A gray-box model for a probabilistic estimate of regional ground magnetic perturbations: Enhancing the NOAA operational Geospace model with machine learning

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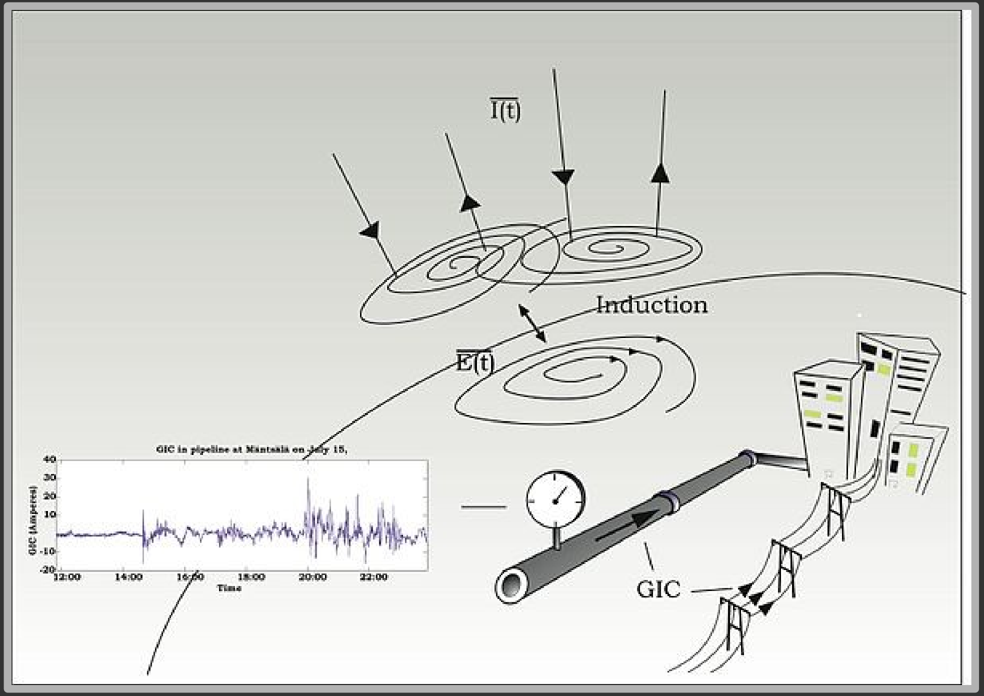
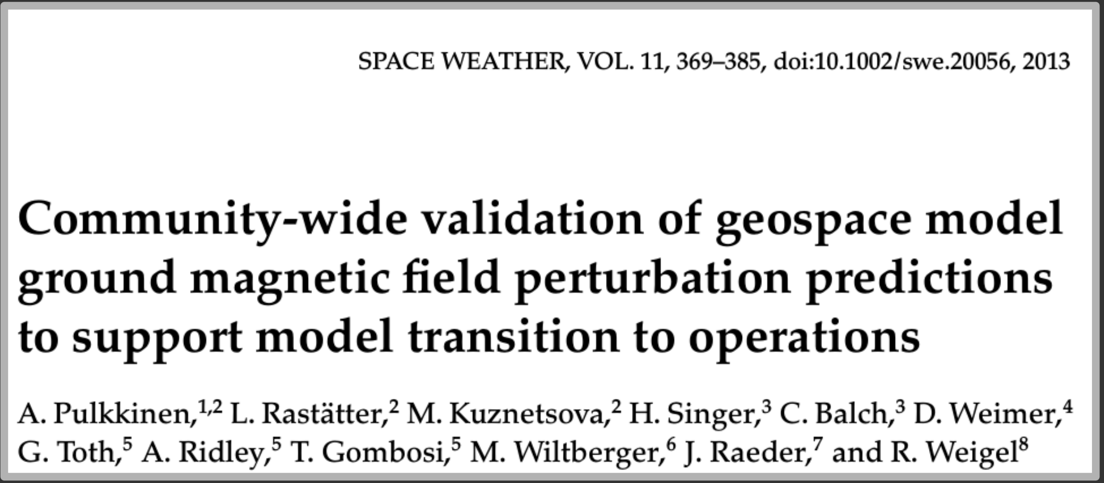
Why do we care about dB/dt?

Sudden changes in the magnetic field induce, via Faraday’s law, an electric field that can generate a Geomagnetically Induced Current (GIC) in long conductors such as electric power lines



Prediction of dB/dt

- Forecast is possible because of the propagation time between L1 (where solar wind is observed) and Earth
- However, an high-cadence (1 min) prediction of dB/dt is too difficult
- The *de-facto standard* for validating dB/dt predictions has been introduced in Pulkkinen et al. (2013)



SPACE WEATHER, VOL. 11, 369–385, doi:10.1002/swe.20056, 2013

Community-wide validation of geospace model ground magnetic field perturbation predictions to support model transition to operations

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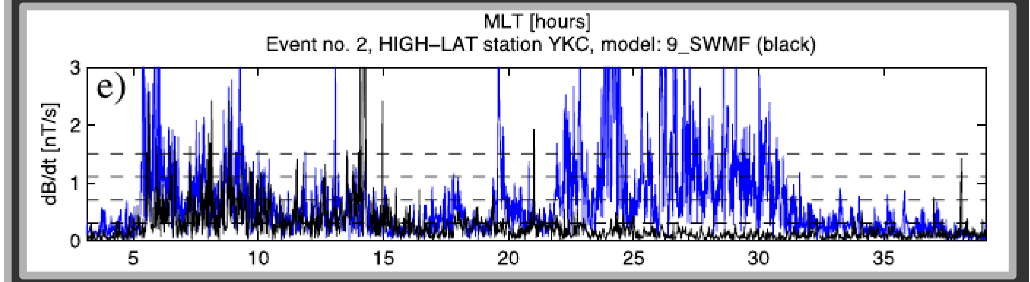


Prediction of dB/dt: problem set-up

$$dB/dt = \max_{\{t,t+\Delta t\}} \sqrt{(dB_n/dt)^2 + (dB_e/dt)^2}$$

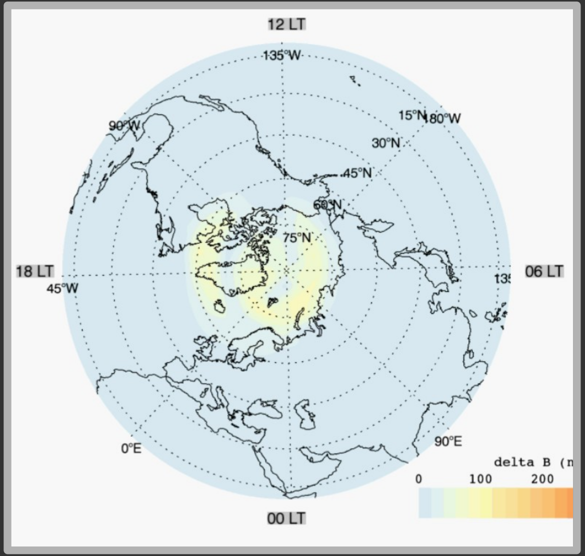
The focus is on predicting whether (the max of) dB/dt will exceed a given threshold in a 20-mins interval (binary classification problem)

