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# Science challenges in modelling of geomagnetically induced currents

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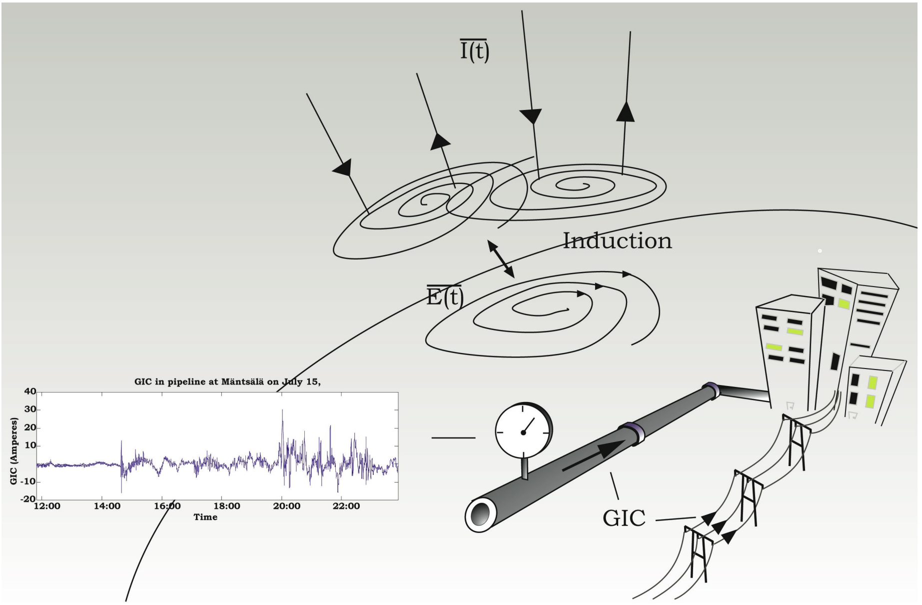
- General modelling scheme
- 3D versus 1D ground conductivity
- Unpredictable ionosphere
- Have we already seen the (Nordic) Carrington storm?



# General modelling scheme

$$\begin{aligned}
\nabla \cdot \mathbf{E} &= \rho/\epsilon_0 \\
\nabla \cdot \mathbf{B} &= 0 \\
\nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\
\nabla \times \mathbf{B} &= \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}
\end{aligned}$$

$$\mathbf{I}^e = \left(U + \mathbf{Y}^n \mathbf{Z}^e\right)^{-1} \mathbf{J}^e$$

$$I_{ij}^n R_{ij}^n = V_{ij} + \sum_{k,l} J_l^e (Z_{ik}^e - Z_{jk}^e)[(U + \mathbf{Y}^n \mathbf{Z}^e)^{-1}]_{kl}$$

## Geophysical step

1) Measured (or simulated) magnetic field on the ground

2) Ground conductivity model
→ Horizontal **electric field** on the ground

3) Quasi-DC description of the power grid
→ Solve Ohm's law for currents driven by the electric field in transmission lines and transformer groundings

(**Engineering and societal steps**)

(Analysis of effects, countermeasures, mitigation measures, preparedness, ...)

