Building a GIC forecasting tool based on geomagnetic and solar wind data: challenges and future avenues

A study in Austria using a combination of geophysical and machine learning methods

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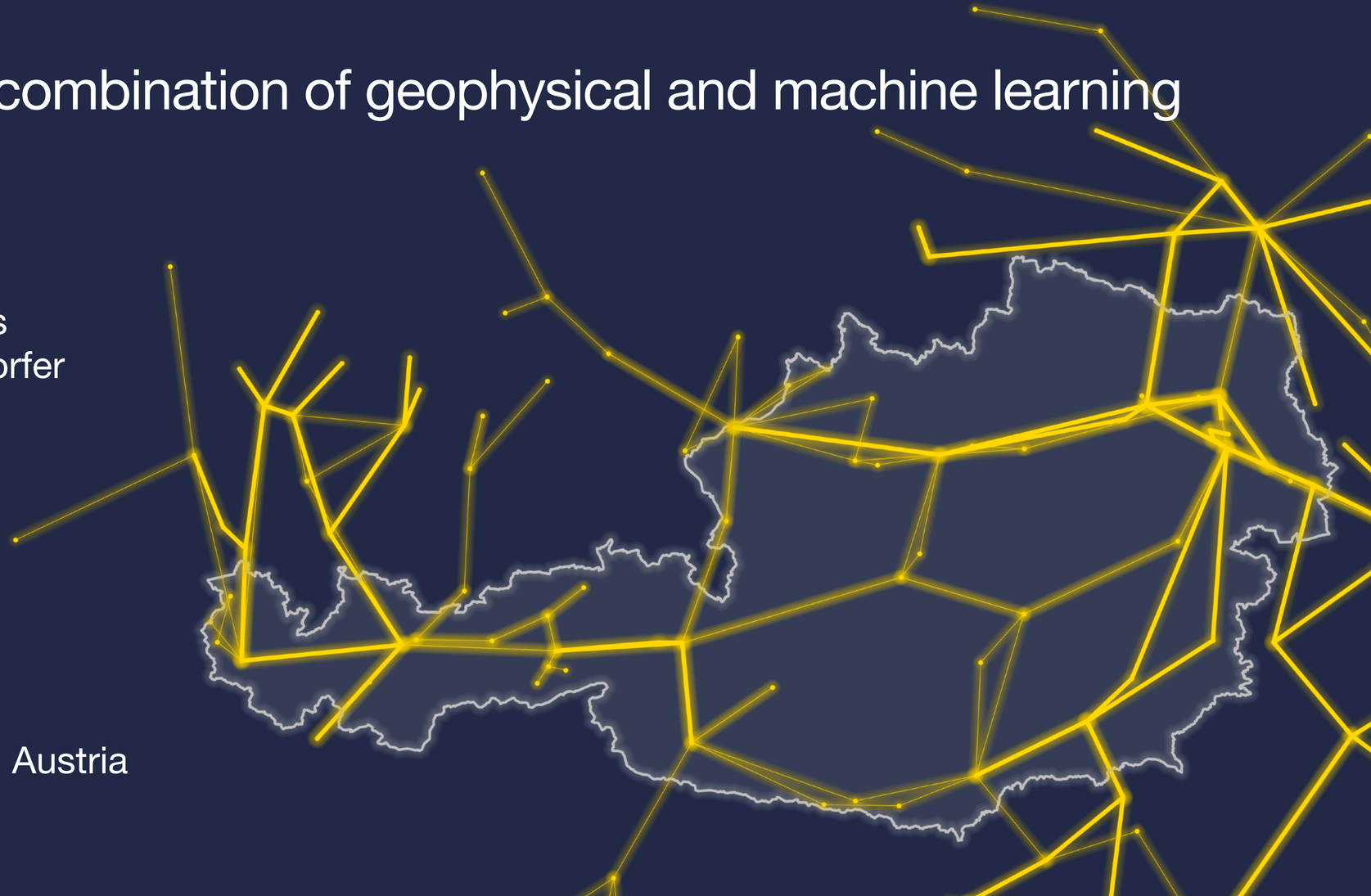