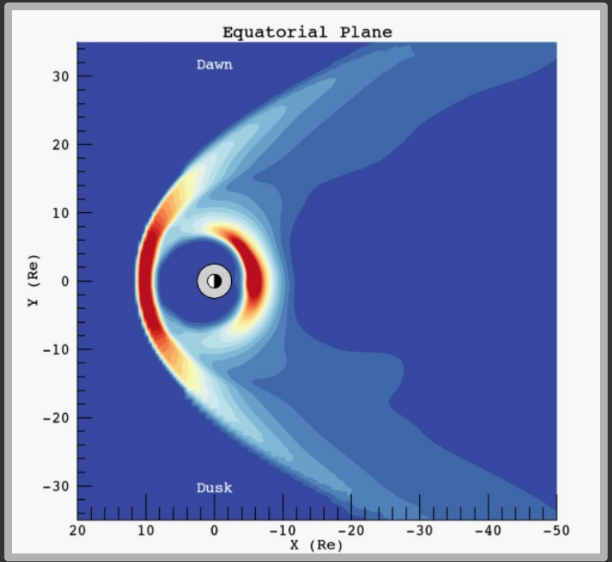
- P = total number of observed positives (event occurrences);
- N = total number of observed negatives (event non-occurences);
- TP = True Positives: number of predicted positives that are observed positives;
- FP = False Positives: number of predicted positives that are observed negatives;
- TN = True Negatives: number of predicted negatives that are observed negatives;
- FN = False Negatives: number of predicted negatives that are observed positives;

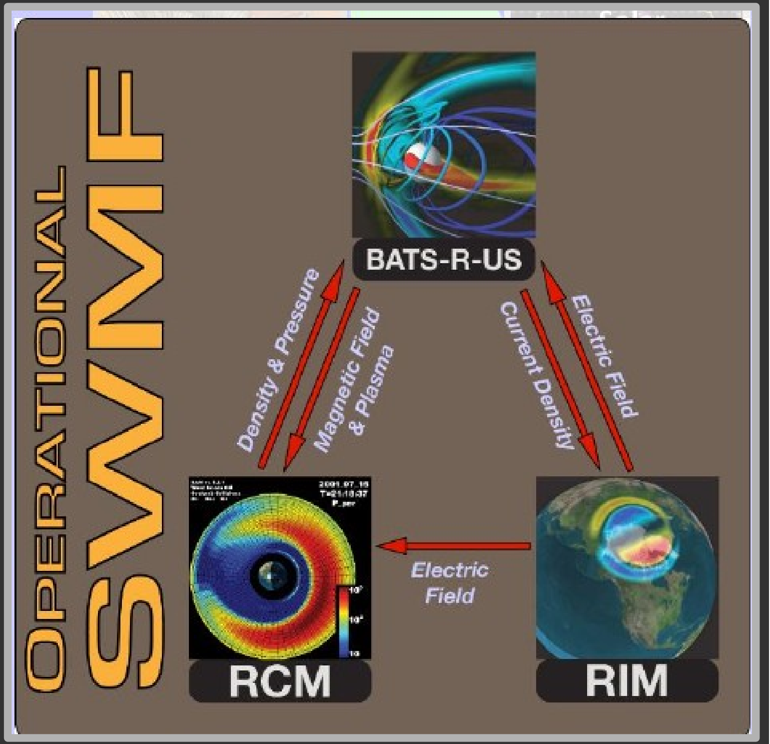
- $TPR = TP/P$ = True Positive Rate (also called Probability of Detection, Sensitivity, Hit Rate);
- $FPR = FP/N$ = False Positive Rate (also called Probability of False Detection);
- $TSS = TPR - FPR$ = True Skill Score.

The operational Geospace model

- MHD model of Earth’s magnetosphere
- 32 Re upstream to ~120 Re down tail
- U. Michigan’s Space Weather Modeling Framework (SWMF)
- Running every minute as long as solar wind data are available







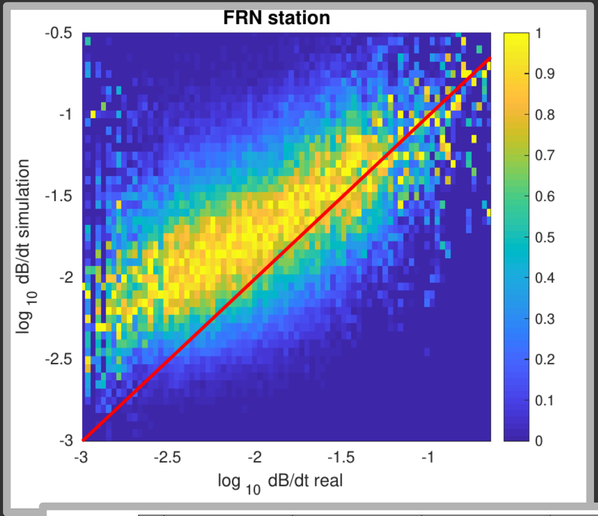
The data

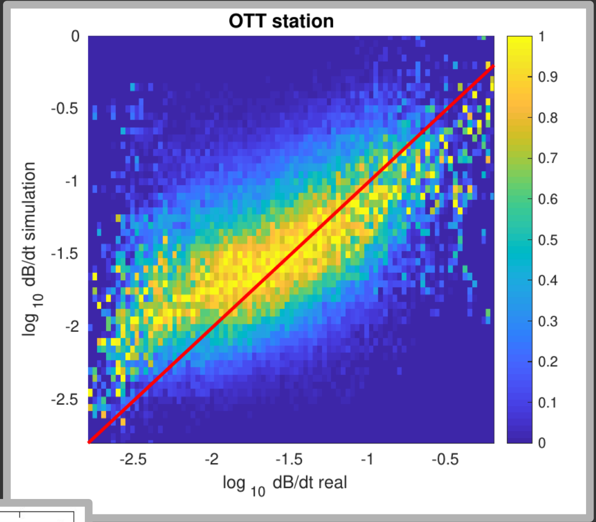
- In this work we focus on three stations:
  - Fresno (FRN, 43.12 N)
  - Ottawa (OTT, 54.88 N)
  - Iqaluit (IQA, 73.25 N)
- Real data: 1-min data for the period 2001-01-01 to 2019-05-05
  ~ 10M data points (INTERMAGNET)
- Archived simulations: 2017-05-28 to 2019-05-05
  ~ 1M data points

