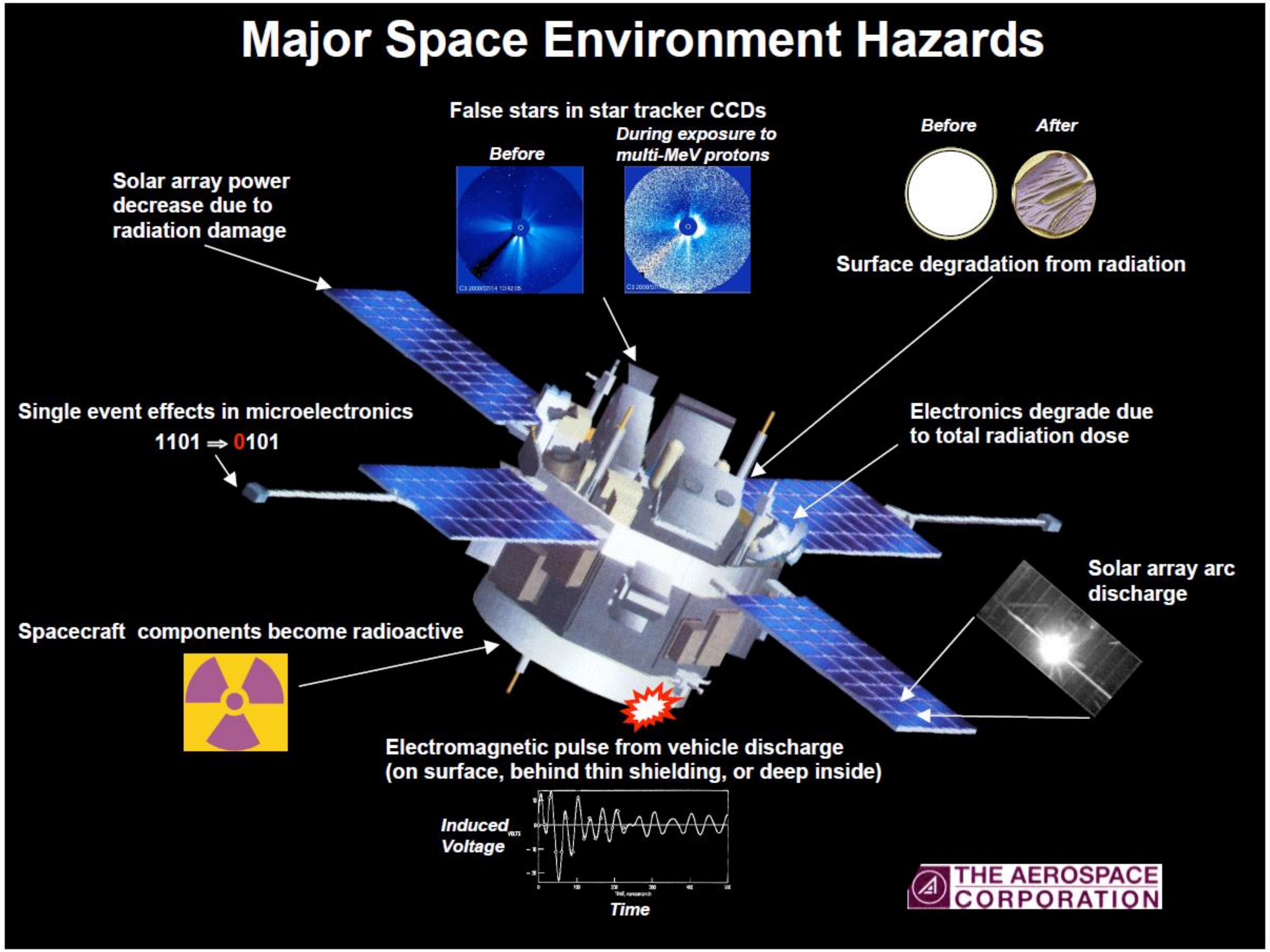
Prediction of Adverse effects of Geomagnetic storms and Energetic Radiation

- PAGER -

Yuri Shprits[1], Ruggero Vasile[1], Michael Wutzig[1], Stefano Bianco[1], Dedong Wang[1], Hayley Allison[1], Melanie Burns[1], Bernhard Haas[1], Tony Arber[2], Kieth Bennett[2], Ondrej Santolik[3], Ivana Kolmasova[3], Ulrich Taubenschuss[3], Mike Liemohn[4], Bart van der Holst[4], Julien Forest[5], Arnaud Trouche[5], Benoit Tezenas du Montcel[5] , Yoshizumi Miyoshi[6] , Miriam Sinhueber[7]

[1]GFZ German Research Centre for Geosciences, DE; [2]University of Warwick, UK; [3]Institute of Atmospheric Physics, CZ; [4]University of Michigan, USA; [5]Artenum, FR, Nagoya University, [7] KIT

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 870452


Major Space Environment Hazards
False stars in star tracker CCDs
Before
During exposure to multi-MeV protons
Before
After
Solar array power decrease due to radiation damage
Surface degradation from radiation
Single event effects in microelectronics
1101 ⇒ 0101
Electronics degrade due to total radiation dose
Solar array arc discharge
Spacecraft components become radioactive
Electromagnetic pulse from vehicle discharge (on surface, behind thin shielding, or deep inside)
Induced Voltage
Time
THE AEROSPACE CORPORATION

Stakeholder Requirements

1. Predictions should be made with sufficient lead-time for the stakeholders to be able to respond to them

2. Predictions should be utilizing all available data and should be reliable

3. Predictions should provide confidence levels so that stakeholders can estimate risks and economic benefits/loss from reacting to the forecast

4. Forecasts should be clear and easy to understand and should provide variables that are usable for stakeholders, not just scientific output

PAGER

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Prediction of Adverse effects of Geomagnetic storms and Energetic Radiation **(PAGER)** – EU Horizon 2020

Ensemble forecast from the Sun will allow a long-term probabilistic prediction.

Predictions at 20.5 $R_\odot$

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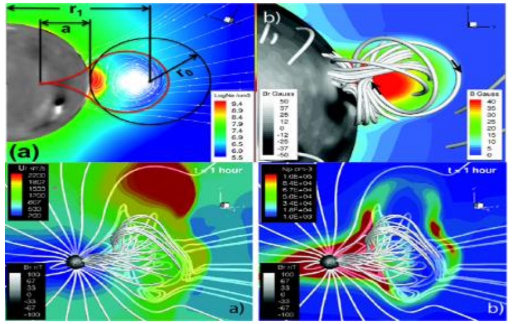
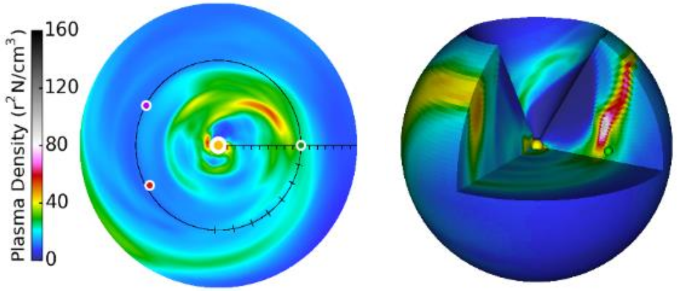
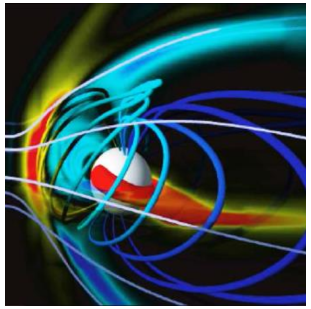


Ensemble predictions of the heliosphere



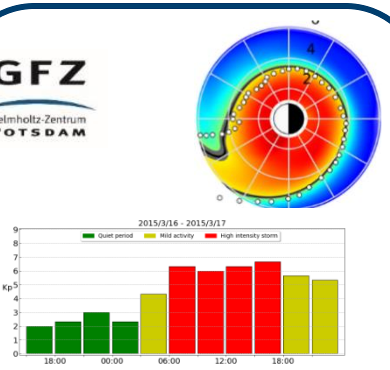
WARWICK
THE UNIVERSITY OF WARWICK

Global modelling of the magnetosphere dynamics



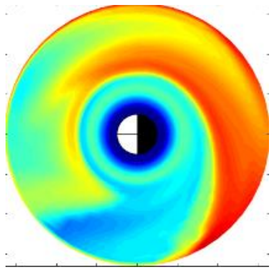
UNIVERSITY OF MICHIGAN

GFZ
Helmholtz-Zentrum
POTSDAM



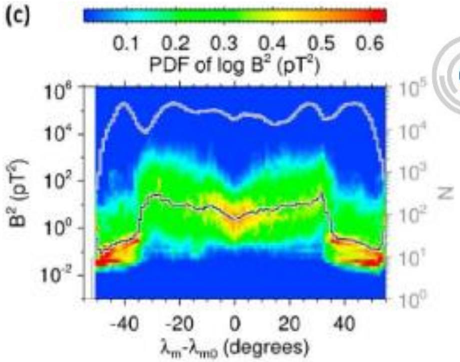
Ensemble predictions of the Plasmasphere and Kp

GFZ
Helmholtz-Zentrum
POTSDAM



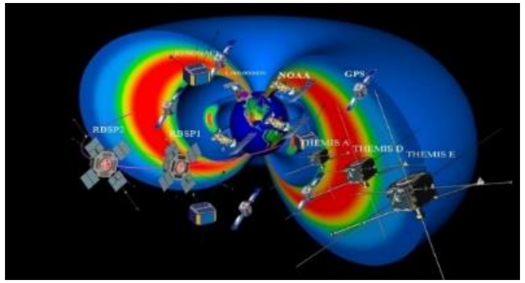
Ensemble predictions of the Ring Current

VERB-4D



IAP

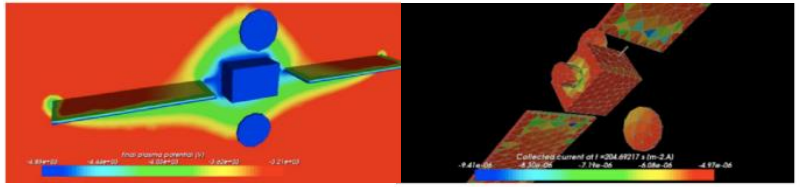
Statistical models of waves from multiple spacecraft



GFZ
Helmholtz-Zentrum
POTSDAM

Ensemble predictions of the Radiation Belts with VERB-3D

3D engineering analysis of spacecraft charging

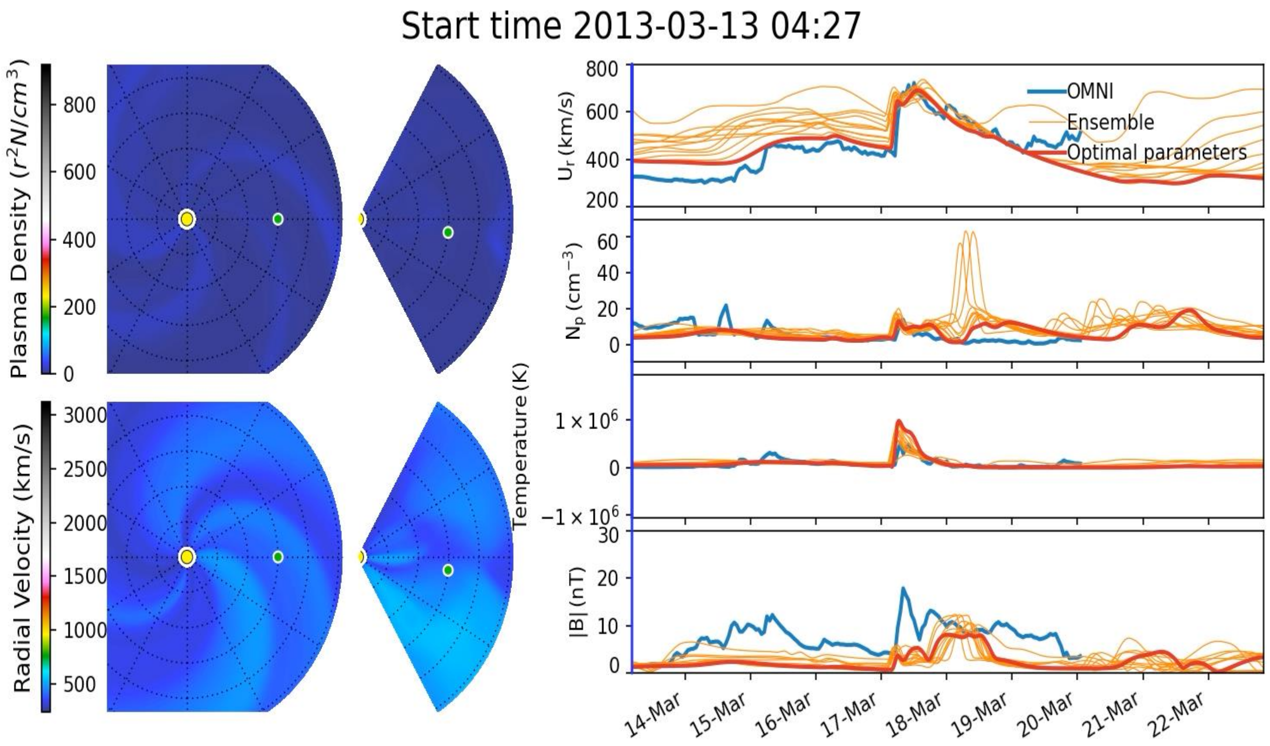


ARTENUM, PARIS
Science & Groupware

Various Space Weather applications (e.g. GIC, TEC, Kp prediction, etc.)

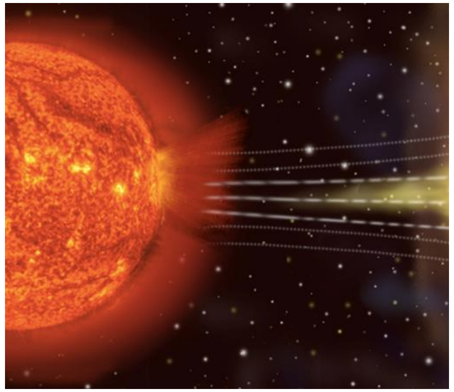
St Patrick’s day CMEs 2013/2015

Hindcasts of ensemble CMEs each with 20 ensemble members
The optimal parameters are based on fitting to previous 21 days of OMNI data
Ensemble predictions give realistic ensamble predictions for strong CME (2013)
Weaker CME in 2015 has many ensemble members missing the Earth and arrival late by ~12 hours

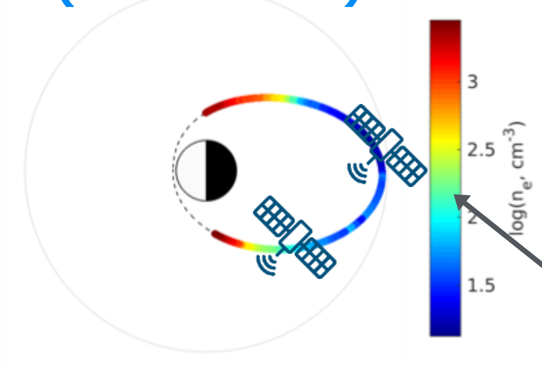


Machine Learning Model of the Plasma Density

Input: Solar wind



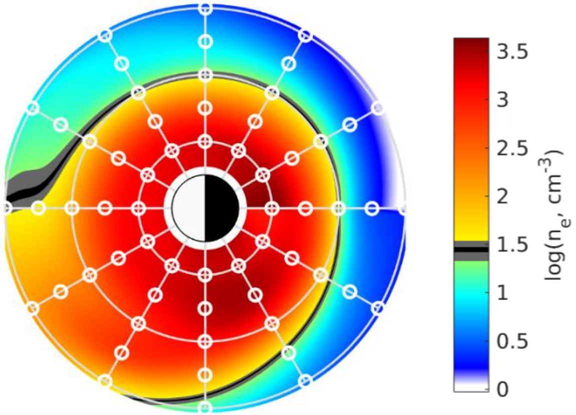
Training dataset: Plasma density (2012-2016)



