A Machine Learning based model for Large Scale Travelling Ionospheric Disturbances forecasting

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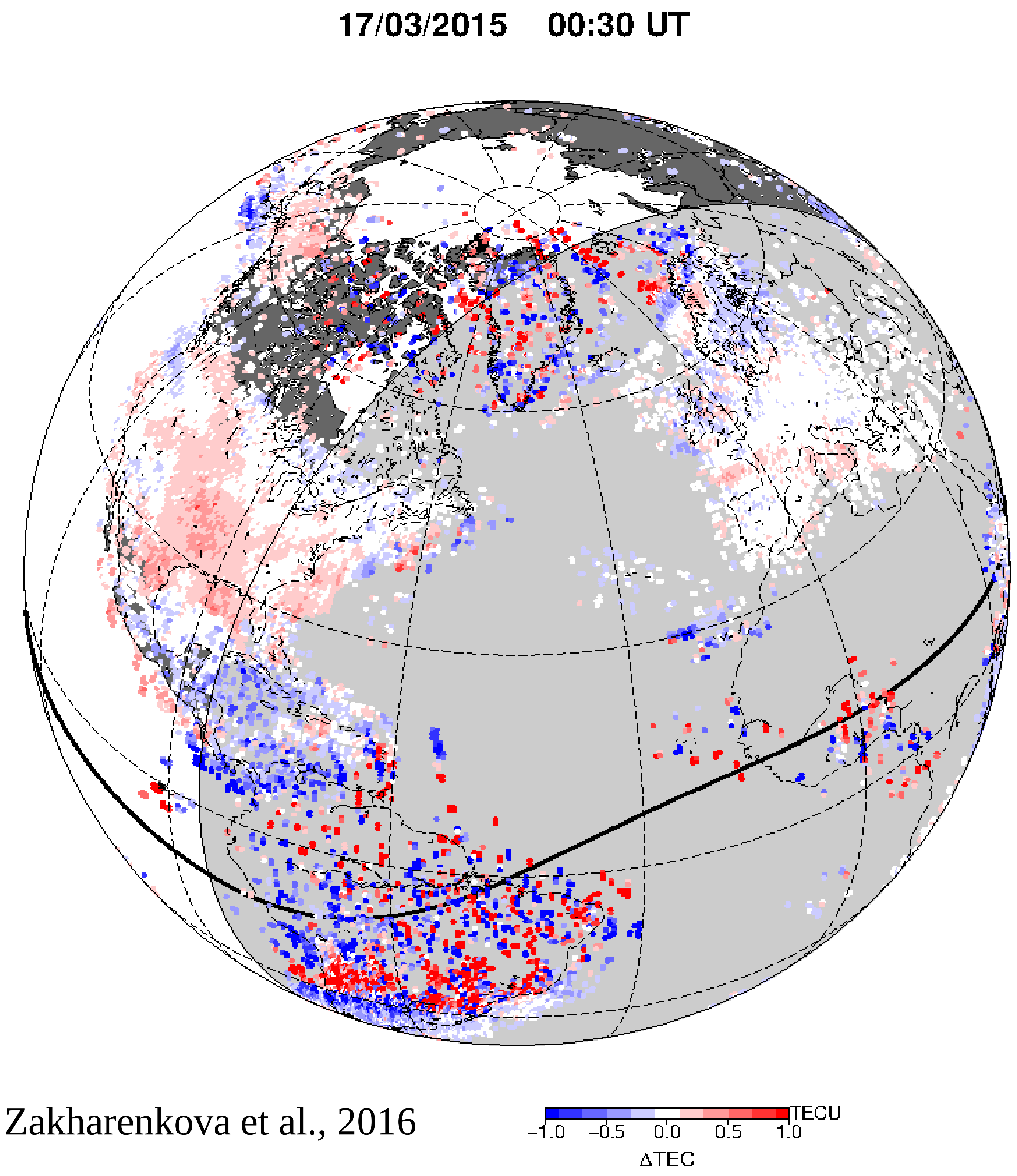
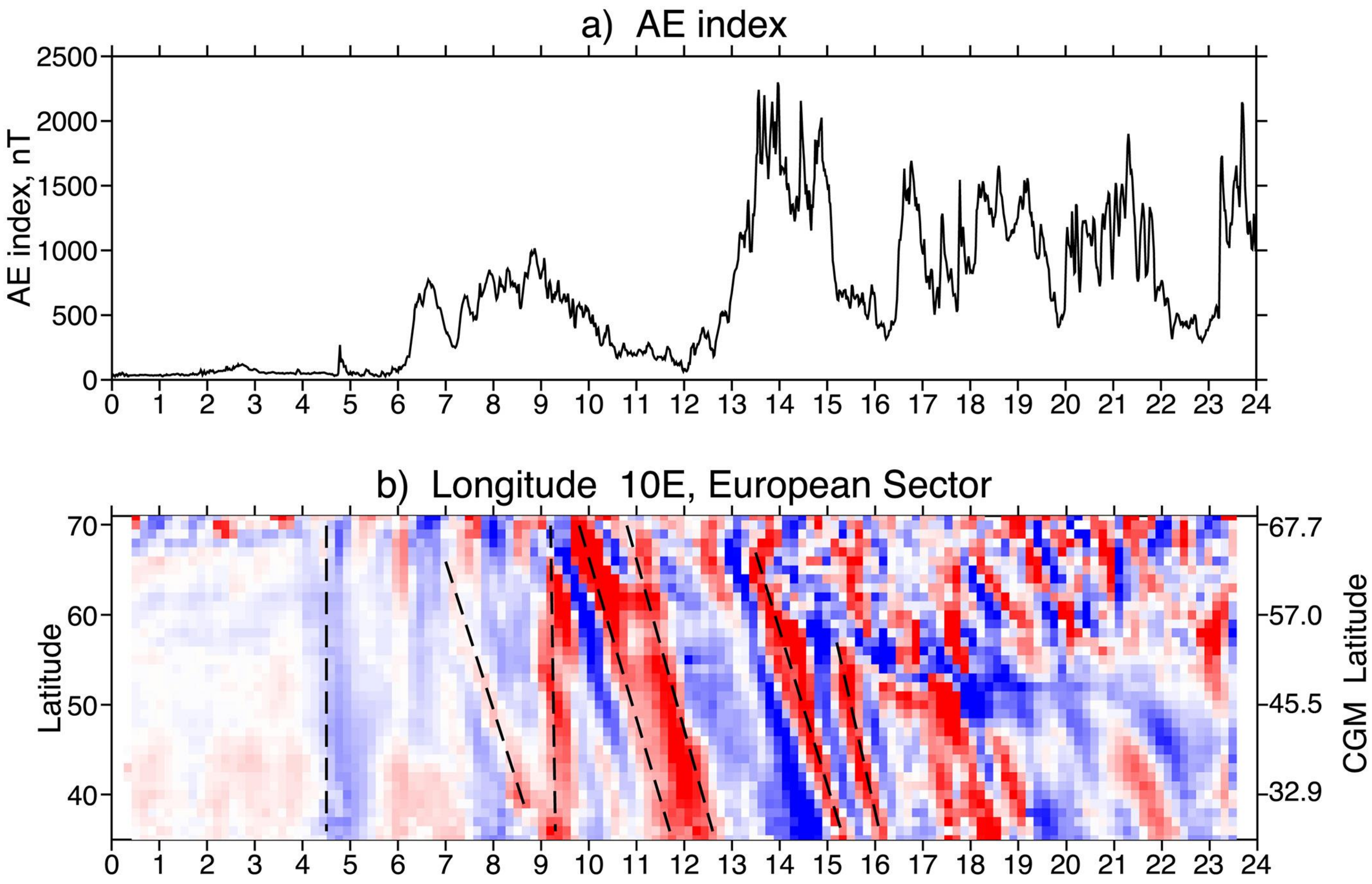
Large-scale Travelling Ionospheric Disturbances



