A real-time, data assimilation-based geomagnetic field disturbance service

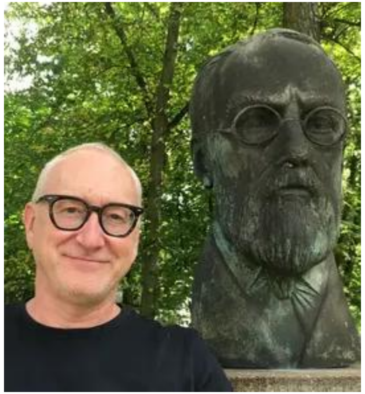
Jürgen Matzka and Alexander Grayver

Leomagnetics GmbH

Speaker Bio

Jürgen Matzka

- Founder, Leomagnetics
- INTERMAGNET OpsCom Chair
- Senior Scientist, Kp, global networks



Alexander Grayver

- Scientific Advisor, Leomagnetics
- Heisenberg Research Fellow
- Geophysical Modelling and Inversion

leomagnetics

esa space solutions

ESA Project MagWatch3D

esa
space solutions

Global and regional maps of geomagnetic disturbance

- Based on near real-time geomagnetic observatory data
- Based on subsurface 3D electric conductivity models
- Very fast physics-based data assimilation method

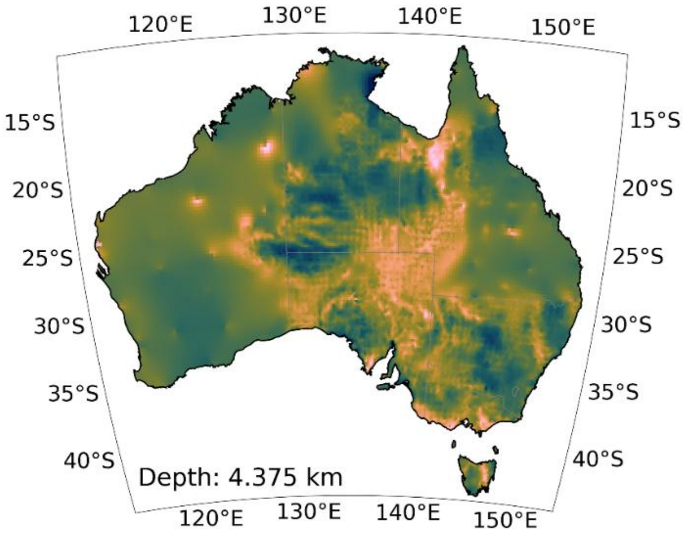
The project

- Funded by ESA, started in February 2026
- Use of space weather data for directional drilling, geophysical surveys, etc.
- Industry stakeholders and potential users are invited to follow the project

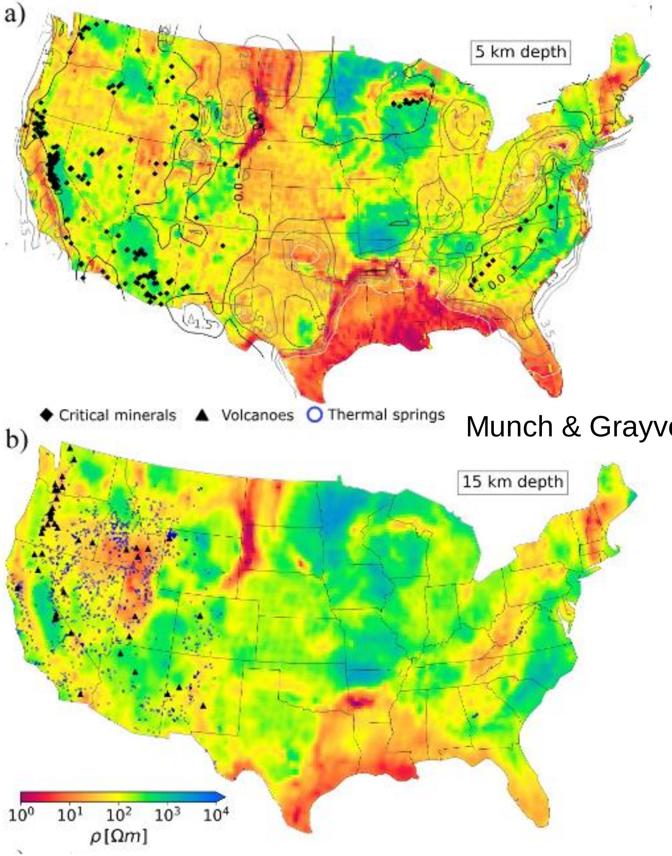
3D Conductivity models

Continental scale, based on

- Magnetometer data
- Magnetotelluric data



Conductivity of Australia, Grayver et al., in prep.