NASA's Van Allen Probes

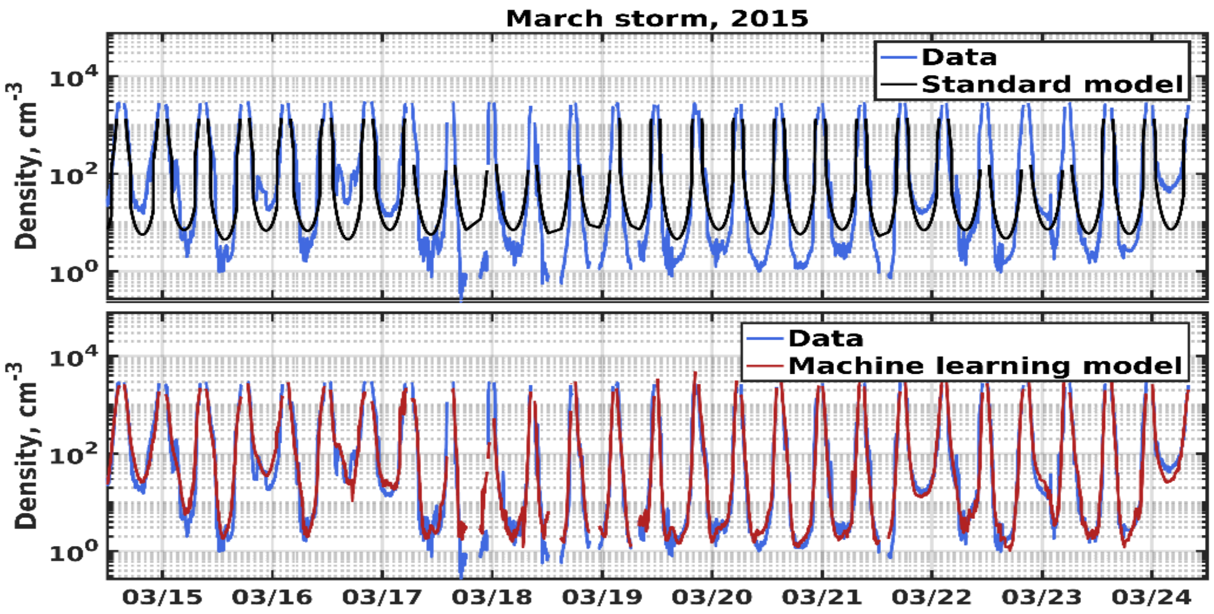
ML

Global model of the plasmasphere



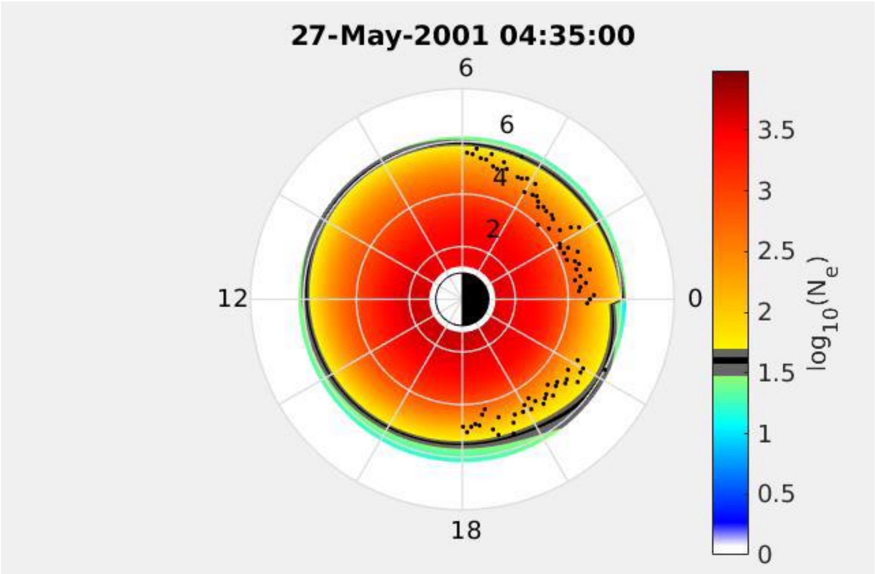
Machine Learning Model of Plasma Density

ML model outperforms the legacy statistical models



Reconstruction of plasma density along the satellite orbit

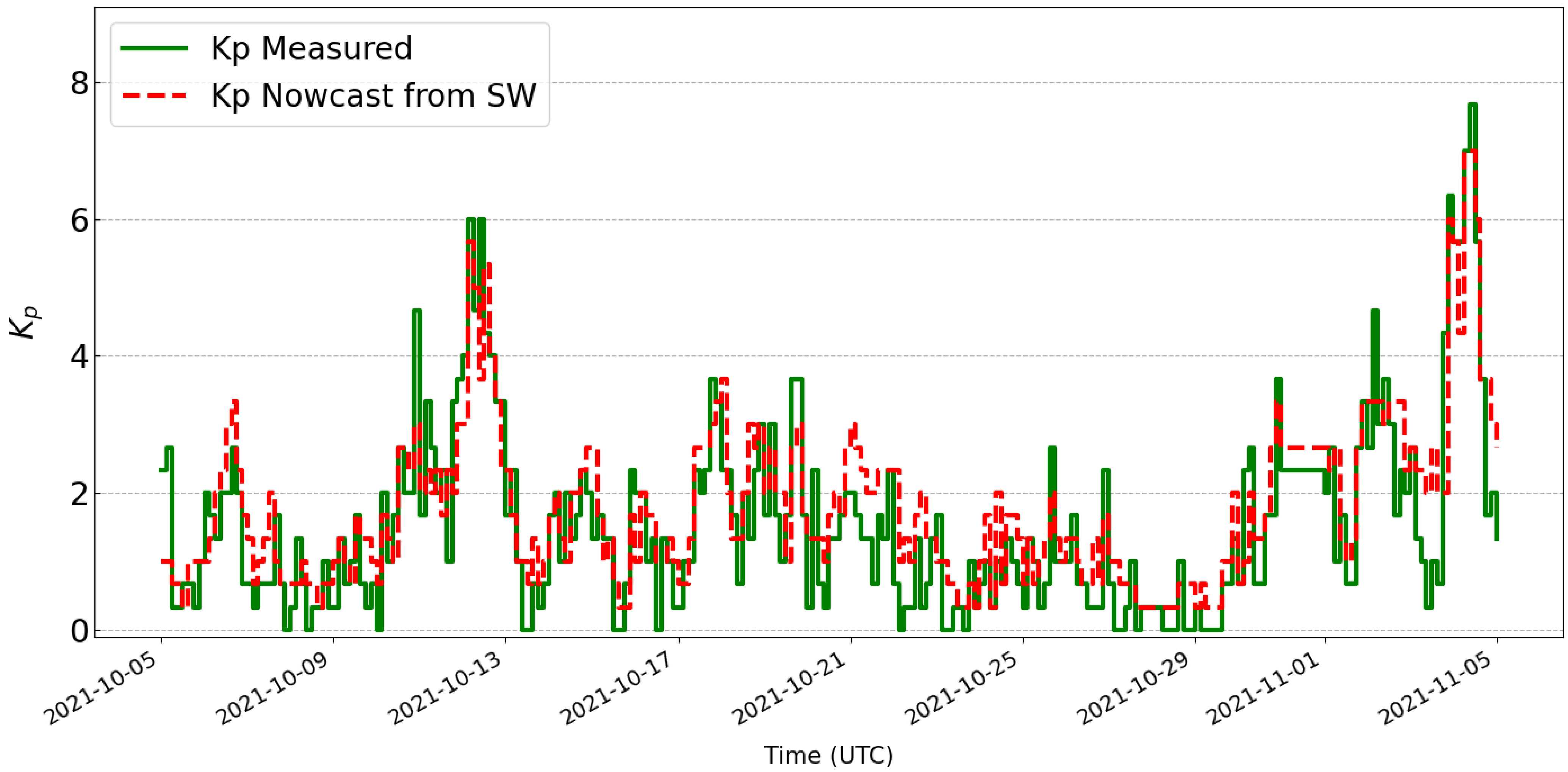
Example output



Zhelavskaya et al., 2017

The model trained on single point measurements from 2012 to 2016 reproduces the global dynamics observed in 2001

Machine Learning Model of Kp



VERB-DA Radiation Belt Model

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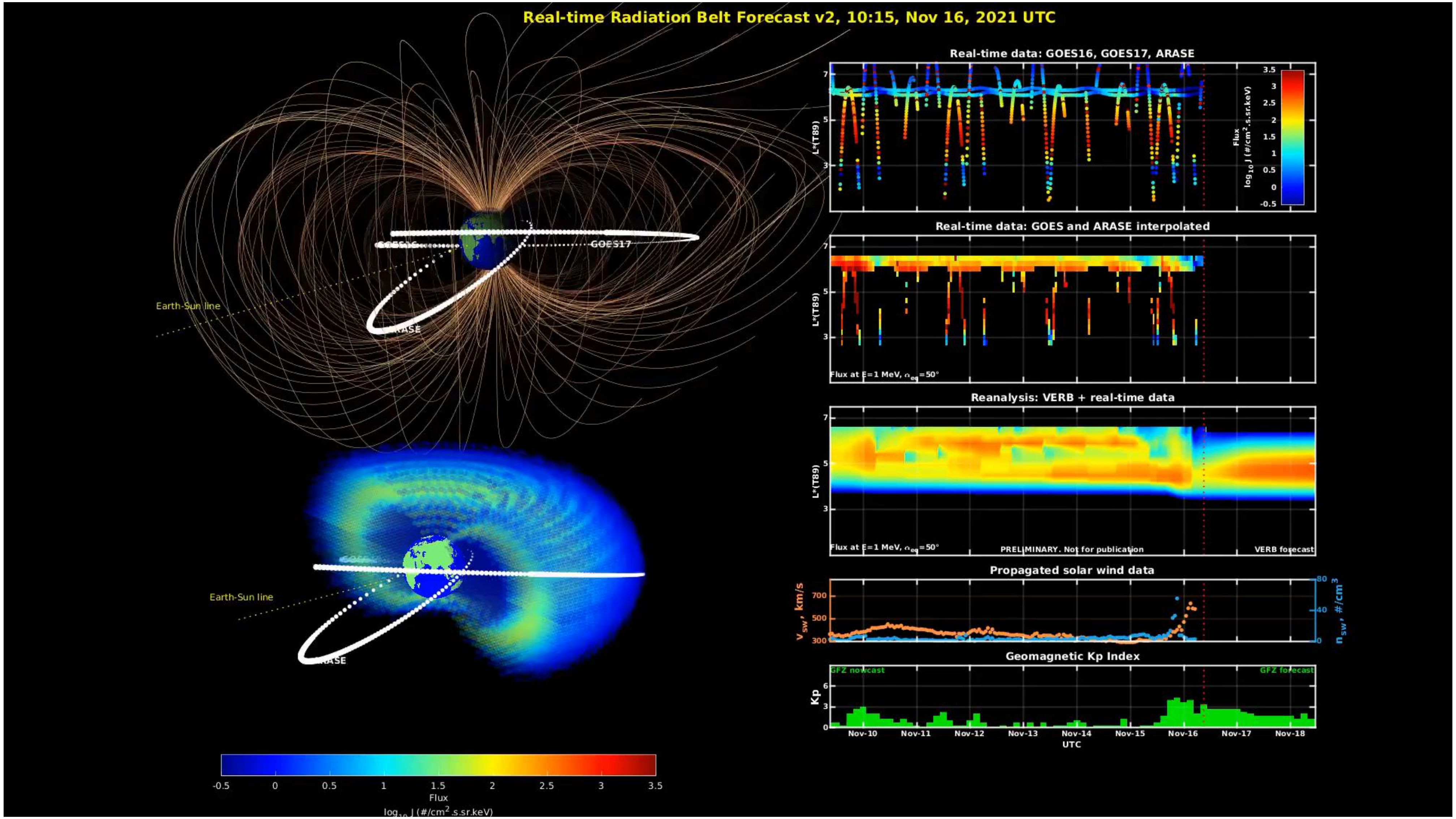
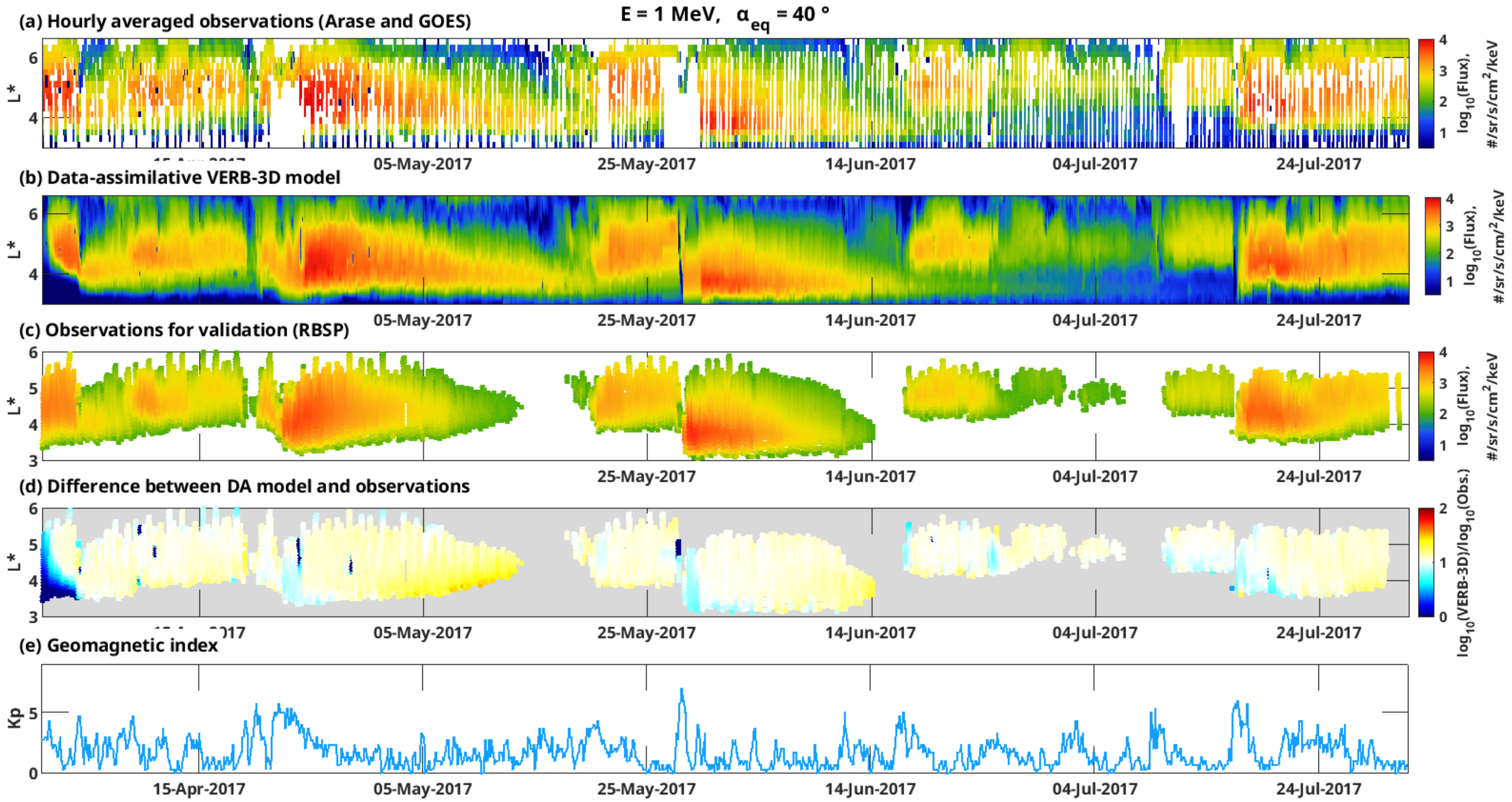
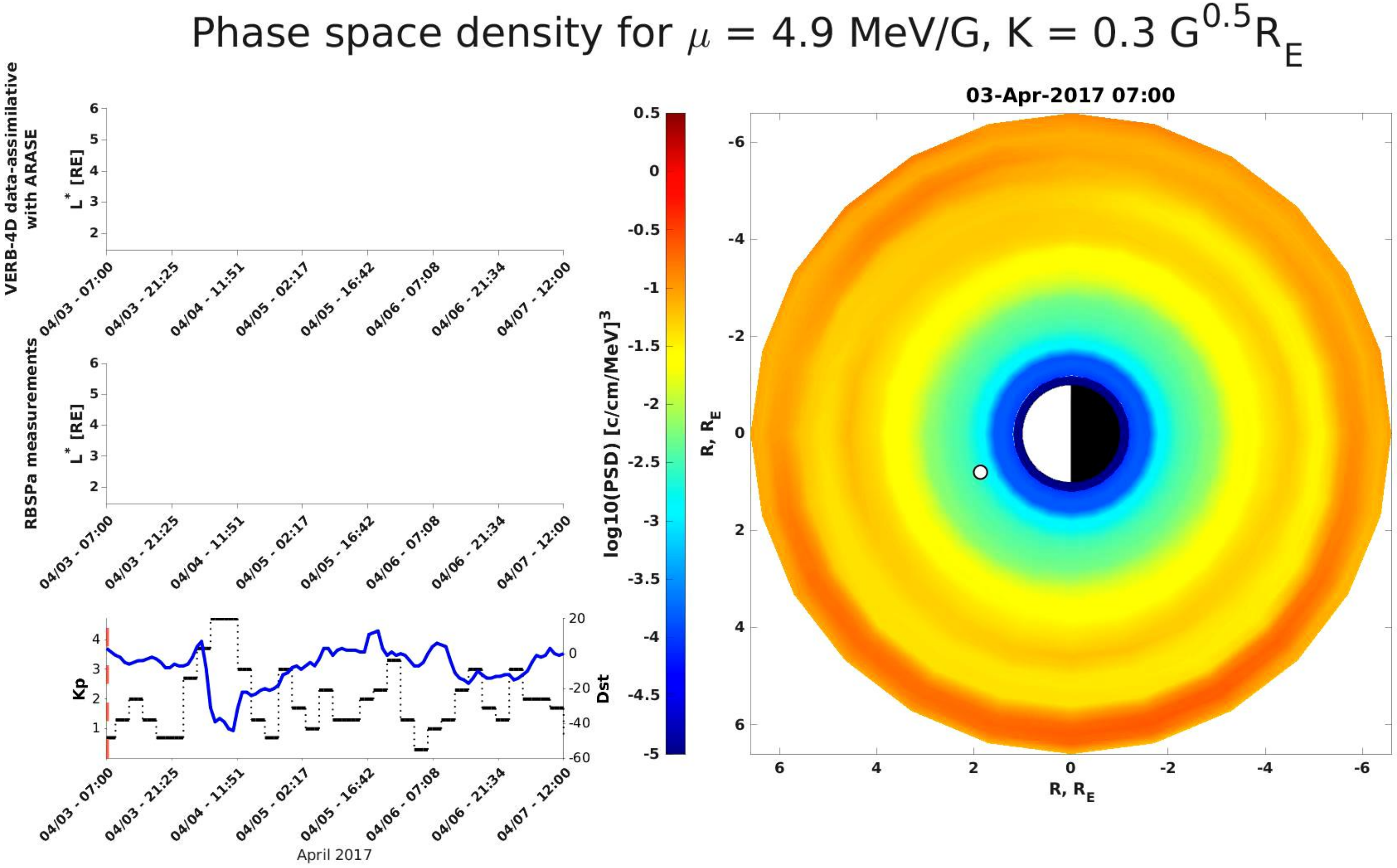


