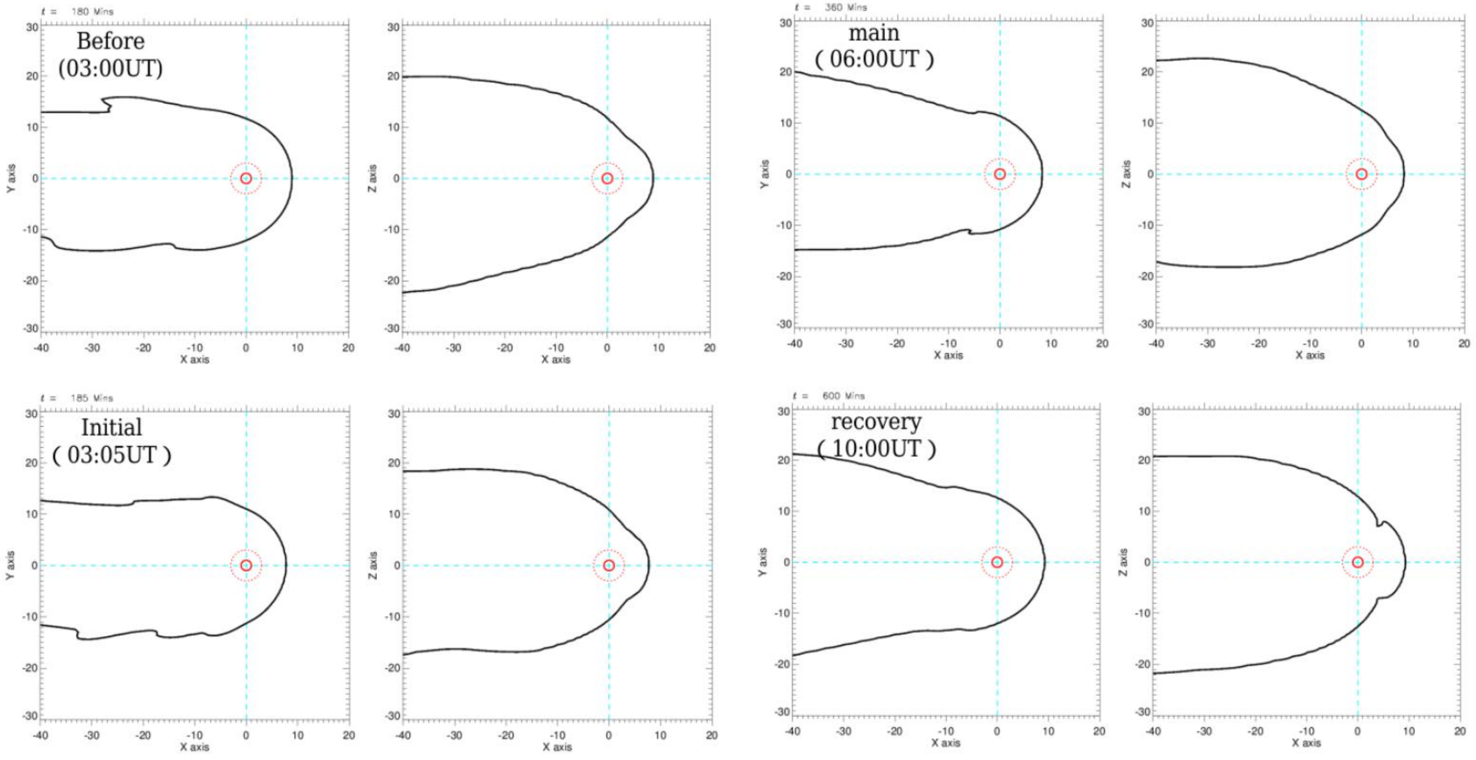


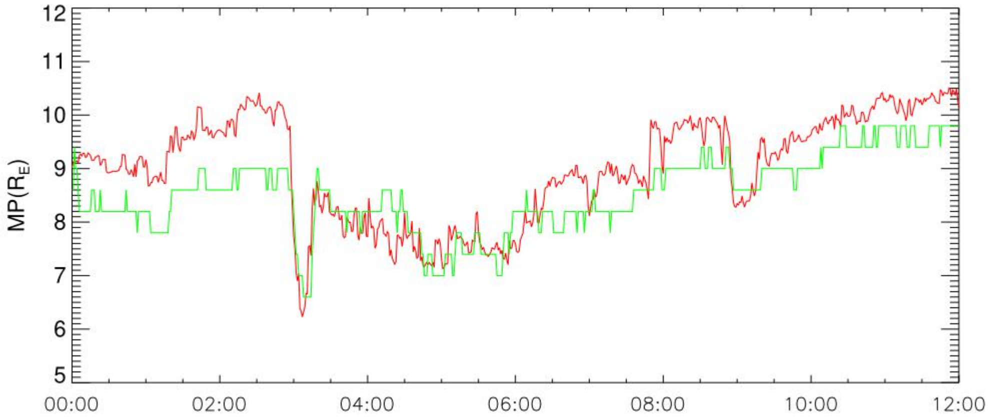


Red: emperical data [Farris&Russell,1994];
green: simulation

* 2022-04-10 case