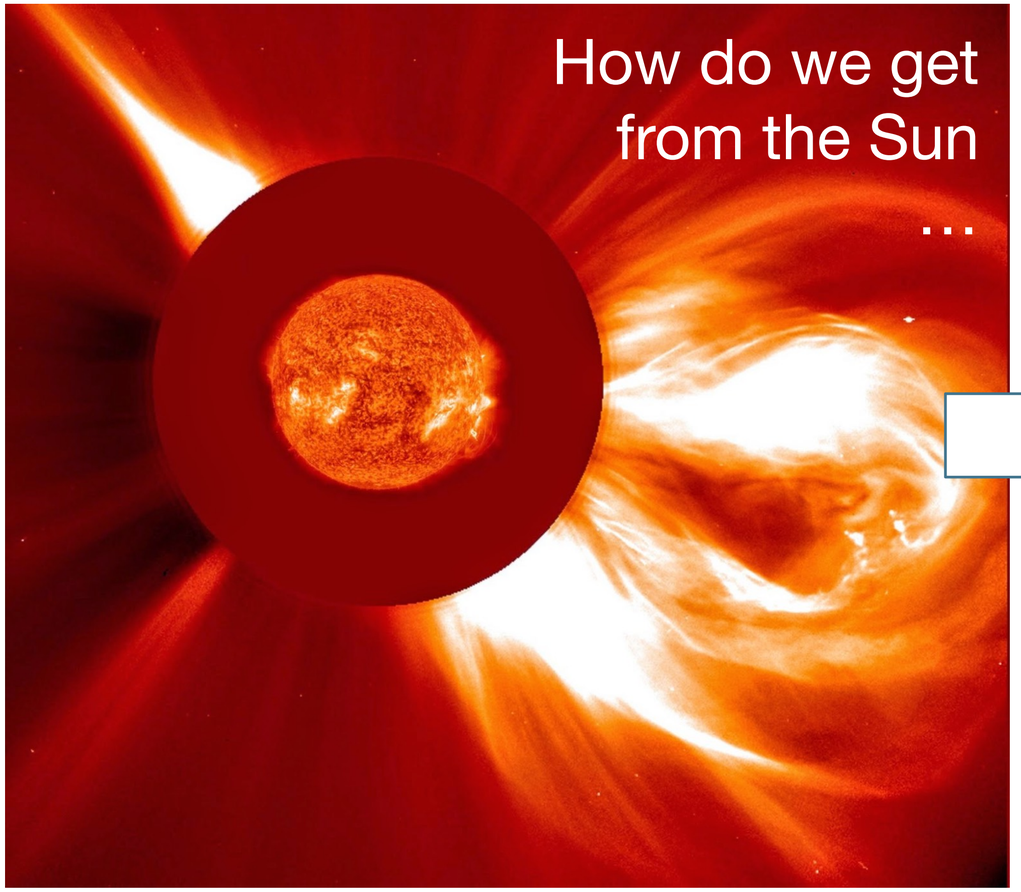
GICs are a modern-day phenomenon

March 13, 1989

March 9th: coronal mass ejection leaves Sun
March 12th: mild geomagnetic disturbances

March 13th:
- 01:00: Hydro-Quebec power grid operation problems
- 02:44: geomagnetic storm starts
- 02:45: sequence of HV transformers and lines trip, within 60s collapse of entire network, **power blackout**
- …
- 12:00: 83% of power restored

GICs are a modern-day phenomenon



Credit: SOHO, 2003-12-02

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Credit: PSE&G

Rapid geomagnetic variations cause GICs

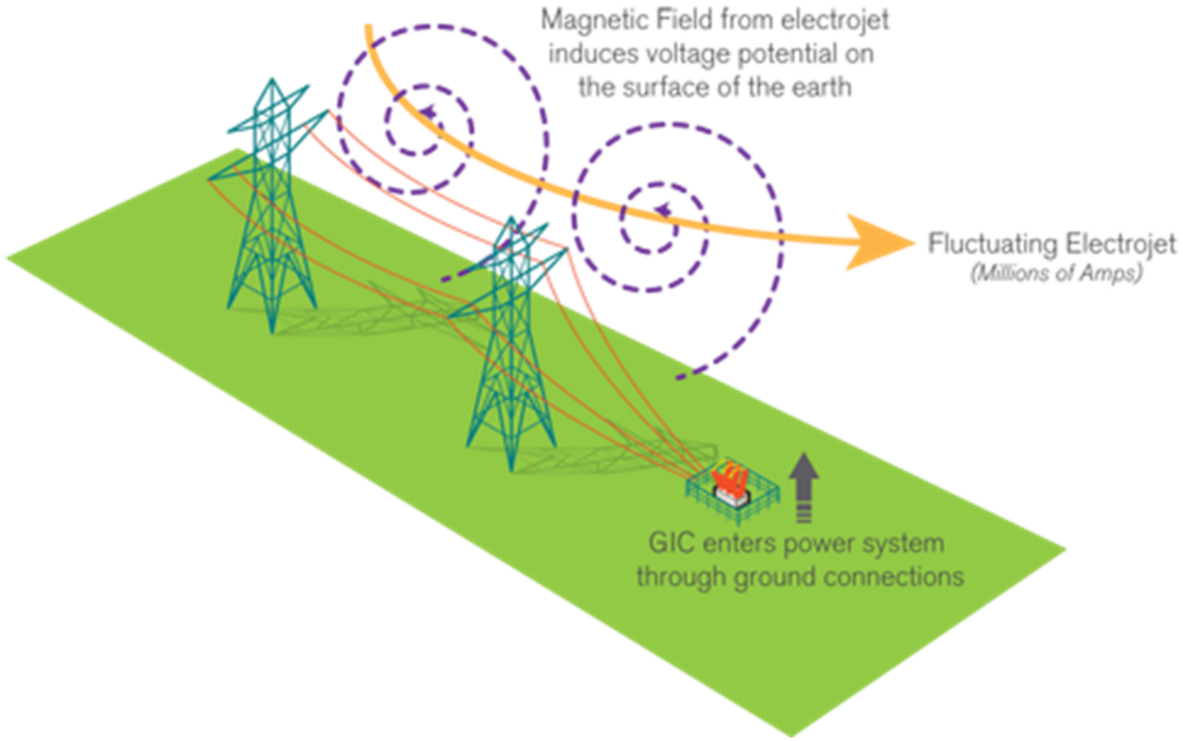
Geomagnetic storms lead to **rapid magnetic field variations**