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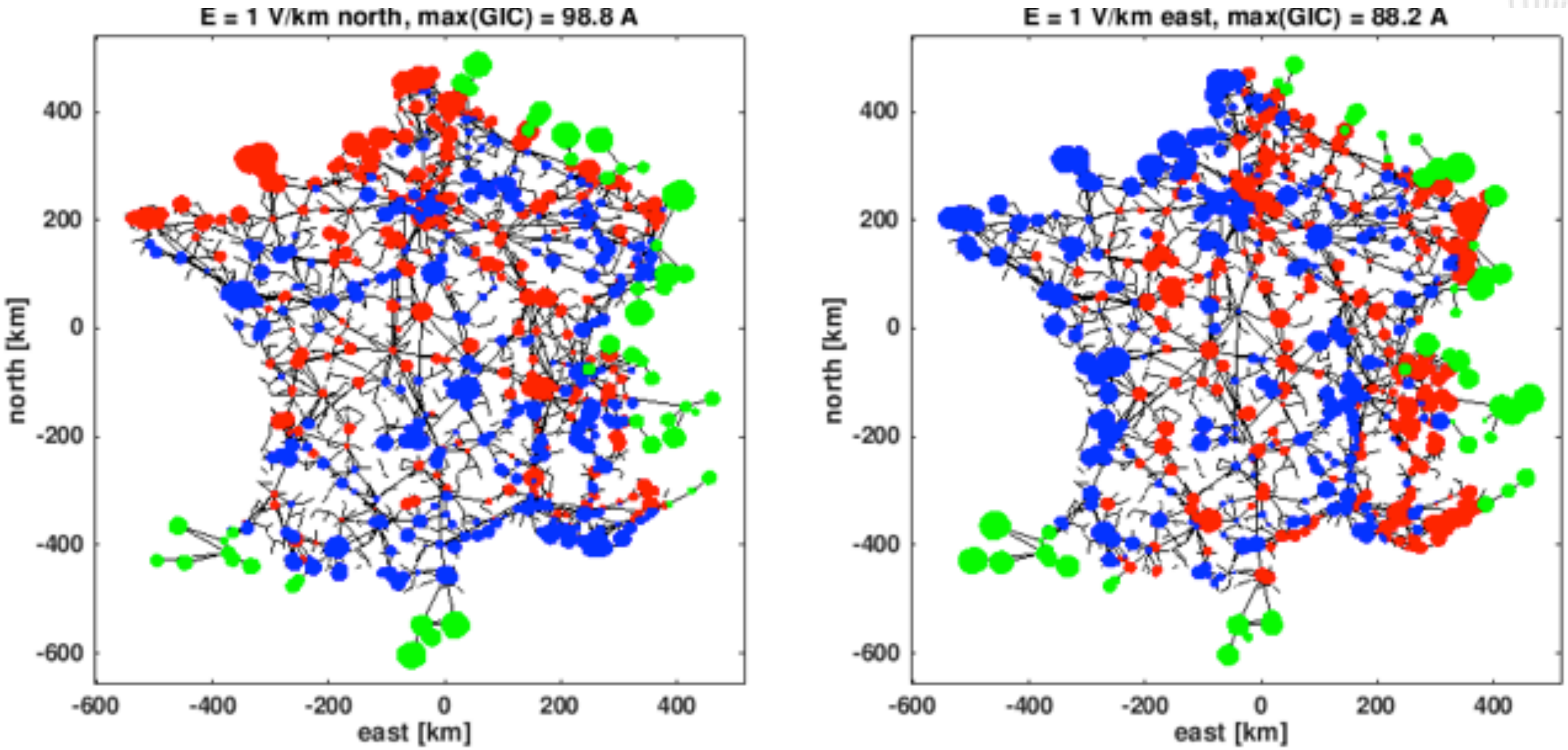
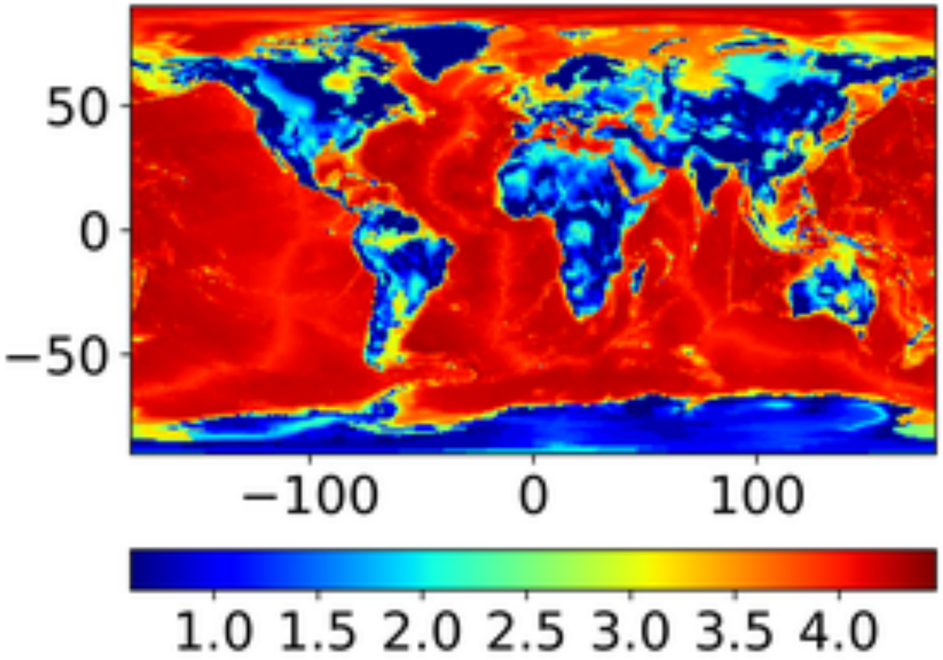
Very large grids are manageable.
France 400/225/150/90/63 kV: 3480 substations, 4463 lines.