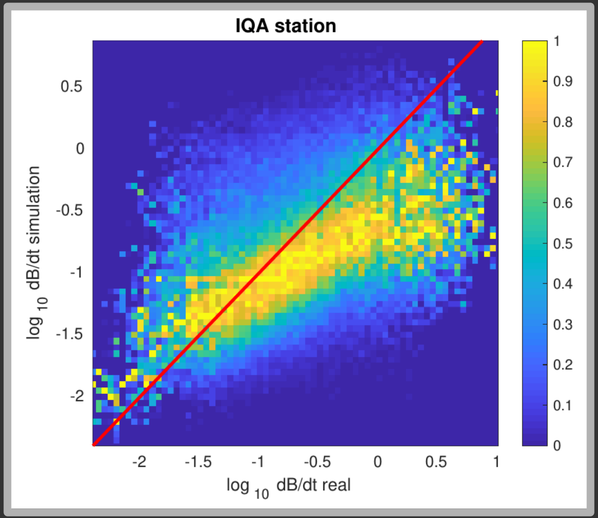
2001 – 2017 : training and validation

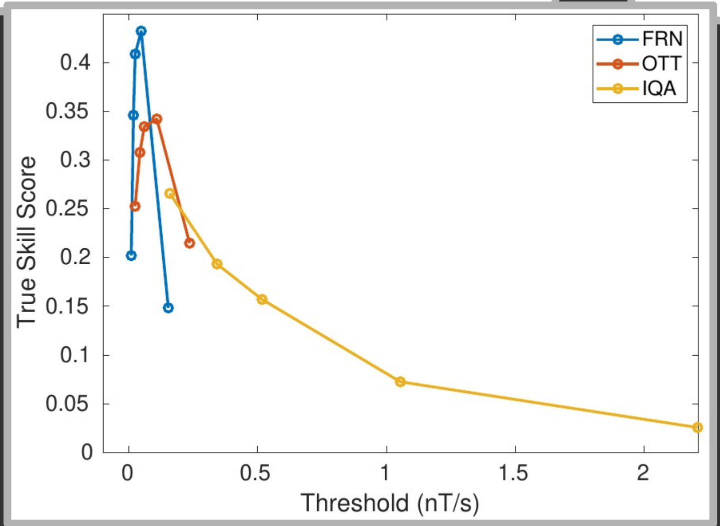
2018 – 2019 : testing

The baseline: TSS of Geospace model



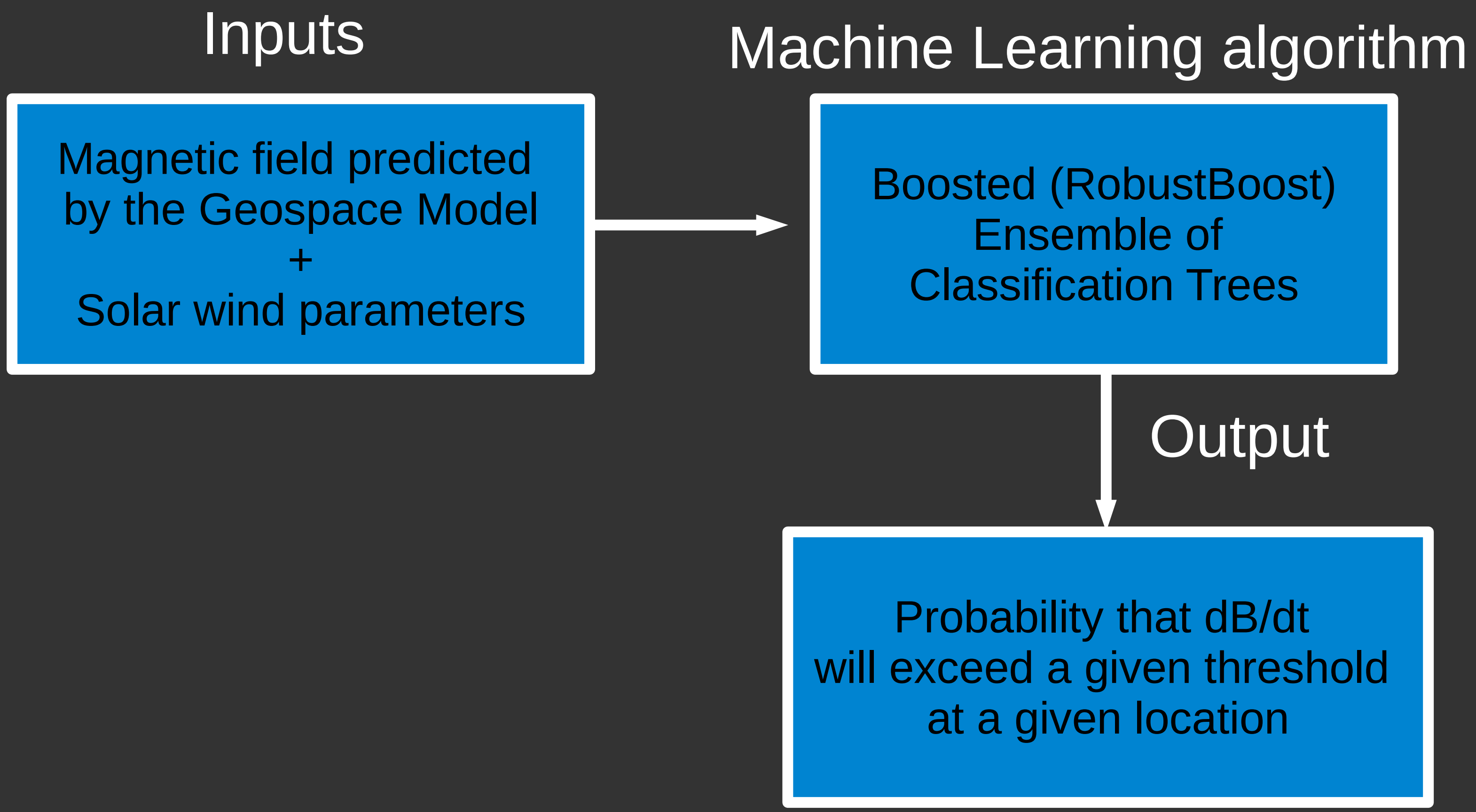






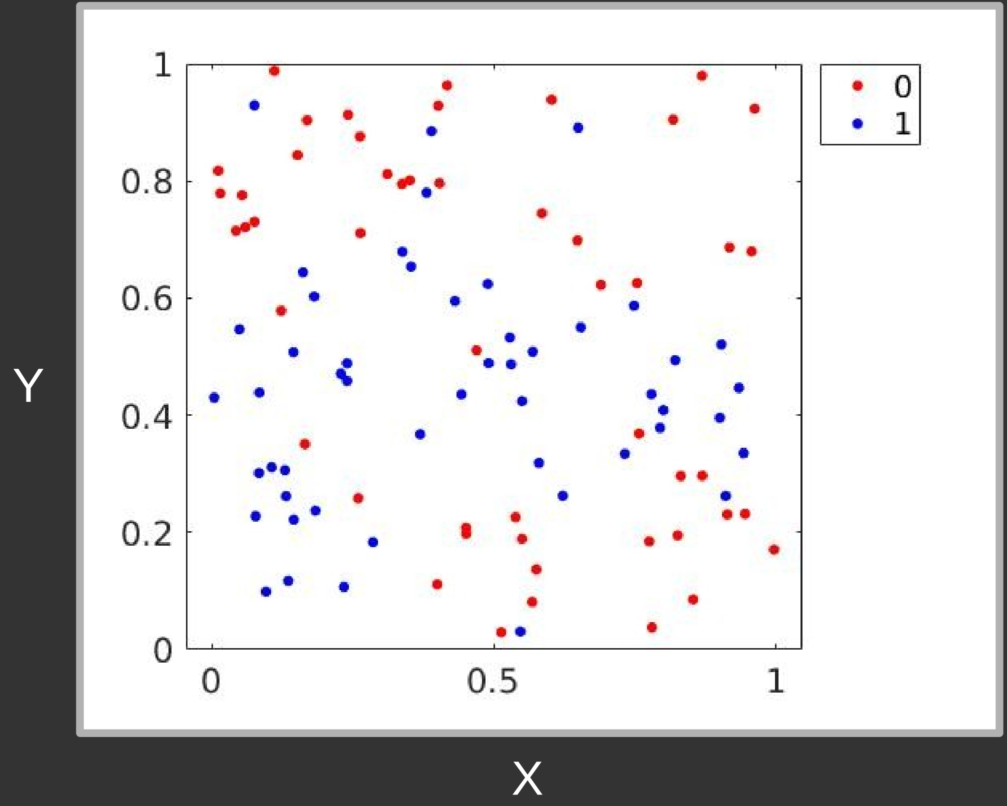
The goal of this work is to obtain a systematic improvement over this baseline for all stations and any threshold

Basic idea: Grey-box approach!