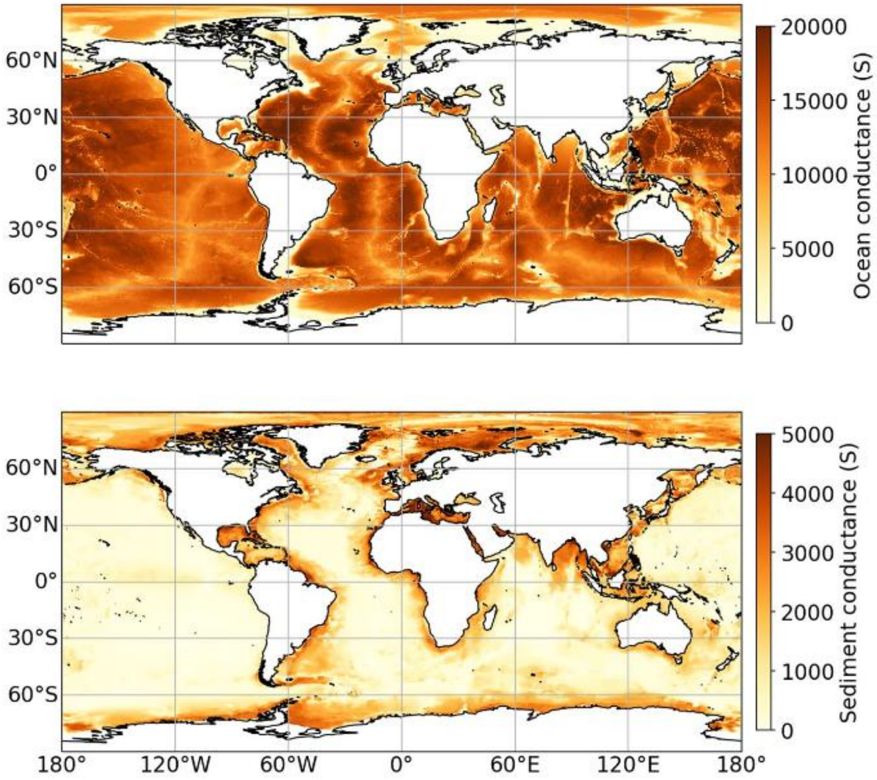


Munch & Grayver, 2026

3D Conductivity models

Oceans, based on

- Seawater conductivity
- Bathymetry
- Sediment lithology
- Sediment thickness



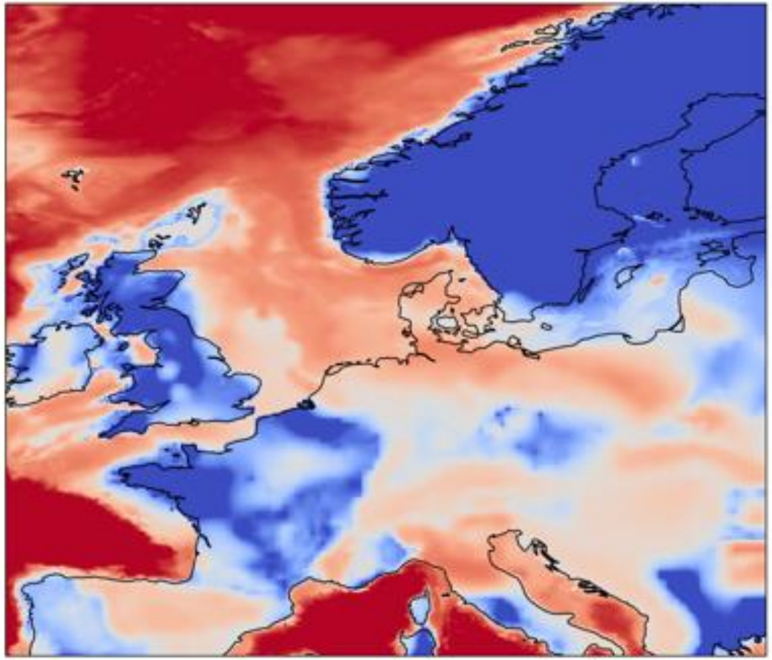
Grayver, 2021

3D Conductivity models

Combined continent / ocean

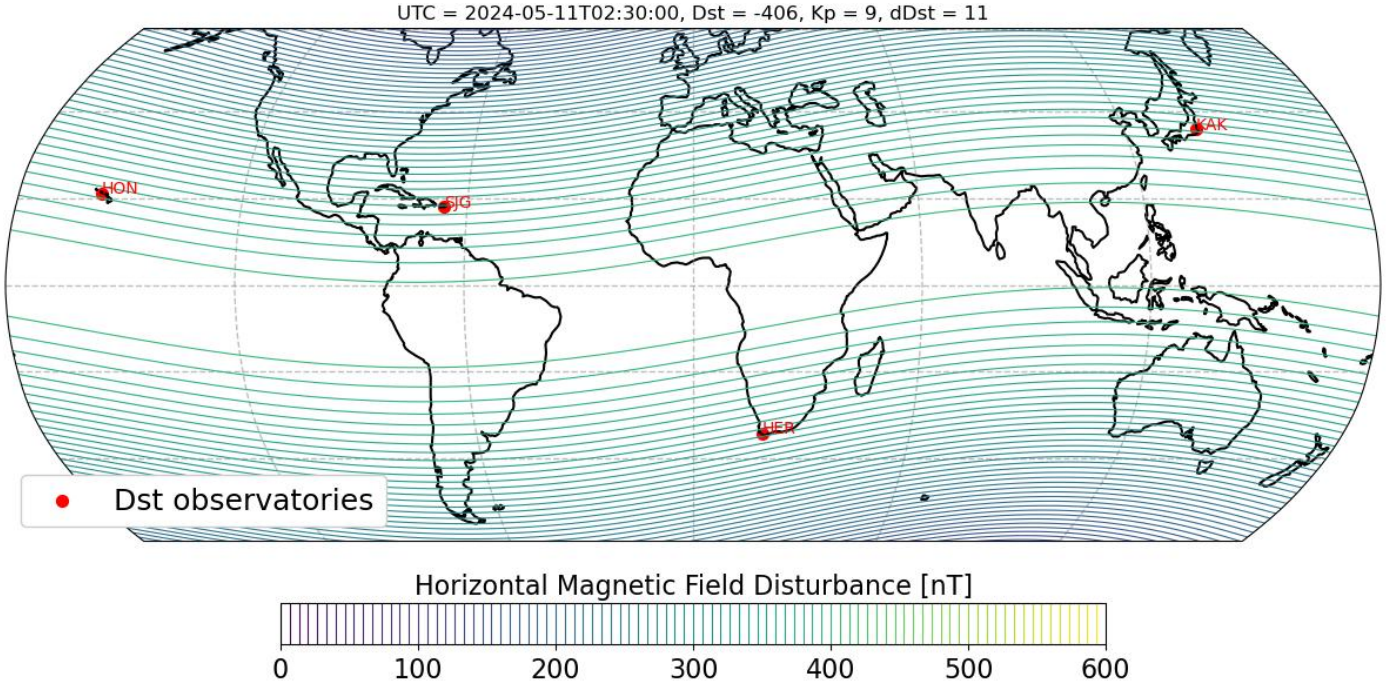
- Existing continental models
- Ocean model
- Geological input

3D conductivity models are developed and translated into induction kernels.



Simple global model of a geomagnetic storm

- Global model excl. high latitudes
- Based on four low-latitude magnetic observatories (Dst index)



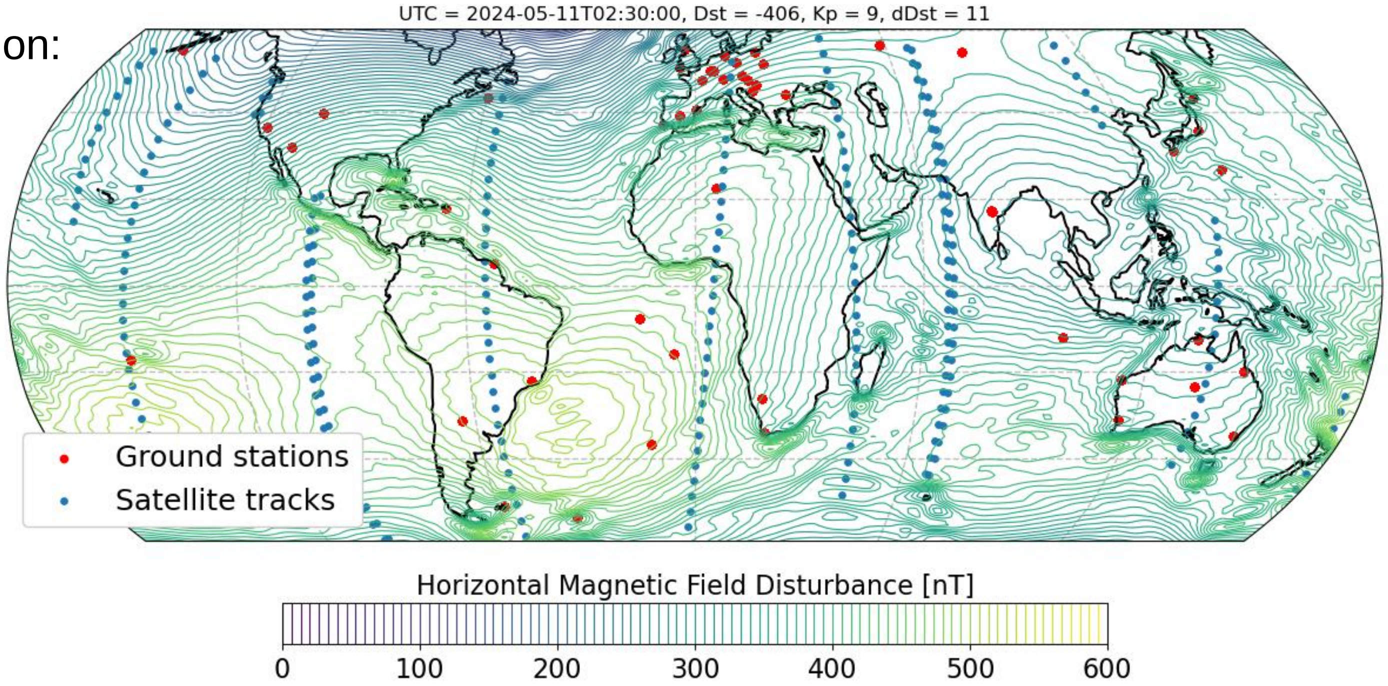
MagWatch3D global model of a geomagnetic storm

Excl. high latitudes, based on:

- Observatories
- Satellite data
- 3D conductivity model
- Physics-based data assimilation
- Cadence: 1 h

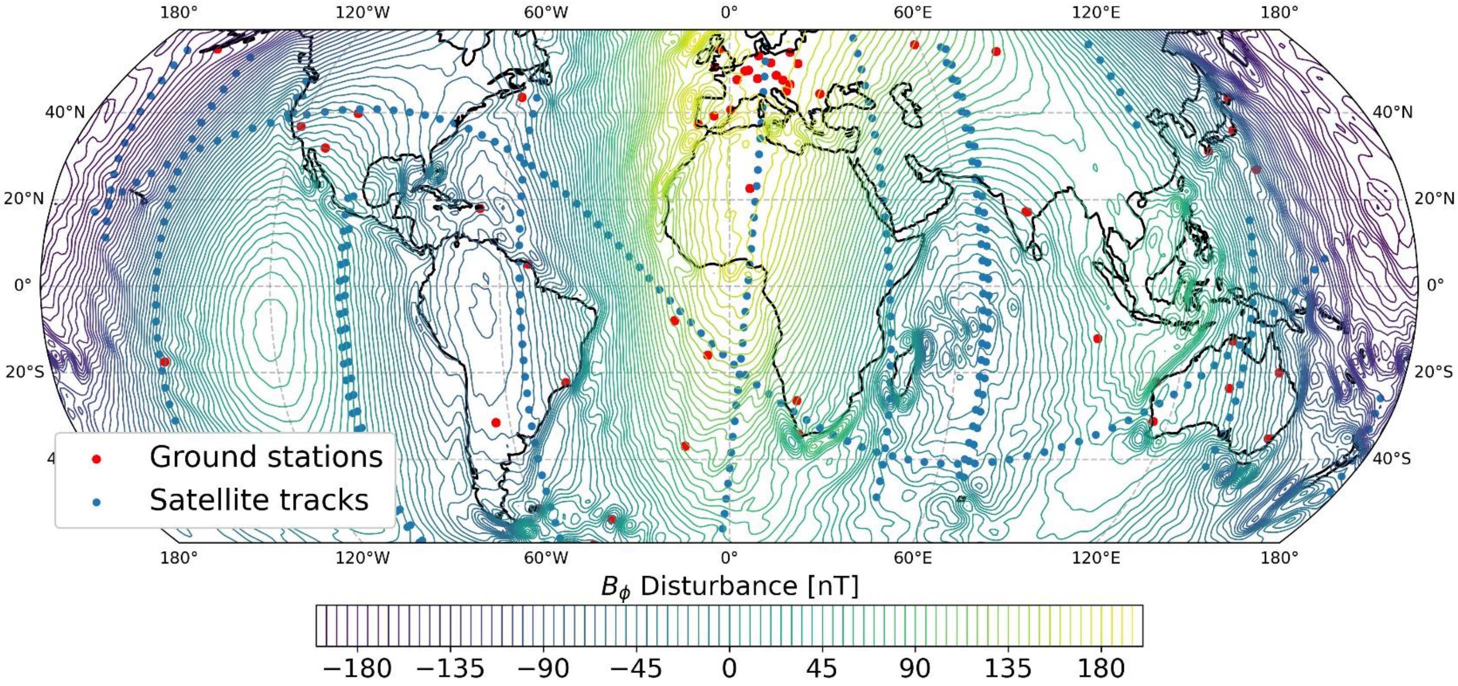
Planned in MagWatch3D:

- Cadence 1 min
- Latency: 20 min (excl. satellite)



MagWatch3D global model of a geomagnetic storm

- East component of the geomagnetic field
- Declination error in large areas exceeds 1˚
- Model is useful for low and mid-latitudes.