Validation of the Radiation Belt Data Assimilation



Validataion of VERB-4D with Data-assimilative Ring Current Simulations Using VERB-4D



Assimilation of Arase data is validated on Van Allen Probes

Haas et al., 2024, Scientific Reports

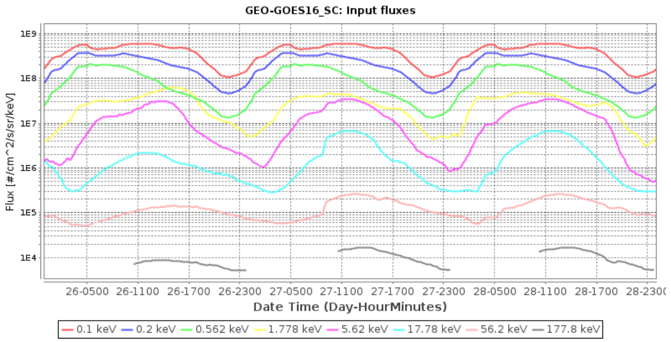
Simulation results

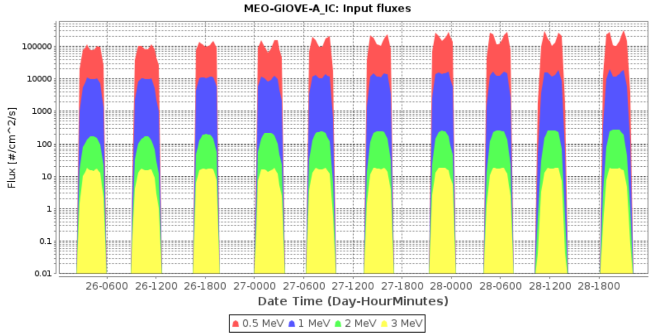
WP7

Surface charging

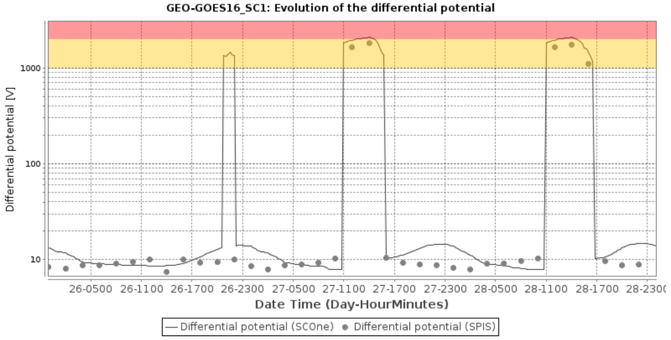
Internal charging

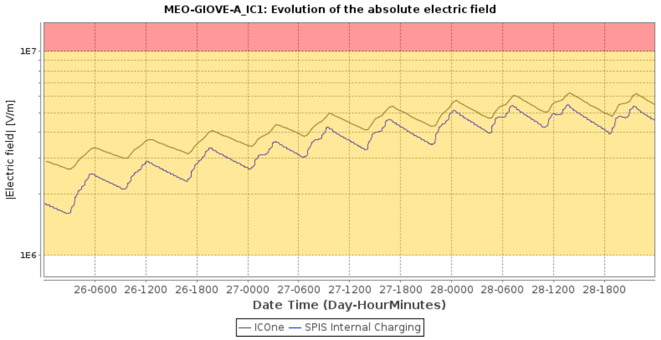
Local fluxes

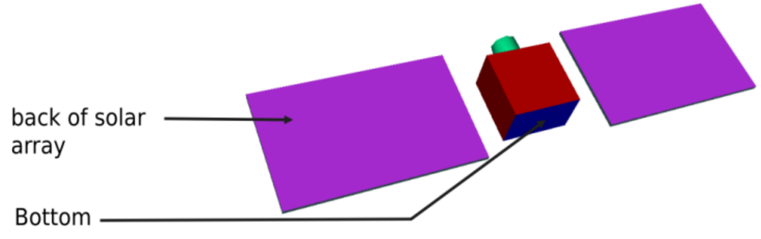




Outputs





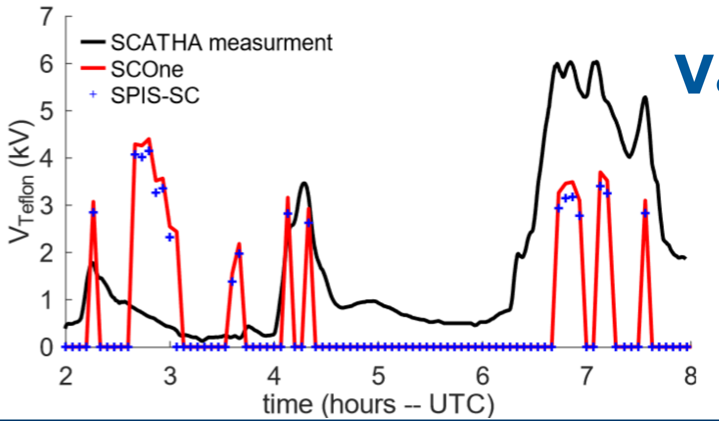


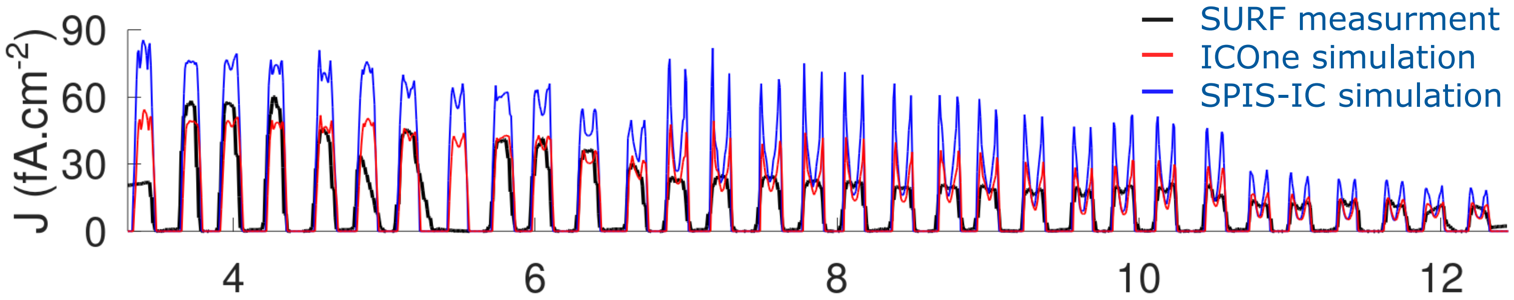
Published risk indicators

Internal Charging results

Orbit	Mission	Platform	2023-07-05 0000	0600	1200	1800	2023-07-06 0000	0600	1200	1800	2023-07-07 0000	0600	1200	1800
		IC1:0.50mm Shield Detector	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠
		IC2:0.75mm Shield Detector	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠
		IC3:1.00mm Shield Detector	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠	🟠
	ARASE	IC4:1.25mm Shield Detector	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
		IC5:1.50mm Shield Detector	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
		IC6:1.75mm Shield Detector	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢

Validation





			2022-04-25				2022-04-26				2022-04-27			
Orbit	Mission	Platform	0000	0600	1200	1800	0000	0600	1200	1800	0000	0600	1200	1800
GEO	GOES16	S1-Double Sphere	🔴	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🔴	🔴
	GOES17	S1-Double Sphere	🔴	🔴	🟢	🟢	🔴	🔴	🟢	🟢	🟢	🟢	🟢	🟠

This page gathers the key Surface Charging Indicators (SCI) for the whole set of surveyed Reference Missions. For each Reference Mission and each six-hours time slot, the SCI is symbolised by simple tricolour indicators:

- **Green disk** means no surface charging risk is expected, according the ECSS standards, i.e. strongest differential charging remains lower than 1kV;
- **Orange disk** indicates that, if no charging risk is expected, the strongest differential charging is between 1 and 2kV and the system is below the margin recommended by ECSS;
- **Red disk** means a surface charging risk may occurs, according to the ECSS standards, i.e. one differential charging is higher than 2kV.

The flags are triggered considering if at least ONE of the Charging Models find that the differential potential between two elements of the selected Modelled Platform is upper or lower the ECSS reference threshold voltages.

CAUTION: The present service is still currently under validation and results cannot be guaranteed. Please take care as well that the presented risk evaluation is relative to the Modelled Platform and Reference Mission. Actual charging risk depends on the platform design, the selected/sensitive technologies and the mission profile. The actual charging risk may differ for your own mission/modelled system. Please also remind that the risk indicators should be considered as a primary indicator of the

Summary of Publications

Journal	# papers	Impact factor
Science Advances	1	13.12
Journal of Geophysical Research: Space Physics	10	2.8
Geophysical Research Letters	6	4.58
Space Weather	2	3.58
Journal of Atmospheric and Solar Terrestrial Physics	2	1.5
Earth and Space Science	1	2.35
Frontiers in Astronomy and Space Sciences	3	2.50
Scientific Reports	1	4.379
Surveys in Geophysics	1	6.673

Awards for ECS

2023

Dr Hayley Allison: Karls Scheer Prize of Physics Society of Berlin/ Brandenburg
Mr. Artem Smirnov Outstanding Student and PhD candidate Presentation (OSPP) EGU
Mr. Artem Smirnov URSI GASS Young Scientist Award

2022

Angelica Castillo: EGU Outstanding Student and PhD candidate

2021

Dr Hayley Allison: Leopoldina Preis für junge Wissenschaftlerinnen und Wissenschaftler
Dr Irina Zhelawskaya: Friedrich-Robert-Helmert-Prize the Association of Friends and Sponsors of the GeoForschungsZentrum Potsdam e. V. (FFGFZ)

2020

Dr Hayley Allison: Humboldt Postdoctoral Research Fellowship
Dr Dedong Wang: URSI GASS Young Scientist Award, VERSIM Outstanding Poster Award

2019

Dr Nikita Aseev: AGU-funded Dr. Edmond M. Dewan Young Scientist Scholarship for Atmospheric Sciences and Space Physics
Dr Dedong Wang: GFZ Young Scientist Award

Karl-Scheel Medal

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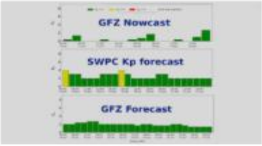
PAGER Data Products

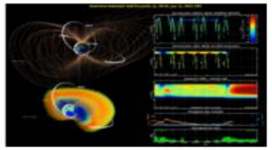
The following products are available:

- Forecast of the Kp Index
- Data assimilative forecast of the near-Earth radiation belts
- Electron Ring Current forecast
- Ensemble predictions of the Solar Wind at L1
- Forecast of plasma density



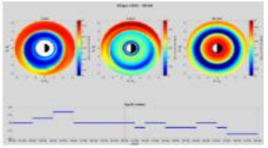
Forecast of the Kp Index

Prediction of Kp forecast. Neural network is trained to predict Kp values using historical solar wind and interplanetary magnetic field data.



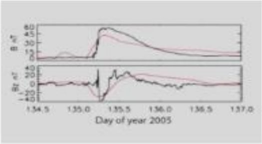
Data assimilative forecast of the near Earth radiation belts

Two-day radiation belt forecast of 1 MeV electrons using the data-assimilative VERB code, real-time ARASE, ACE, GOES and POES data.

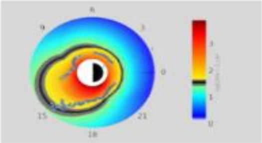


Electron ring current forecast

Three days forecast of ring current electron flux for 1keV, 6keV and 30keV particles at 85° pitch angle using the VERB-4D code.