What is a decision tree for classification?

A decision tree partitions your input space in the optimal way to find cluster of labels



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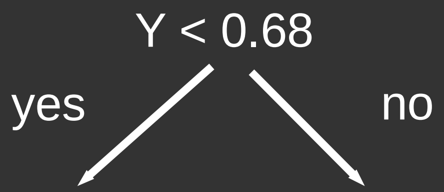
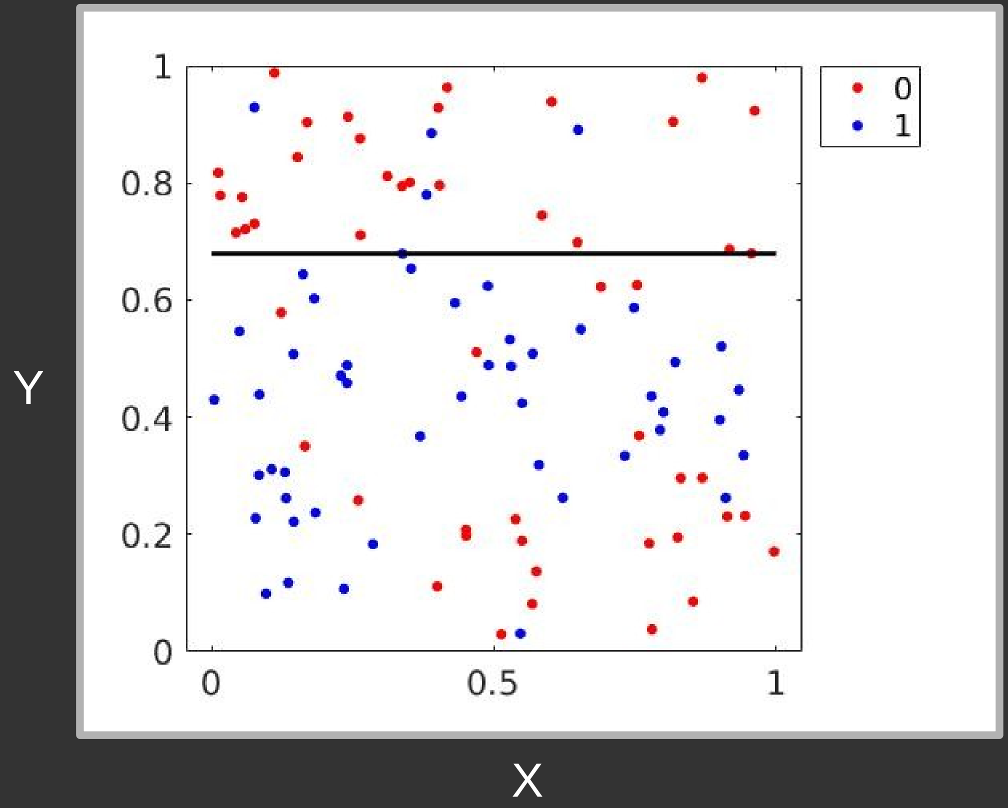


The cuts are always parallel to the axes and try to maximize the ratio between blue and red in each subset



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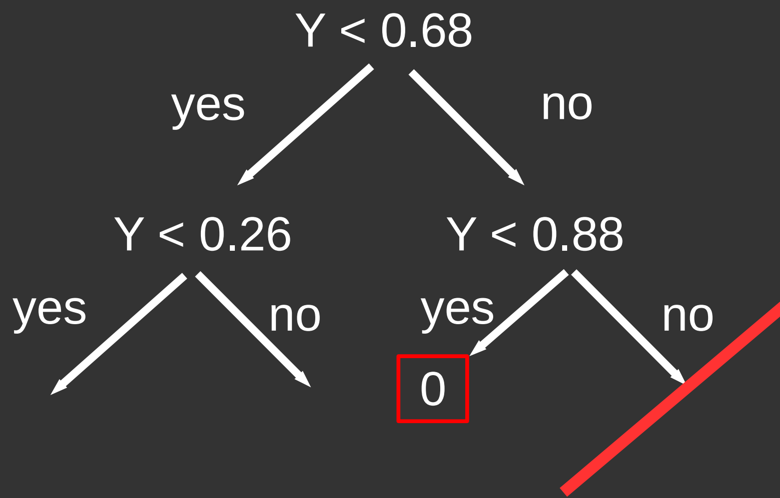

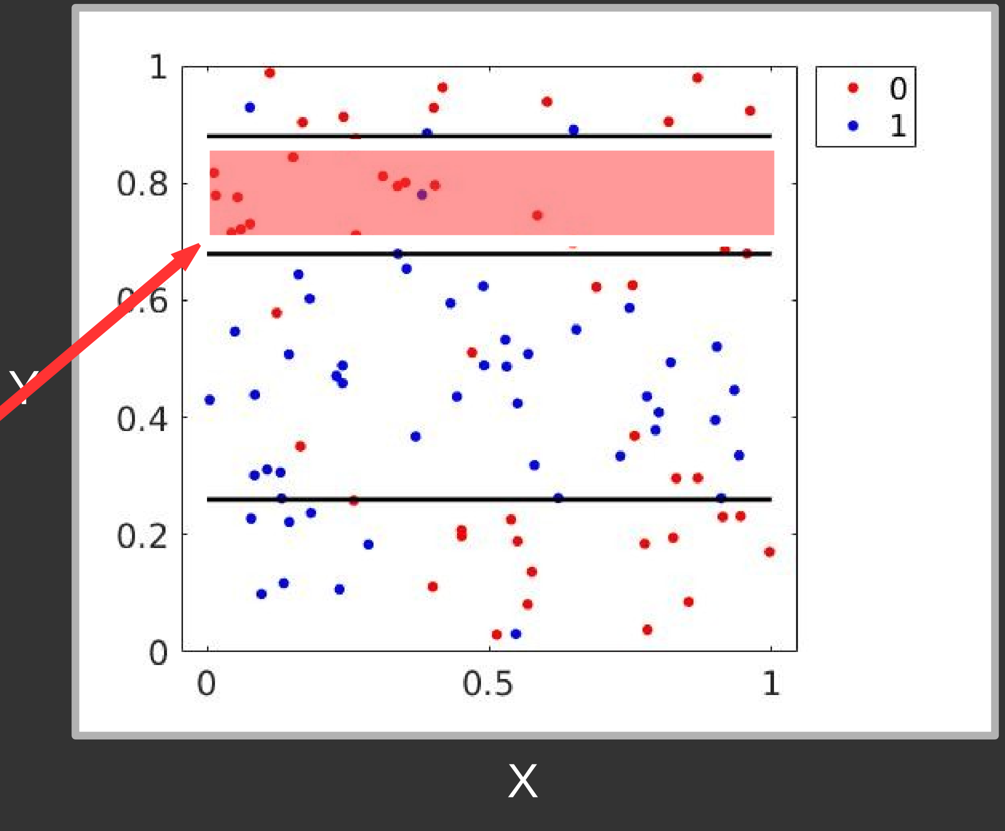

The ratio here is 2 blue vs 17 red.
No possible further cut can do better than this