P1. Large-scale structure - magnetopause position

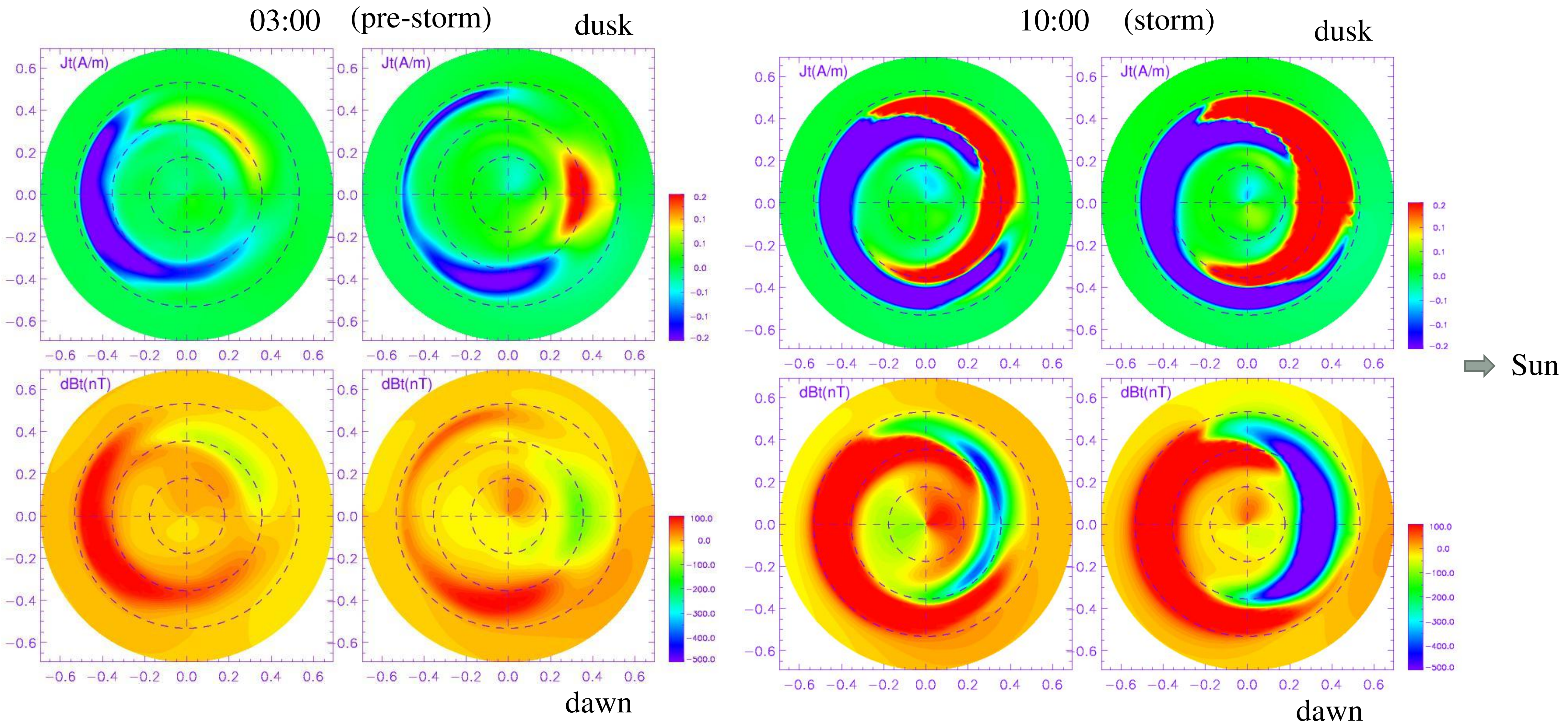




Red: emperical data [Shue+,1997];
green: simulation

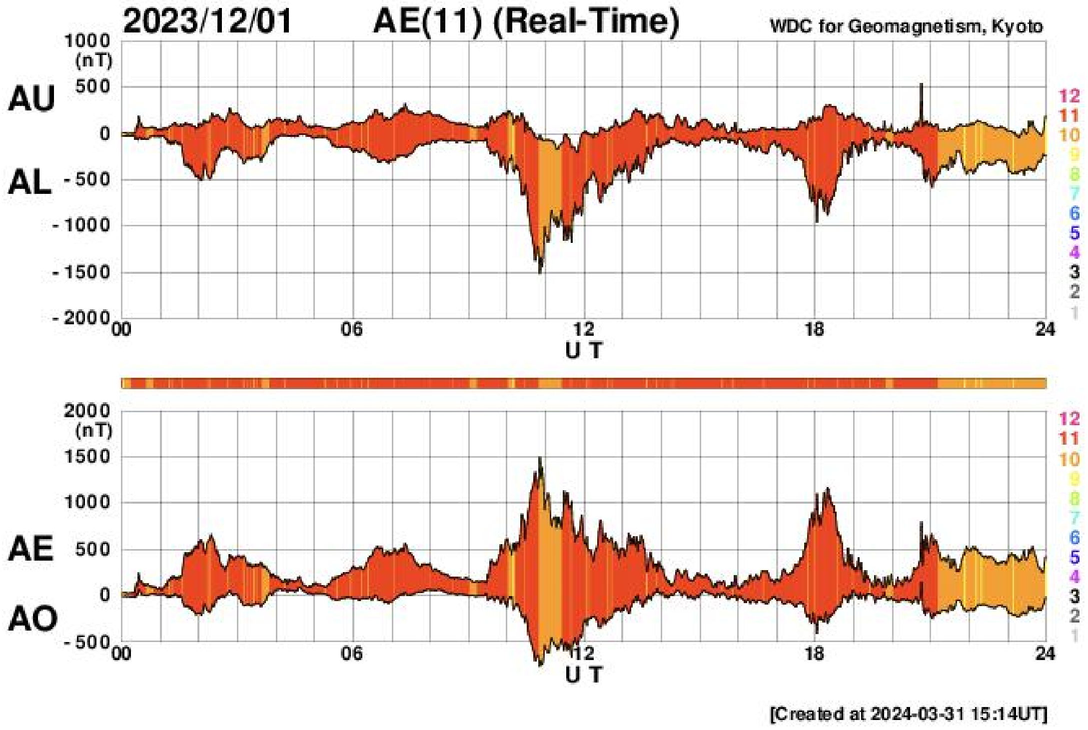
* 2022-04-10 case