Zakharenkova et al., 2016



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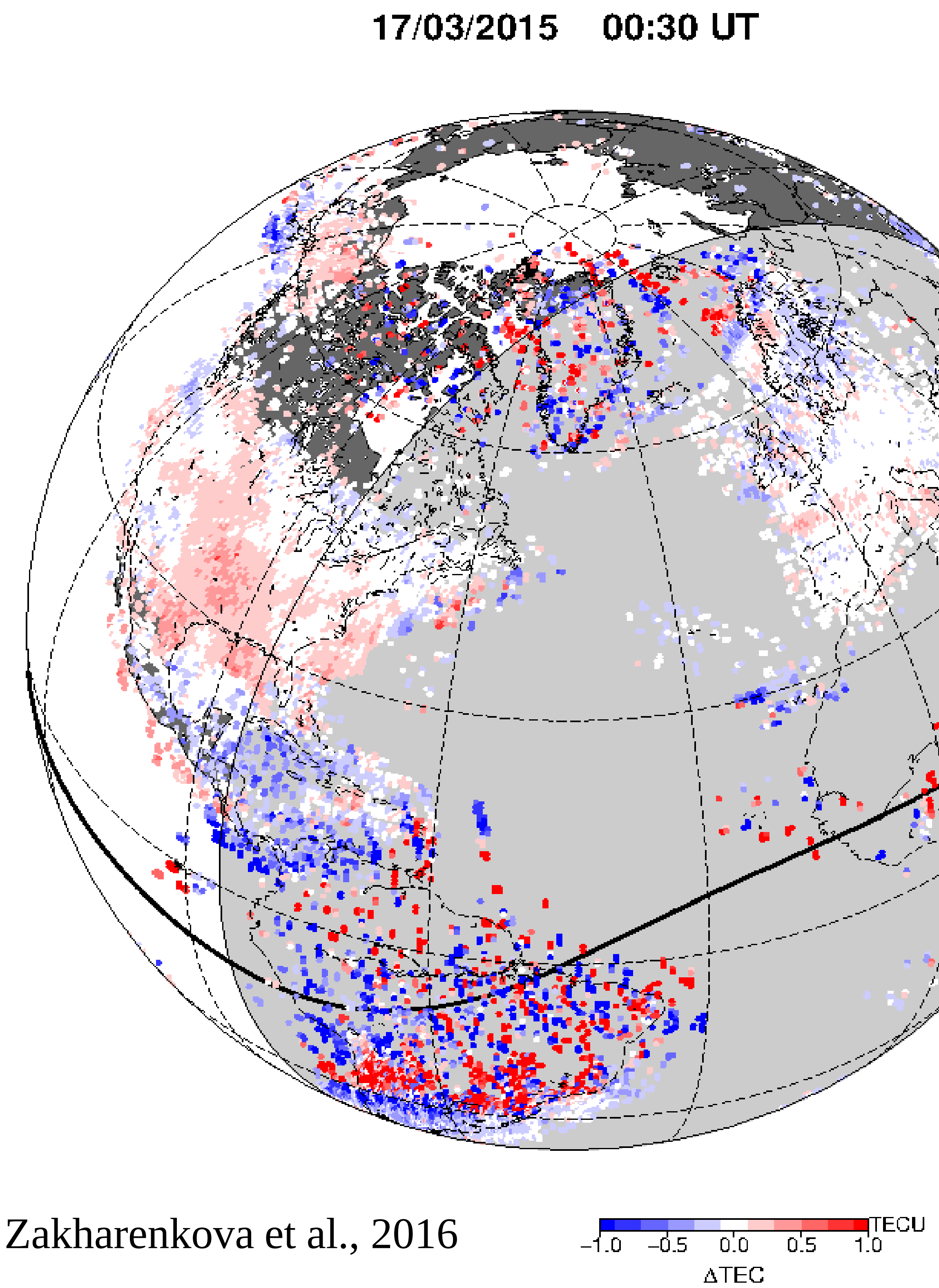


Zakharenkova et al., 2016

TIDs physical characteristics:

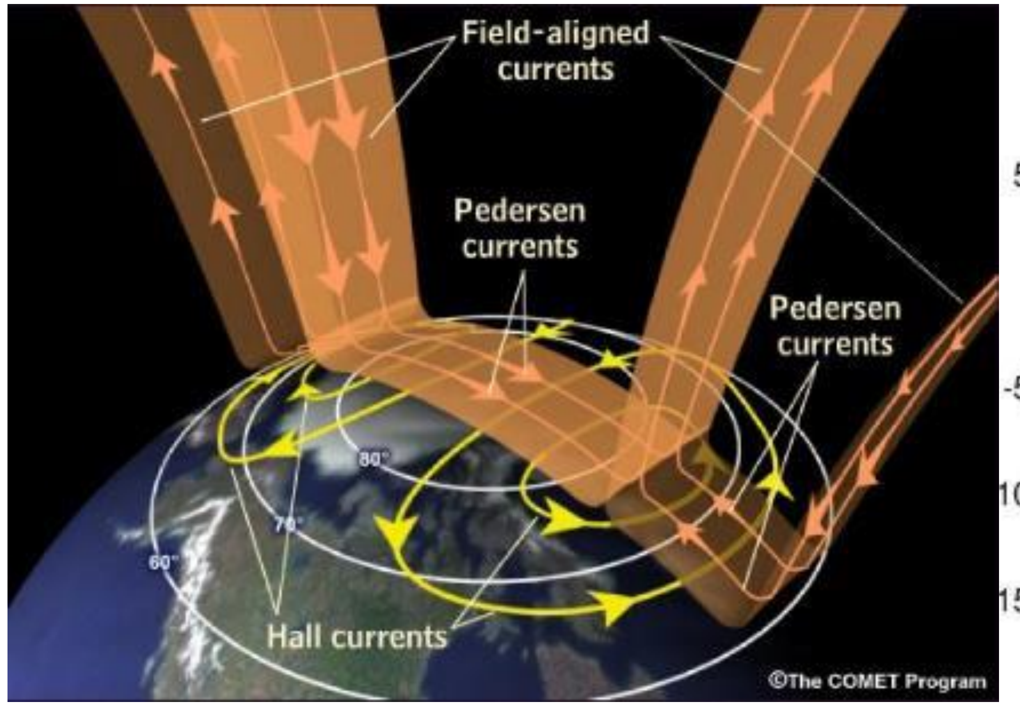
- Wavelength ~1000 km
- Period 0.5 – 2 hours
- Velocity several hundreds m/s