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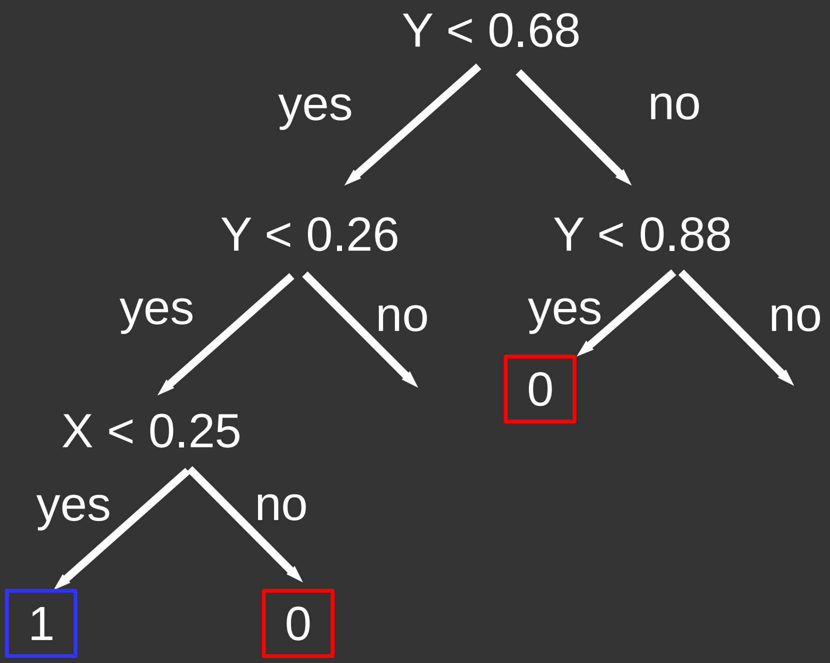

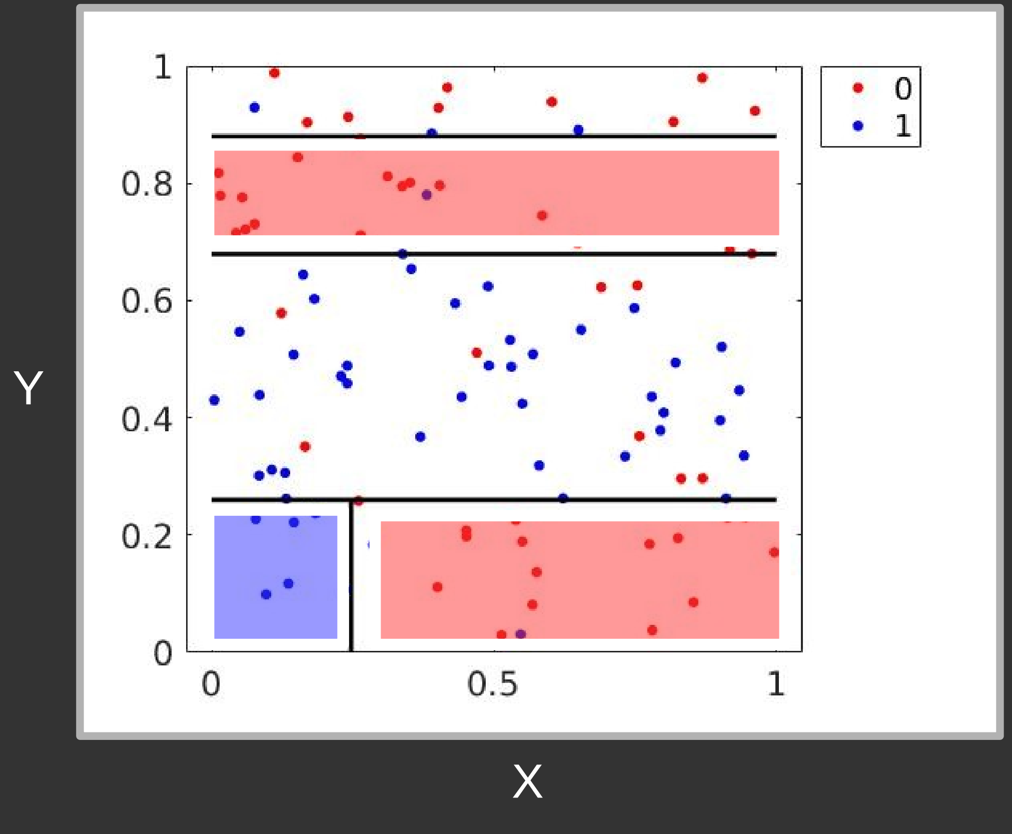

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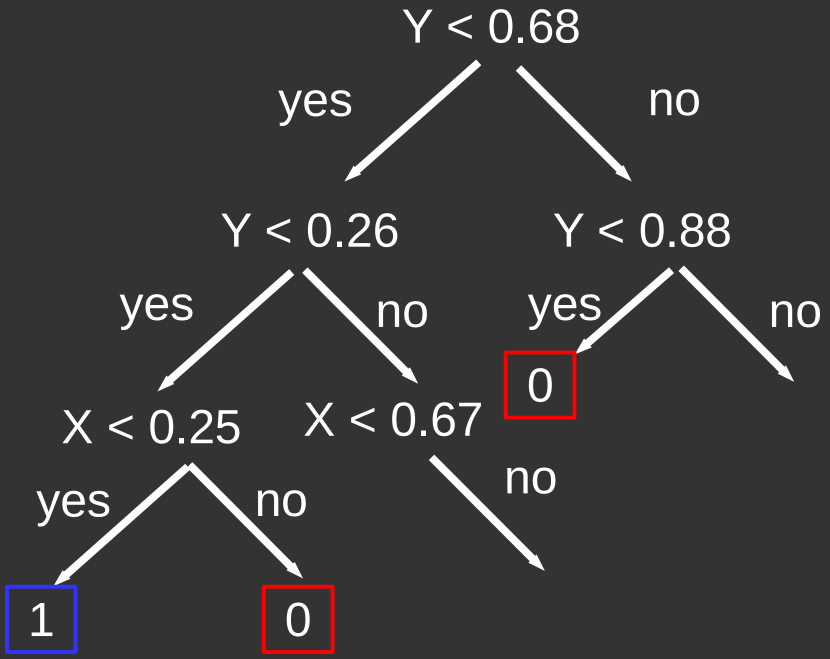