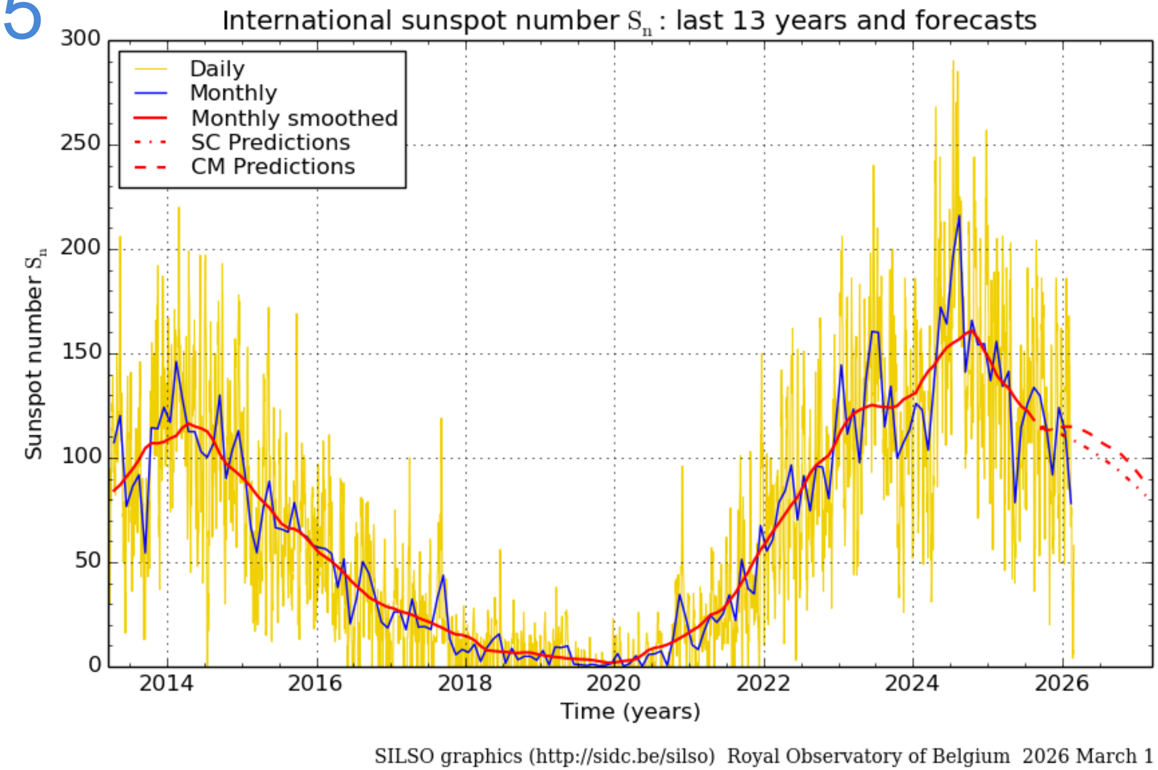
Soaring Solar Cycle 25

Sunspot numbers and recent geomagnetic storms

- April 2023
- May 2024
- October 2024
- November 2025
- January 2026

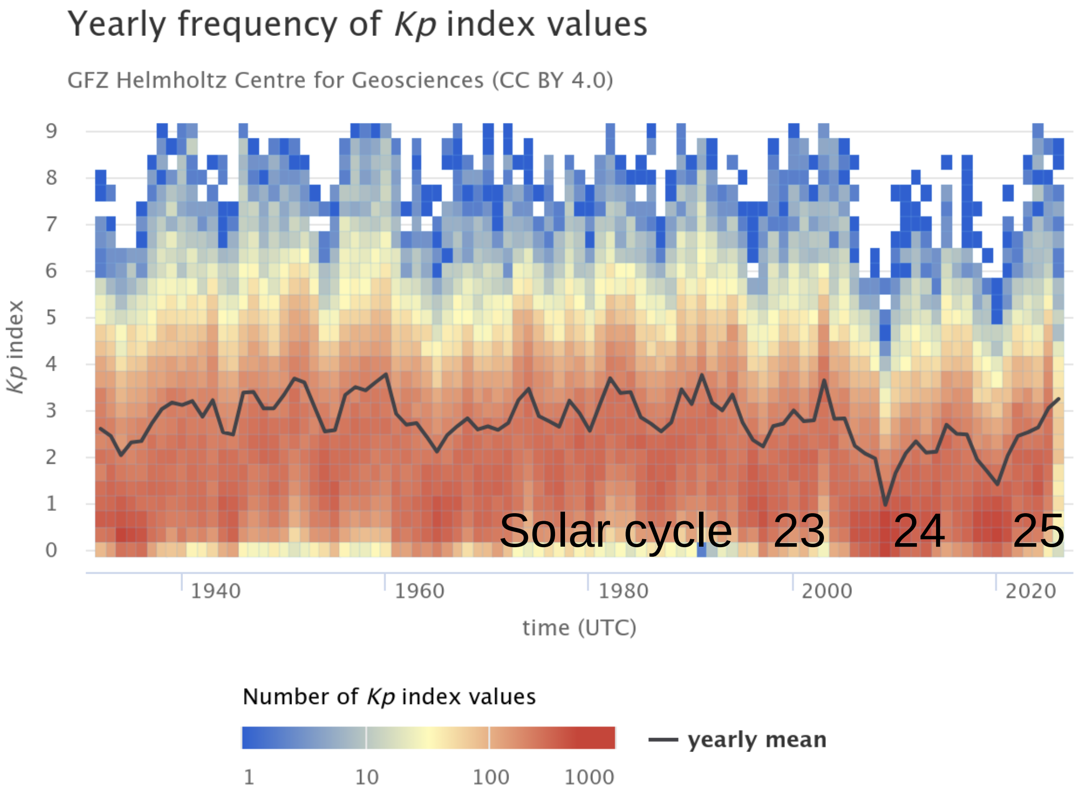
Solar maximum at end of 2024

- Expect solar min in 2030
- Next solar max in 2035



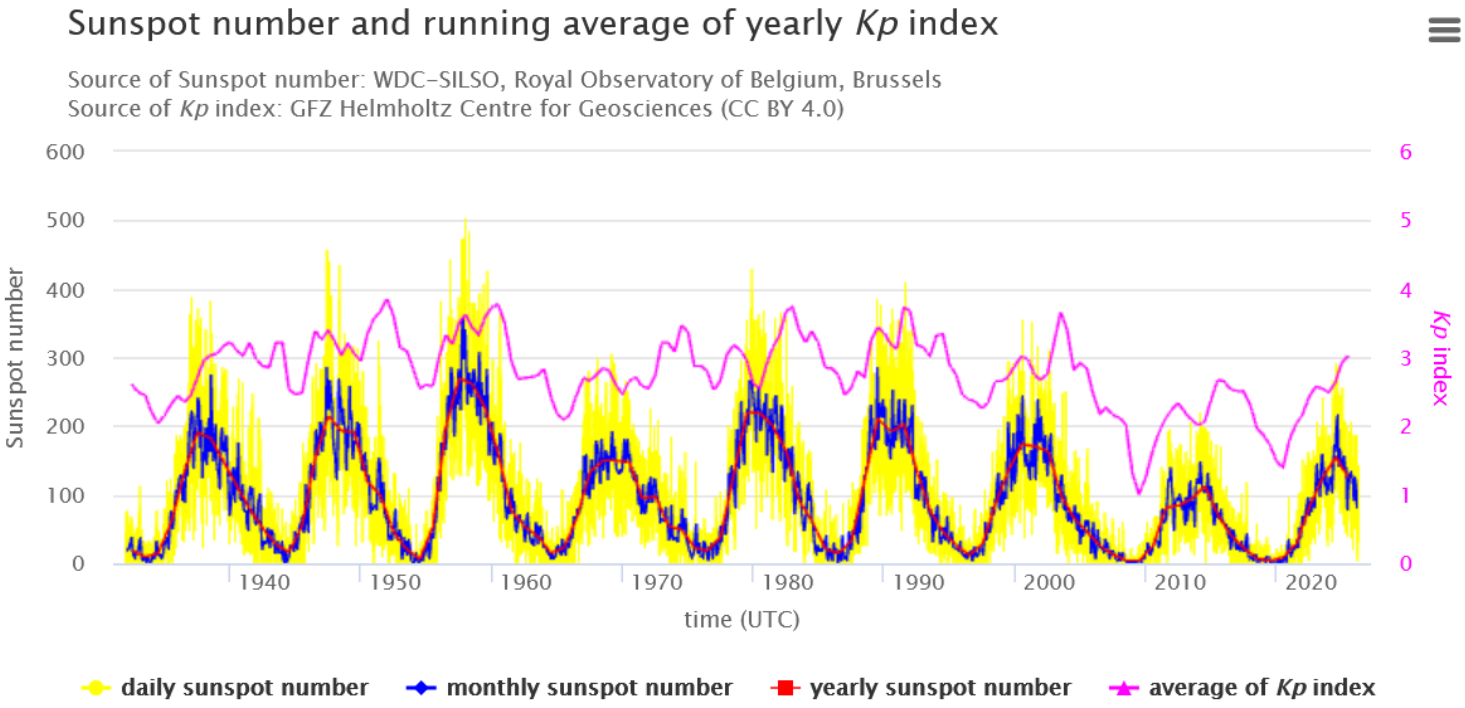
Soaring Solar Cycle 25

- Previous solar cycle 24 (2008 to 2019) was very weak
- The current solar cycle 25 is back to a “normal” level
- We need to go 25 years back for comparable levels of geomagnetic activity



Magnetic activity peaks 3 to 4 years after solar max

- Geomagnetic activity trails sunspot number by 3 to 4 years
- **Expect more magnetic storms until 2027/2028**