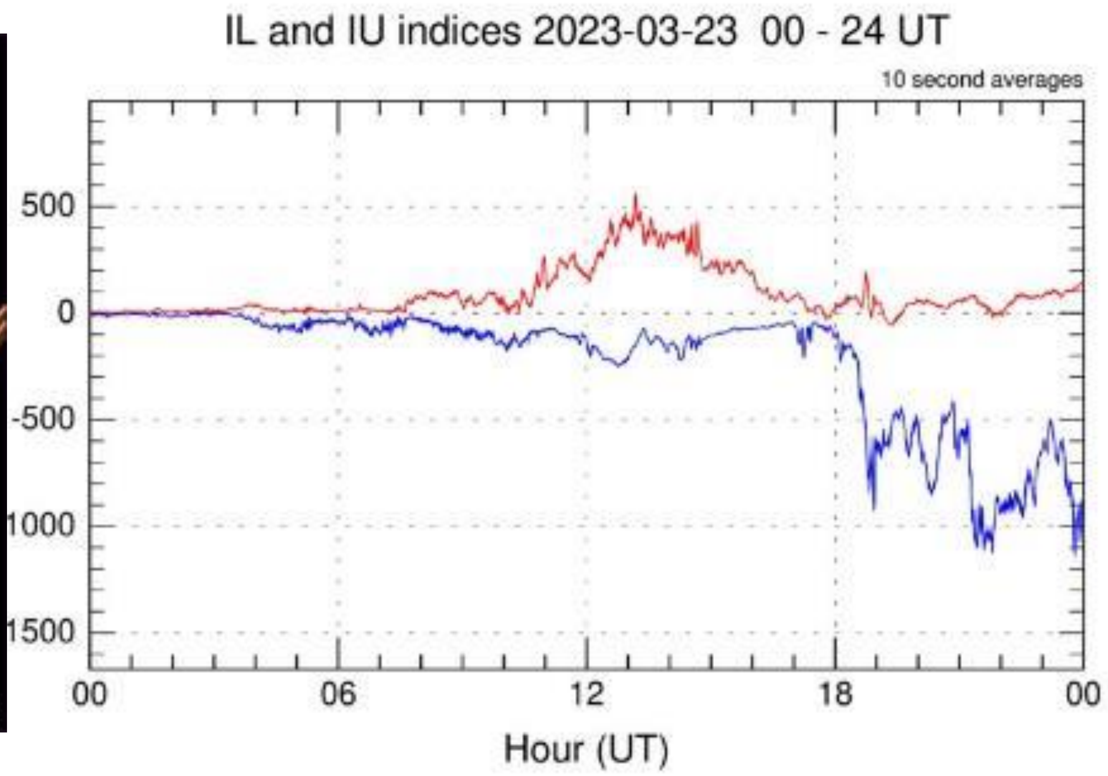
TIDs constitute a threat for operational systems using trans-ionospheric signals as they can impose disturbances with:

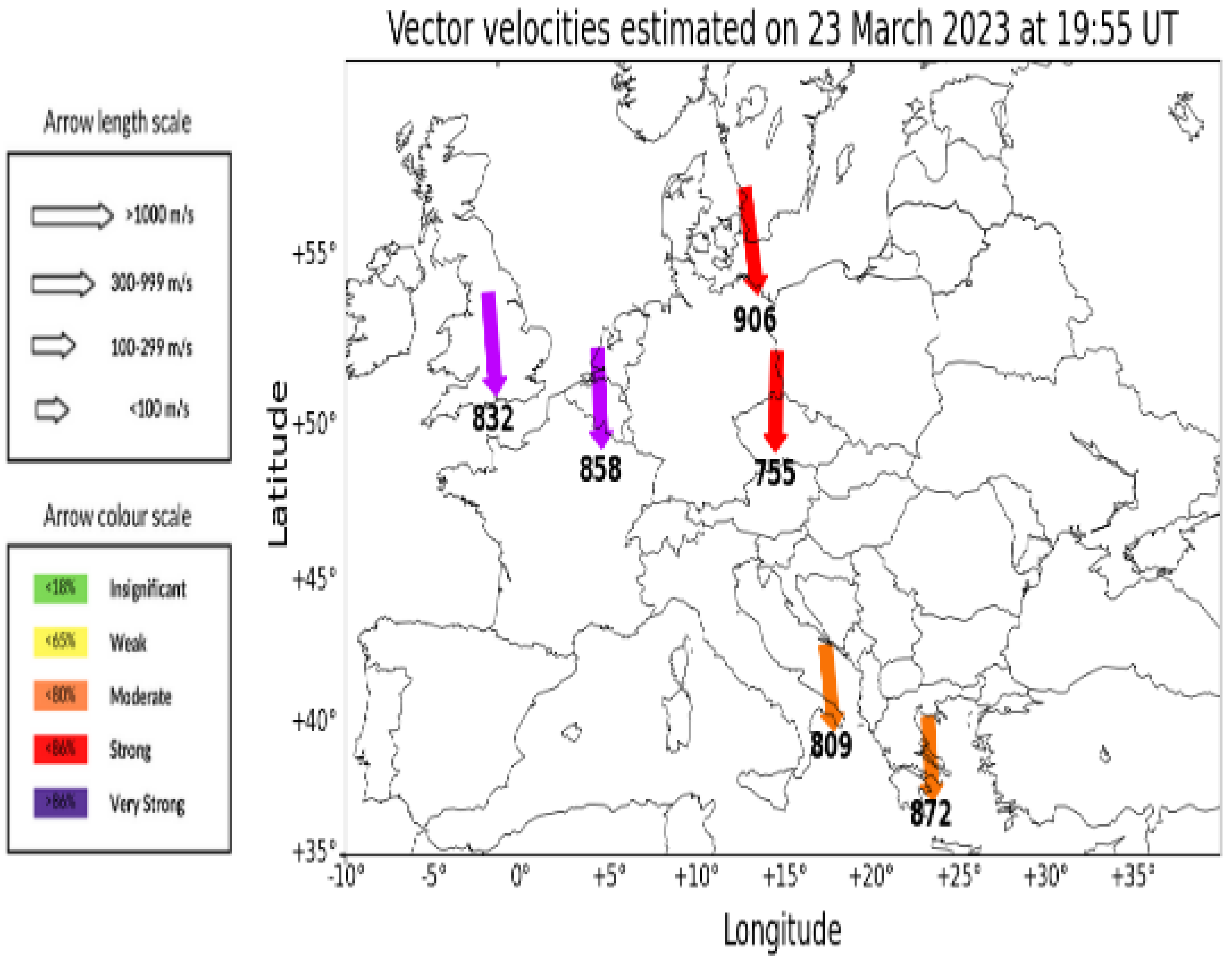
- Amplitudes of up to ~20% of the ambient Ne
- Doppler frequency ~ 0.5 Hz on HF signals
- ΔTEC from ~ 1 up to 10 TECU.