Varying magnetic field → induced electric field

$$\frac{E_x}{B_y} = Z_{xy} = \sqrt{i\rho\omega\mu}$$

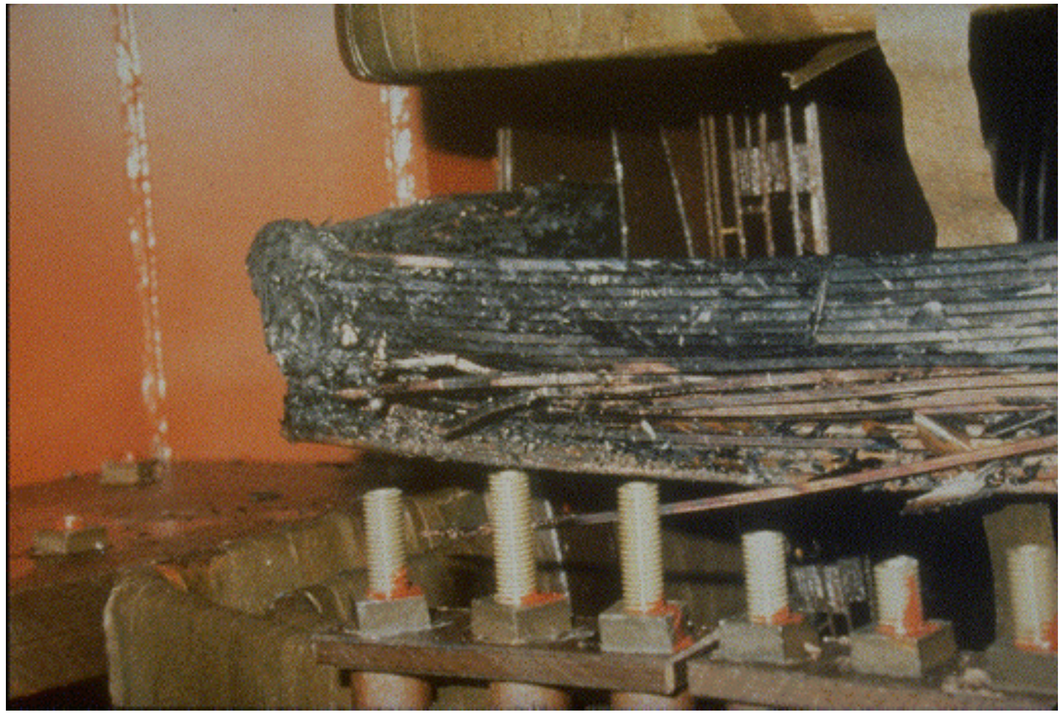
(ρ = ground resistivity, ω = angular freq., μ = magnetic permeability)

Geoelectric field leads to electro-motive force in grounded conductive network
→ currents through lines / transformers



GICs flow through transformers

- GICs **flow from Earth to power grid** and vice versa —> DC is flowing through transformers
- Transformers are not built to handle large amounts of DC
- GICs can be **damaging** when flowing through transformers
- Large GICs cause overheating —> burnout (e.g. Quebec)