P2. Ground Magnetic Perturbation Maps

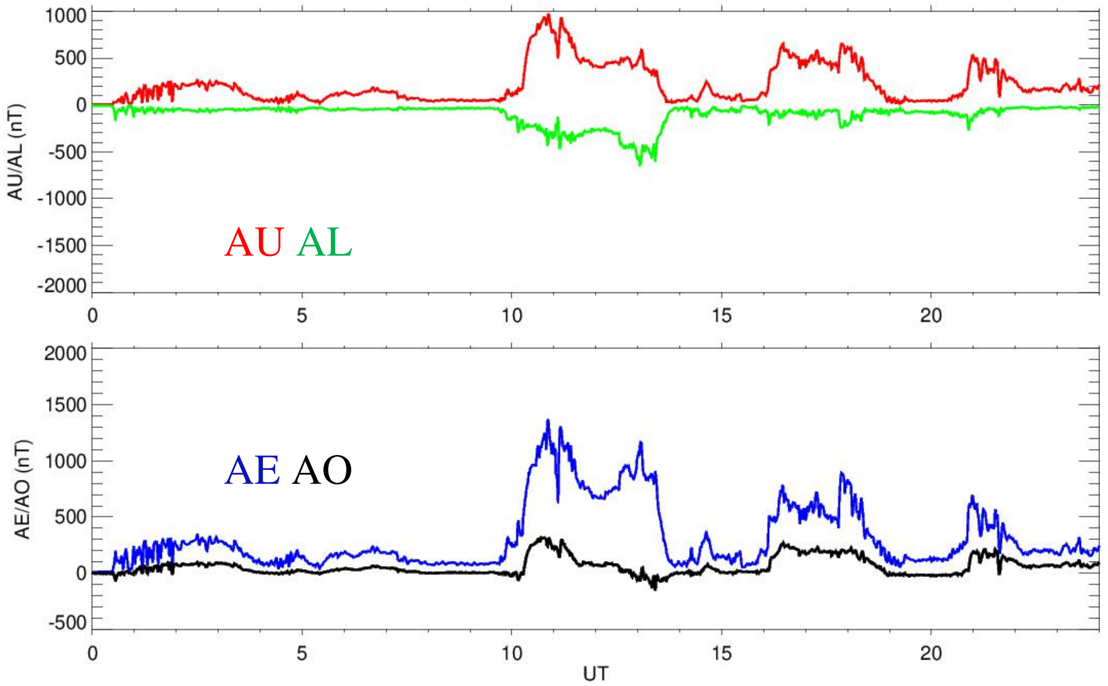


P3. AE(AO/AU/AL) index

observation



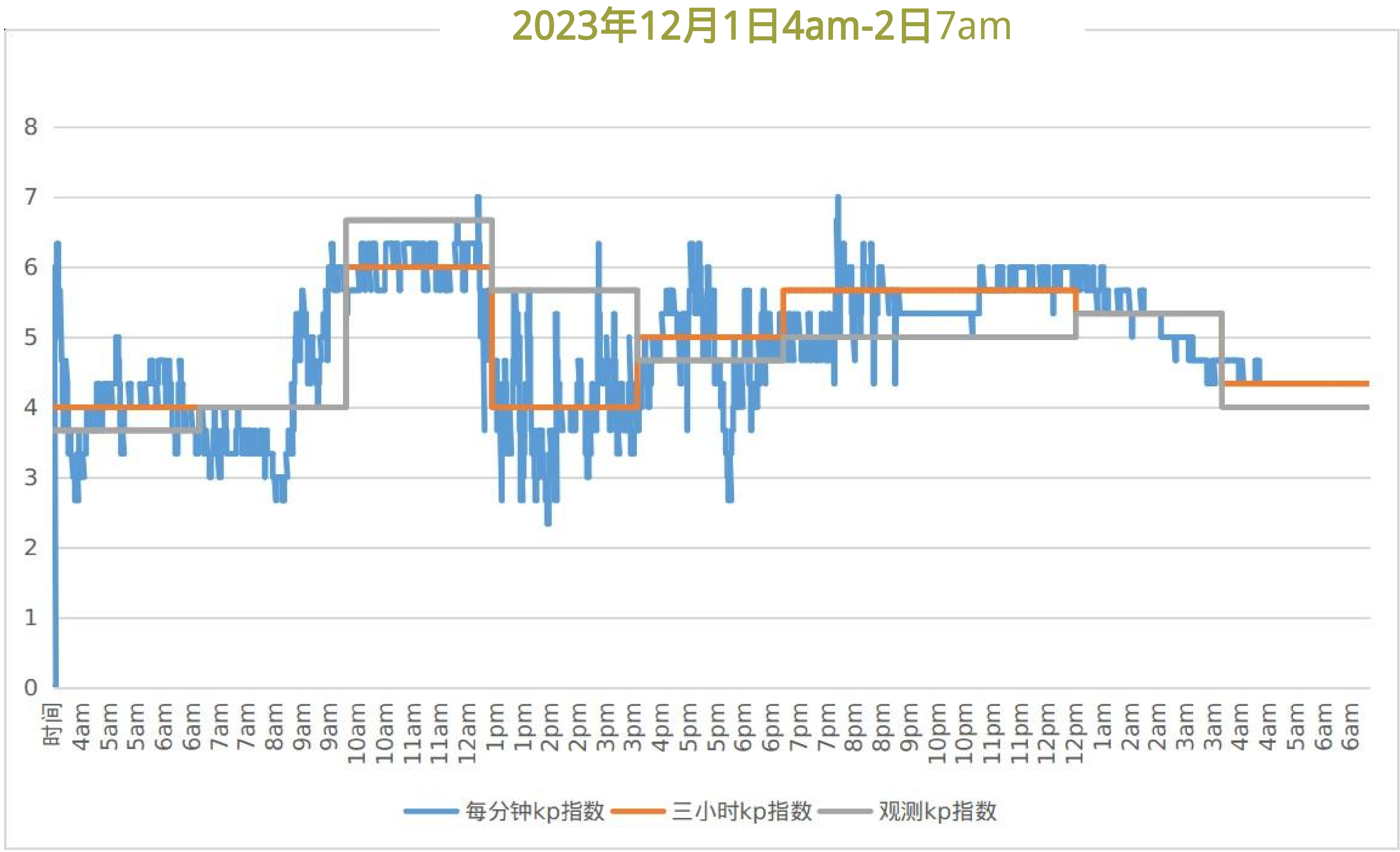
simulation



MLAT: 60 - 70 degree

P3. Kp index

time	obs.	sim.
4-6 am	3.667	4
7-9 am	4	4
10-12 am	6.667	6
13-15 pm	5.667	4
16-18 pm	4.667	5
19-21 pm	5	5.667
22-24 pm	5	5.667
0-3 am	5.333	5.333
4-6 am	4	4.333