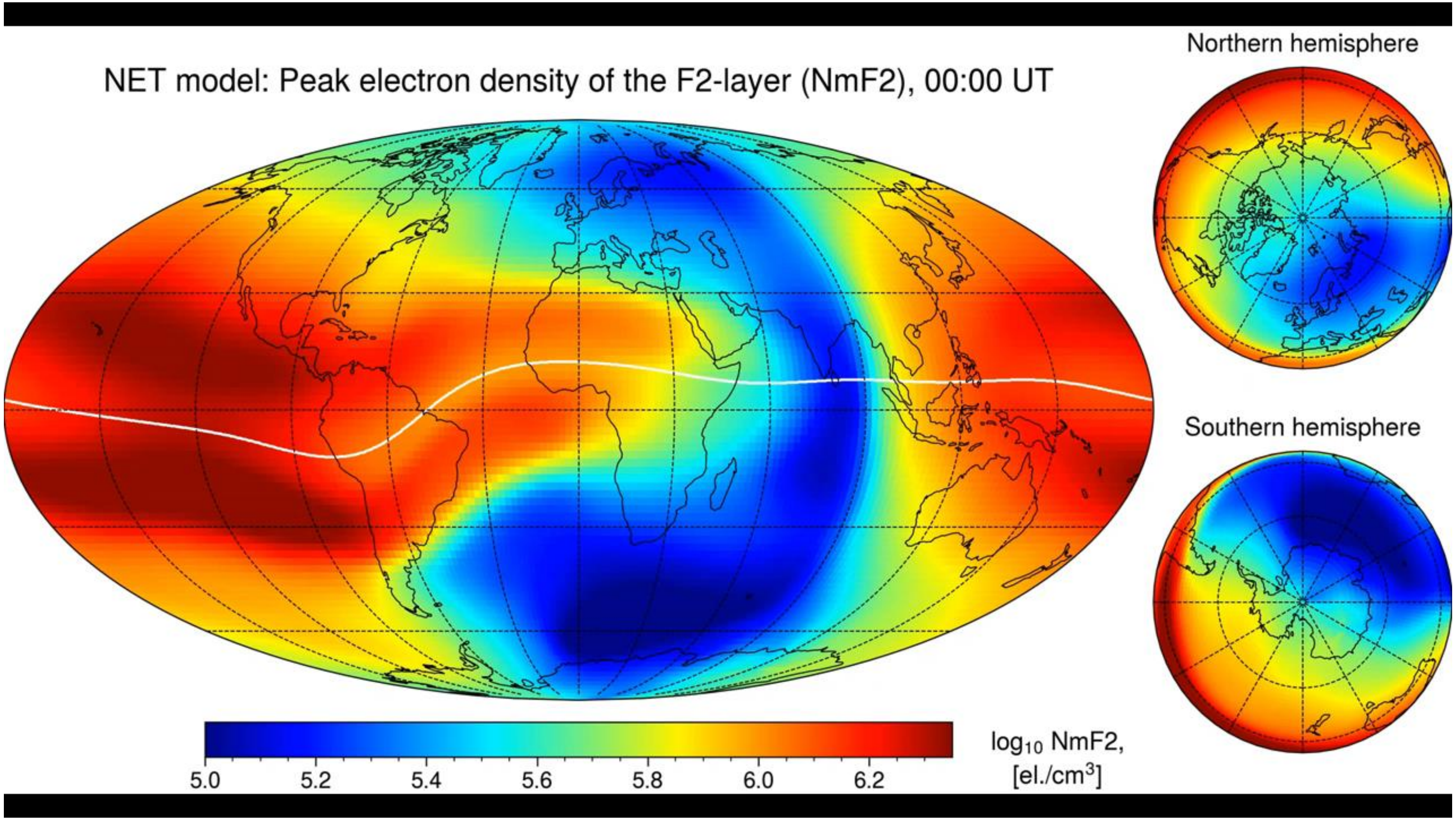
Ensemble predictions of the Solar Wind at L1

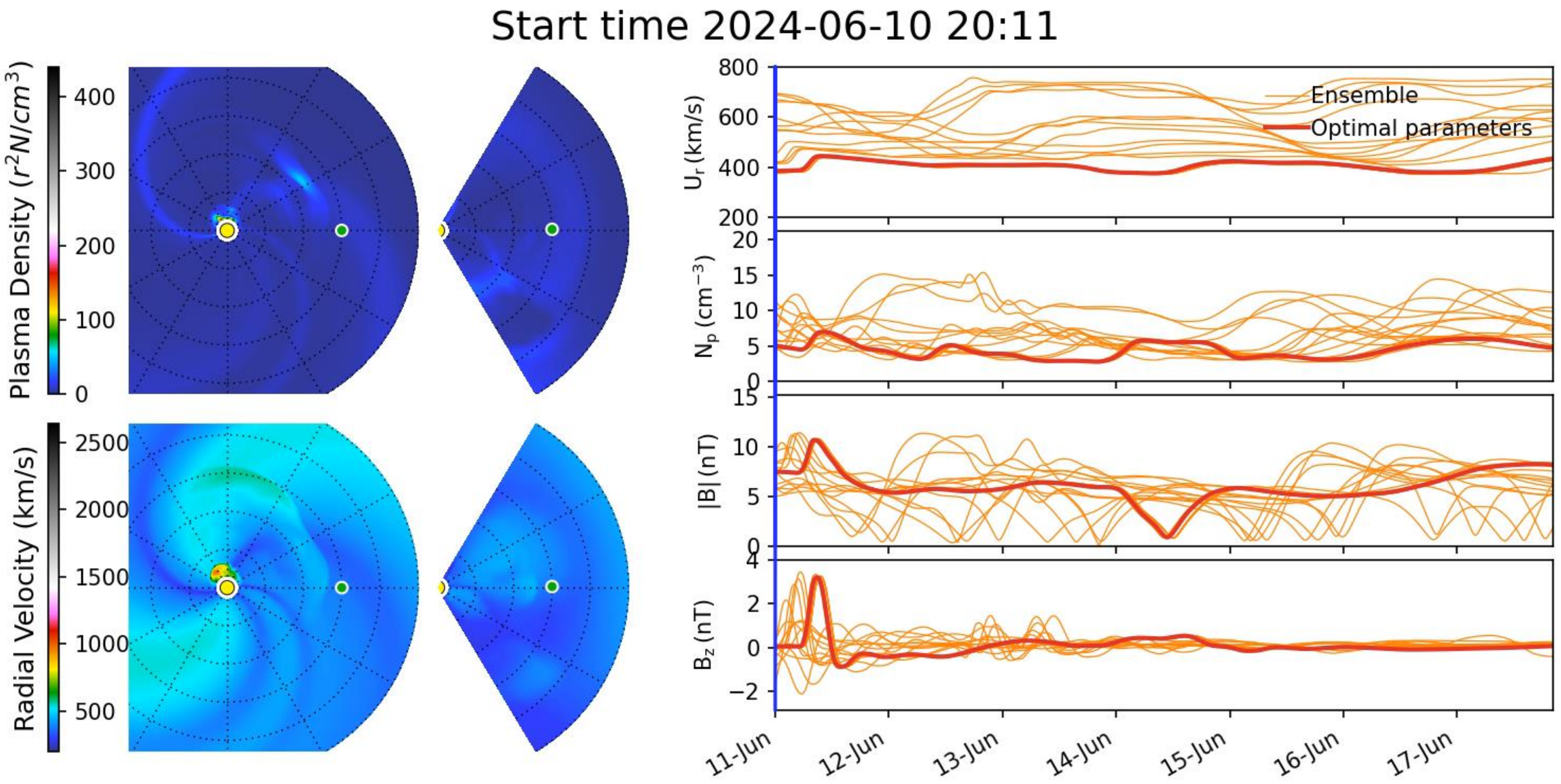


Forecast of plasma density

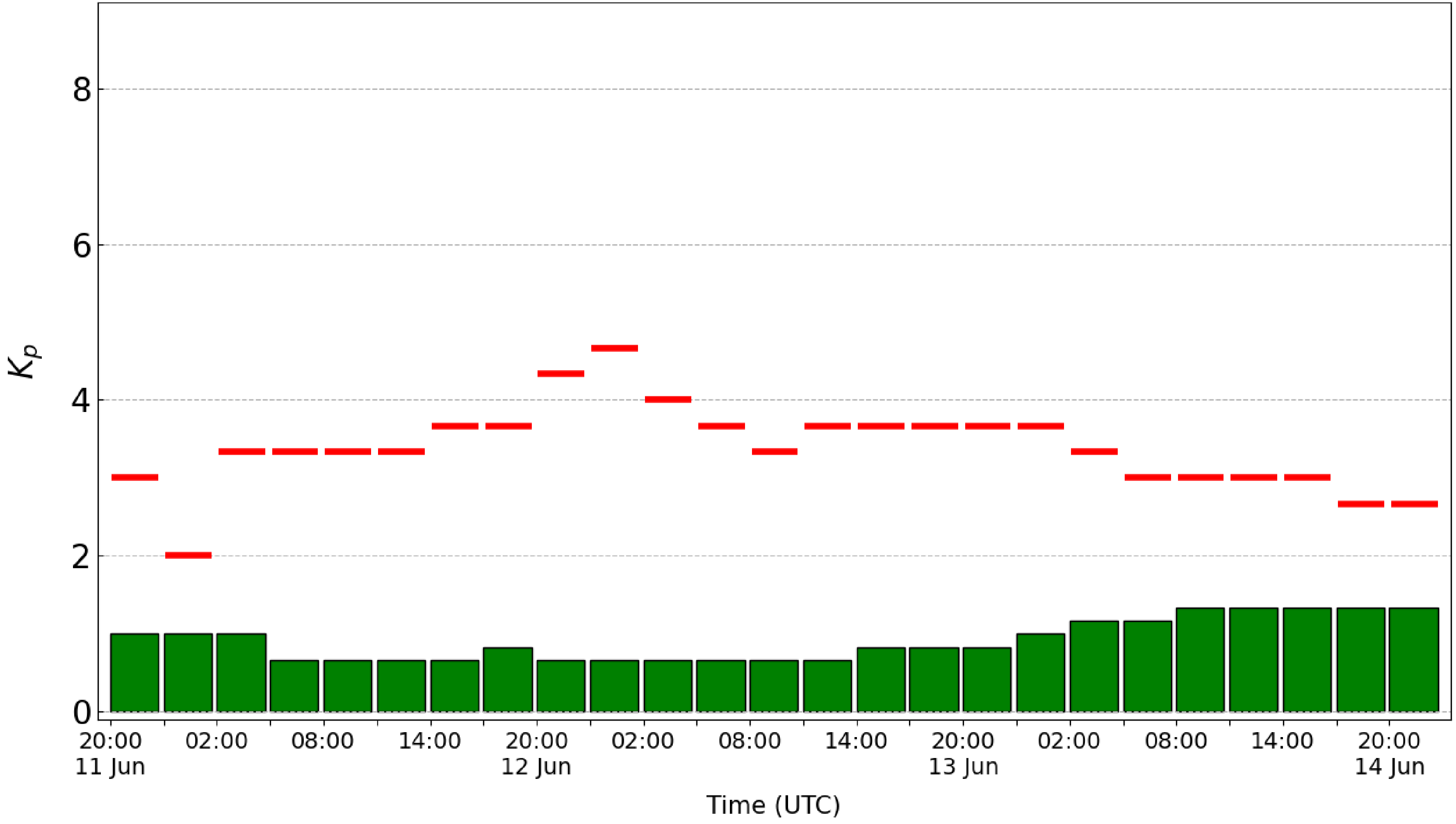
The visualization and result of real-time predictions for plasmaspheric PINE model, data assimilative ring current simulations with VERB-4D, data assimilative radiation belts forecast with VERB-3D, solar wind predictions with SWIFT and predictions of Kp are already available on our web site at *www.spacepager.eu.*

Machine Lerning Predictions of NmF2




Start time 2024-06-10 20:11
Plasma Density (r^2N/cm^3)
400
300
200
100
0
Radial Velocity (km/s)
2500
2000
1500
1000
500
U_r (km/s)
800
600
400
200
Ensemble
Optimal parameters
N_p (cm^{-3})
20
15
10
5
0
|B| (nT)
15
10
5
0
B_z (nT)
4
2
0
−2
11-Jun
12-Jun
13-Jun
14-Jun
15-Jun
16-Jun
17-Jun

Ensemble Predictions of Kp

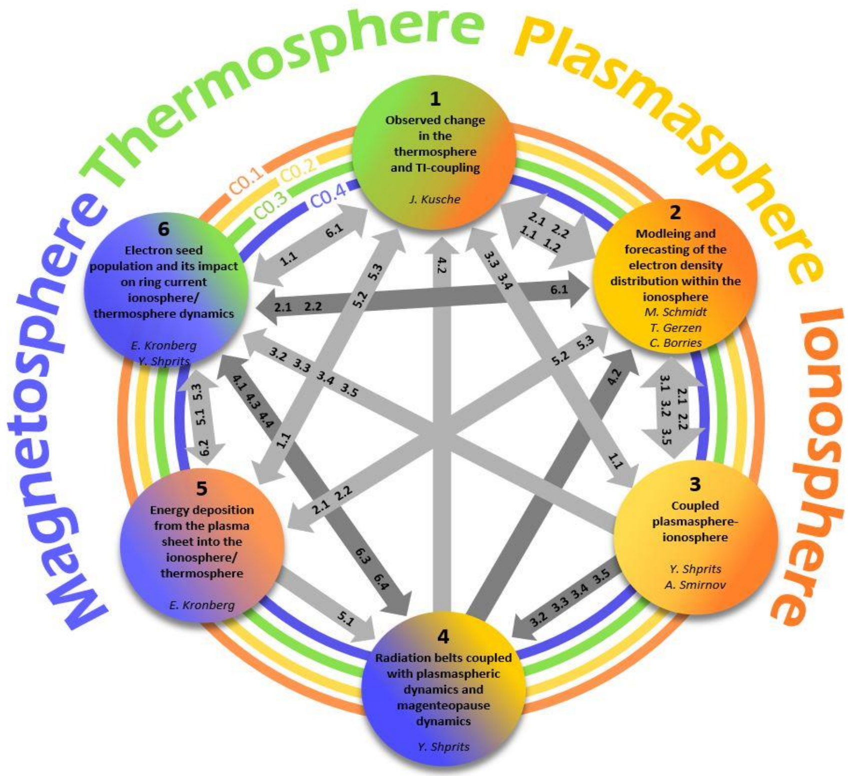


DFG-Funded Research Unit:

Magnetosphere, Ionosphere, Plasmasphere, Thermosphere as a Coupled System (MIPT)

Yuri Shprits[1,2], Michael Schmidt[3], Claudia Borries[4], Tatjana Gerzen[3], Elena Kronberg[5], Jürgen Kusche[6]

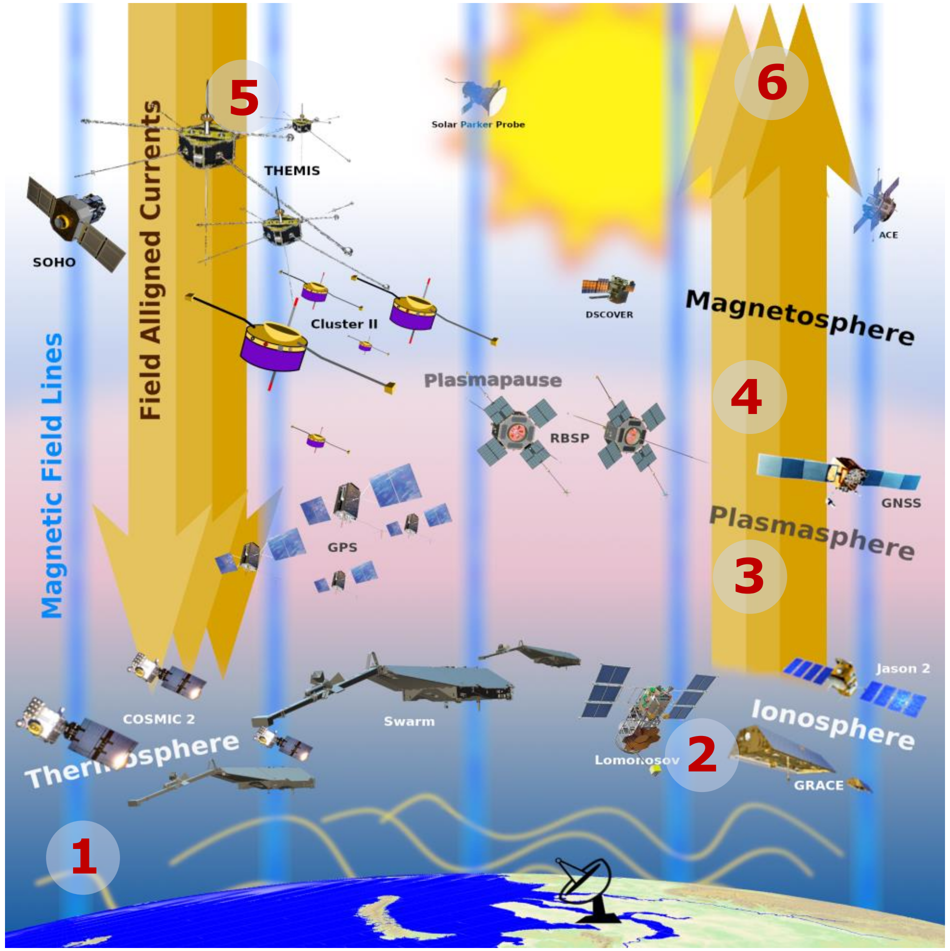
[1]GeoForschungsZentrum (GFZ) Potsdam, [2]Universität Potsdam, [3]Technische Universität München (TUM), [4]Deutsches Zentrum für Luft- und Raumfahrt (DLR), [5]Ludwig-Maximilians-Universität (LMU) München, [6]Universität Bonn



- **C0.1** The coupled system is driven by the solar wind.
- **C0.2** Joint event analysis.
- **C0.3** and **C0.4** Utilization of ML and DA.
- Exchange of measurements and codes in all projects.