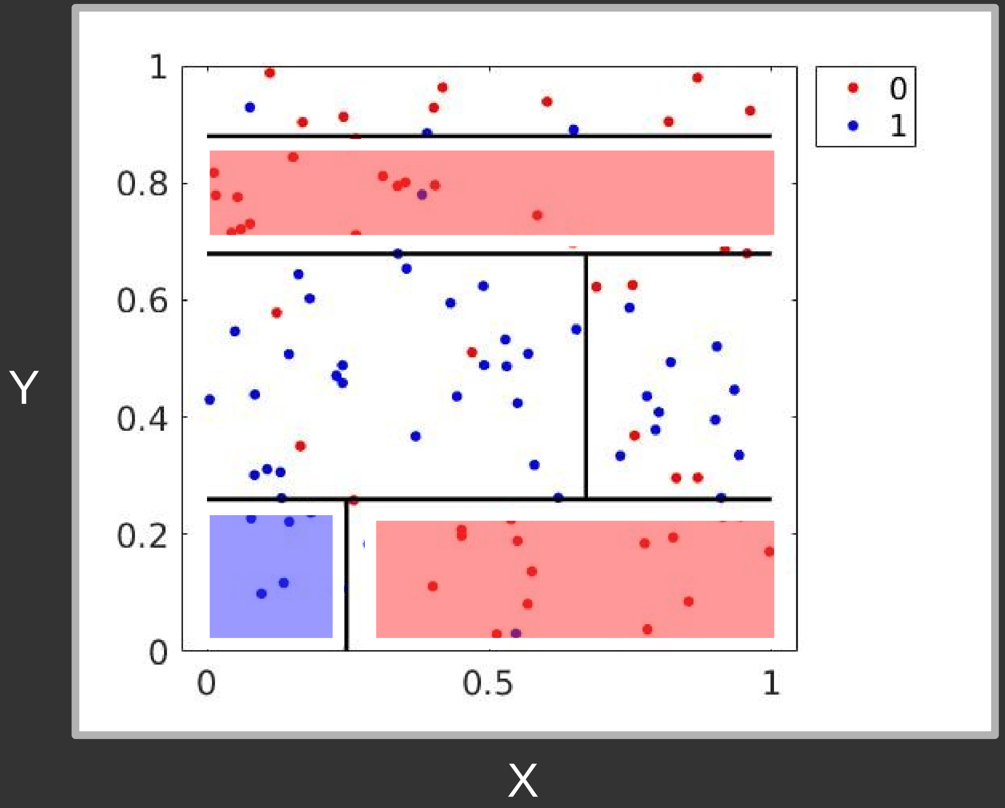

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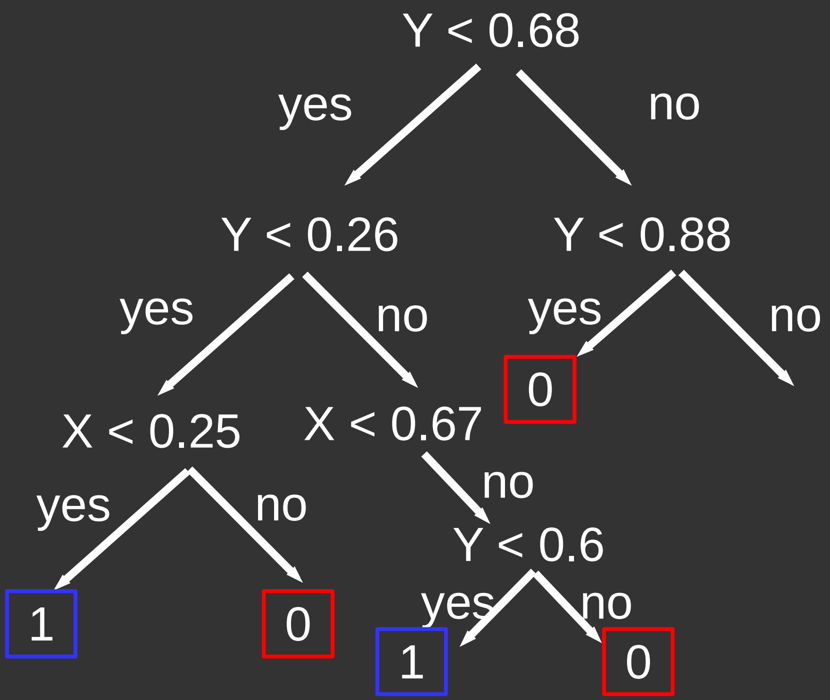