LSTIDs: chain of events from the auroral oval to mid-latitudes

Energy injection at high latitude inducing Joule heating → Geomagnetic field disturbances detected along a meridional chain of magnetometer at ground → Equatorward Propagation of LSTIDs from auroral latitudes → Detection of LSTIDs





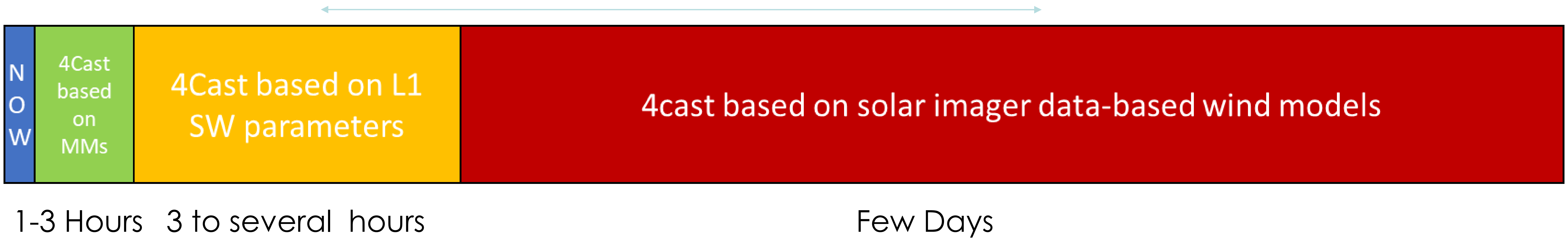


LSTID forecasting: general strategy

- From solar imagers data, one can obtain the solar wind speed and following the estimated time of arrival at the Earth together with the expected magnetic field vector. This is the first possible driver of LSTIDs. Highest time horizon, smallest reliability/accuracy.

- From L1 spacecraft, we can calculate the values forecasted by solar imagers-based models. Medium time horizon, medium reliability/accuracy.

- From magnetometers, we can understand the current state of the Magnetosphere-Ionosphere system. Smallest time horizon, highest reliability/acuracy.



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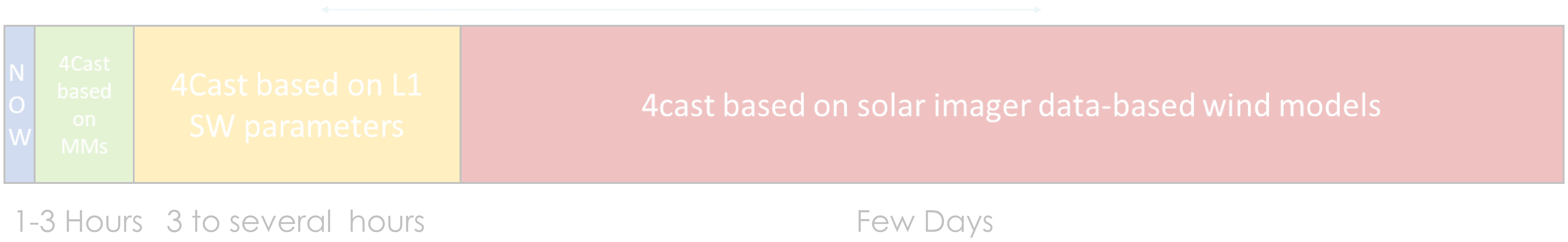


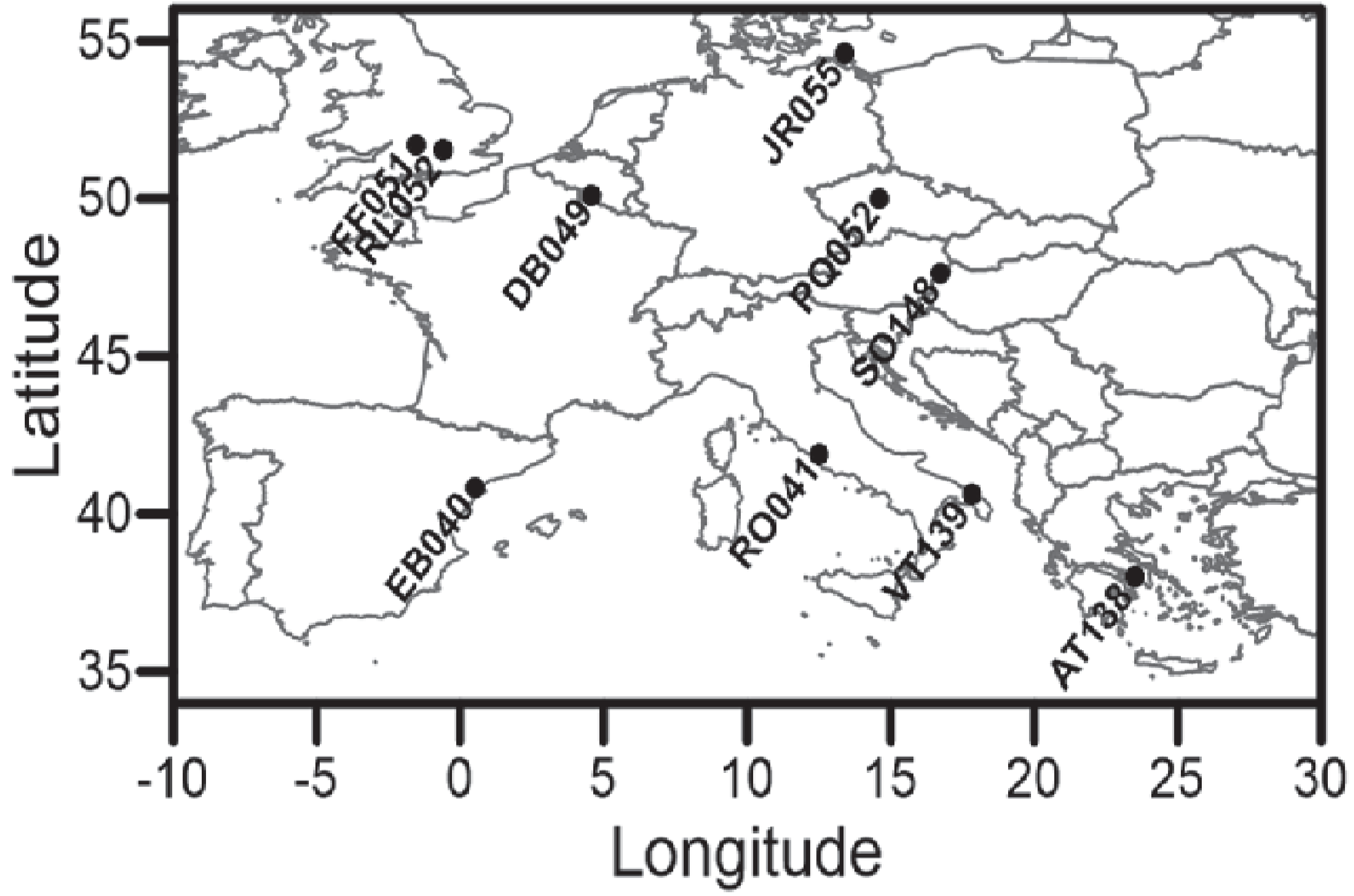
Developing the ST ML models: catalogue-based forecasting

- ➢ The problem is handled as a binary classification

- ➢ We are working with the **HF-INT refined LSTID catalogue** provided by Ebro Observatory

- ➢ In the catalogue, there are **760 TIDs events** detected and recorded above Europe between **FEB 2014 to DEC 2022 (update in progress)**

- ➢ The database is generated by leveraging a **network of ionosondes** covering the European sector



Our features and labels so far…

Variables **input (features)** to the model fall into the following categories:

- **Geomagnetic indices**: IE, IL, IU, HP-30, SMR and moving averages for those variables;
- **HF related**: HF-EU index; single station spectral contribution, azimuth, velocity
- **Solar**: F10.7, solar zenith angle;

Given the time series (30 mins time resolution), we create the **target (label)** taking on 2 values:

- **1** from 3 hours before the start of an LSTID until its end;
- **0** otherwise;

Our Machine Learning stack

- Easily understandable and adaptable syntax
- One of the top languages for training ML models