MIPT RU as a coupled system

RU will help advance our understanding of MIPT as a coupled system



Project code	Project title	Researchers	Research areas
1	Observed change in the thermosphere and TI-coupling	J. Kusche	**TI** (PI)
2	Modeling and forecasting of the Electron Density distribution within the Ionosphere	M. Schmidt C. Borries T. Gerzen	**IP** (MT)
3	Coupled plasmasphere-ionosphere dynamics	Y. Shprits	**PI** (MT)
4	Understanding the acceleration of the radiation belt electrons to ultra-relativistic energies and its dependence on the plasma density	Y. Shprits	**MP** (TI)
5	Energy deposition from the magnetotail into the ionosphere/thermosphere	E. Kronberg	**MIT** (P)
6	Electron seed population and its impact on the ring current, ionosphere/thermosphere dynamics	E. Kronberg Y. Shprits	**MIT** (P)

VERB-4D (Shprits et al., 2015)

Fokker-Planck diffusion equation with modified terms:

$$\frac{\partial f}{\partial t} = -\overbrace{\langle v_\phi \rangle \frac{\partial f}{\partial \phi}}^{\text{longitudinal drift}} - \overbrace{\langle v_R \rangle \frac{\partial f}{\partial R}}^{\text{radial drift}} + \overbrace{\frac{1}{G}\frac{\partial}{\partial L} G \langle D_{LL} \rangle \frac{\partial f}{\partial L}}^{\text{radial diffusion}}$$

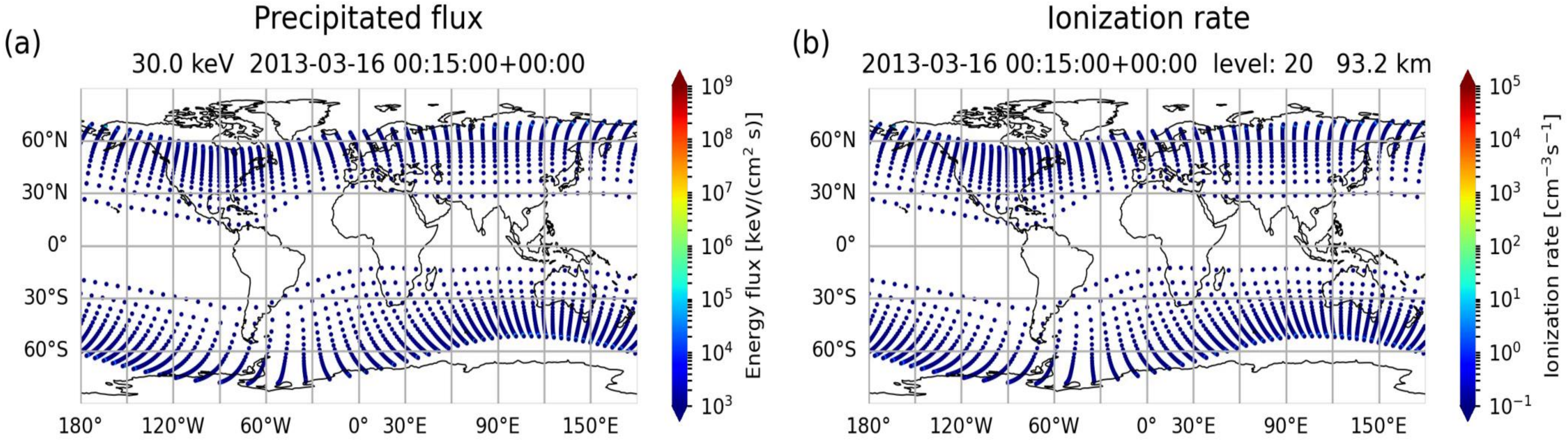
$$+ \underbrace{\frac{1}{G}\frac{\partial}{\partial V} G\left(\langle D_{VV} \rangle \frac{\partial f}{\partial V} + \langle D_{VK} \rangle \frac{\partial f}{\partial K}\right) + \frac{1}{G}\frac{\partial}{\partial K} G\left(\langle D_{VK} \rangle \frac{\partial f}{\partial V} + \langle D_{KK} \rangle \frac{\partial f}{\partial K}\right)}_{\text{local diffusion}} - \underbrace{\frac{f}{\tau}}_{\text{loss}}$$

$$K = J/(8\,\mu m_0)^{\frac{1}{2}}$$

$$V = \mu \cdot (K + 0.5)^2$$

$$G = -2\pi B_e (8\mu m_0 c^2)^{\frac{1}{2}}/(K + 0.5)^3/L^2$$

parameter	**setup**
Date	16 - 18.03.2013 (3 days)
Electric field	Volland; Stern; Maynard & Chen [VSMC, 1975]
Magnetic field	dipole
Initial conditions	RBSP-B
Boundary conditions for R	GOES-13,-15 + Denton [2015]
E domain	200 eV - 10 MeV
Radial diffusion coefficients	Brautigam and Albert [2000]
Local diffusion	Wang [2019] chorus + Orlova [2016] hiss
Loss	Magnetopause (LCDS)


(a)
Precipitated flux
30.0 keV 2013-03-16 00:15:00+00:00
60°N
30°N
0°
30°S
60°S
180°
120°W
60°W
0°
30°E
90°E
150°E
Energy flux [keV/(cm^2 s)]
10^9
10^8
10^7
10^6
10^5
10^4
10^3
(b)
Ionization rate
2013-03-16 00:15:00+00:00 level: 20 93.2 km
60°N
30°N
0°
30°S
60°S
180°
120°W
60°W
0°
30°E
90°E
150°E
Ionization rate [cm^-3 s^-1]
10^5
10^4
10^3
10^2
10^1
10^0
10^-1

Summary

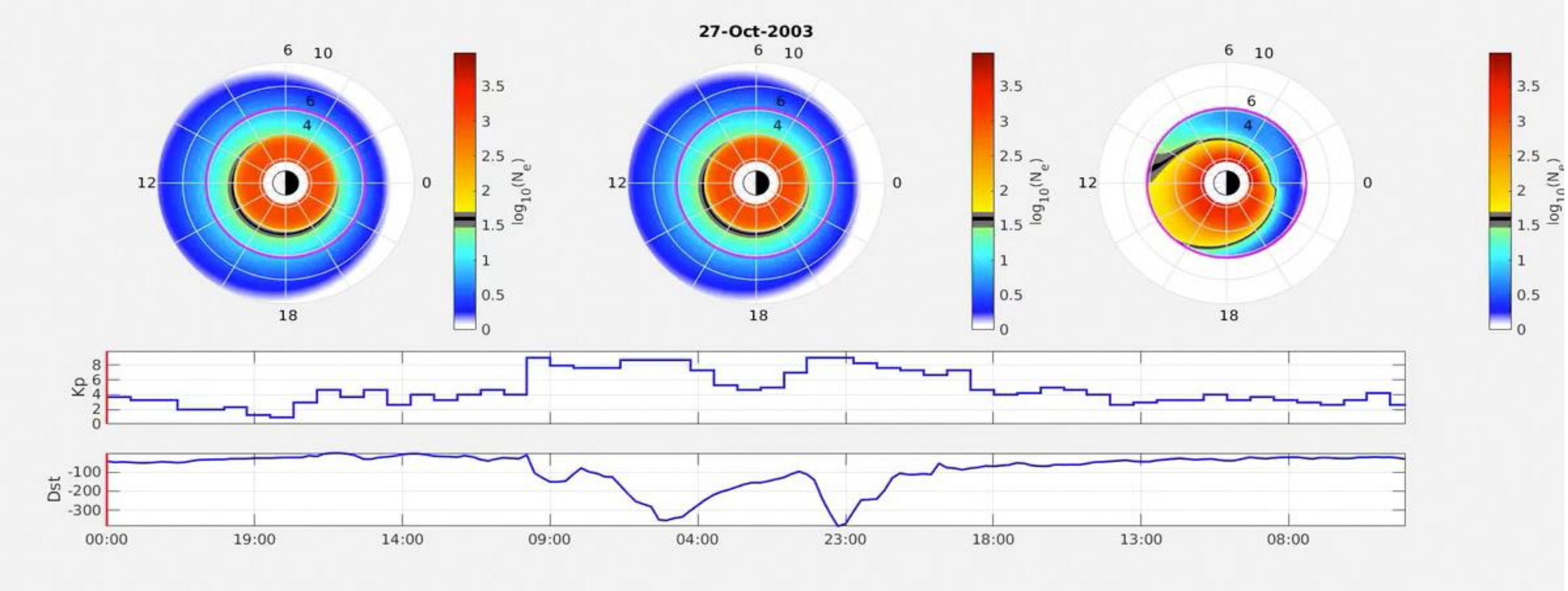
- PAGER project responds to stakeholder requirements by: providing coupled simulations, performing ensemble simulations, using data assimilation in the solar wind and in the inner magnetosphere and providing simple indicators of radiation in space.
- Predictions of Kp, Plasmasphere conditions, radiation belt fluxes, and ring current are already available at ***www.spacepager.eu*** .
- Full chain of PAGER simulations including ensamble CMEs is operational since July 2023.
- Similar codes help us understand the effect on NOx and climate.

Plasma density

Calculation of plasma density using ML, VERB-CS, and assimilative VERB with ML

ML model may not preform well during extreme events outside of the training dataset

Assimilative code | Physics-based model | ML model



[Zhelavskaya et al., 2021]

VERB-4D (Shprits et al., 2015)

Fokker-Planck diffusion equation with modified terms:

$$\frac{\partial f}{\partial t} = -\overbrace{\langle v_\phi \rangle \frac{\partial f}{\partial \phi}}^{\text{longitudinal drift}} - \overbrace{\langle v_R \rangle \frac{\partial f}{\partial R}}^{\text{radial drift}} + \overbrace{\frac{1}{G}\frac{\partial}{\partial L} G \langle D_{LL} \rangle \frac{\partial f}{\partial L}}^{\text{radial diffusion}}$$

$$+ \underbrace{\frac{1}{G}\frac{\partial}{\partial V} G \left(\langle D_{VV} \rangle \frac{\partial f}{\partial V} + \langle D_{VK} \rangle \frac{\partial f}{\partial K} \right) + \frac{1}{G}\frac{\partial}{\partial K} G \left(\langle D_{VK} \rangle \frac{\partial f}{\partial V} + \langle D_{KK} \rangle \frac{\partial f}{\partial K} \right)}_{\text{local diffusion}} - \underbrace{\frac{f}{\tau}}_{\text{loss}}$$

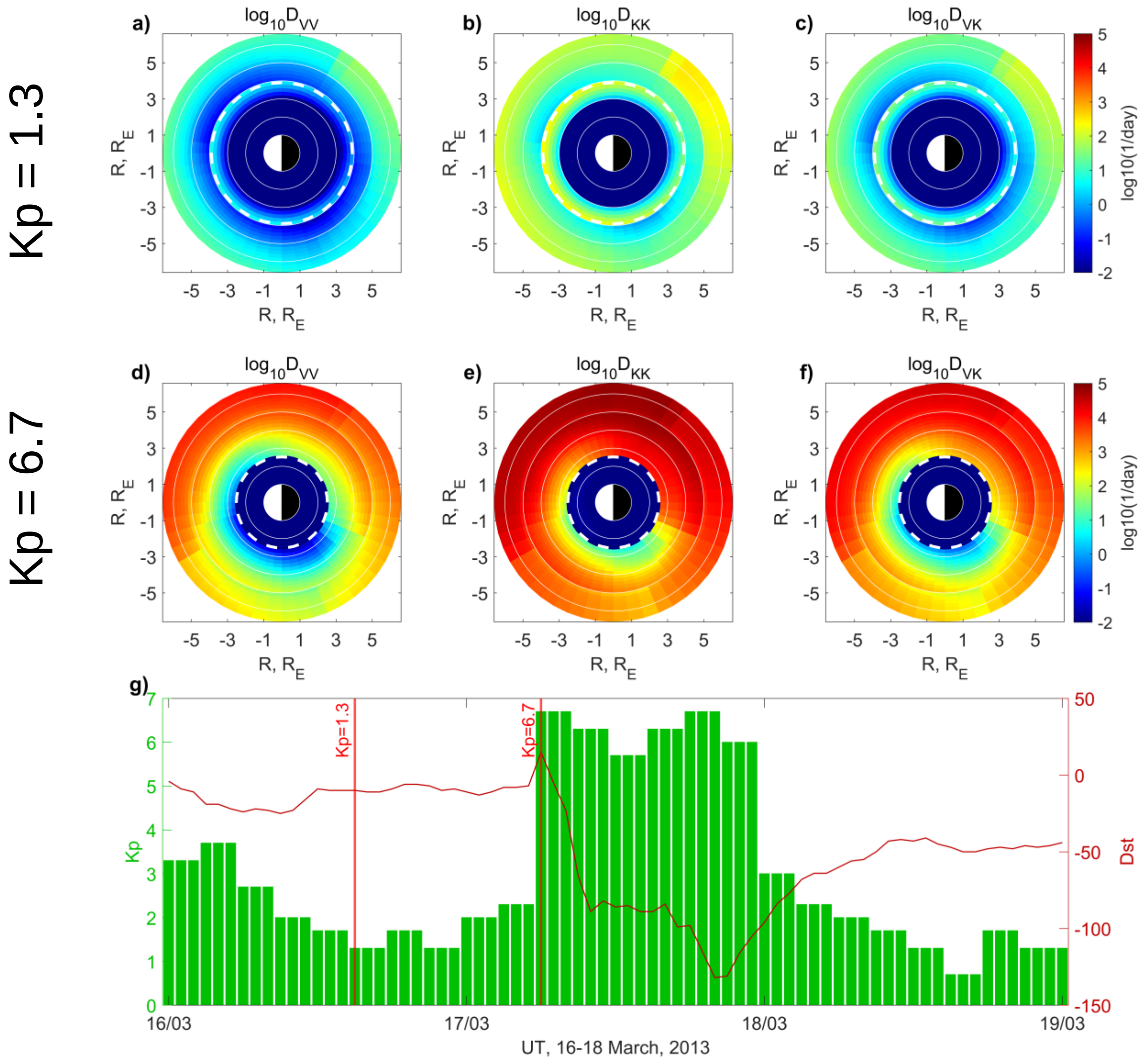
$$K = J/(8\,\mu m_0)^{\frac{1}{2}}$$

$$V = \mu \cdot (K + 0.5)^2$$

$$G = -2\pi B_e (8 \mu m_0 c^2)^{\frac{1}{2}} / (K + 0.5)^3 / L^2$$

parameter	setup
Date	16 - 18.03.2013 (3 days)
Electric field	Volland; Stern; Maynard & Chen [VSMC, 1975]
Magnetic field	dipole
Initial conditions	RBSP-B
Boundary conditions for R	GOES-13,-15 + Denton [2015]