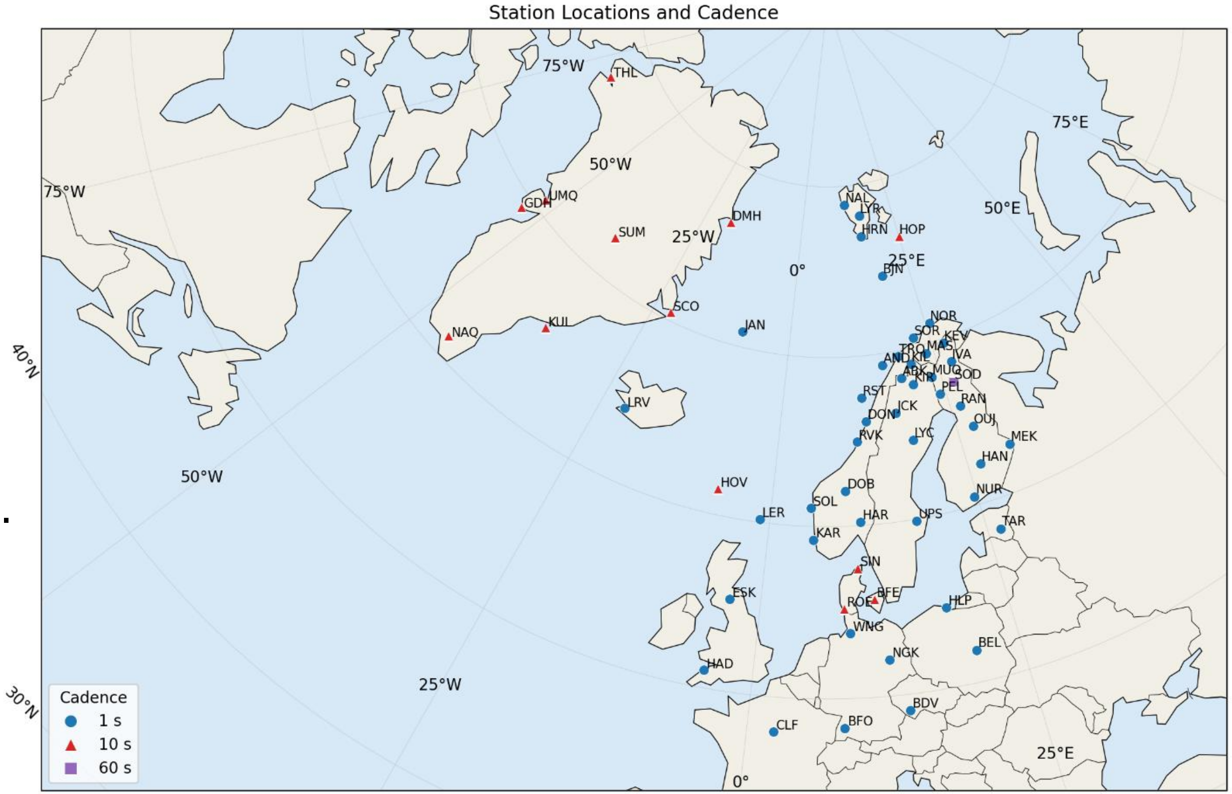
High latitude study

High latitudes:

- Magnetic activity throughout the solar cycle, not limited to geomagnetic storms

Model study

- Regional geomagnetic disturbance field model
- Ca. 50 magnetometer stations.
- Testcase within the MagWatch3D project.



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High latitude study:

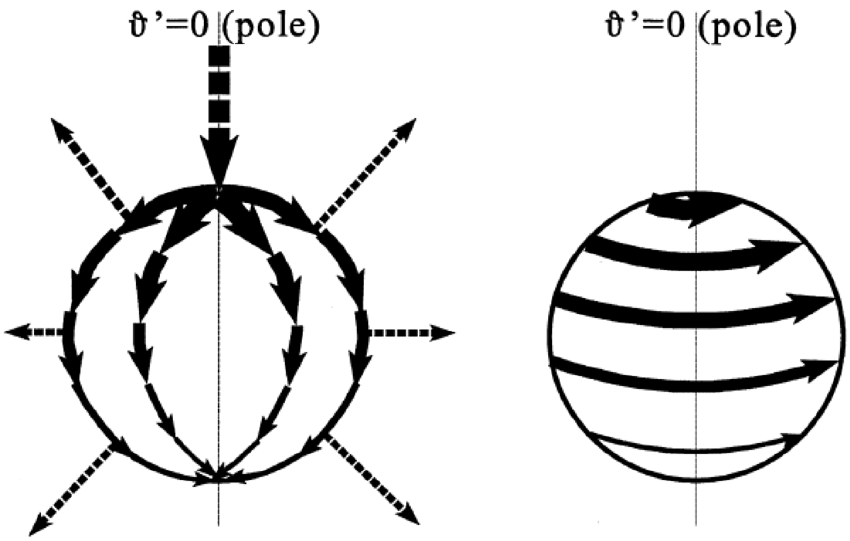
The strong high-latitude geomagnetic disturbance is caused by

- electric currents in the ionosphere (~100 km altitude, primary from solar wind interaction, external)
- simultaneously induced electric currents in the ocean and ground (secondary, internal)

The currents can be described by

- Spherical Elementary Current Systems (Amm and Viljanen, 1999; Laundal 2022)

O. AMM AND A. VILJANEN: DISTURBANCE MAGNETIC FIELD CONTINUATION



Curl-free elementary system (with associated FACs)

Divergence-free elementary system

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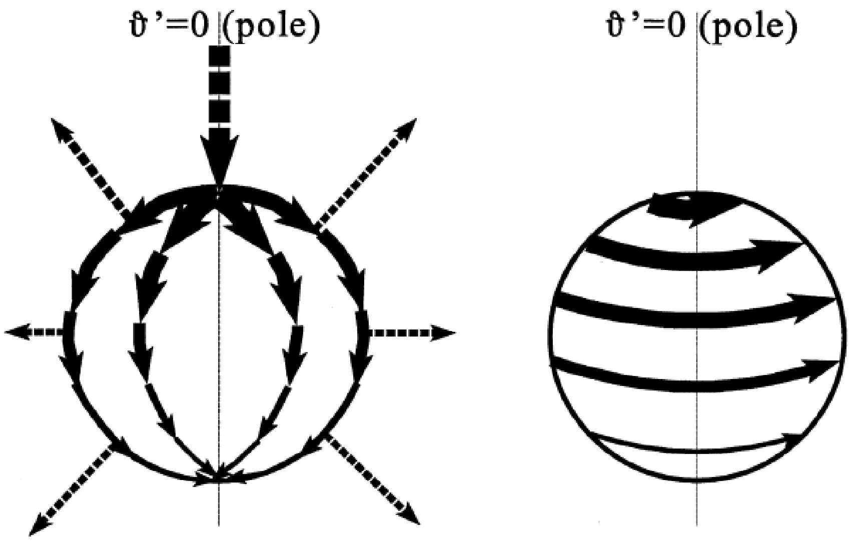
- Here denoted as **ELCS**

O. AMM AND A. VILJANEN: DISTURBANCE MAGNETIC FIELD CONTINUATION

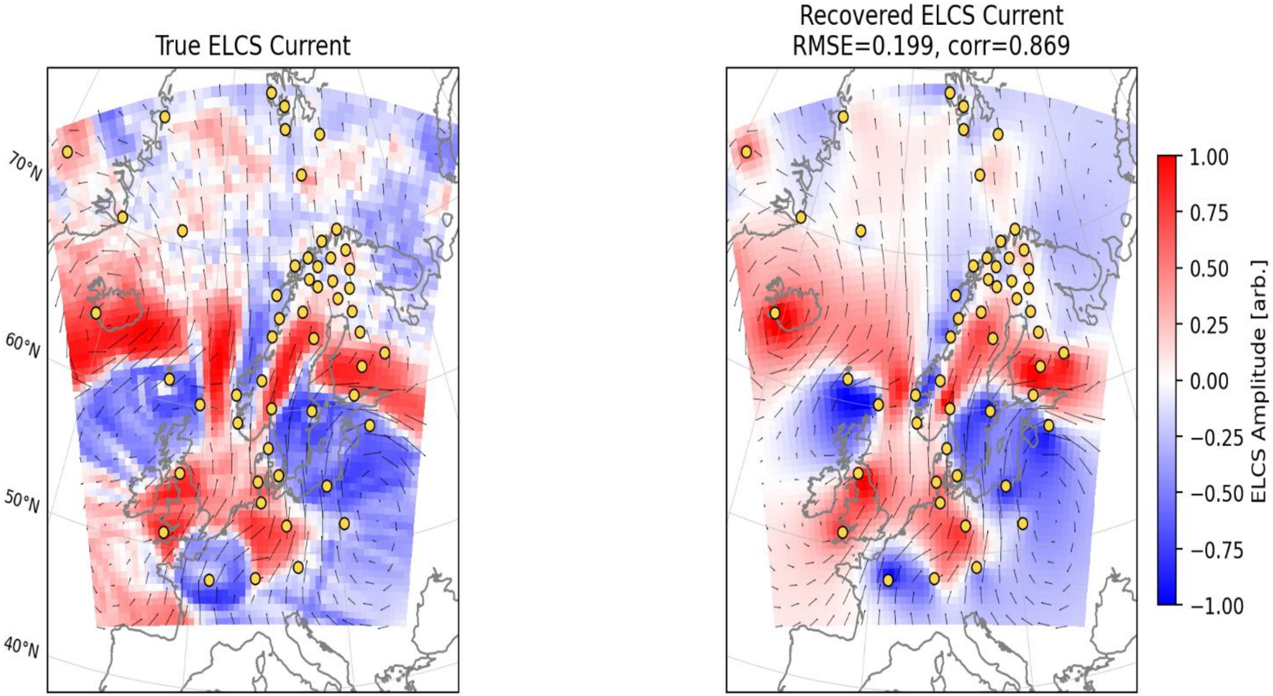


Curl-free elementary system (with associated FACs)