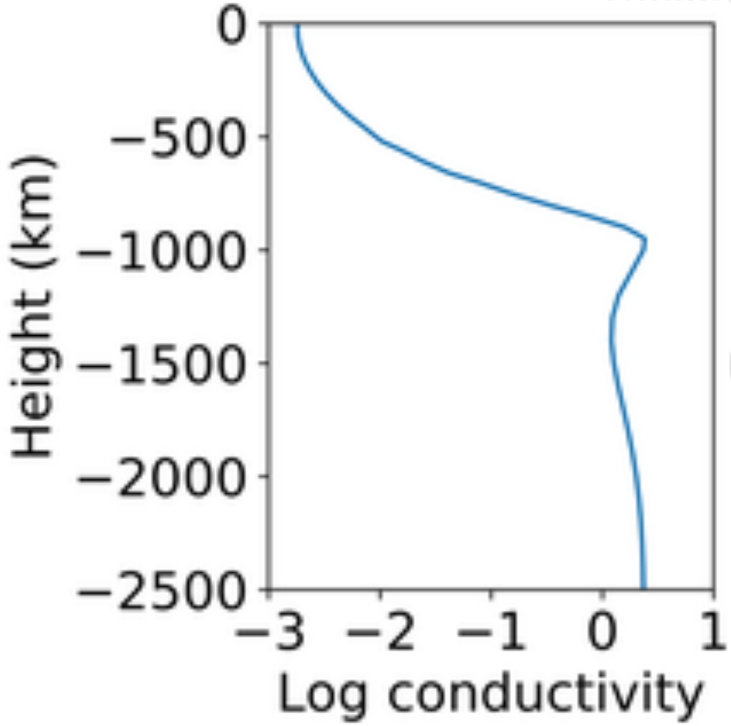



Data sources: RTE Open Data, RTE Static Grid Model

BGS project NEE6840R, funded by EDF Energy R&D UK Centre

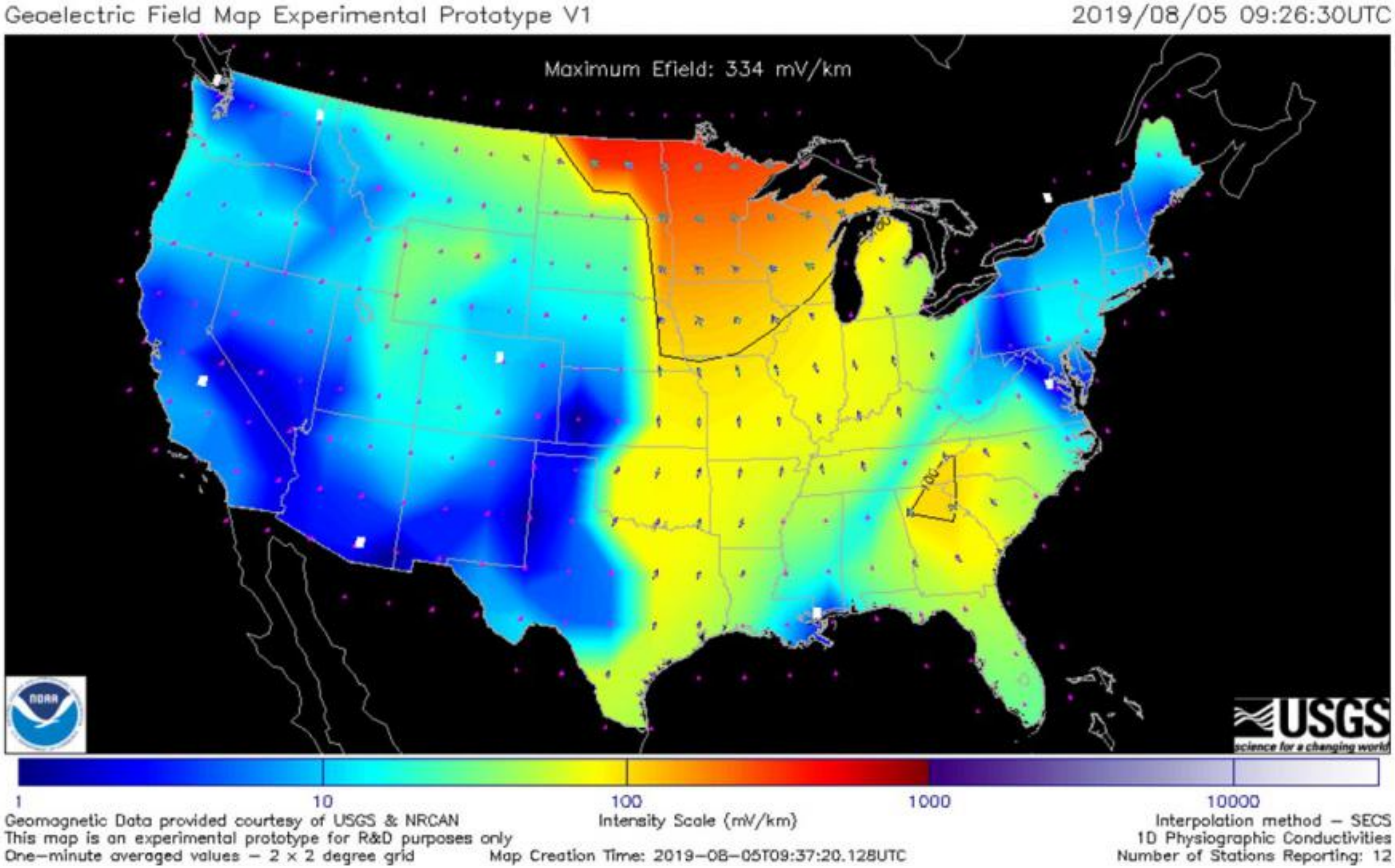
## 3D versus 1D ground conductivity




Balancing between accuracy and feasibility.

Spherical Elementary Current Systems (SECS) + 1D ground conductivity



SECS + 1D ground is a powerful combination.
However, it cannot take into account effects of the true 3D conductivity.