MLAT: 50 - 60 degree

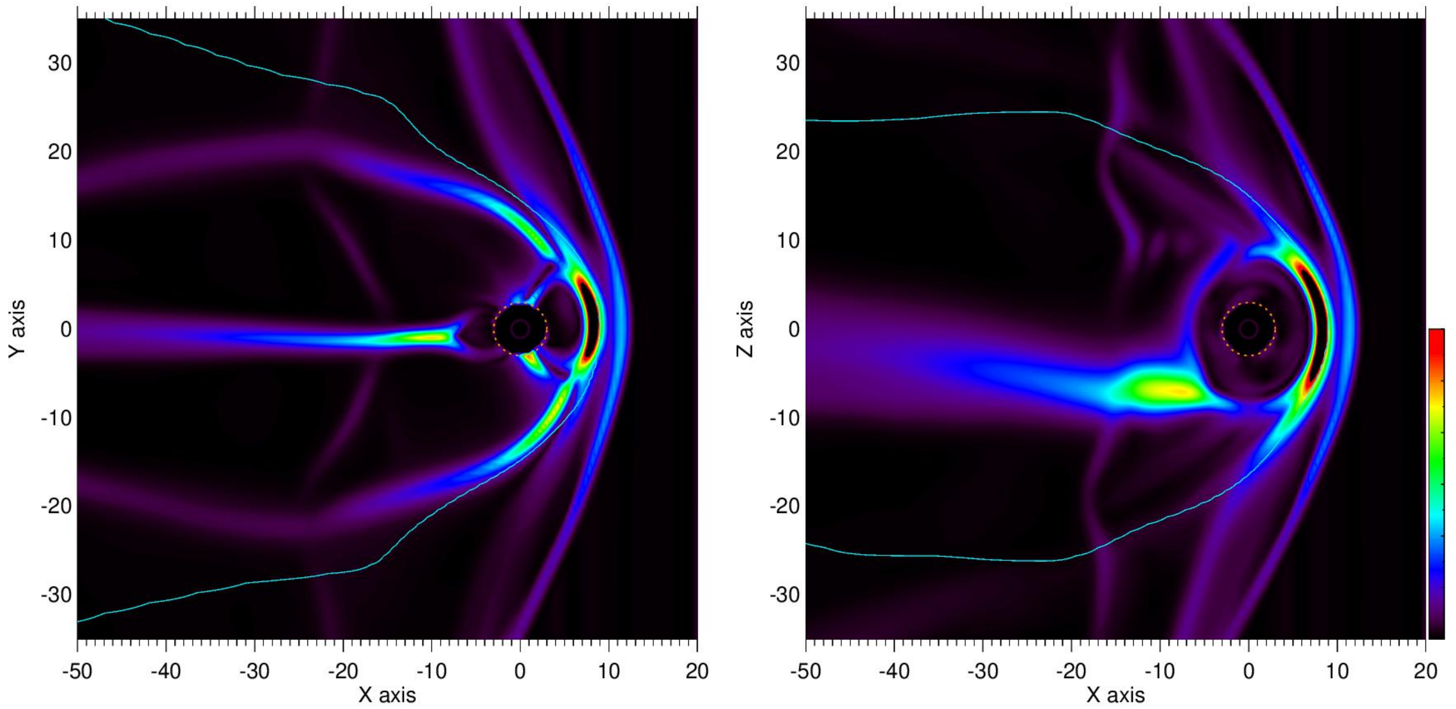
P3. Dst index

1. All the MHD currents in the magnetosphere

$$\boldsymbol{j} = \frac{1}{\mu_0}\nabla \times \boldsymbol{B}$$

2. The z component of magnetic disturbances at earth center calculated through

$$\boldsymbol{B} = \frac{\mu_0}{4\pi}\sum \frac{\boldsymbol{J} \times \boldsymbol{R}}{R^3}dV$$



Dst index variation from all the MHD currents

An empirical Dst model

Time-dependent equation for Dst:

$$dDst^*/dt = F(E) - a\, Dst^*$$

where

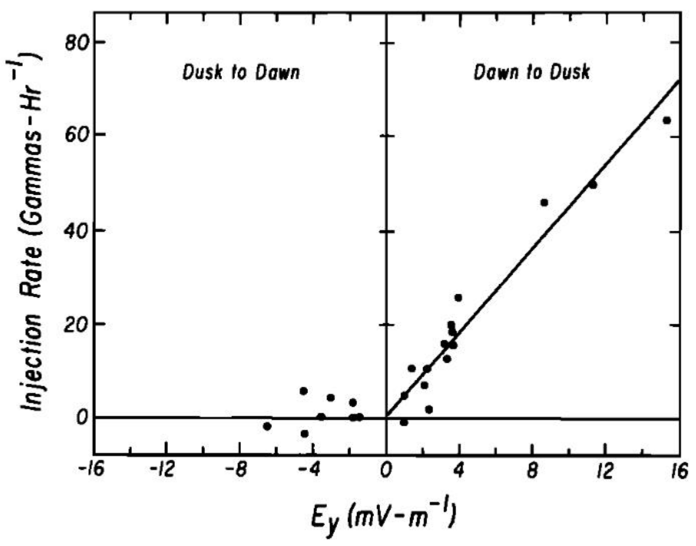
$$Dst^* = Dst - b\sqrt{P} + 20\ nT$$

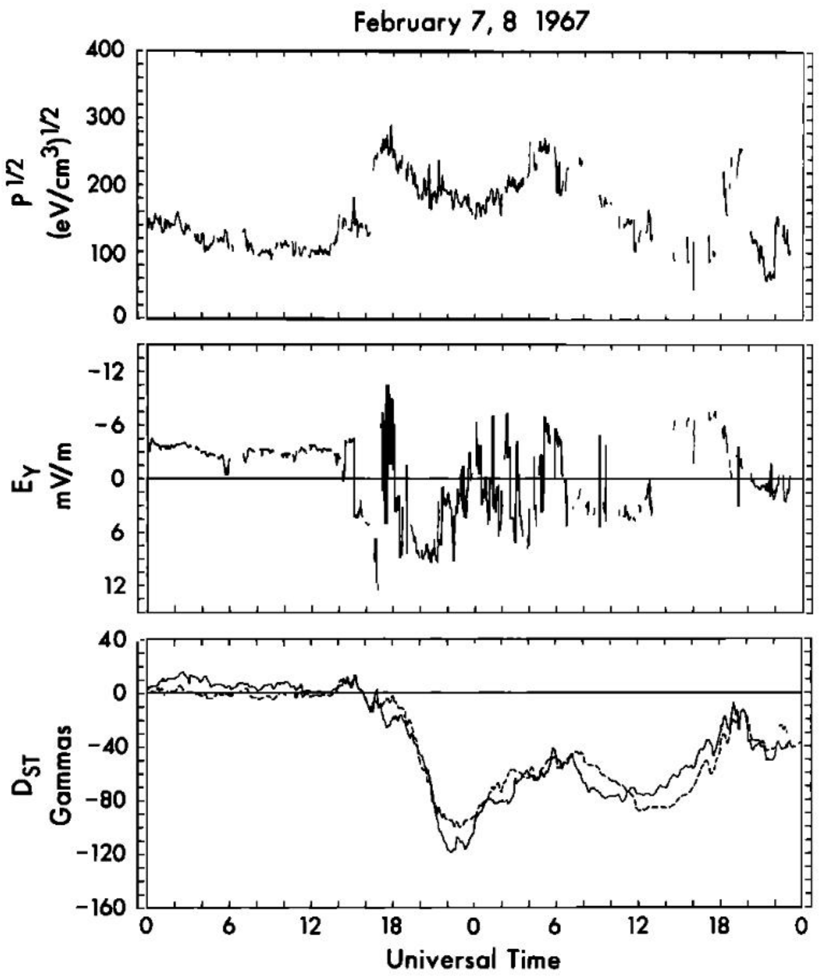
$$F(E) = \begin{cases} 0 & E_y < 