Divergence-free elementary system

High latitude study: synthetic test

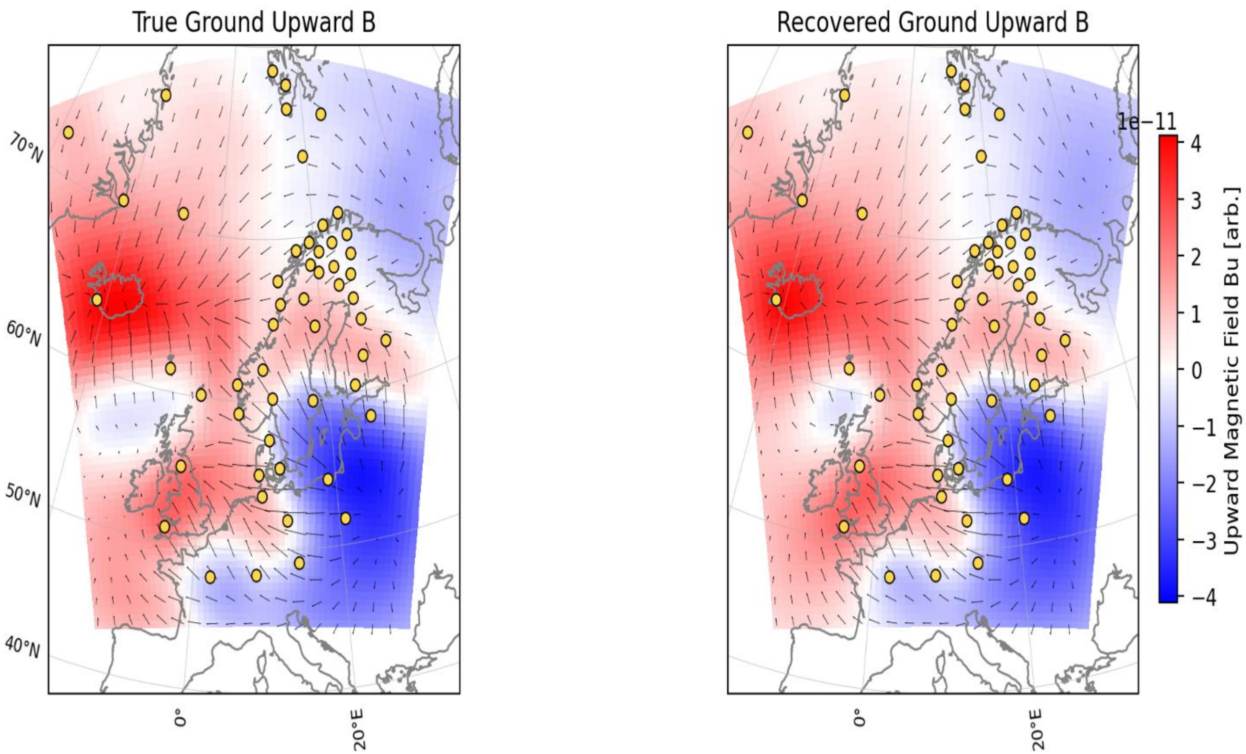
- Put synthetic ELCS into the ionosphere (pattern resembles a Raccoon, left)
- Calculate resulting magnetic disturbance at ground stations (yellow dots) to reproduce ELCS in the ionosphere (right)
- Validation: recovered Raccoon



High latitude study: synthetic test

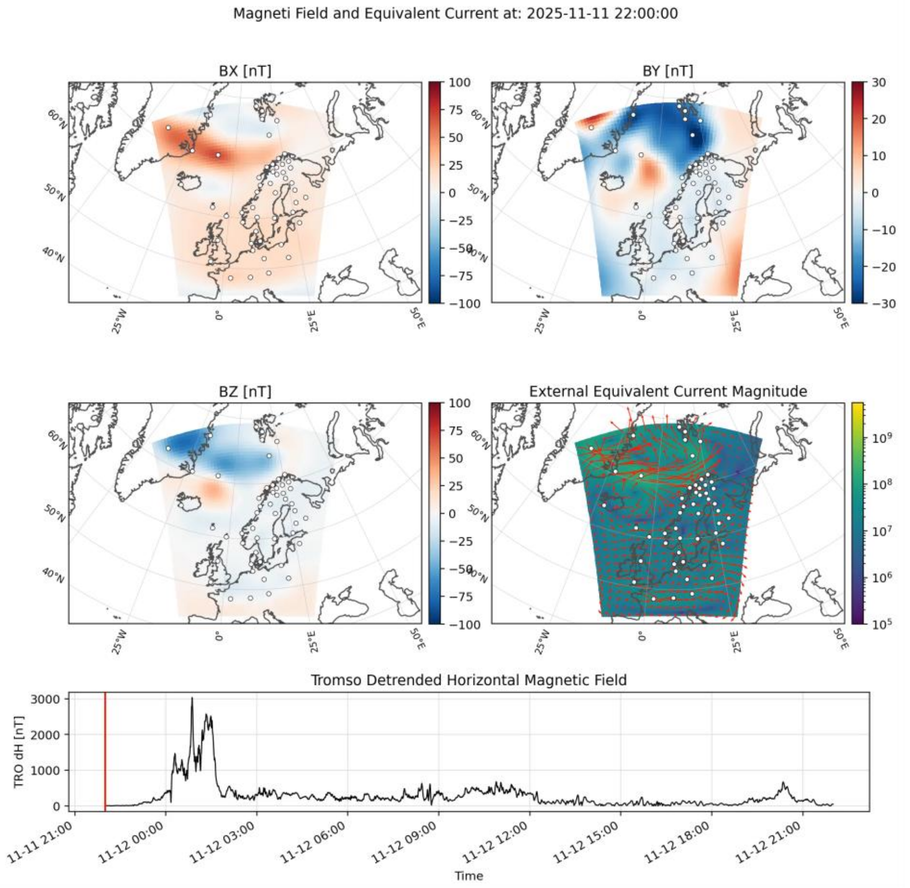
Raccoon test ground level

- True magnetic field disturbance (left)
- Recovered magnetic field disturbance (right)
- Remarkable similarity between true and recovered
- Sufficient number of ground stations.
- Appropriate modelling technology.

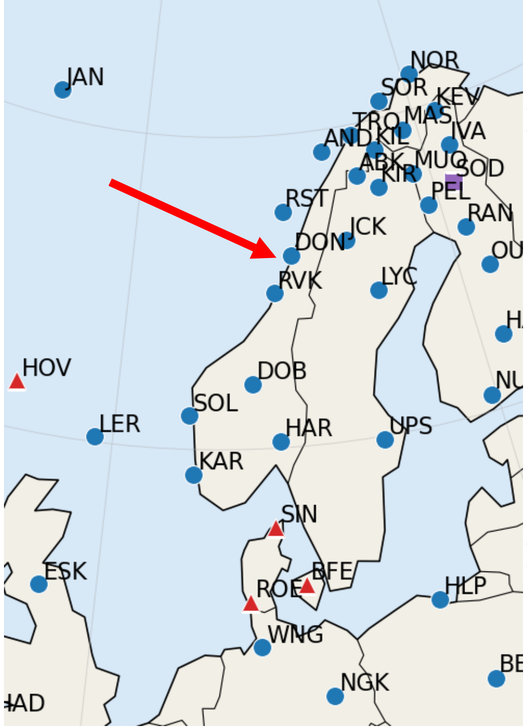


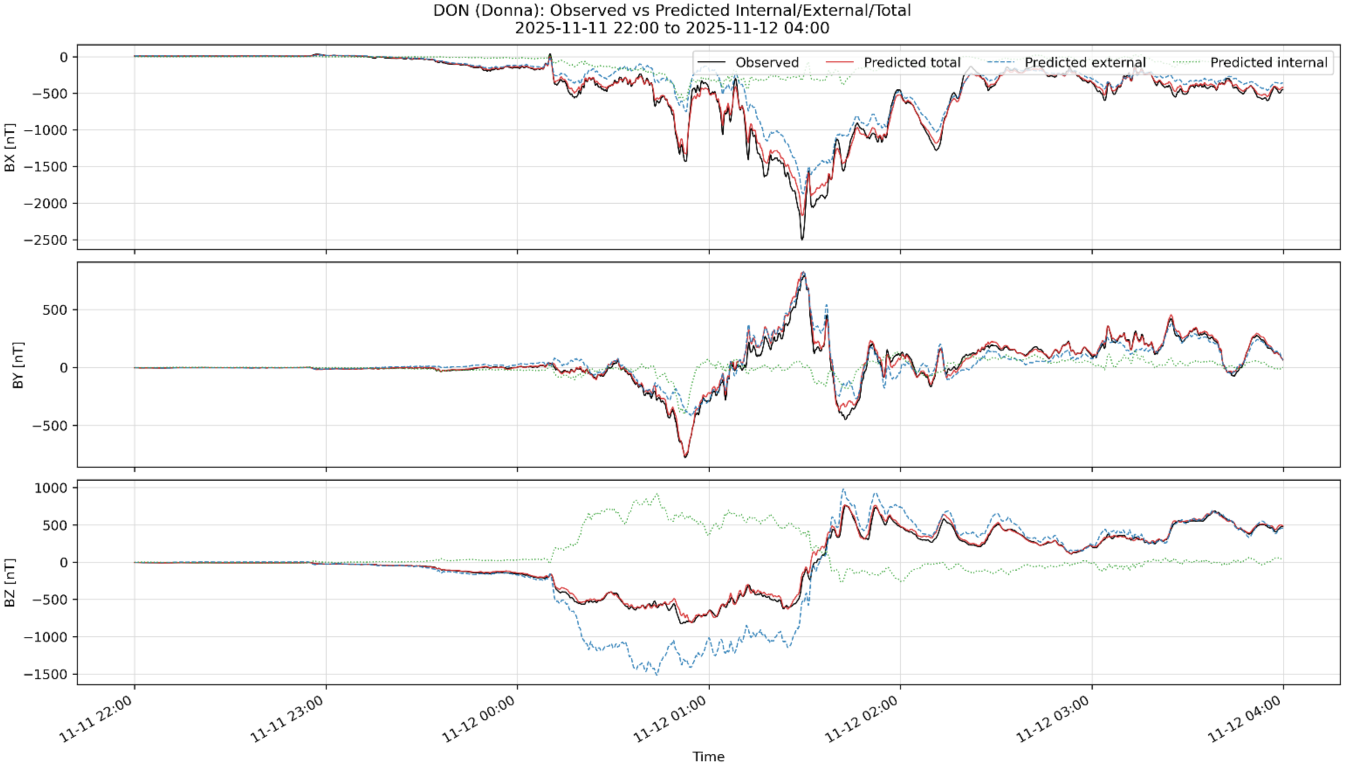
Real magnetic storm, 11 November 2025

- A strong westward auroral electrojet develops during the onset phase of the storm and then migrates southward during the storm.