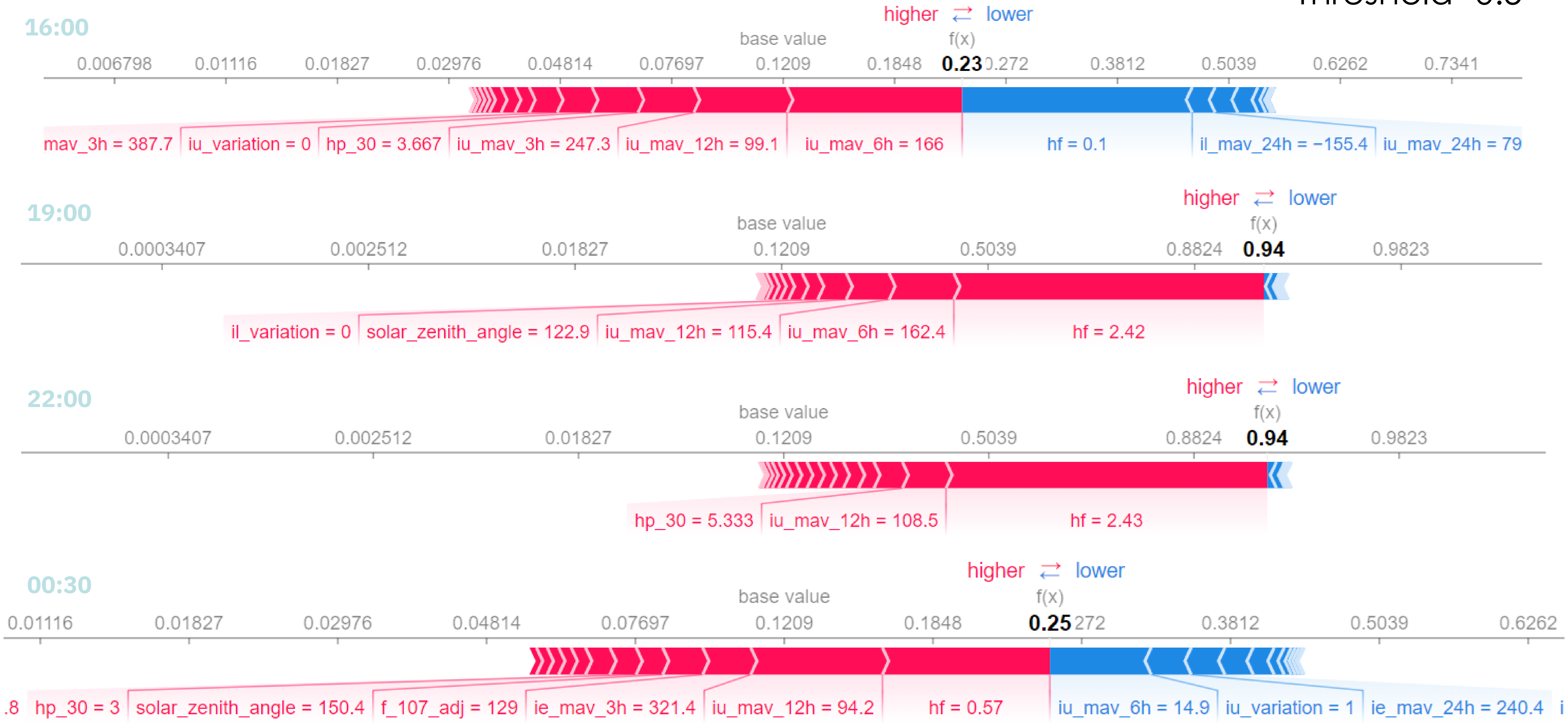
- **Cat**egory & **Boost**ing (gradient boosting on decision trees)
- A symmetric balanced tree architecture leads to an efficient CPU implementation, decreases prediction time (great for real-time inference) and controls overfitting
- Categorical and missing values are handled natively

- Efficient optimisation framework for model hyper-parameters tuning
- **M**achine **L**earning **Op**eration**s** (MLOps) to organise and manage ML experiments

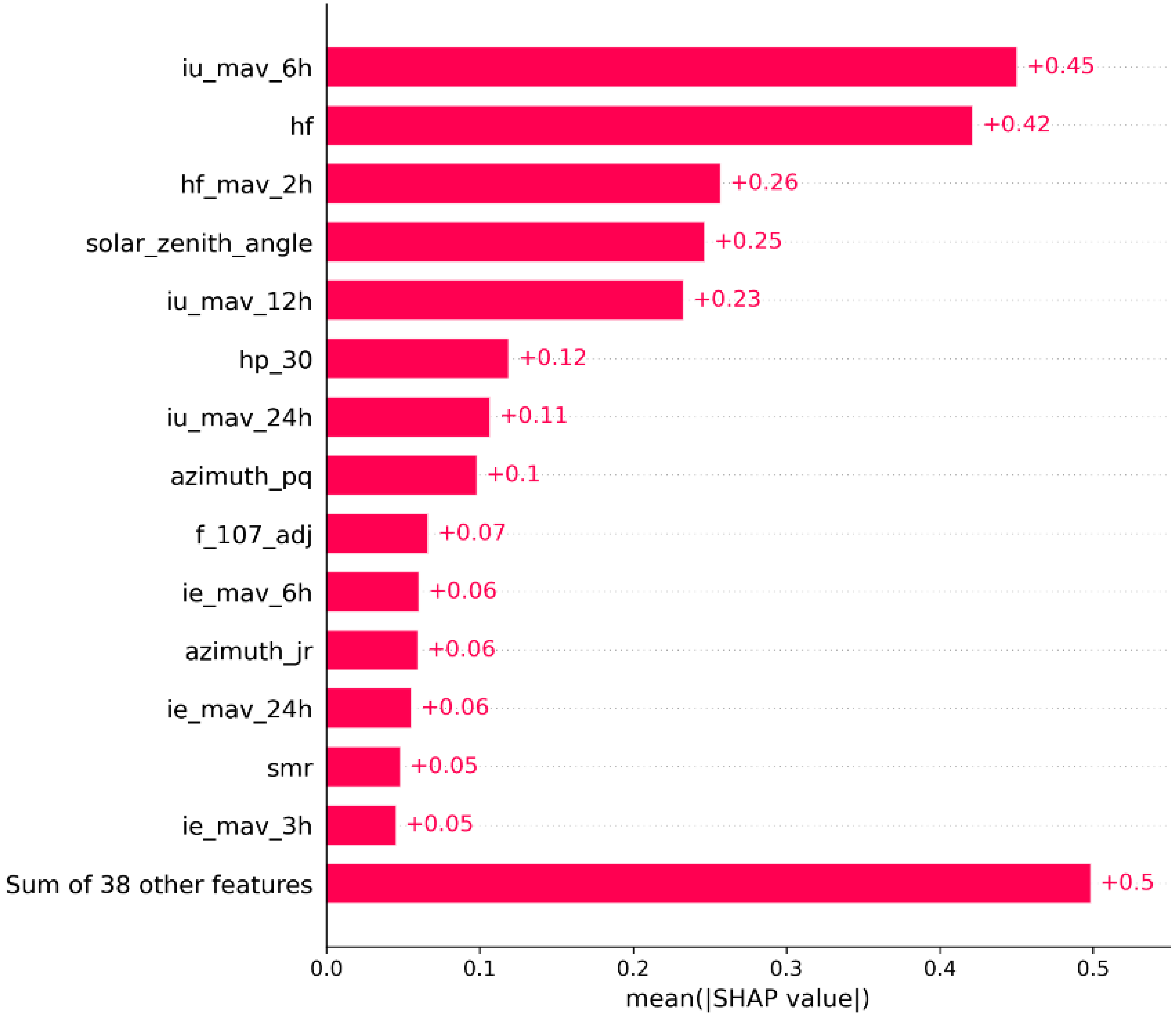
- The **SH**apley **A**dditive ex**P**lanation (SHAP) framework allows to test features influence on the model output from both global and local aspects
- **Enhancement for interpretability and explainability of the model** – very desirable features in potentially high-risk settings