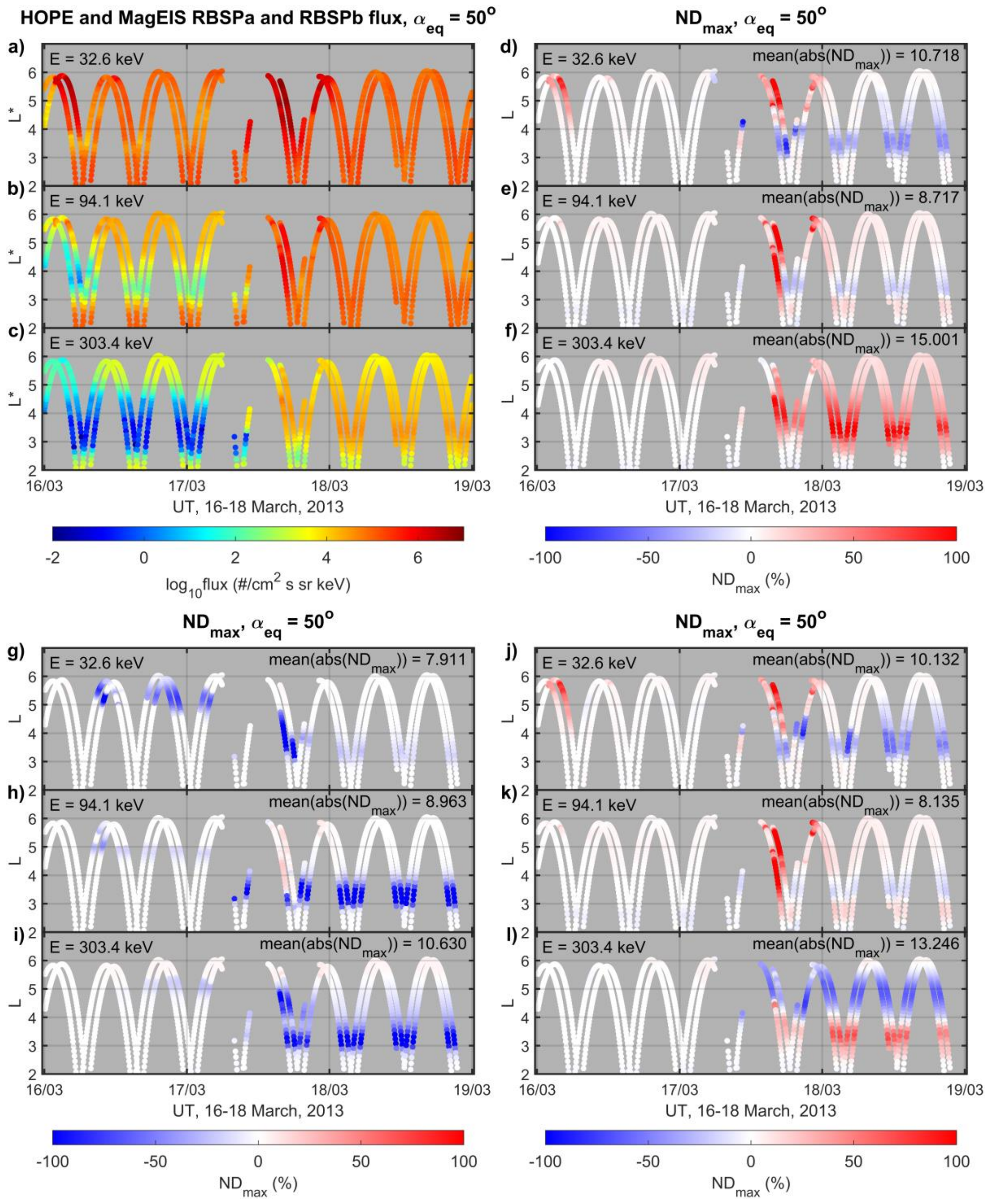
Wang et al. 2019 chorus wave model
Orlova et al. 2016 hiss wave model



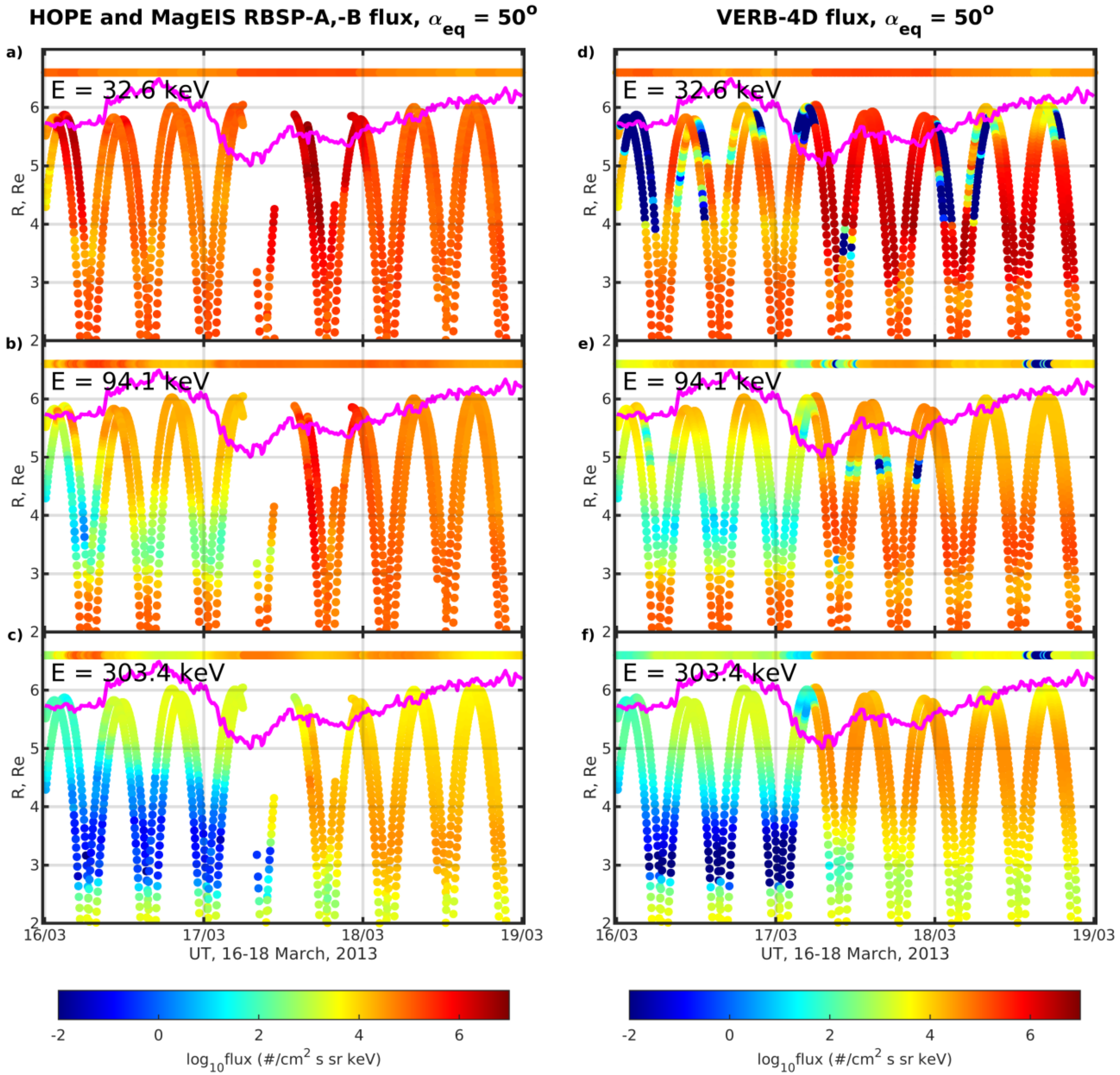
Boundary conditions sensitivity

$$ND_{max}(l^*,t) = \frac{J_O(l^*,t) - J_S(l^*,t)}{max\,|_{over\ L^*\ every\ 8\ hours}\ \frac{J_S(L^*,T)+J_O(L^*,T)}{2}},$$

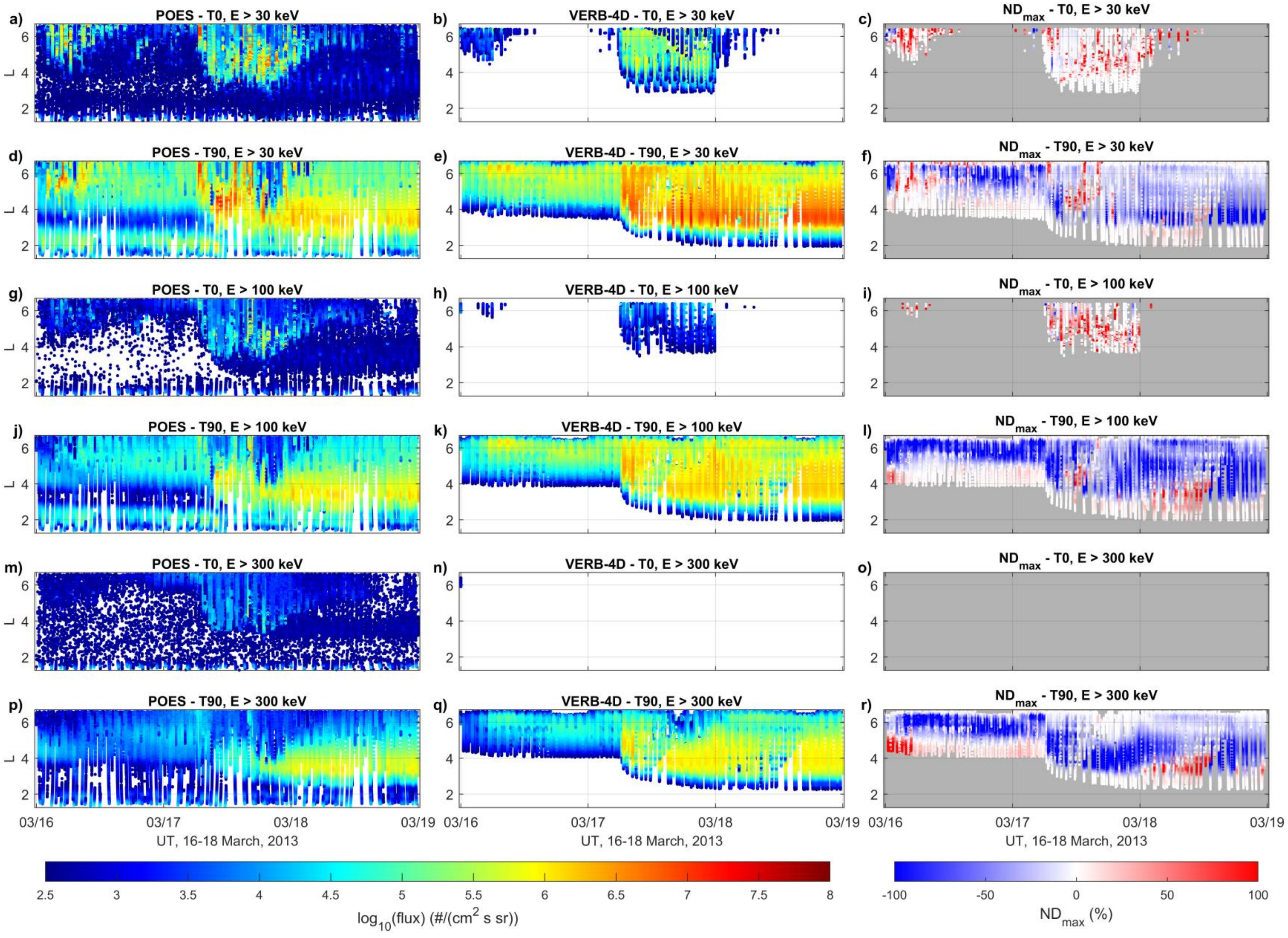
$J_O -$ observed flux
$J_S -$ simulated flux



Validation with Van Allen Probes



Validation with POES



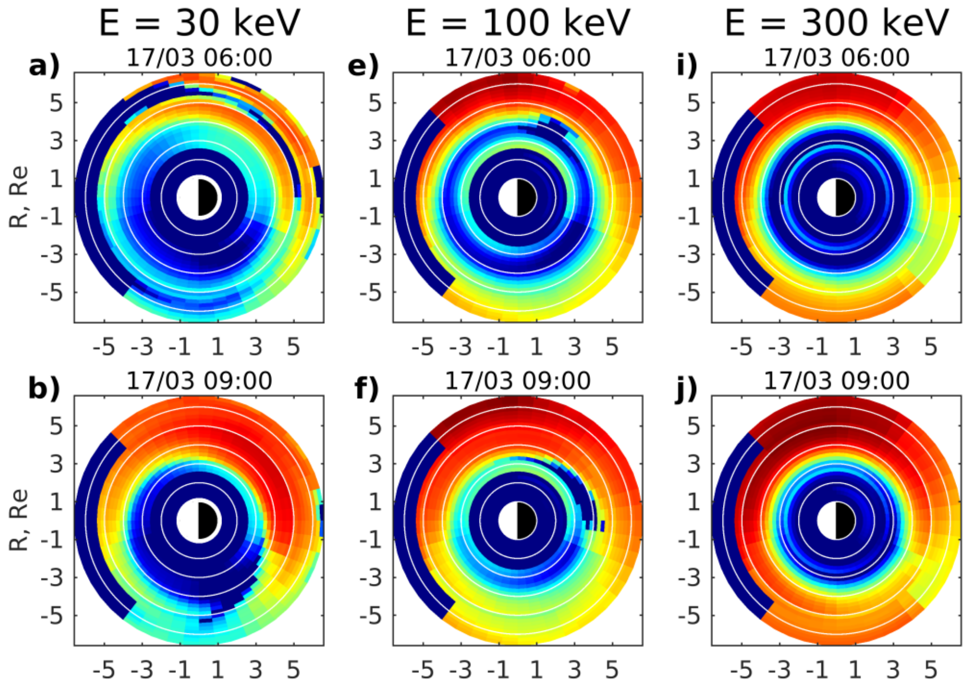
Precipitated flux

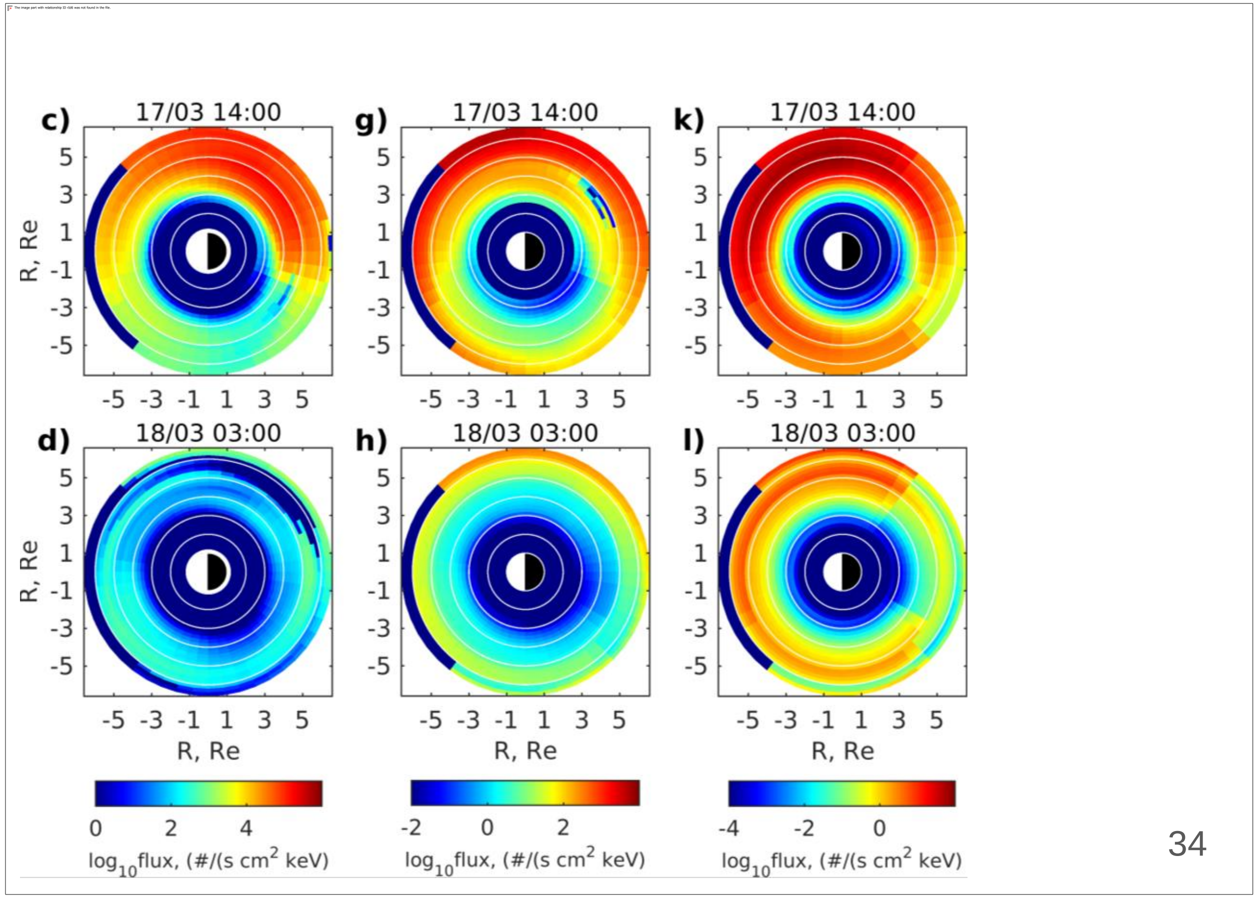
$$J_{prec}(t,P,R,E) = \frac{1}{\sin^2\alpha_{LC}} \underbrace{\int^{2\pi}\int^{\alpha_{LC}}}_{\text{flux tube conctraction}} f(E,t,\alpha)\, \cos\alpha\, \sin\alpha\, \underbrace{d\alpha\, d\varphi}_{\text{area} \perp \text{to } B_0}$$