Real magnetic storm, 11 November 2025 at Donna



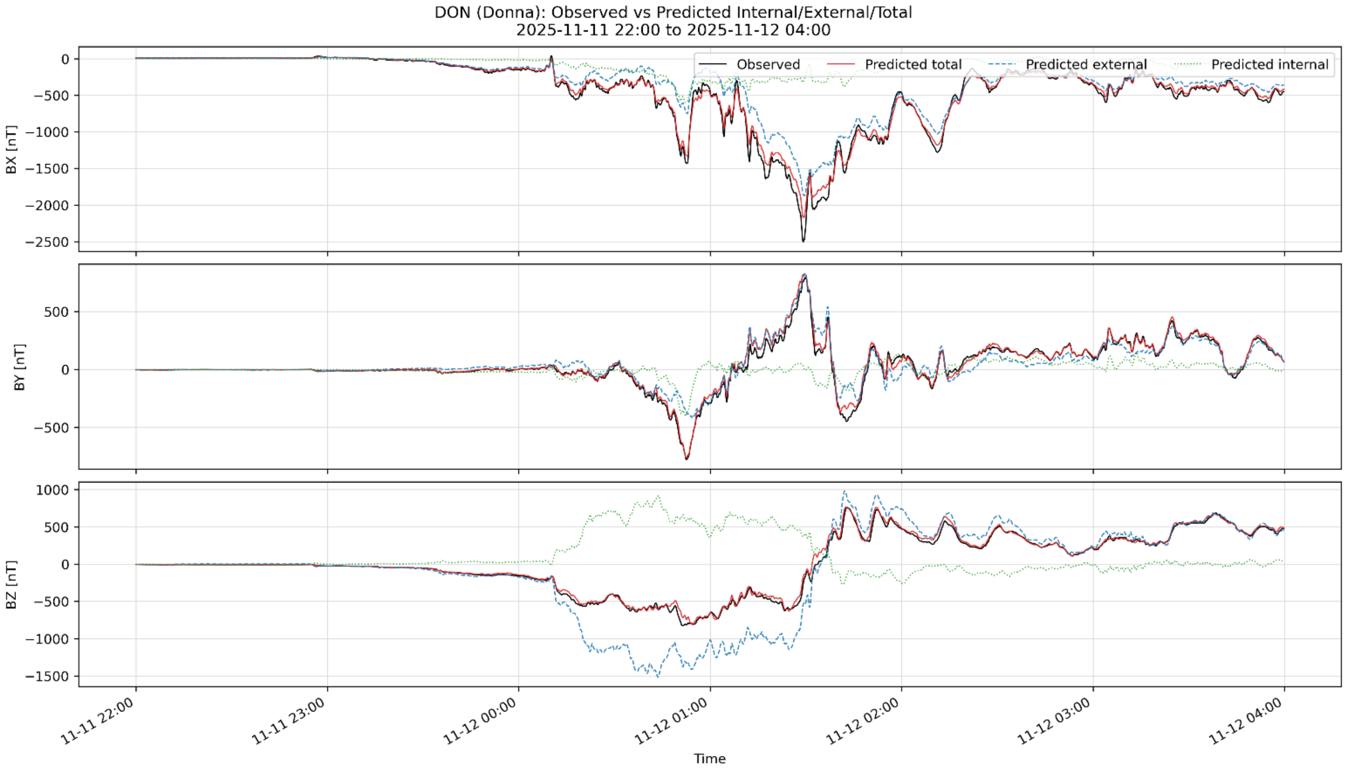


Real magnetic storm, 11 November 2025 at Donna

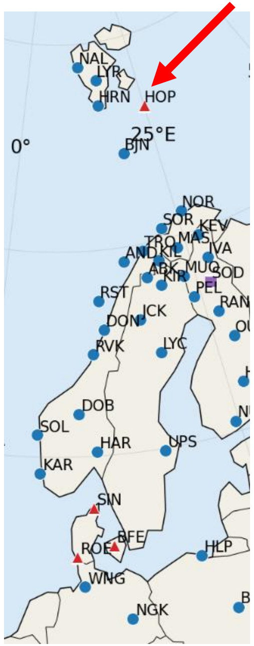
Measured at Donna
- black

Modelled at Donna
- ionospheric ELCS (external, blue)
- Subsurface, induced ELCS (internal, green)
- ionospheric plus ground ELCS (red)

Neglecting induced ELCS will push modelling errors into regions without data (ocean).



Dropout test Hopen (Barents Sea)



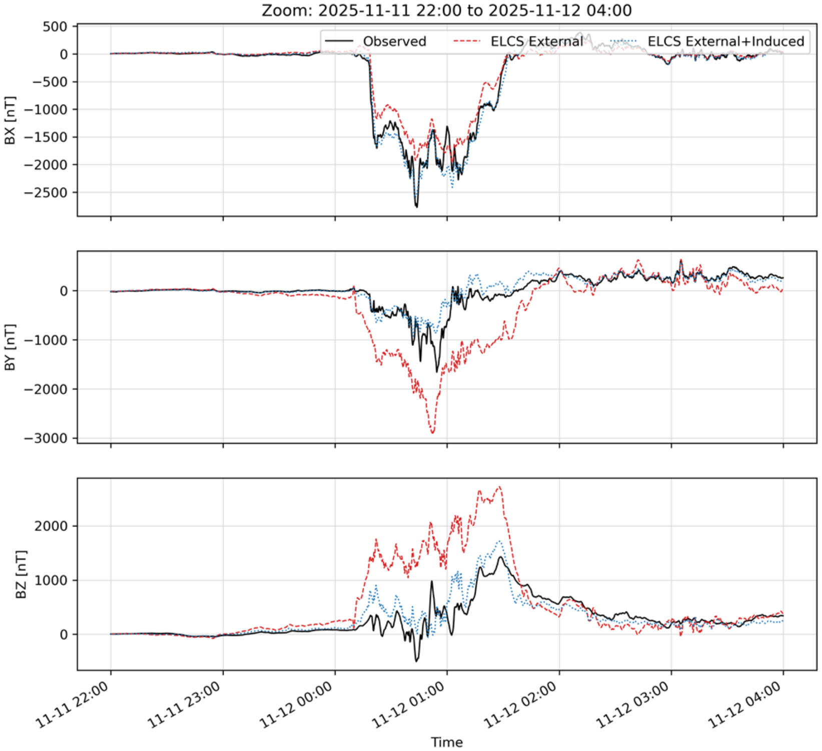
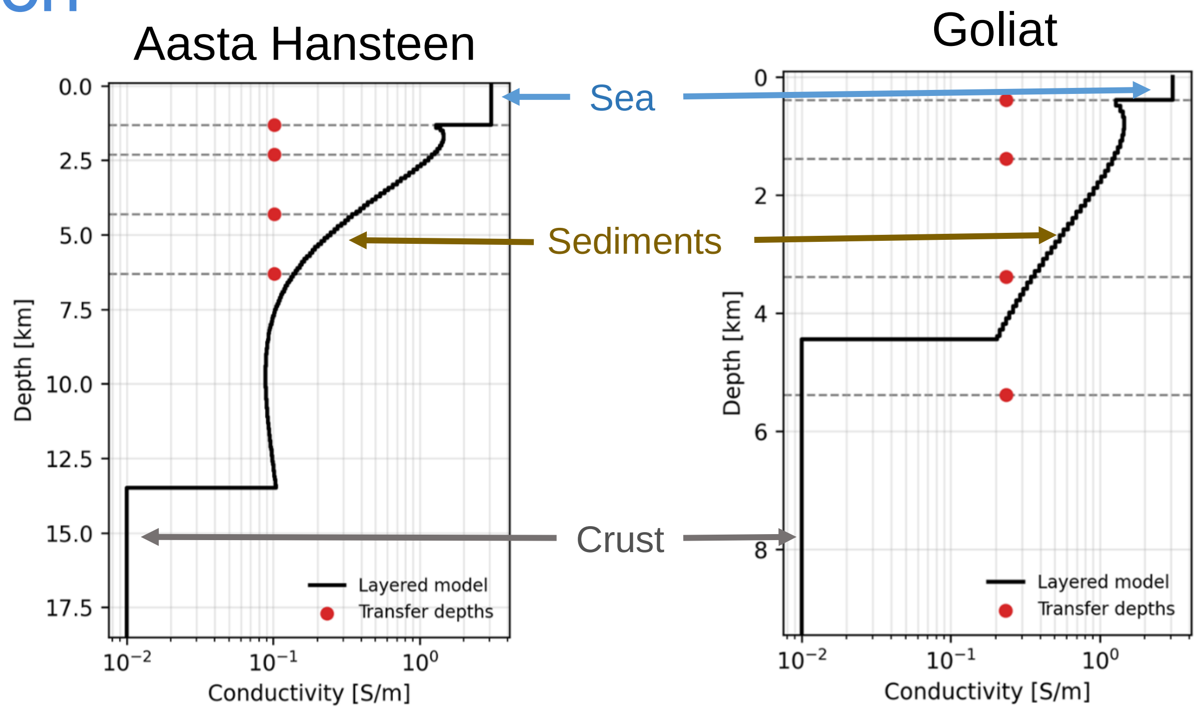