Options to overcome this shortage:

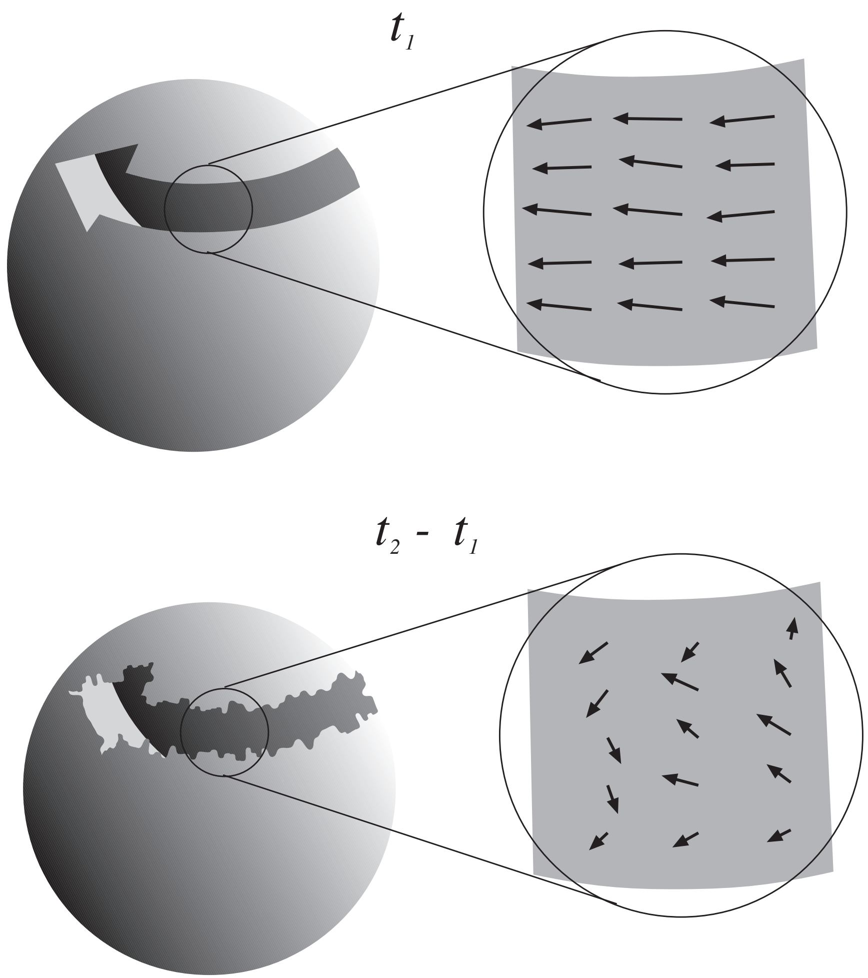
- Empirical MT impedances (*Kelbert et al.*, 2017).
  Whenever available, as fast as 1D. No explicit ground model needed.

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \frac{1}{\mu_0} \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} B_x \\ B_y \end{bmatrix}$$

- First-principles modelling: Primary magnetic field and ground conductivity given. Precise approach, but can be time-consuming (*Honkonen et al.*, 2018; *Rosenqvist and Hall*, 2019). Facilitates understanding of physics.

3D versus 1D in different scales: $\mathbf{E}(\mathbf{r})$, voltage in a single line, GIC in a full grid.

# Unpredictable ionosphere

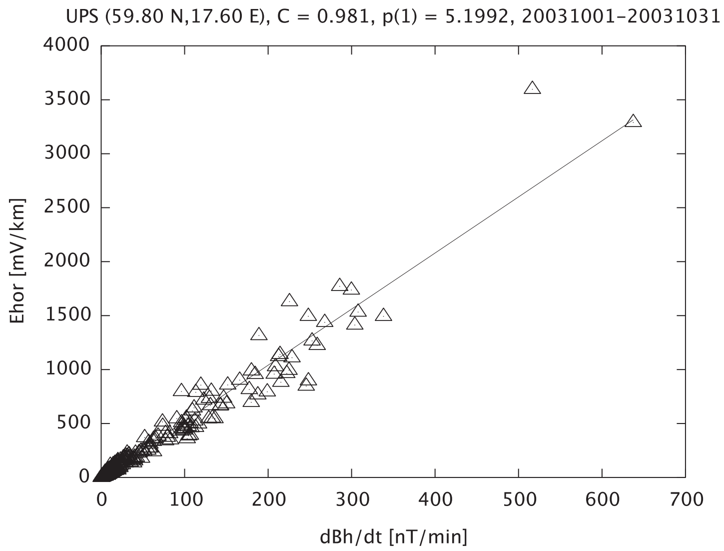


Predicting $d\mathbf{B}(\mathbf{r}, \mathbf{t})/dt$ (magnitude and direction) precisely may be impossible.

Try something empirical (*Wintoft et al.*, 2015):

Use solar wind data as input and predict maximum $|d\mathbf{B}/dt|$ within the next 30 min.

Given a ground conductivity model, we get an estimate for maximum $|\mathbf{E}|$ too.




How much does $|\mathbf{E}|$ tell about GIC?