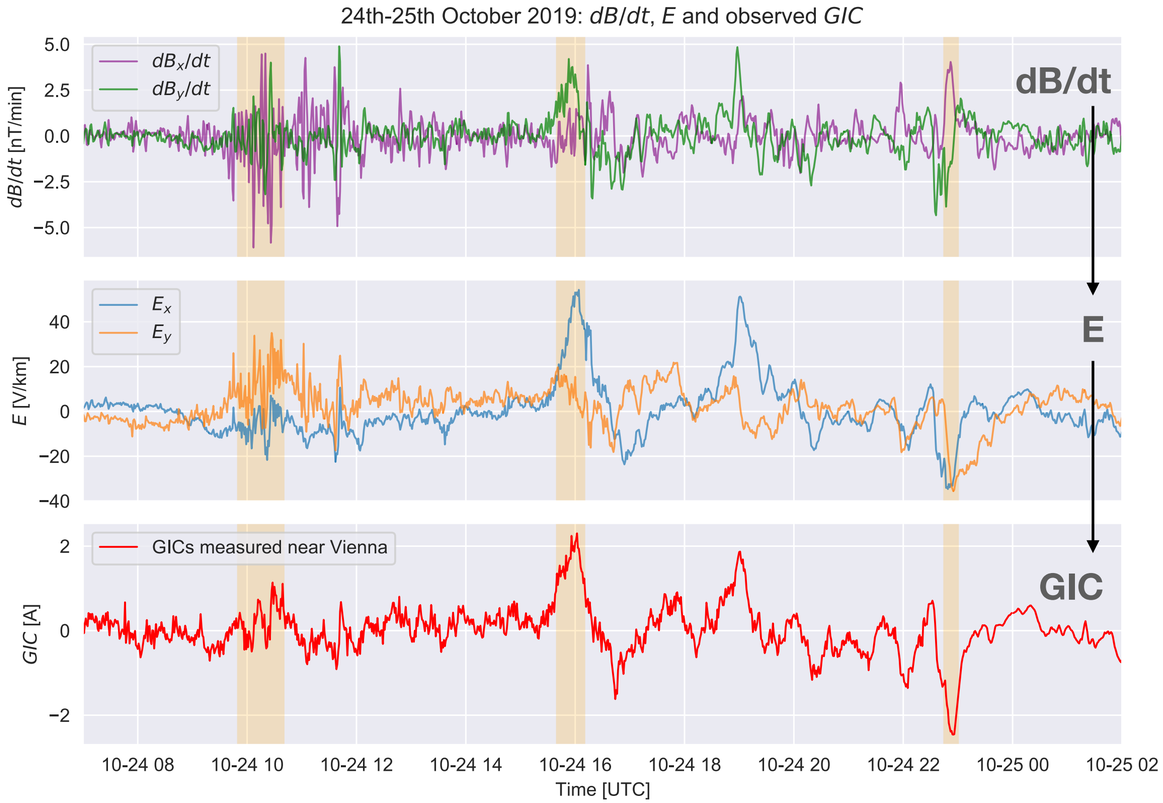


Credit: PSE&G

Forecasting GICs

The history

- Solar wind plasma and B-field data measured at L1 gives advance warning (30-60 minutes) of incoming geoeffective events.
- Many have tackled this problem before using solar wind data to **forecast *dB/dt* as a proxy**[1].
- ***dB/dt* is not ideal** - it does not contain the same frequency content as the geoelectric field[2], the primary driver behind GICs.
- For a local grid forecast, the geoelectric field or the GICs themselves will be more accurate.



An example from 24th October 2019 of dB/dt (top), modelled geoelectric field E (middle) and measured GICs (bottom). The areas where **dB/dt would either over- or underestimate the risk of high GICs** are highlighted in orange.

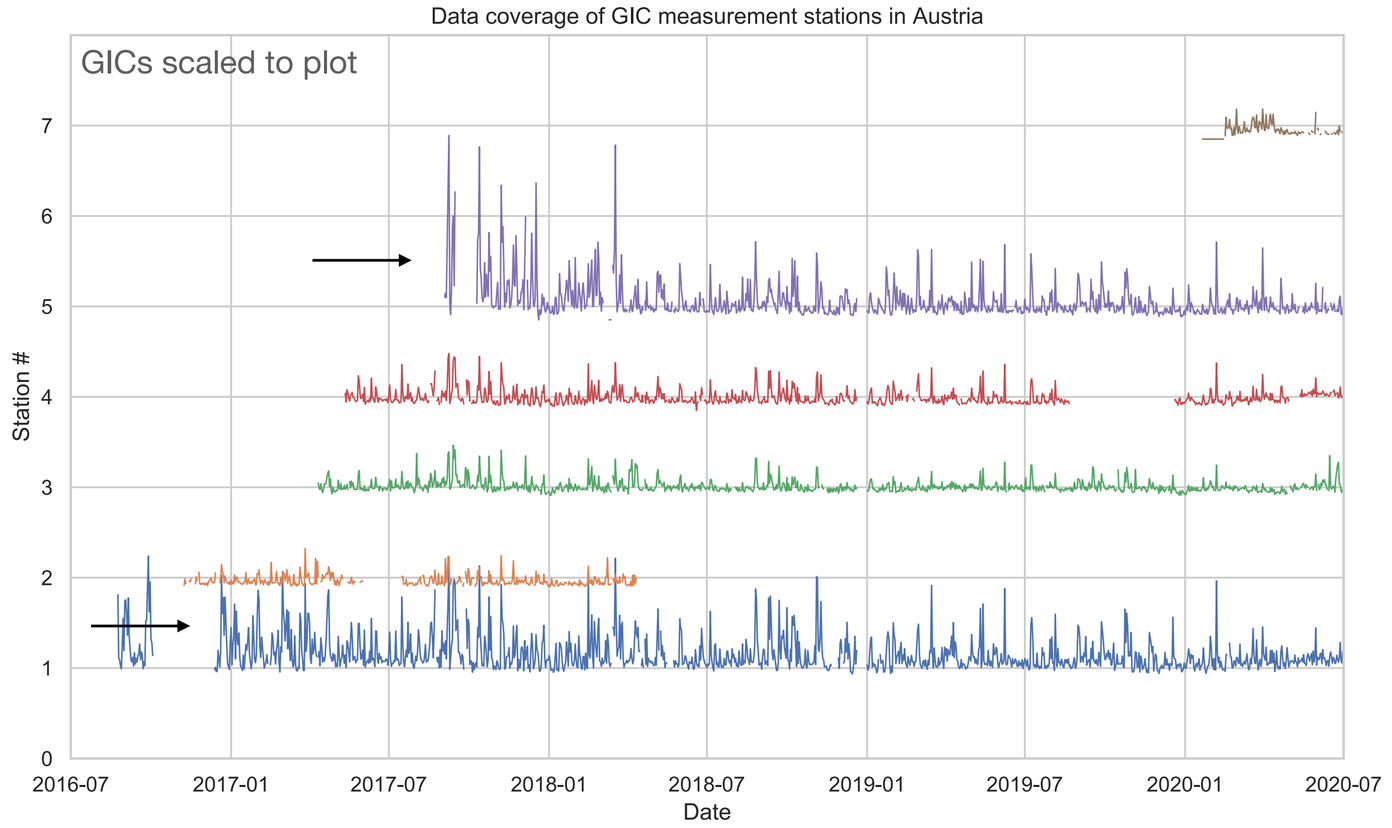
1)
Wintoft+(2005)
Lotz+(2015)
Wintoft+(2015)
Camporeale+(2019)
Keesee+(2020)