solid angle

[Ristić-Djurović et al, 1998]

$$\alpha_{LC} - loss\ cone\ pitch\ angle$$

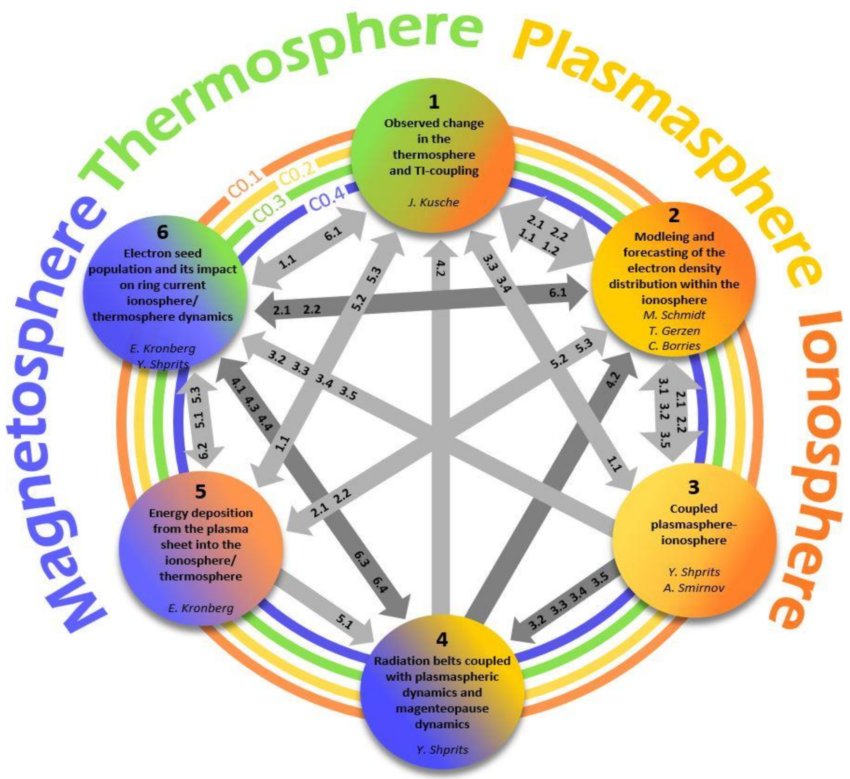




Connections between projects

Projects in MIPT are strongly interconnected

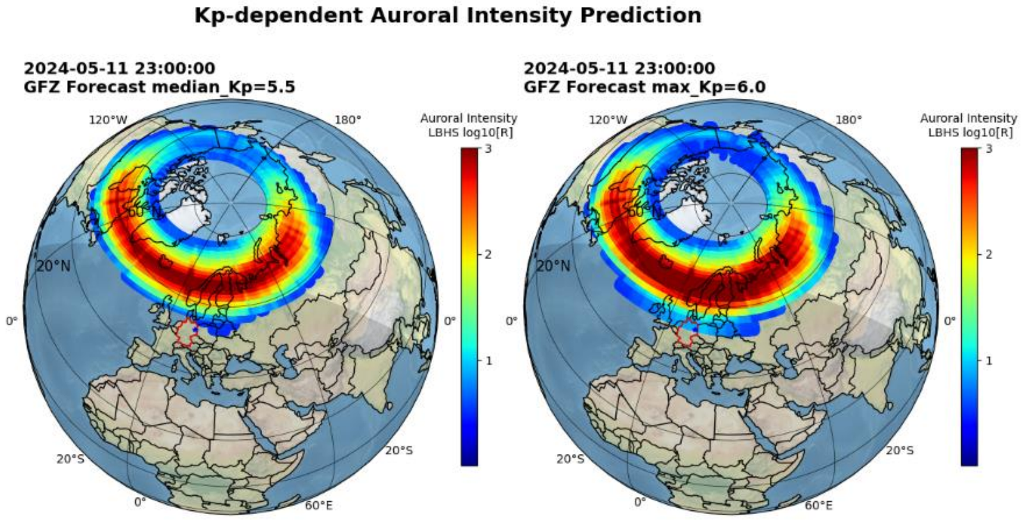
Connection	Nr	Connected to
C0.1 Solar and geomagnetic parameters (M3/M12)	All	All
C0.2 Event analysis(M6/M24)	All	All
C0.3 Machine Learning ongoing up to M48	All	All
C0.4 Data Assimilation ongoing up to M48	All	1, 3, 4, 6
C1.1 Thermosphere neutral density variations (M22/M27)	1	2, 3, 5, 6
C1.2 Assimilative model TIEGCM-PDAF (M19/M36)	1	2
C2.1 First package of electron density variations within the ionosphere (M18/M24)	2	1, 3, 5, 6
C2.2 Second package of electron density variations within the ionosphere (M39/M45)	2	1, 3, 5, 6
C3.1 Preliminary models of the plasmasphere (M01/M03)	3	2
C3.2 Electron density in the plasmasphere (M25/M42)	3	2, 4, 6
C3.3 Calculated plasmapause location (M25/M30)	3	4, 6
C3.4 Calculated maps of electric fields (M15/M18)	3	1, 4, 6
C3.5 VERB-CS and the PINE models (M20/M30)	3	2, 4, 6
C4.1 Diffusion coefficients (M21/M24)	4	6
C4.2 Precipitation (M12/M24)	4	1, 2
C4.3 Density dependent modules (M12/M24)	4	6
C4.4 Precipitation modules (M12/M24)	4	6
C5.1 An empirical model for plasma beta (M12/M18)	5	4, 6
C5.2 Poynting flux approximation produced by high-beta magnetospheric plasma in the ionospheric coordinates (M32/M38)	5	1, 2
C5.3 Time series of beta parameter (M12/M18)	5	6
C6.1 Integrated electron precipitation energy flux maps (M32/M38)	6	1, 2
C6.2 PSD maps in L-shell/MLT coordinates (M12/M24)	6	5
C6.3 Results of the VERB-4D at ~100s of keV (M30/36)	6	4
C6.4 Results of the VERB-4D at 10s of keV (M30/36)	6	4



- **C0.1** The coupled system is driven by the solar wind.
- **C0.2** Joint event analysis.
- **C0.3** and **C0.4** Utilization of ML and DA.
- Exchange of measurements and codes in all projects.

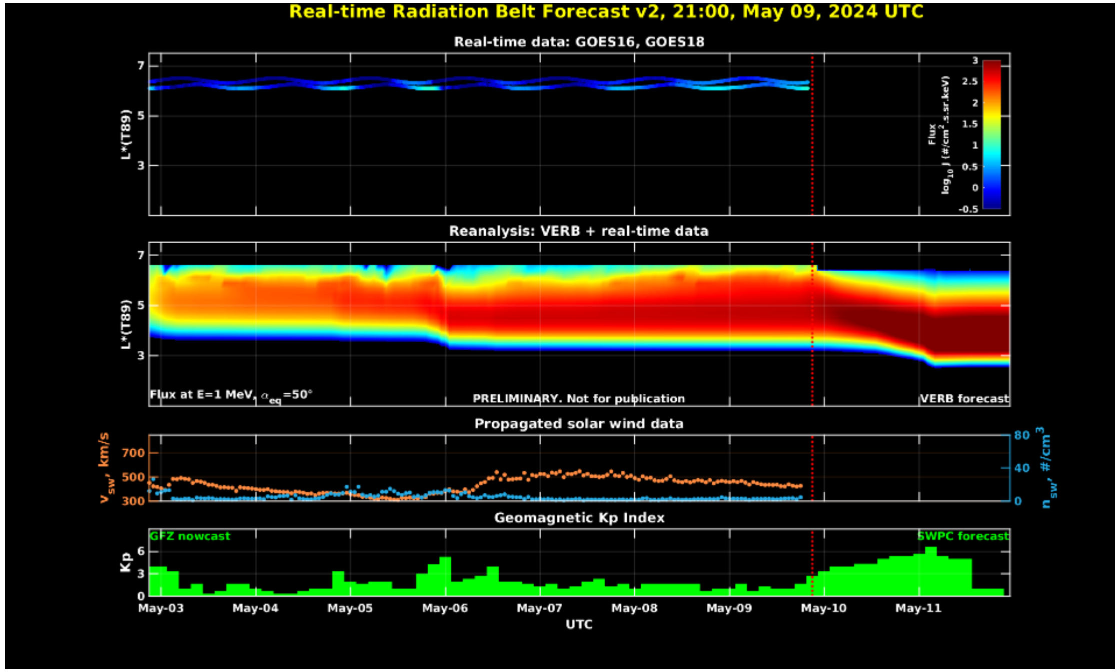
Section 2.7 Space Weather Forecasts for the geomagnetic storm of May 10-11, 2024