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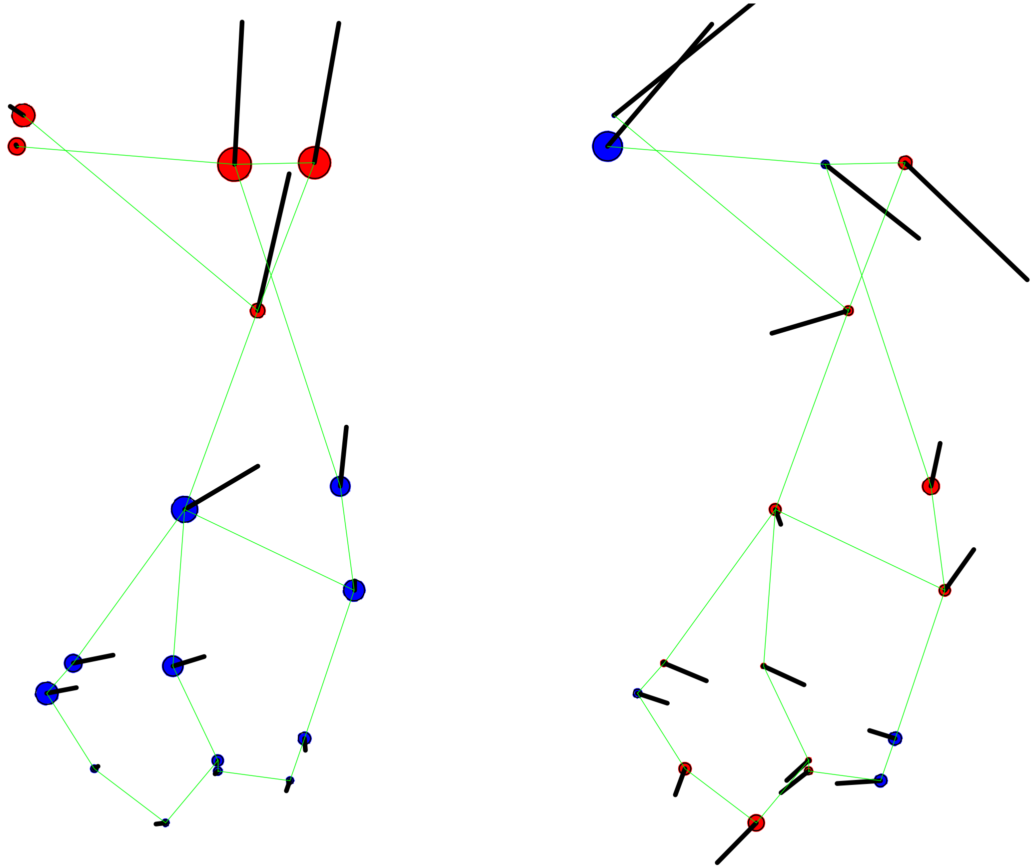
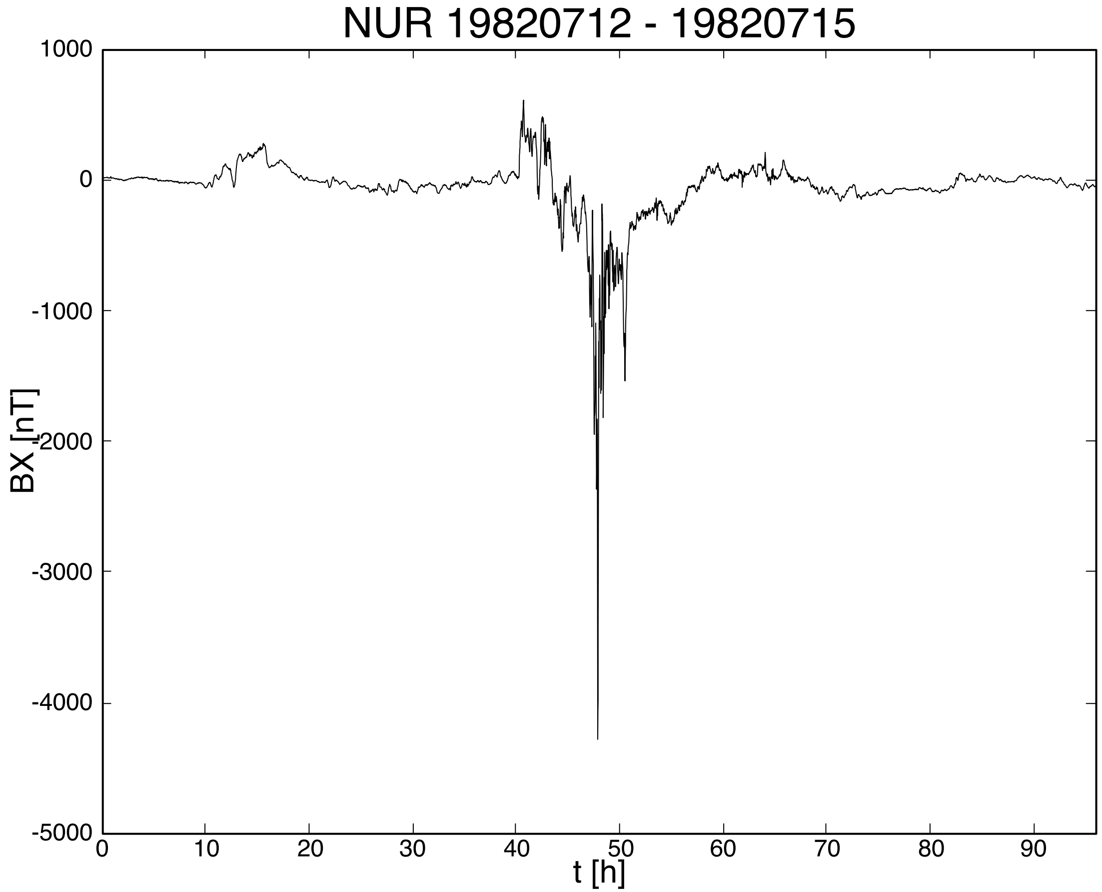
Two cases with an equal regional average of $|\mathbf{E}|$ (1 V/km), sum of GIC 1164 A and 481 A (*Viljanen and Pirjola*, 2017).