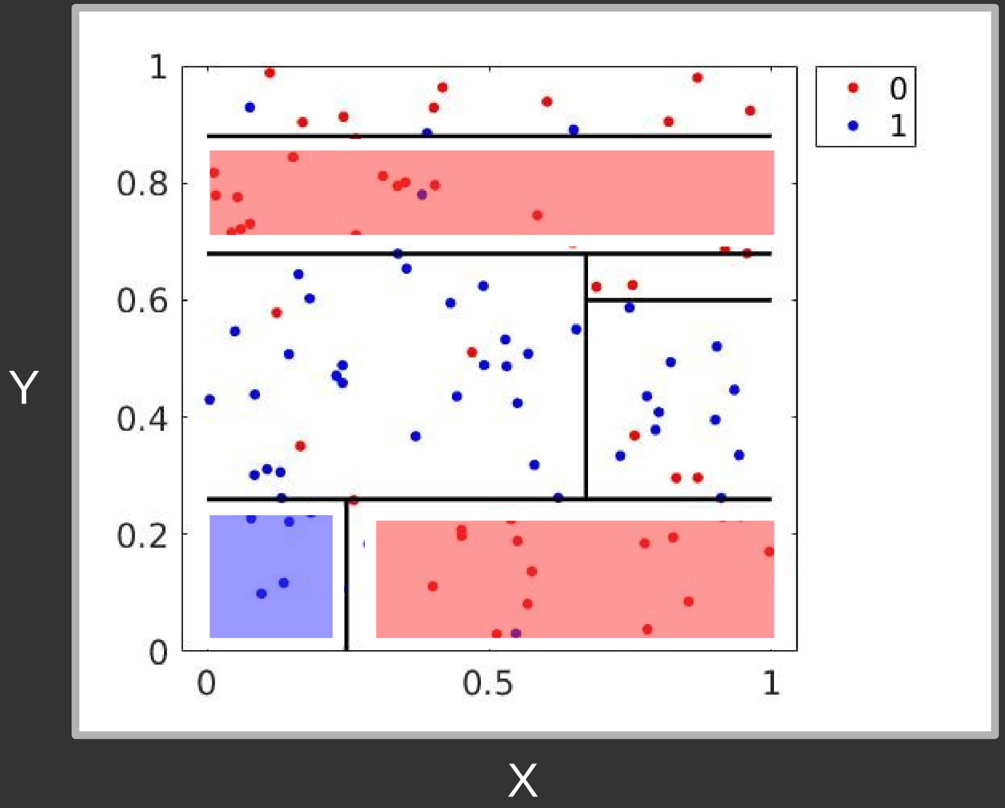

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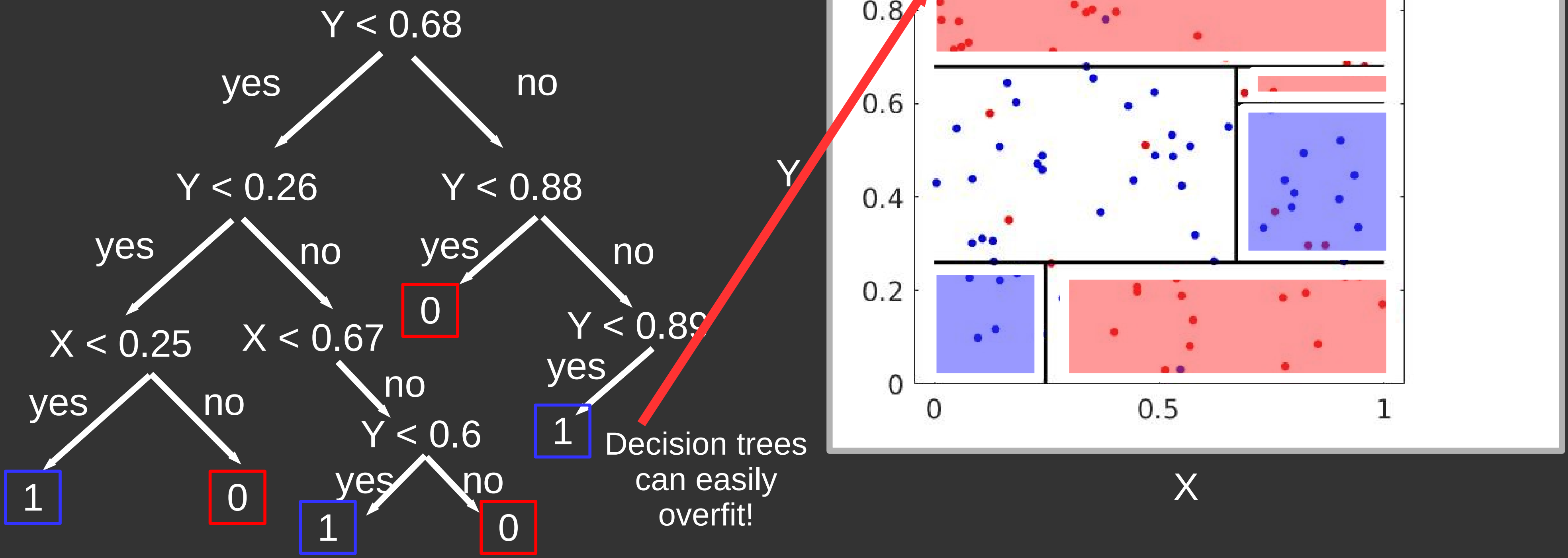


What is boosting?

- ‘Weak learners’ are trees that are grown only to a few levels
- Each weak learner performs only slightly better than random chance. However, an ensemble of weak learners can perform much better than a full-grown tree.
- An iterative algorithm boosts a weak learner increasingly focusing on the data that was mis-classified at the previous iteration

Freund, Y., & Schapire, R. E. (1997). A decision-theoretic generalization of on-line learning and an application to boosting, *Journal of computer and system sciences*, 55 (1), 119–139.

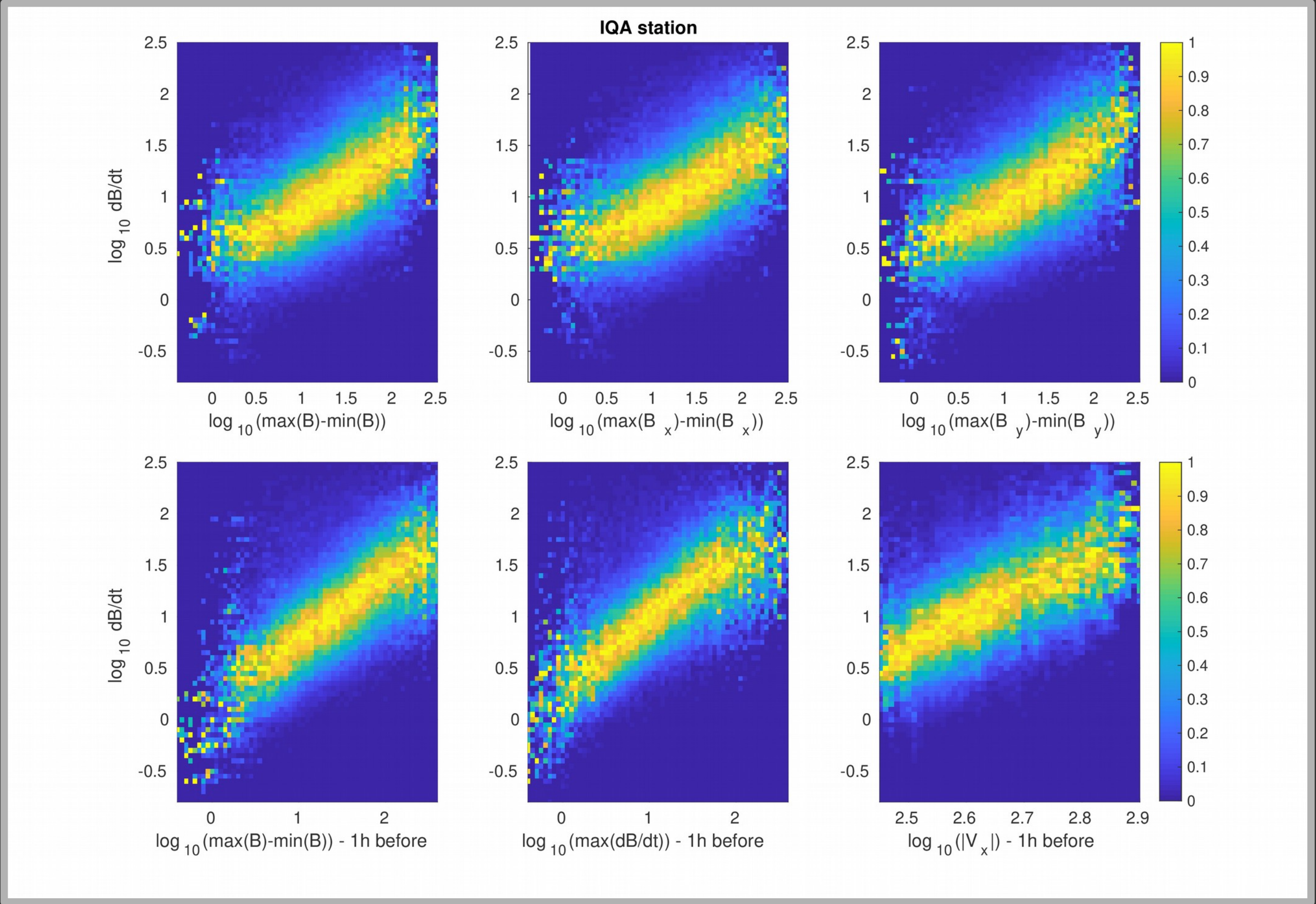
Freund, Y. (2009). A more robust boosting algorithm. *arXiv:0905.2138* .

Feature selection

1. log10 (max(B)−min(B)) (obtained from the Geospace simulation output)
2. log10 (max(Bx) − min(Bx)) (same as 1. but the x-component only)
3. log10 (max(By)−min(By)) (same as 1. but the y-component only)
4. log10 (max(B)−min(B)) - 1hr before (same as 1. but calculated in the time window 1 hour preceding the target window, obtained from magnetometer)
5. log10 (max(dB/dt)) - 1hr before (the same quantity as the target, but calculated in the time window 1 hour preceding the target window, obtained from magnetometer data)
6. log10 (|Vx |) - 1hr before (the x-component of the solar wind speed, measured one hour before the target window)

Tóth, G.,et al. (2014). Predicting the time derivative of local magnetic perturbations. *Journal of Geophysical Research*, 119 (1), 310–321.