Aurora Forecast

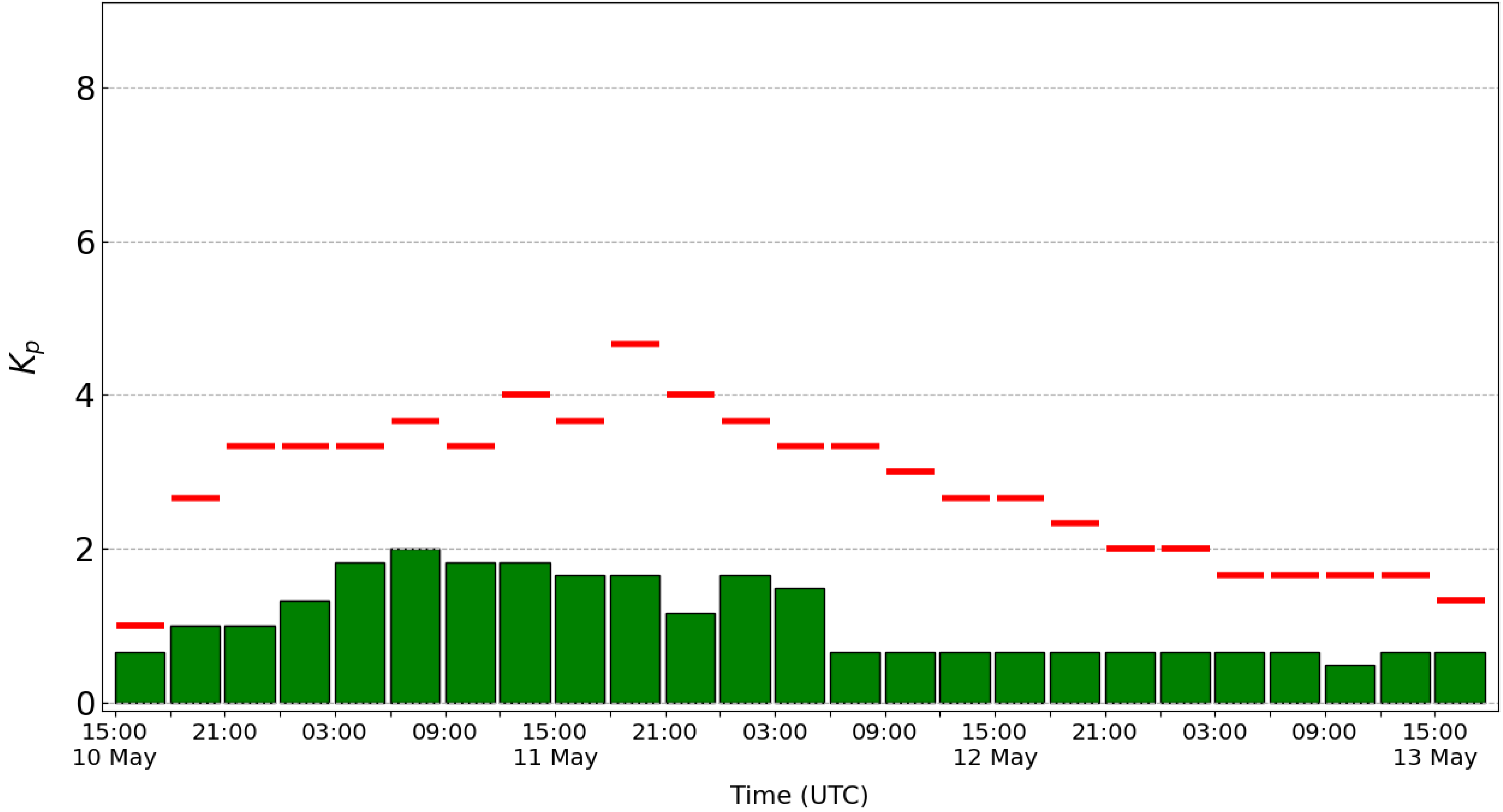


Forecast on May 11 at 23:00
Auroras were predicted to be visible in Germany

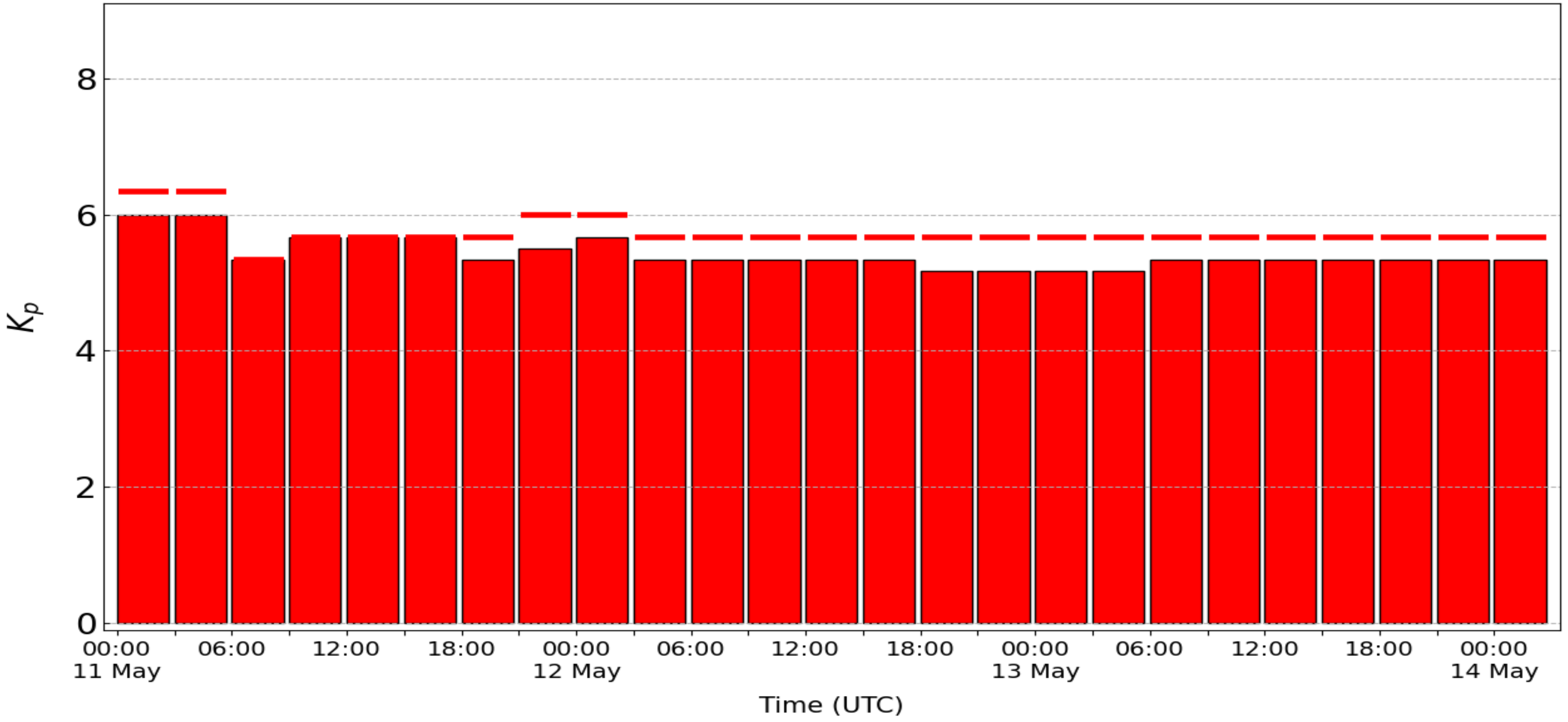
Radiation Belt Forecast



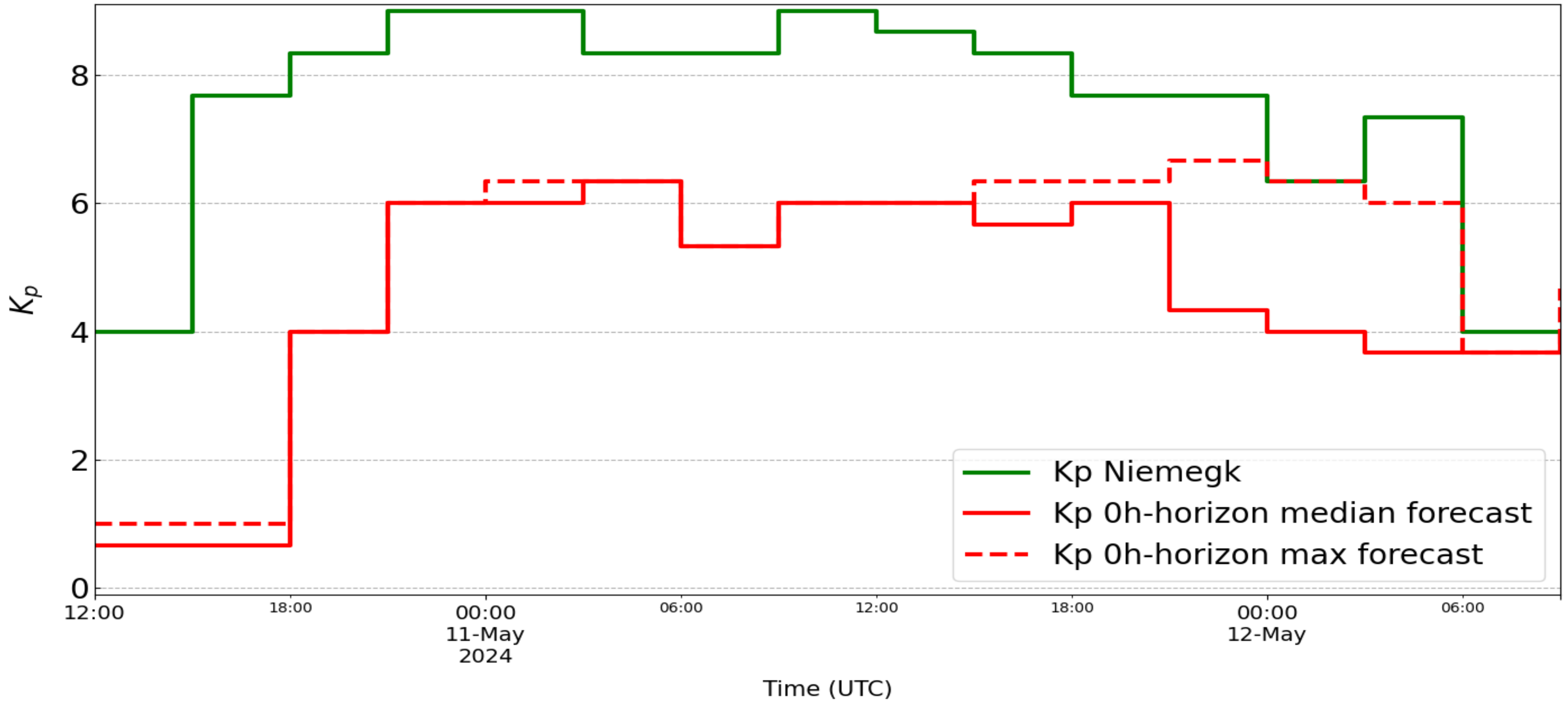
3-days-ahead forecast just before the start



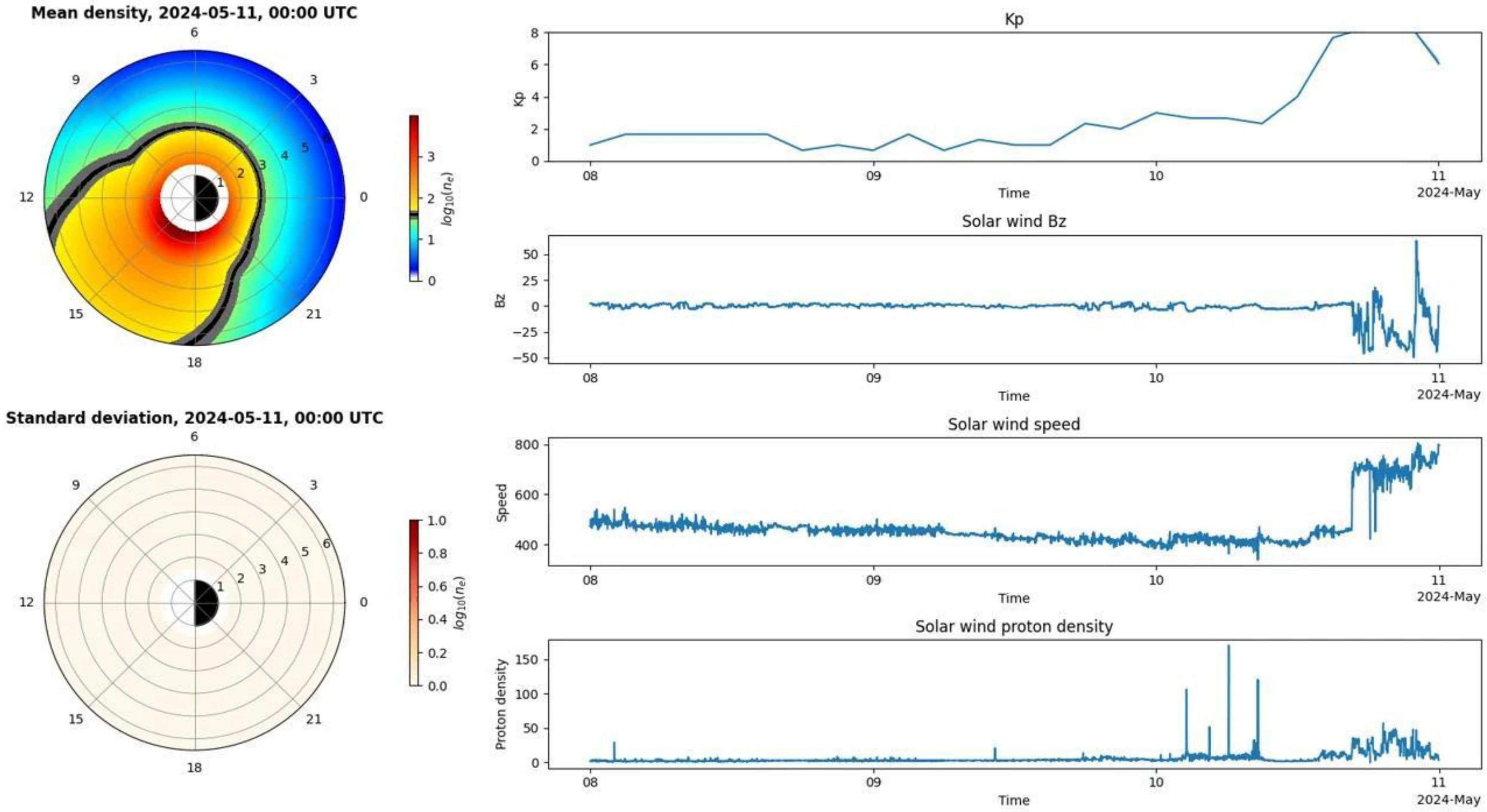
3-days-ahead forecast a bit after the storm start (highest Kp predicted)



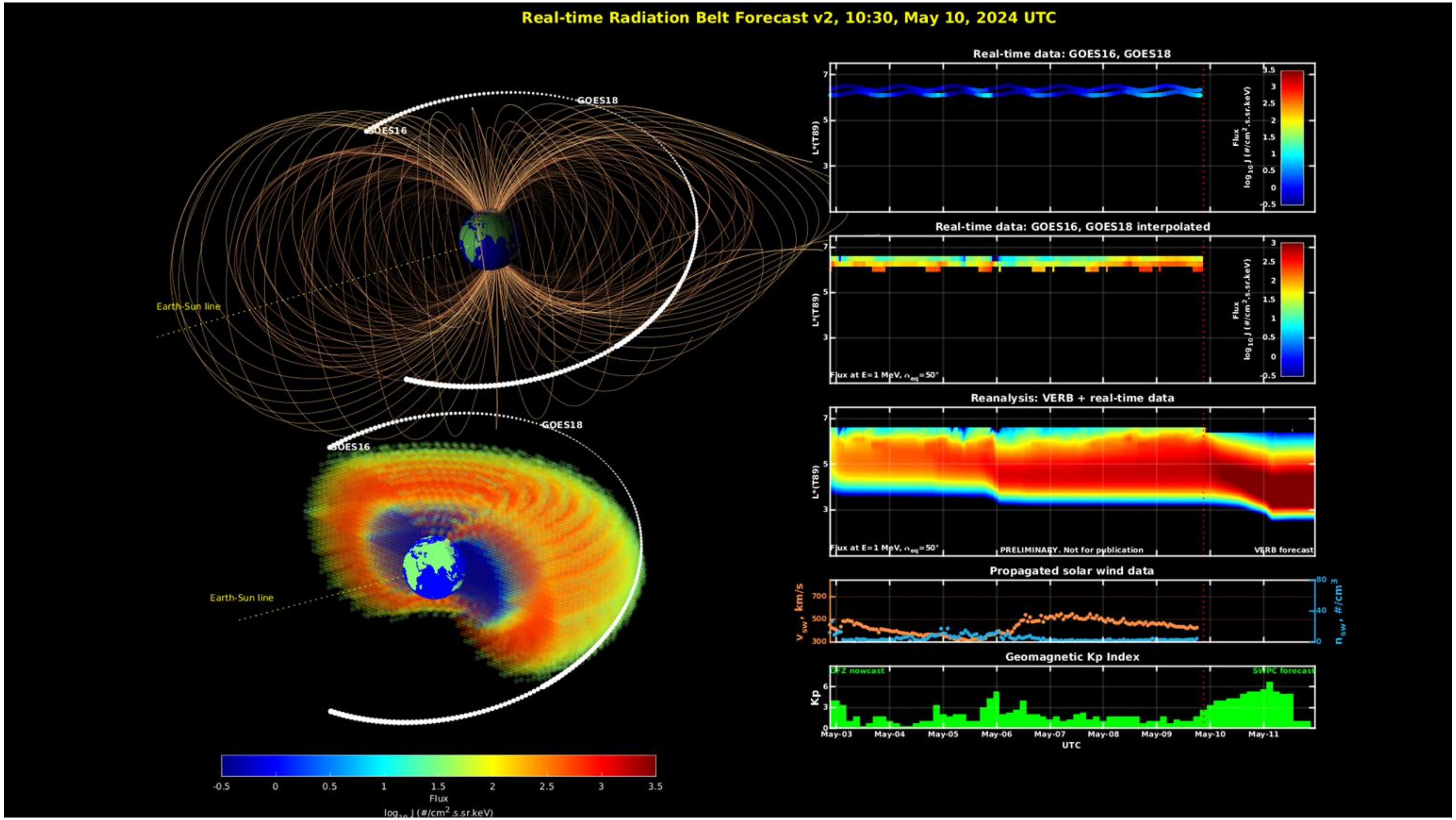
Evaluation of 0-horizon forecast



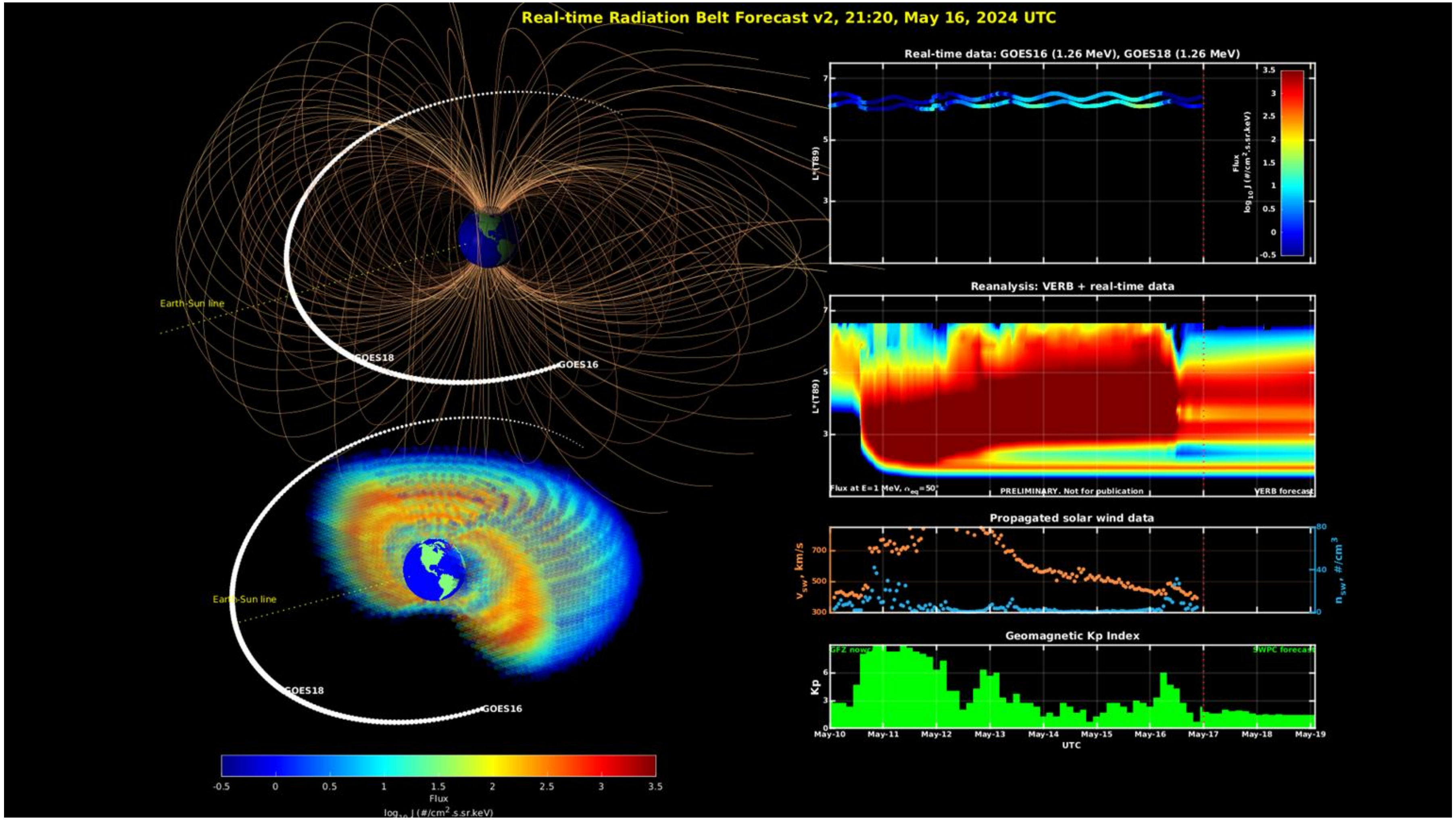
Forecast just after the start of the storm, same date as highest Kp forecast



I am afraid this figure is from the GFZ forecast, NOT Pager ensemble forecast (Angelica)



Modelling from Nowcast



Start time 2024-05-09 20:13