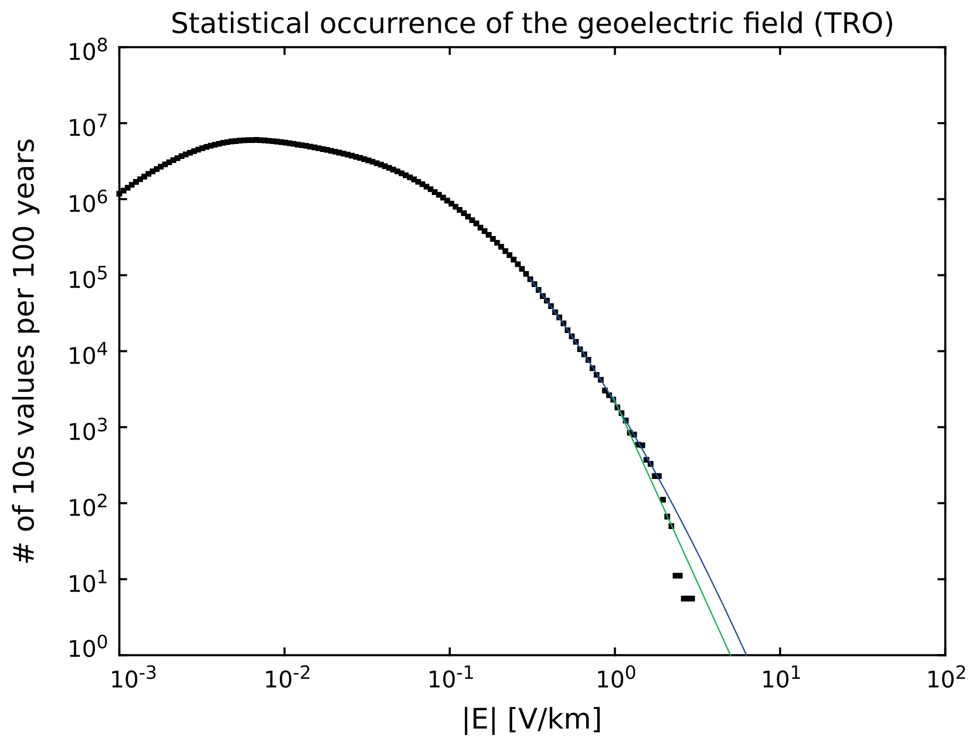
$\rightarrow$ Without vector $\mathbf{E}$, always some uncertainty