0.5\ mV/m \\ -1.5\times10^{-3}\,(E_y - 0.5) & E_y > 0.5\ mV/m \end{cases}$$

a = $3.6\times10^{-5}s^{-1}$, $b = 0.2\ nT/\sqrt{eV\ cm^{-3}}$

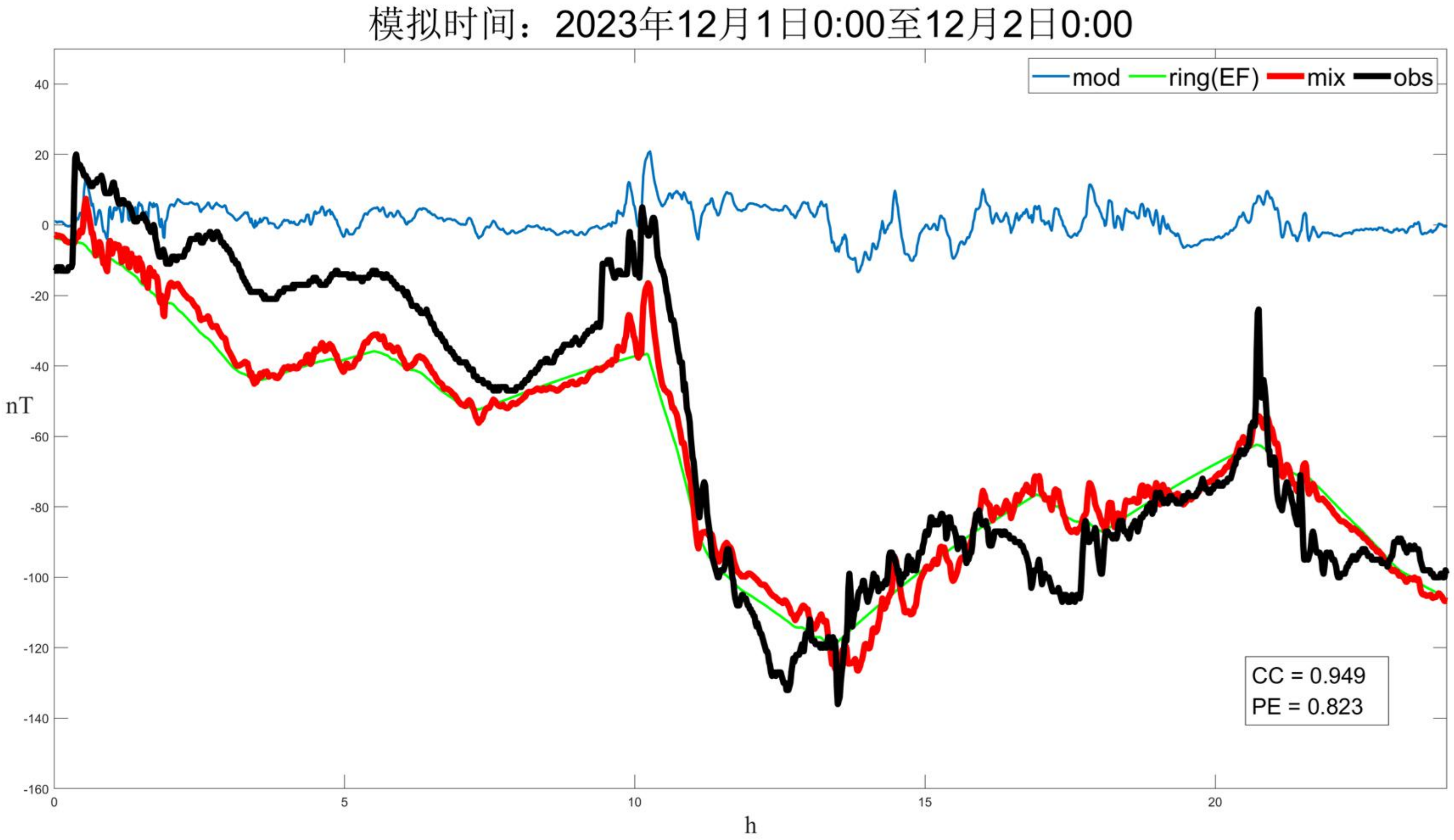
[Burton+, 1975]