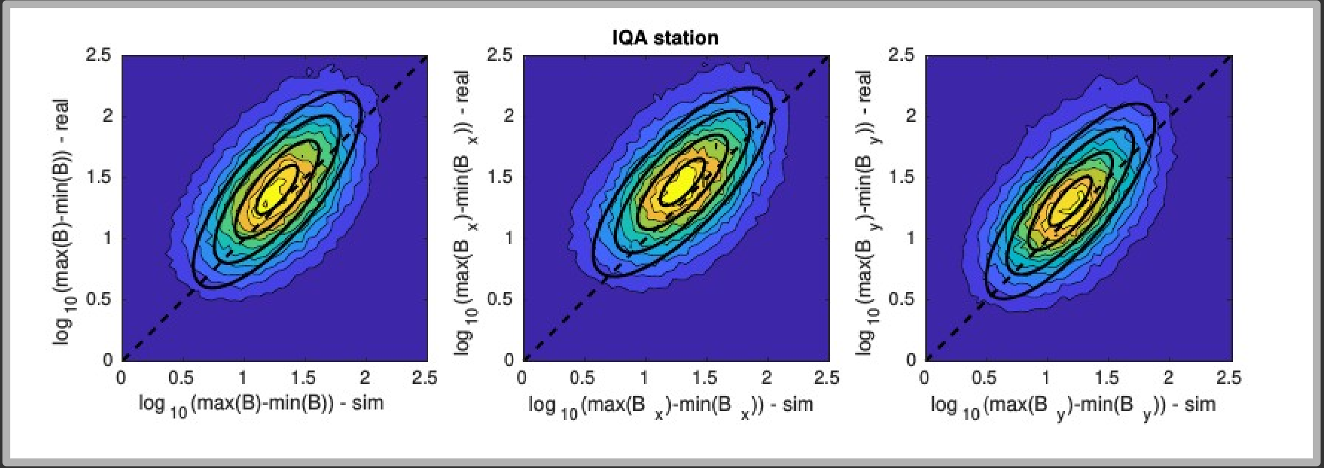
Feature selection

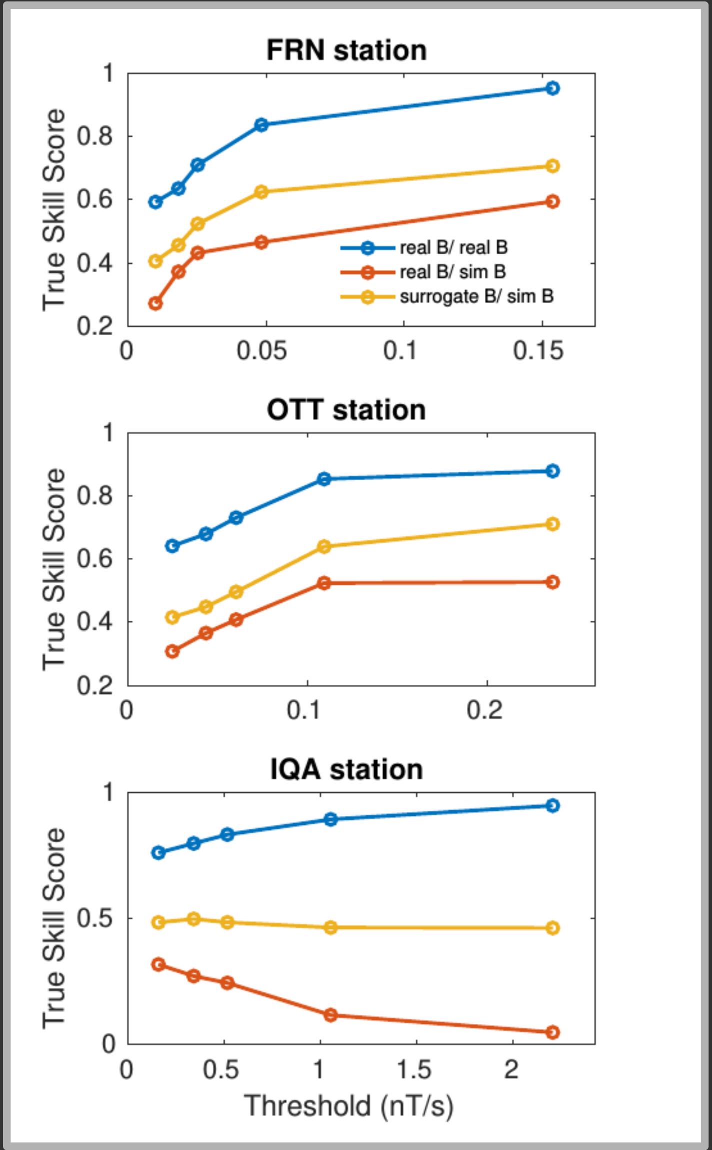


Surrogate Geospace data
(a small technicality...)

2001 – 2017 : training and validation

- We want to train our model on a time period for which we do not have the runs of the operational Geospace model
- We produce surrogate Geospace output by assuming a multivariate Gaussian distribution in the input-output space





Results: True Skill Score

Blue line → Theoretical upper limit in the case the Geospace model would produce perfect predictions

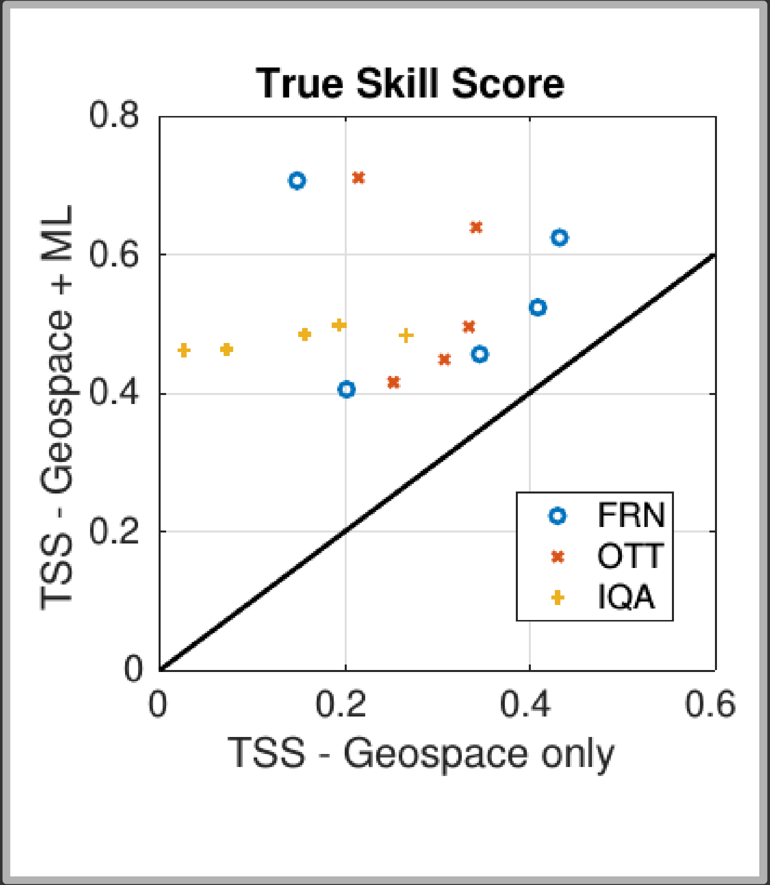
Red line → The result without producing surrogate model (train using real data but predict using Geospace)

Yellow line → The results of this work!

Comparing white vs grey-box models

- The Geospace + ML method consistently enhances the score for all three stations, for any threshold
- The method will be extended to more stations
- We plan to make it operational

The paper will be on arXiv by AGU
(~ 2 weeks !!)



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