# There was a Nordic Carrington storm in the 20th century (1-in-100 year event - ground B, dB/dt, E)



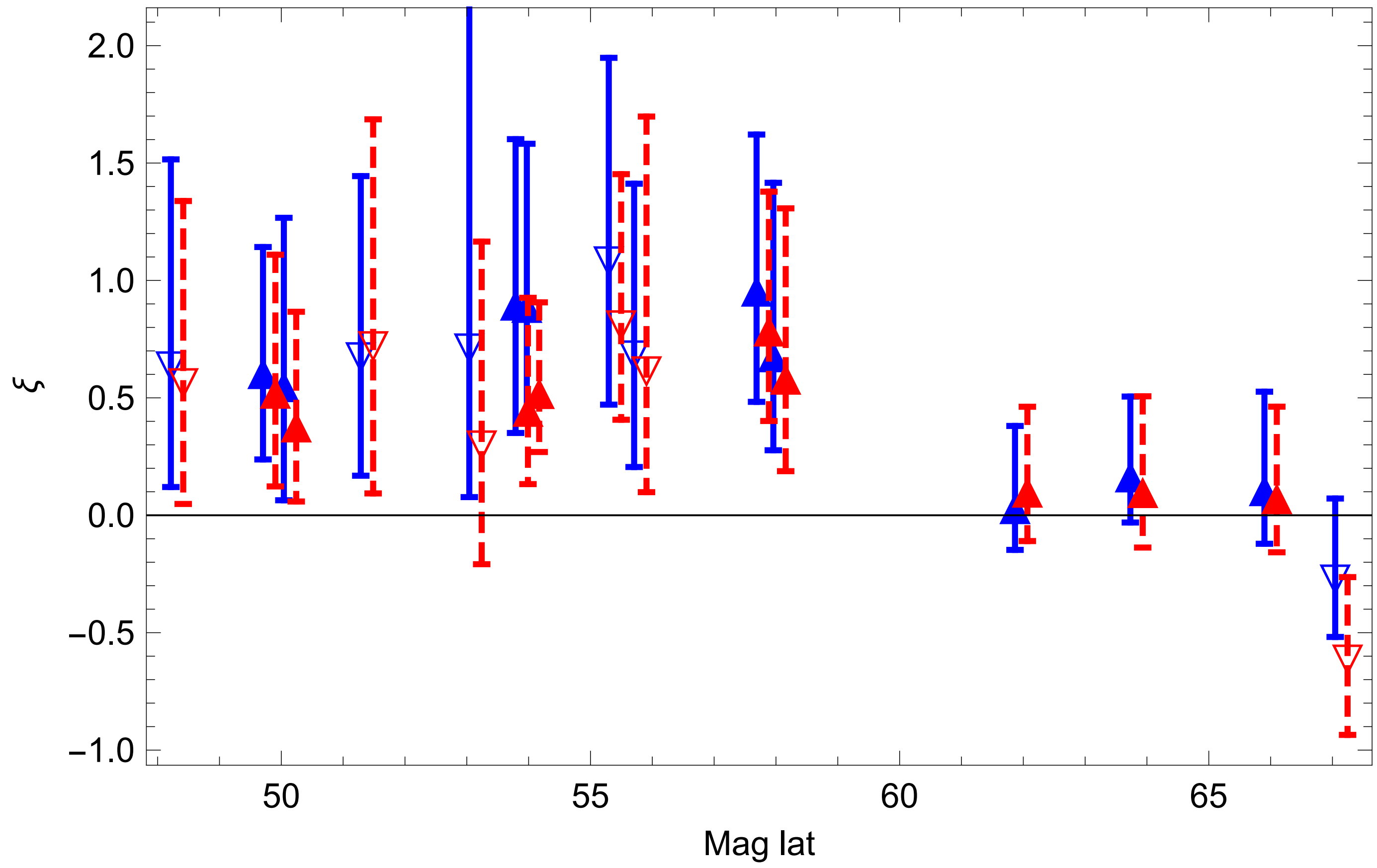
How big is the 1-in-100 year event?
Empirical approach: time series of $B$, $dB/dt$ or (modelled) $E$.

Modelled $|\mathbf{E}|$ (Tromsø 1994-2011) extrapolated to 100 years (*Myllys et al.*, 2014):



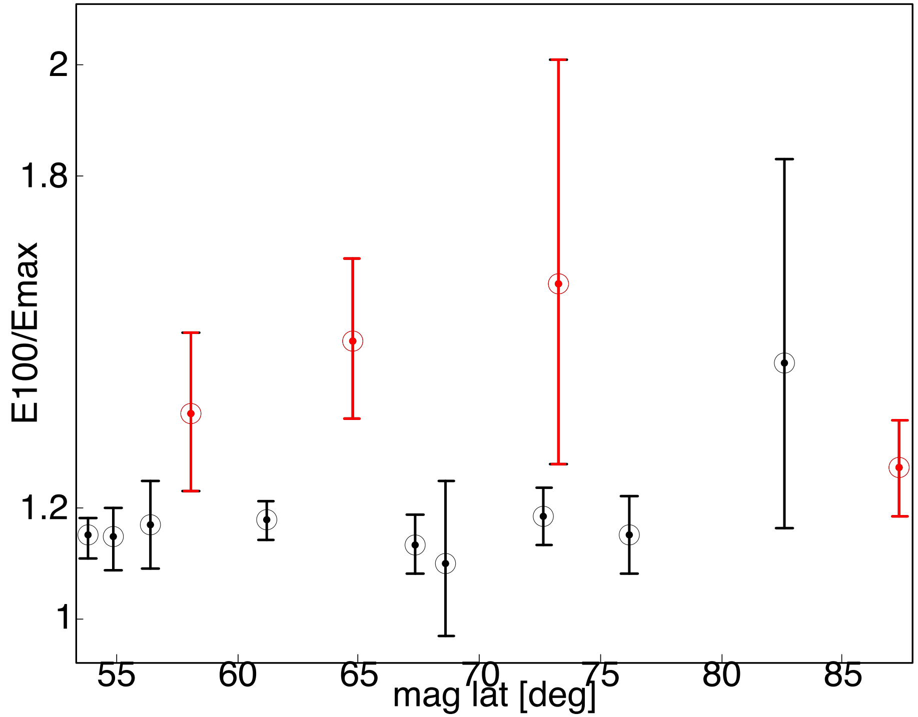

100-year maximum $\approx$ 2 x maximum value in 1994-2011.