Table: RMSE of ELCS methods

ELCS Method	Bx (nT)	By (nT)	Bz (nT)
external	78	226	288
ext. + ind.	46	66	99

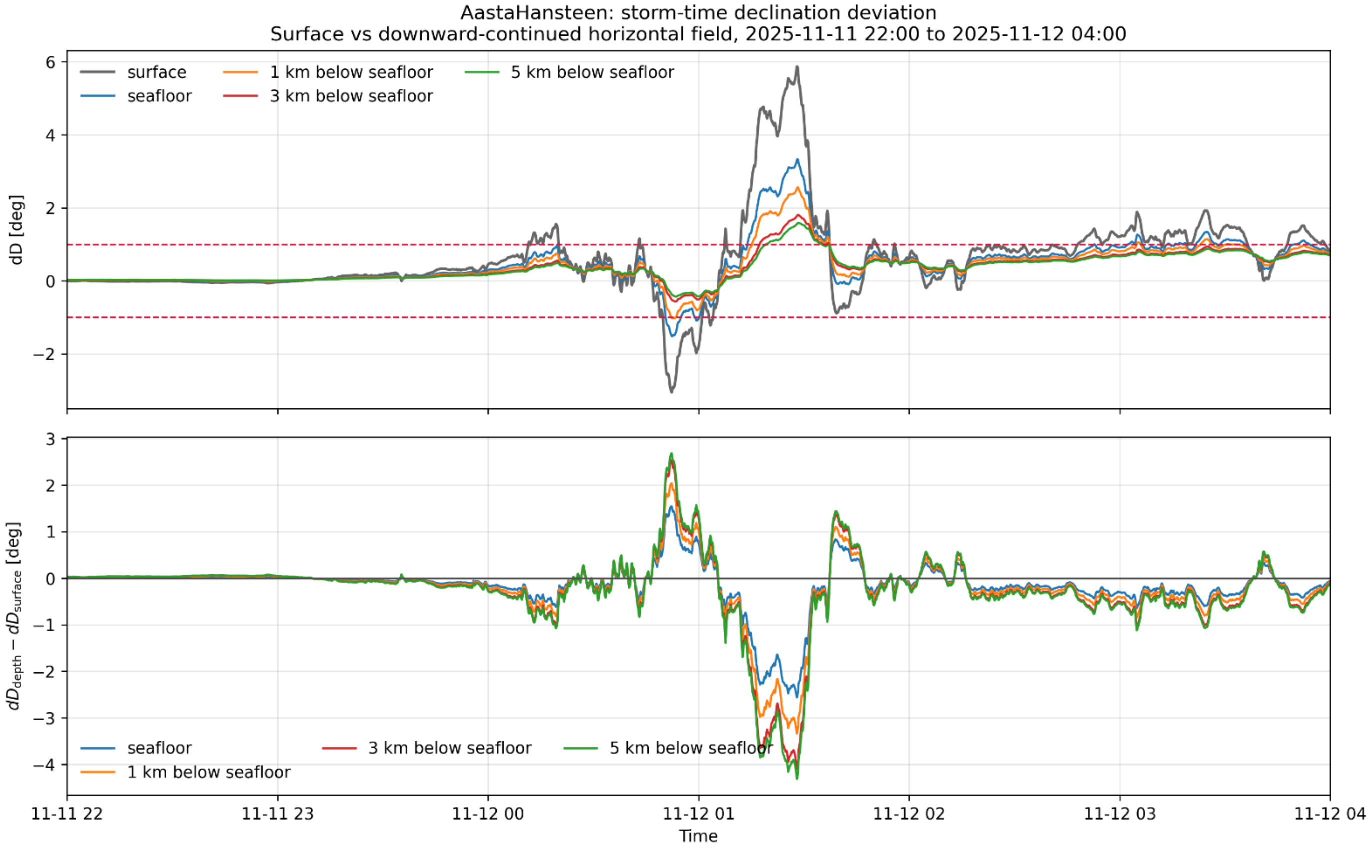
Downward continuation

- Magnetic disturbance downhole must account for the EM induction physics.
- This depends on the subsurface conductivity.



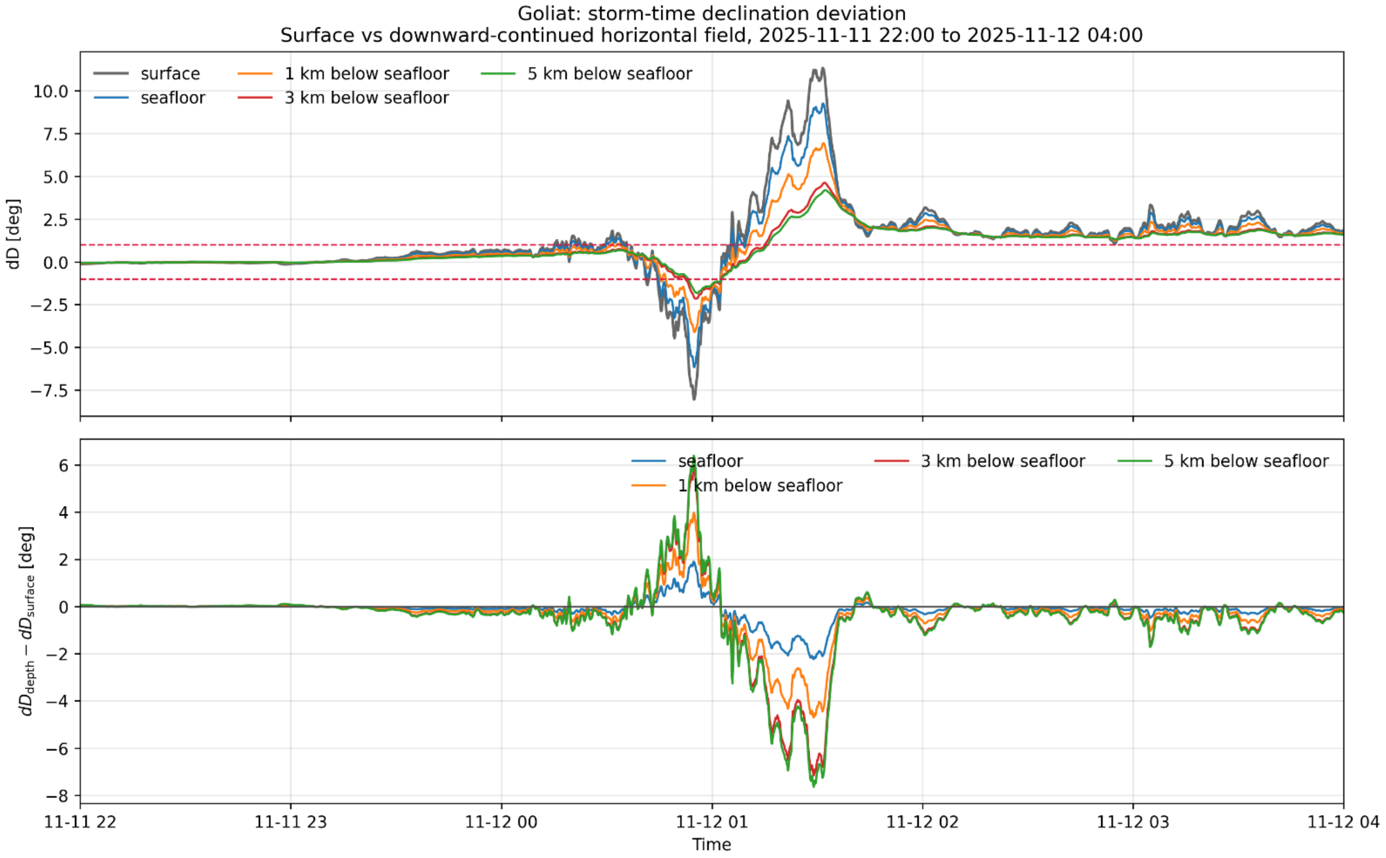
Downward continuation

- Magnetic disturbance downhole must account for the EM induction physics.
- This depends on the subsurface conductivity.
- Using magnetic disturbance measured at the surface results in up to 3,3° error at 1 km below the seafloor.