2)
Pulkkinen+(2006)
Pulkkinen+(2013)

GIC Measurements in Austria

An overview

- Measurements since Aug. 2016 with some small breaks at individual stations
- Up to **five stations** running in parallel
- Two stations (#s **1** and **5**) experience larger (> 10 A) GICs during geomagnetic storms —> Can we make **forecasts of max(GIC)** for these stations?



Which variable do we want to forecast?

GIC from raw station data?

+ Real measurements (~4 years) define the ground truth

- No extreme events and few events with large values

- Very noisy data and often a cap on max. value

… OR …

Local modelled geoelectric field E_x & E_y?

- No measurements as ground truth

+ Can model extreme events with good accuracy

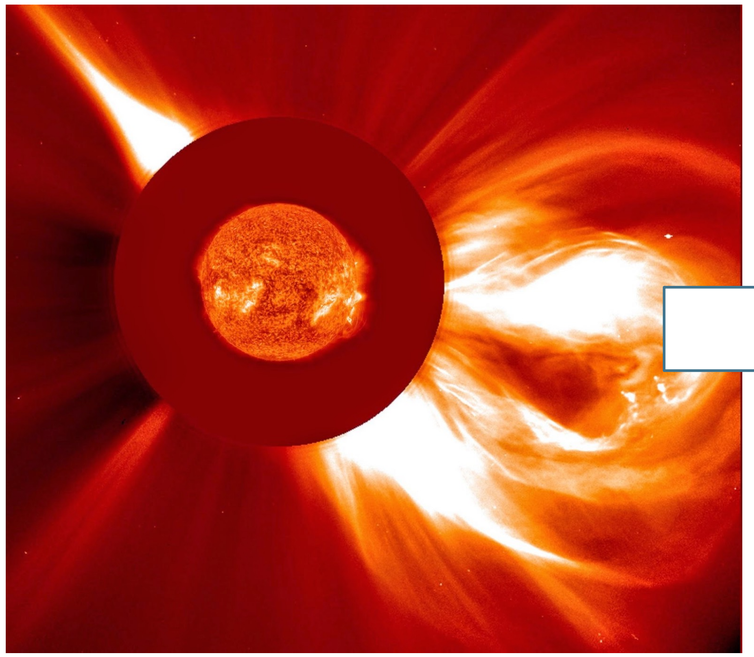
+ LOTS of magnetic field data (>20 years) for modelling

$$GIC_j = a_j \cdot E_x + b_j \cdot E_y$$

So… try both, compare and optimise!

Forecasting GICs

The end result should essentially be a transfer function between solar wind and the local geoelectric fields or GICs. The question is:
—> **How well can it work?**



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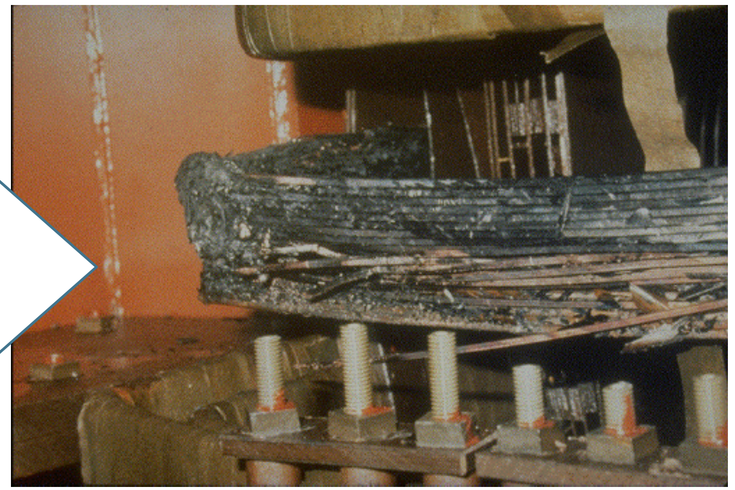


Credit: PSE&G

LSTM Neural Net for predicting GICs

- Develop a neural network (LSTM) to map from solar wind variations to a measure of GIC at the Earth
- LSTMs have memory of past data - they are a good tool for this problem and have been used in similar studies
- Use past **120 mins of solar wind data** to **predict max(GICs)**
- In data preparation: balance quiet events with active events to not overtrain on quiet times