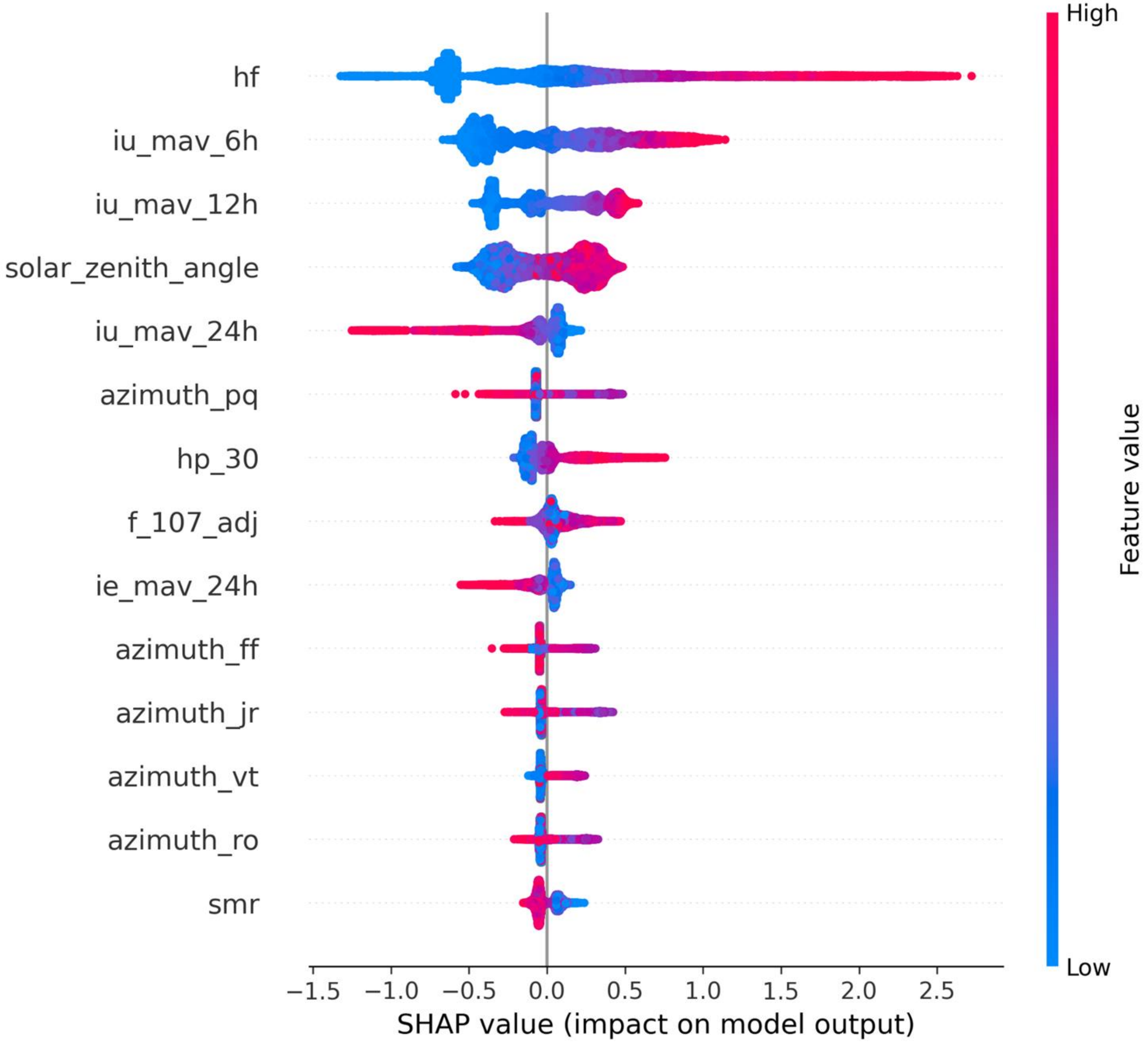
Local interpretation: 23/12/2022 22:20, LSTID lasted 1.5h