Downward continuation

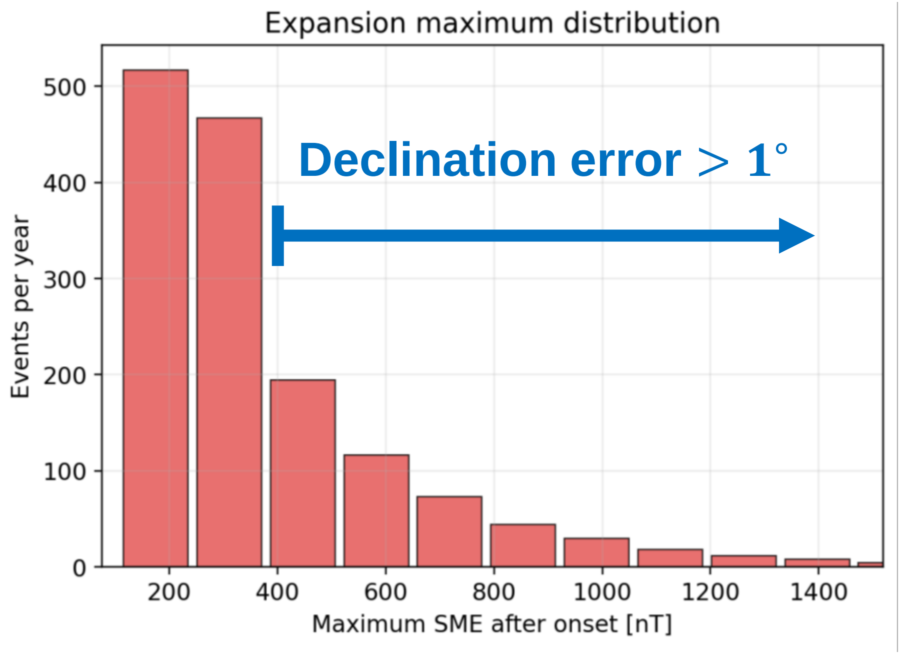
- Magnetic disturbance downhole must account for the EM induction physics.
- This depends on the subsurface conductivity.
- Using magnetic disturbance measured at the surface results in up to 4,2° error at 1 km below the seafloor.



Substorms vs. geomagnetic storms

- Substorms are much more frequent than geomagnetic storms
- Substorms occur throughout the solar cycle
- Associated with aurora in high latitudes (every few days)

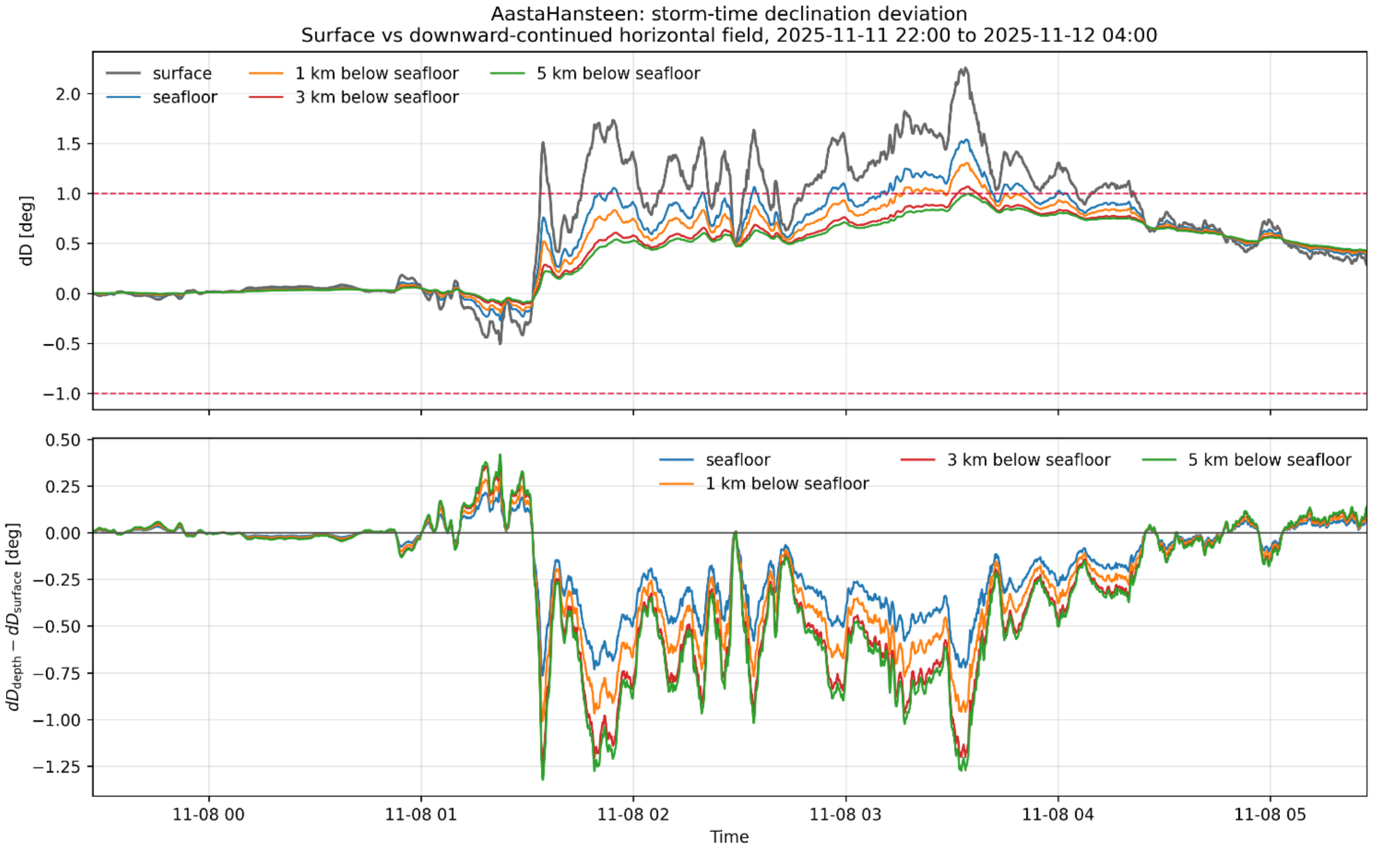
- Right: substorm counts per year for 1976 – 2026 using SuperMAG SME index.



Substorm

Aasta Hansteen

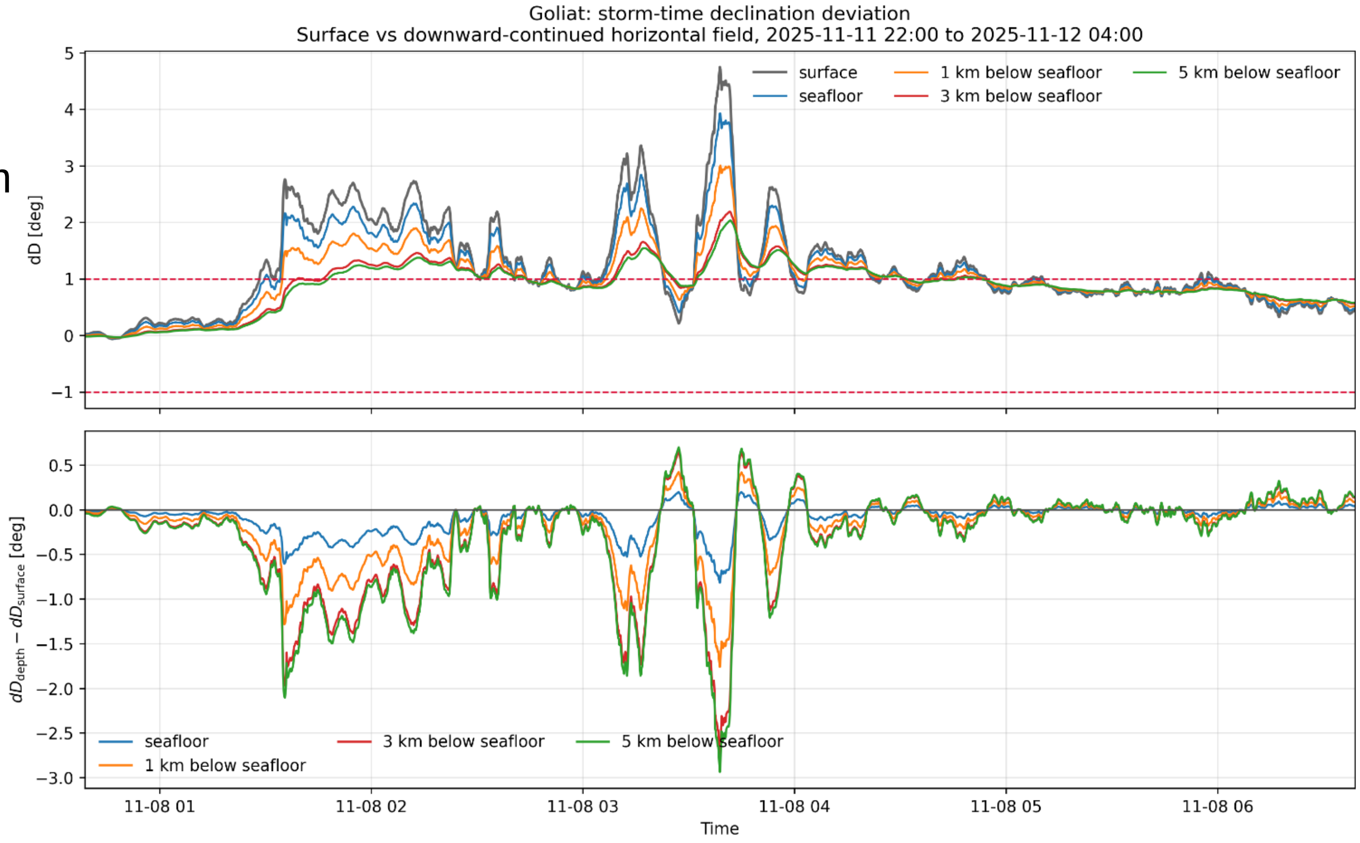
- up to 1° error at 1 km below the seafloor



Substorm

Goliat

- up to 1.7° error at 1 km below the seafloor



Summary/Outlook

We presented a method to model geomagnetic disturbance globally, regionally and at high latitudes

- External/internal ELCS improve models of geomagnetic disturbance: drop-out test for ocean location shows three-fold decrease in RMSE for external+internal ELCS
- Electric conductivity of the ocean and sediments affect magnetic disturbance at the sea surface and at/below the seafloor: declination changes by several degrees
- New ESA project MagWatch3D develops a cloud-based service for real-time geomagnetic field prediction: user engagement welcome

Acknowledgements

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- European Space Agency ESA for funding the MagWatch3D Enabling Study and providing Swarm satellite data.