LSTM Setup

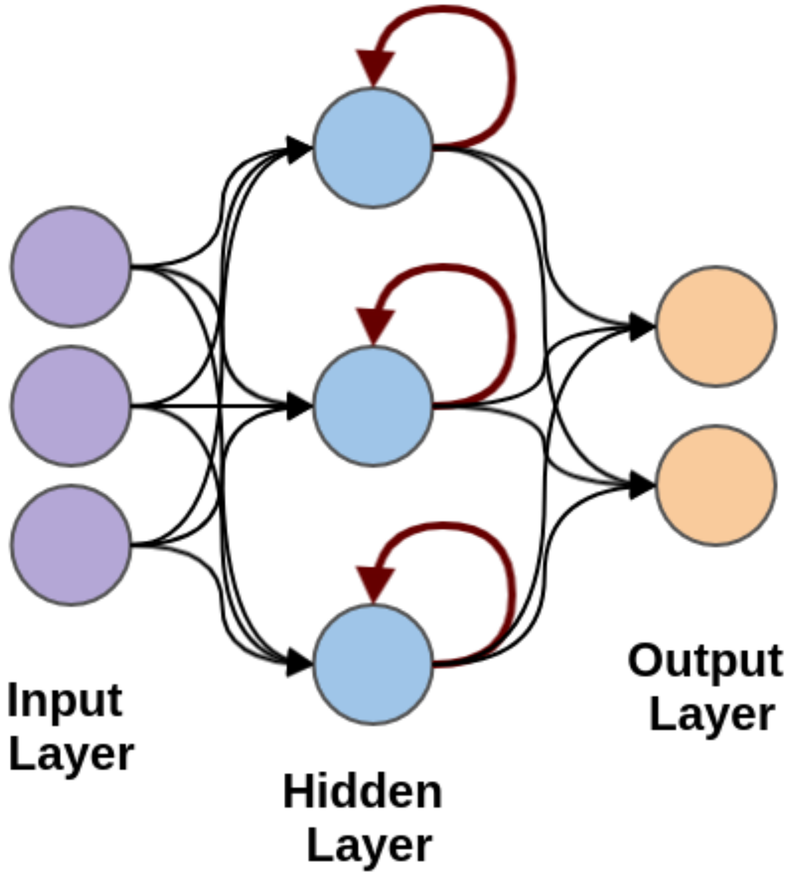
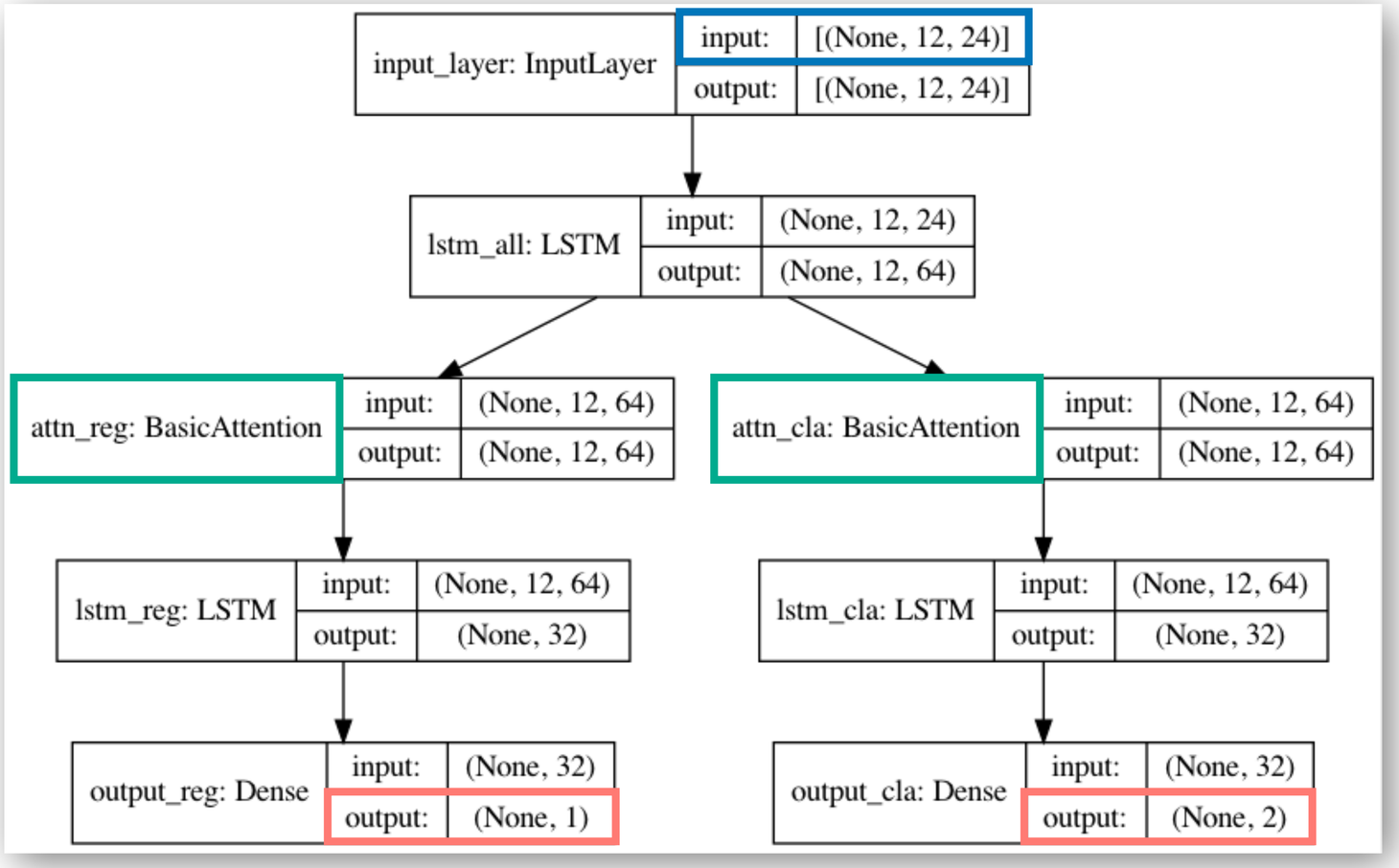