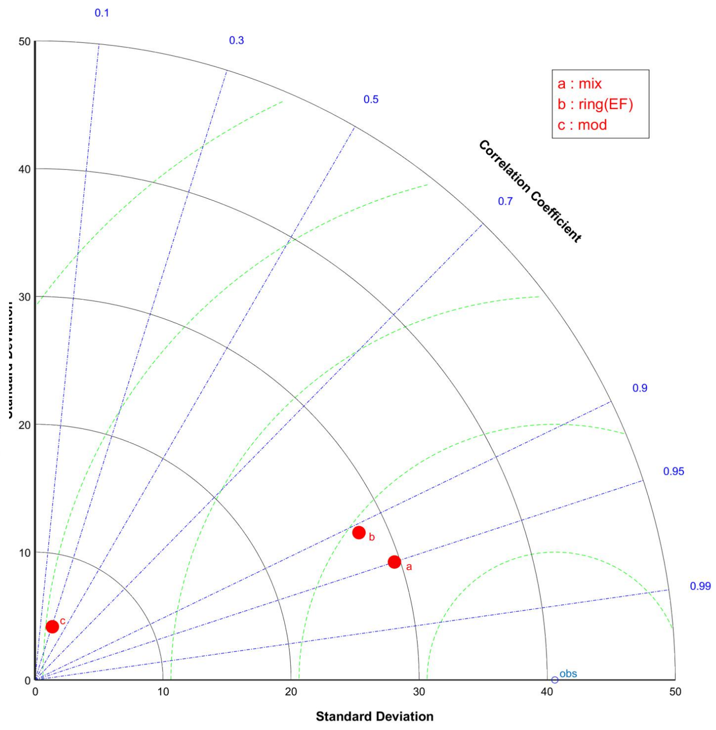
replaced by the MHD contribution in the next.





Dst* index





Taylor diagram

*1 min resolution

Summary

- An extended version of PPMLR-MHD model has been preliminarily used in the application of space weather forecasting, e.g., the gemagnetic indices.
- The ground magnetic perturbation is shown as a consequence of geomagnetic events, by integrating the effects of the ionospheric current, field-aligned current, and magnetospheric current;
- Geomagnetic indices at mid- and high- latitudes, e.g., Kp, AE/AO/AU/AL, are plotted by analyzing the average effects of the geomagnetic perturbation at different latitudes.
- Dst index can be simulated after the cooperation with a developed empirical model for ring current. Inner magnetosphere model is needed for a physical performance of Dst index prediction.

谢谢！спасибо！