*Wintoft et al.* (2016): European observatories (up to 32 years of data)
→ At high latitudes, not much bigger variations expected than already seen



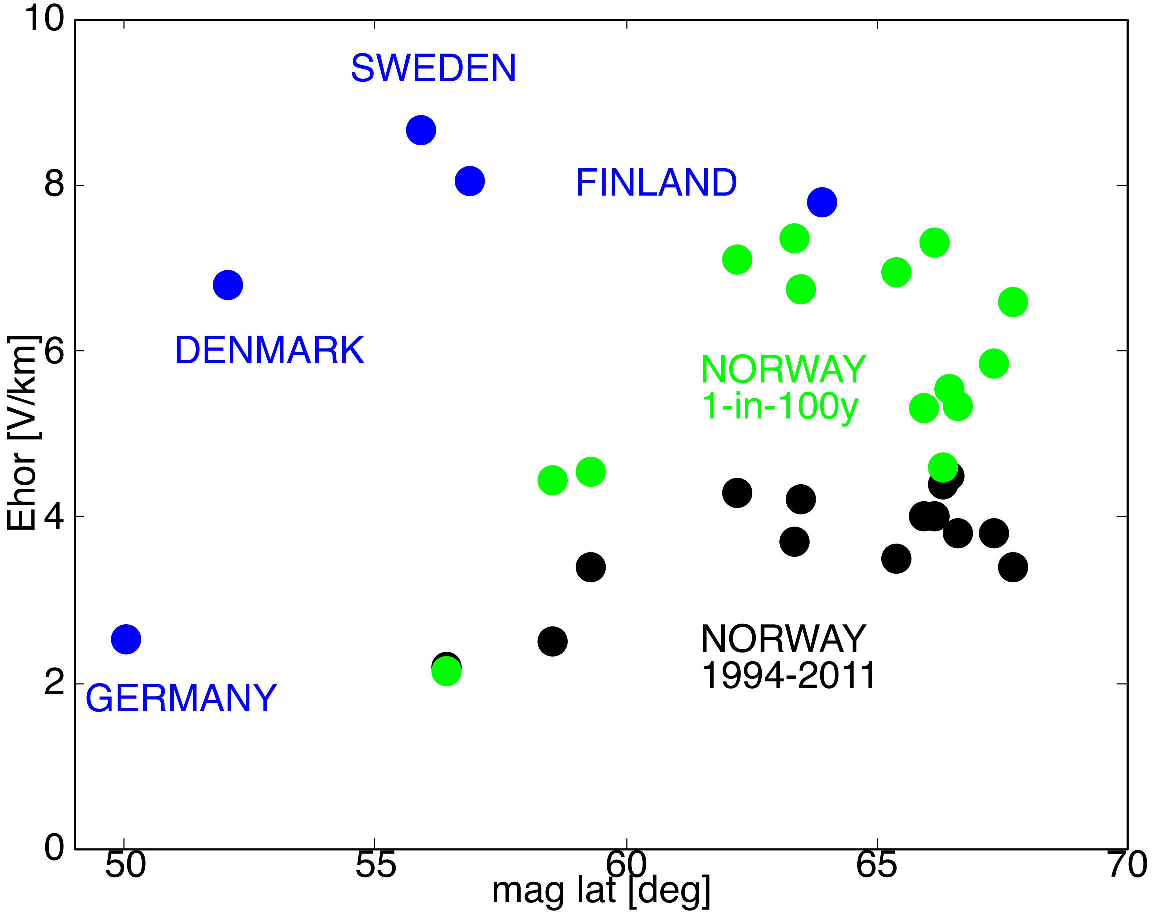

For negative $\xi$, maximum $|d\mathbf{B}/dt|$ and $|\mathbf{E}|$ have upper limits.

## *Nikitina et al.* (2016): Canadian magnetometers
## $\rightarrow$ 1-in-100 year event $\sim 20\%$ larger than maximum observed within ~40 years




Estimated 1-in-100 year $|\mathbf{E}|$ normalised by the maximum value modelled from geomagnetic data in Canada. Red: less than 39 years of magnetic data available (coverage 17-31 years). Derived from *Nikitina et al.* (2016, supporting information, table S3).

# max(E): 1994-2011, E: 1-in-100y, max(E): 13-14 July 1982




Minor impacts in Sweden: 4 high-voltage transformers and 15 lines tripped.

## Conclusions (opinions)

- Basic modelling of past events well-established.
  Geoelectric field ($\mathbf{E}(\mathbf{r}, t)$) is the key quantity.

- Use of 3D ground conductivity models will gradually become the standard.

- Predicting future events provides some work: simulations, empirical methods.
  Much more physical understanding still needed.

- The Nordic Carrington storm occurred (at least) on 13-14 July 1982.
  However, no global Carrington events since 1859 (if not May 1921?).

## References

*Honkonen et al.* (2018), doi:10.1029/2018SW001859

*Kelbert et al.* (2017), doi:10.1002/2017SW001594

*Myllys et al.* (2014), doi:10.1051/swsc/2014007

*Nikitina et al.* (2016), doi:10.1002/2016SW001386

*Rosenqvist and Hall* (2019), doi:10.1029/2018SW002084

*Viljanen and Pirjola* (2017), doi:10.1051/swsc/2017024

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## Acknowledgements to

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