Image courtesy of austingwalters.com

LSTM Neural Net Architecture



|E|

+ or -

- For geoelectric field: predict magnitude E (main target, regression), and direction of E-field (as secondary target, classification) from input solar wind variables (speed, density, B-field)
- Include an attention mechanism (neural net that mimics human attention)
- *Training*:
  21 years of data
  Testing:
  5 years of data

Comparing LSTM Output

- Train three *LSTMs* to predict three targets from the solar wind data:
  1. Modelled max(Ex)
  2. Modelled max(Ey)

  } *(GIC = a*Ex + b*Ey)* = ***GIC$_E$***
  3. Measured max(GICs) = ***GIC$_{OBS}$***

- **Substation #1 is better predicted using LSTM-E trained on E-field data.**

  Substation #5 is better predicted using LSTM-GIC trained on raw GIC data.

  —> Different E-field directions dominate GICs in each station, likely cause of discrepancy.

Error measures: LSTM vs. Meas	GIC$_E$	GIC$_{OBS}$
Pearson's R, #1	0.35	**0.56**
Pearson's R, #5	**0.67**	0.64
RMSE, #1	**0.49 A**	0.67 A
RMSE, #5	**0.59 A**	0.78 A

Results

- The model can predict times of heightened activity, and predicts a daily variation otherwise (see Figure for Sept. 2017 storm —>).
- **Probability of detecting events**: 50% for moderate activity (> 2 A), 15% for strong activity (> 4 A).
- Would need more information on status of magnetosphere and current systems to improve predictions.