Threshold=0.5

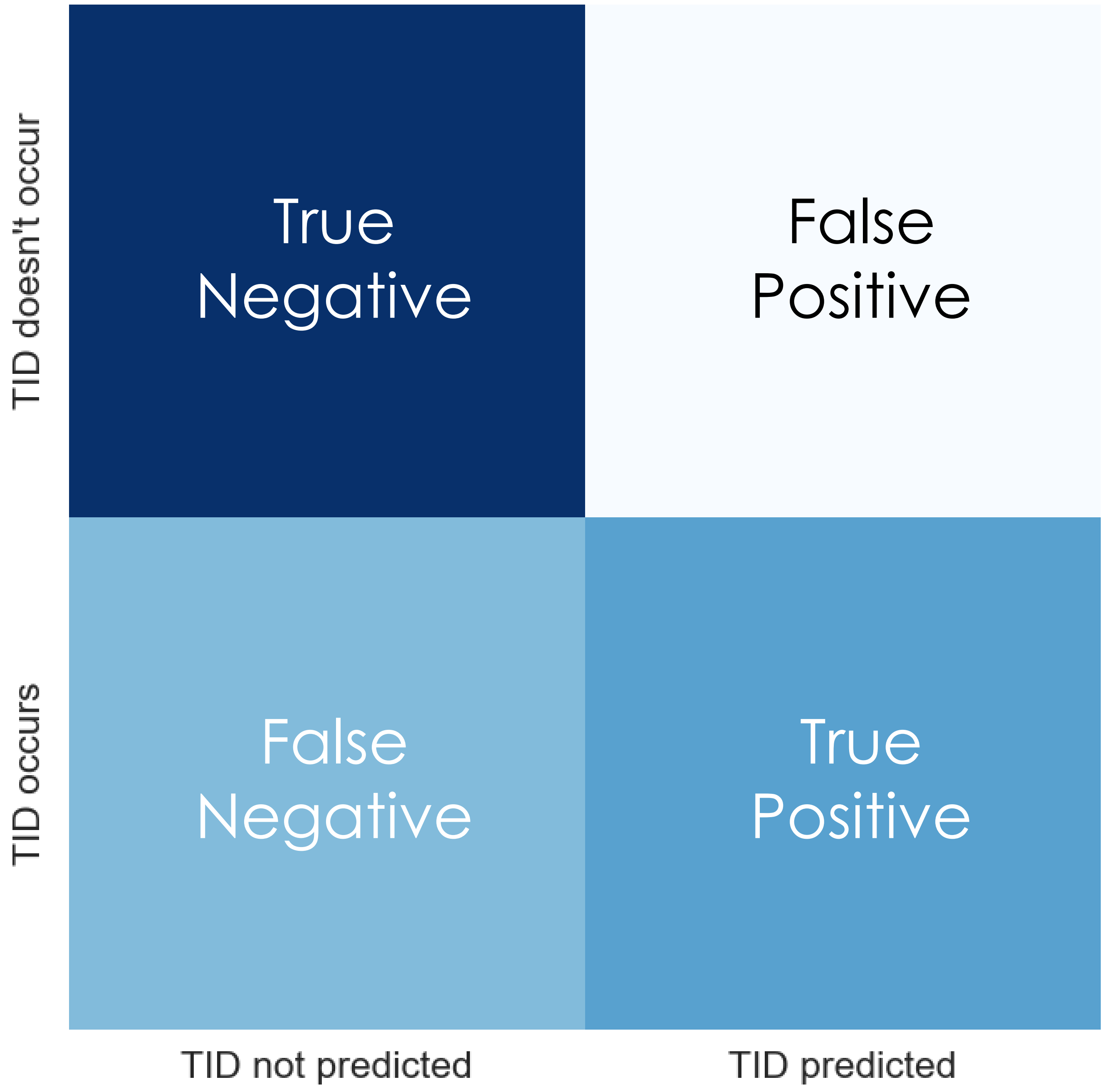


Local to global interpretation: feature importance





Global performance evaluation



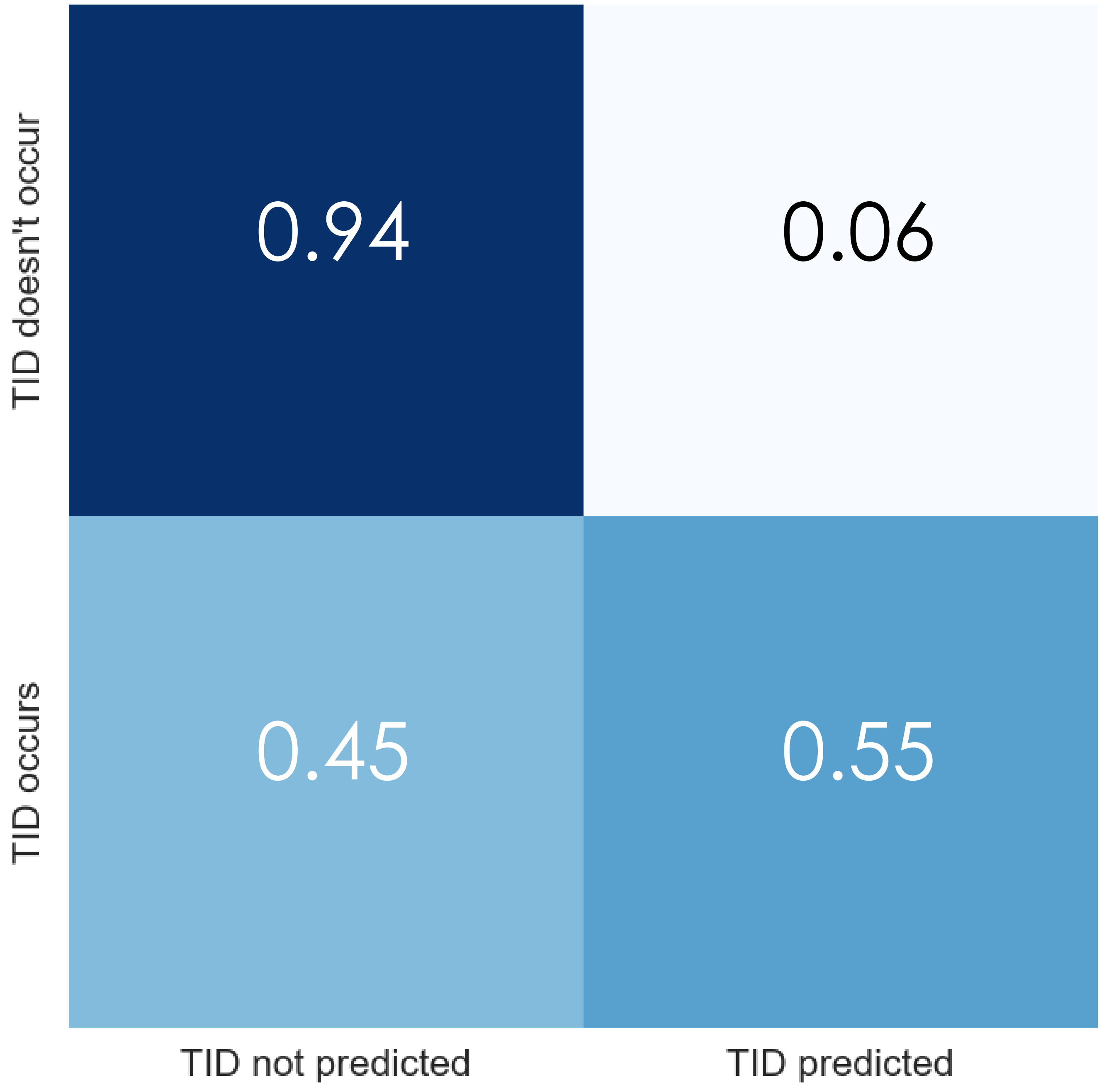
$$P = \frac{TP}{TP + FP} \qquad R = \frac{TP}{TP + FN} \qquad F_1 = \frac{P * R}{P + R}$$

Precision is a good measure to determine, when the costs of False Positive is high

Recall actually calculates how many of the Actual Positives our model capture through labeling it as Positive (True Positive)

F1 Score might be a better measure to use if we need to seek a balance between Precision and Recall AND there is an uneven class distribution (large number of Actual Negatives).

Model performance so far…



	No LSTIDs	LSTIDs
F1 score	0.97± 0.01	**0.49 ± 0.04**
Precision	0.97± 0.01	**0.49 ± 0.01**
Recall (sensitivity)	0.96± 0.02	**0.50 ± 0.07**