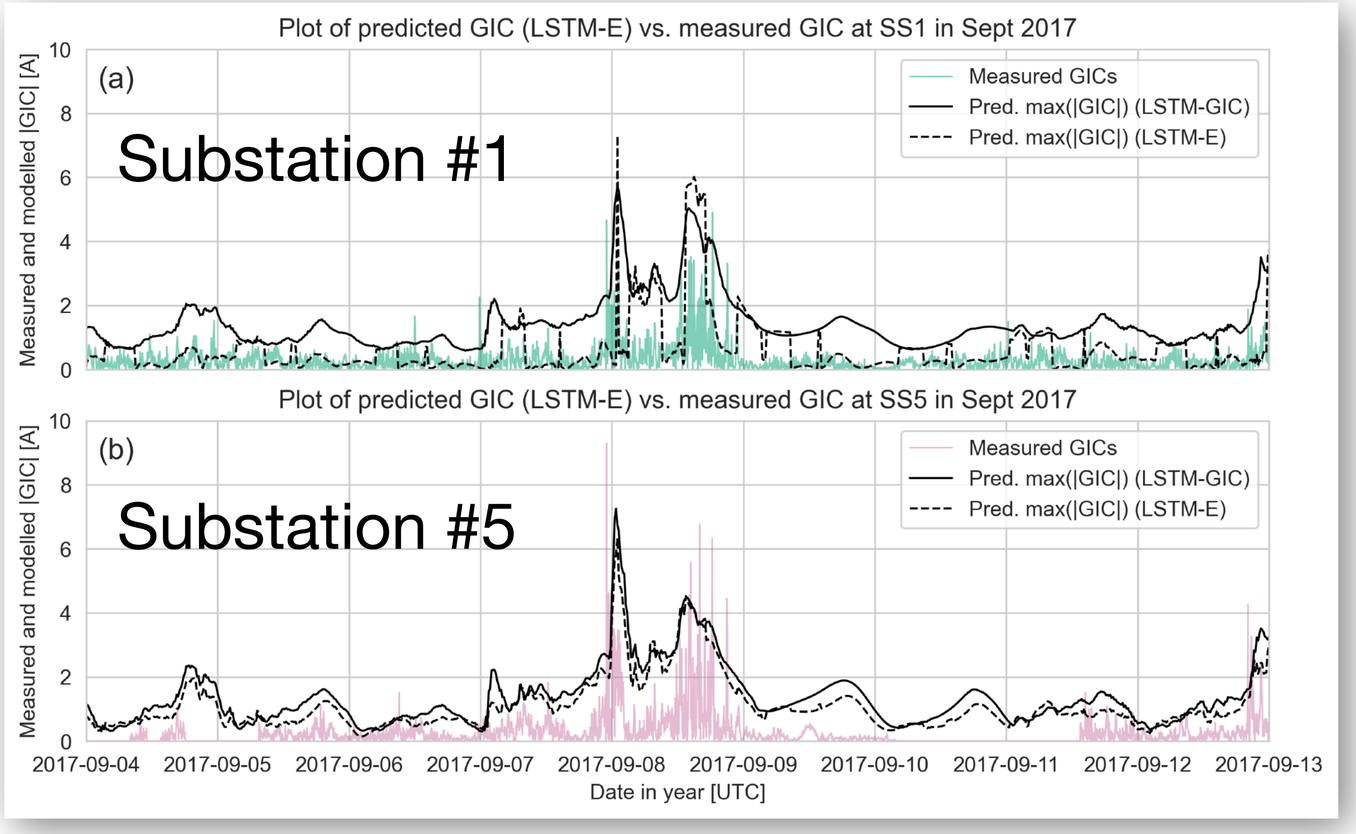
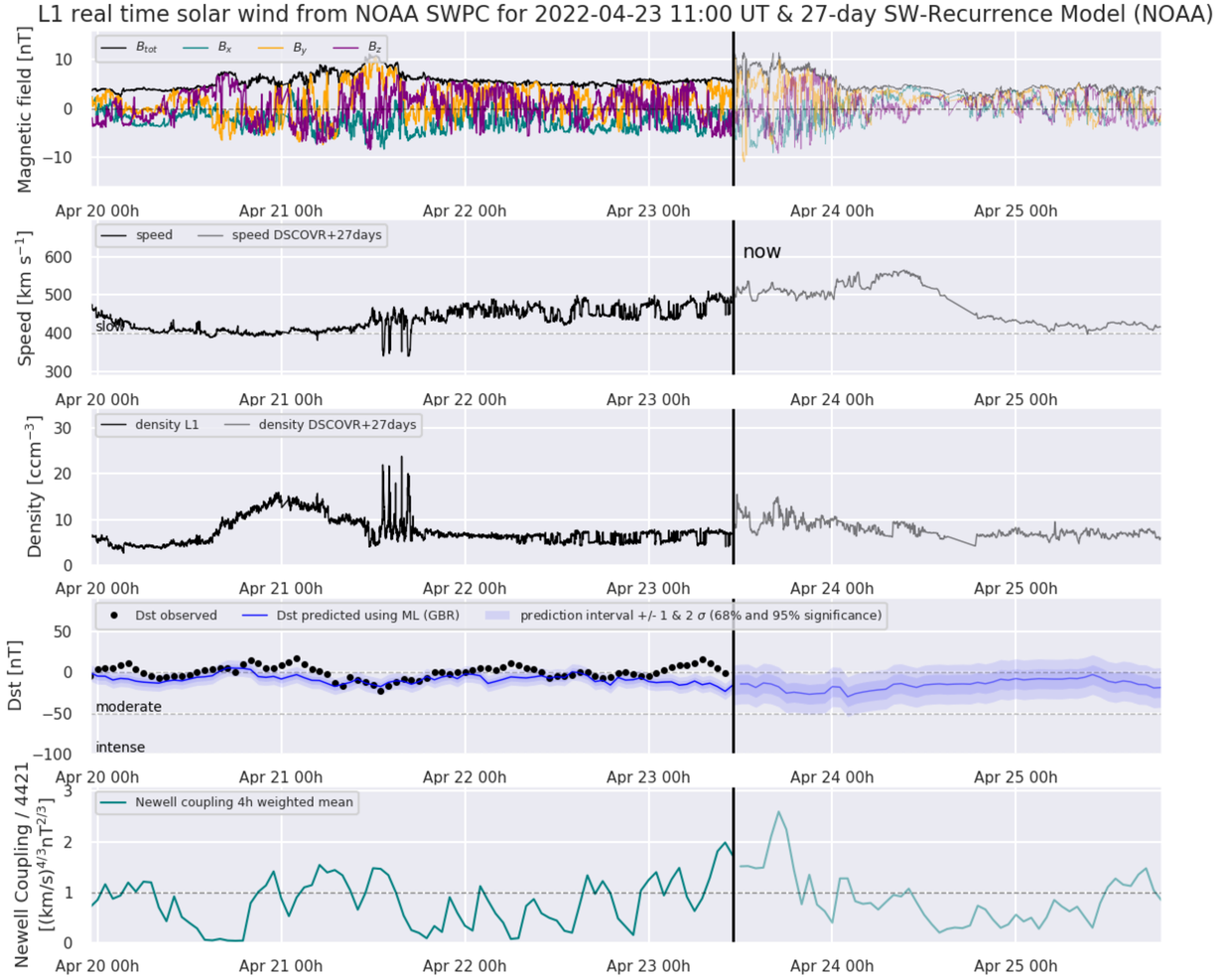


Figure: LSTMs applied in virtual "real-time mode." Output of the forecasting models (black lines) vs. the observed GICs (coloured lines) at two stations (above and below). The solid black line shows results from LSTM-GIC trained on modelled GIC values, while the dashed line shows results from LSTM-E trained on modelled geoelectric field values.

Where are we going with this?

- **PREDSTORM** (Fig.—>) provides forecasts of the in situ solar wind from various methods (STEREO, 27-day recurrence, flux rope modelling, …) https://helioforecast.space/solarwind
- **Incorporate local GIC forecasts into the model** (for nowcast and expected future values)
- See the full study here: https://doi.org/10.1029/2021SW002907
- Code: https://github.com/bairaelyn/SOLARWIND2GIC



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