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$$R = \frac{TP}{TP + FN}$$

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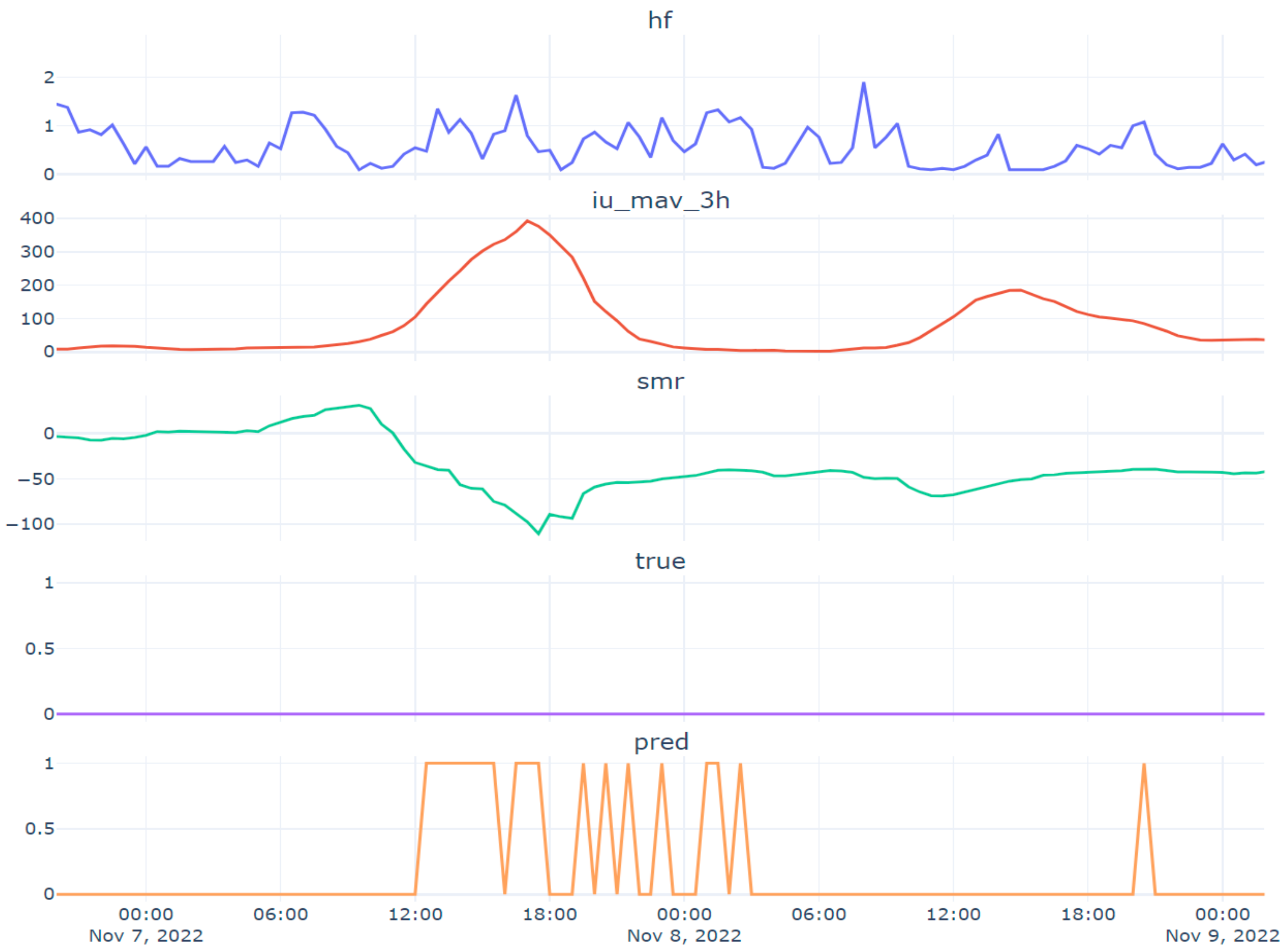
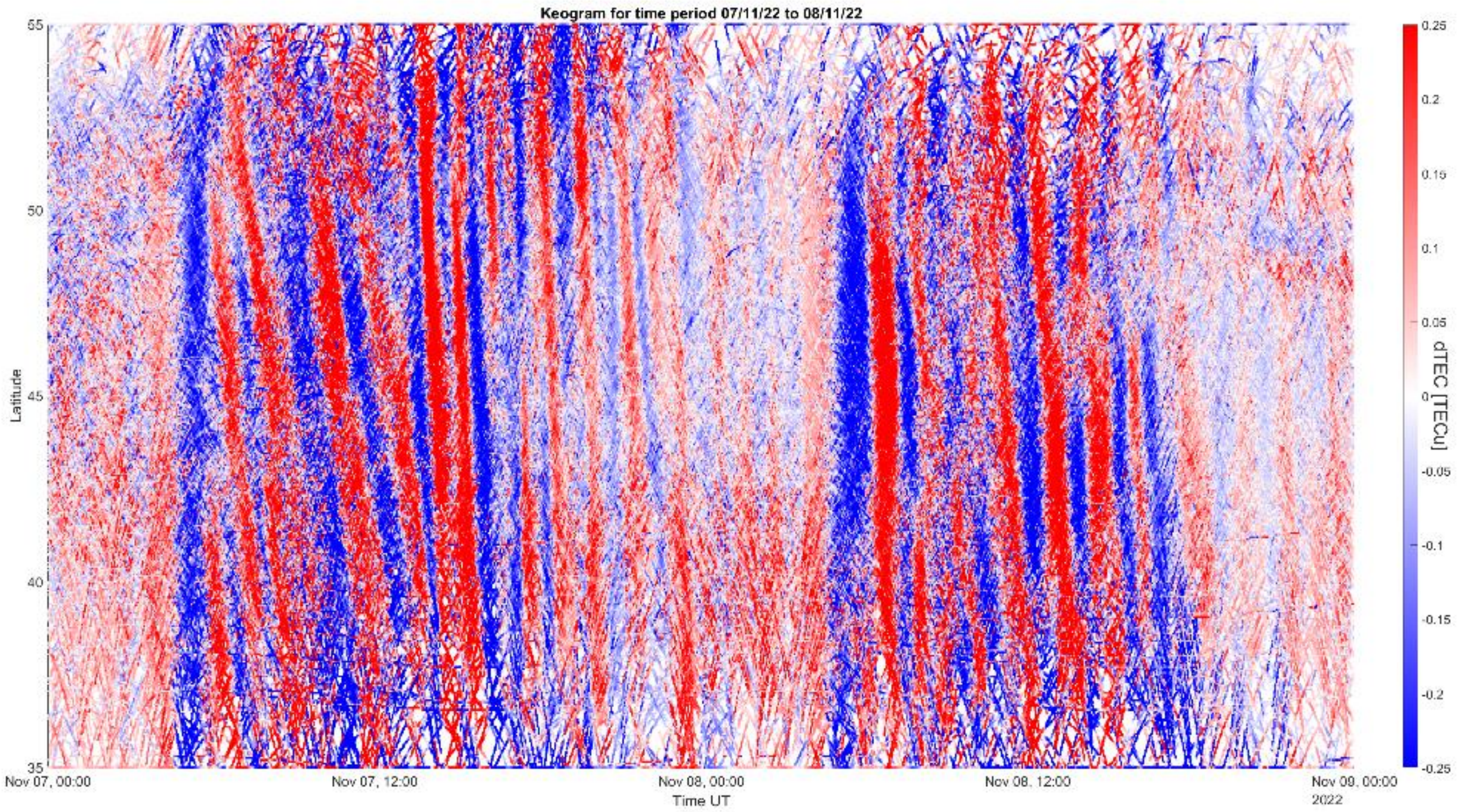
How to improve the model performance…





- The model correctly predicts some LSTID occurrences (12:00 – 03:00), which were not in the HF catalogue (True) but apparent in GNSS-derived dTEC (Keogram)
- Despite that, the model still struggles to confidently predict TID occurrences (the prediction oscillates between true and false)
- Nevertheless, the model does not predict the LSTIDs happening during daytime of the 8th of November

Take home messages and next steps

- LSTIDs are due a complex chain of physical phenomena hardly predictable
- There are no physical models capable of predicting LSTID so far
- The T-FORS project is trying to develop a prototype model based on ML/techniques facing the problem as a binary classification and regression for HF-EU index prediction (not shown in this talk)
- So far, a gradient boosting on decision tree model seems to be promising in predicting the occurrence of LSTID a few hours in advance
- SHAP values give the opportunity to locally interpret the model results and, in turn, to globally define the features importance.
- Ancillary data (e.g. detrended TEC) can be used to identify both failures of the prediction model and LSTIDs not included in the catalogue
- Identify additional important features to drive the model
- Include other data sources to create a more complete and reliable catalogue of the events (automatic detection algorithm based on detrended TEC is under development)

Thanks for your attention!

website

Web app

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