Statistics of extreme geomagnetic field fluctuations: Directionality, timescale dependence, and spatial correlations

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1: Introduction

This poster presents some key findings of statistical analyses predicting the likelihood of extreme rates of change of the horizontal geomagnetic field, dB_H/dt – an important indicator of Geomagnetically Induced Currents. These climatological studies were conducted as part of a four-year UK research programme called Space Weather Impacts on Ground-based Systems (SWIGS). Using a global dataset of measurements from 125 magnetometers in the SuperMAG collaboration (Gjerloev, 2009), each providing between 20 and 48 years of data, we fitted Generalised Pareto distributions to the upper tail of the probability distributions of $|dB_H/dt|$ to predict the magnitude (or 'return level') expected over periods of between 5 and 500 years. Our main objectives were to:

1. Model occurrence rates as functions of **geomagnetic latitude, magnetic local time (MLT)**, and/or **season**, and understand how these change with **solar activity, interplanetary magnetic field (IMF) orientation** and **solar wind velocity**.
2. Study the **compass direction** associated with large dB_H (the change in the horizontal magnetic field vector) and improve statistical estimates of return levels where there is a strongly preferred direction. Ionospheric or magnetospheric electric currents which induce the fluctuation often have a preferred direction – e.g. eastward Chapman-Ferraro currents at low latitudes associated with Sudden Commencements, or westward auroral electrojets in the pre-midnight auroral zones.
3. Model occurrence rates and return levels as a function of the **timescale** of the fluctuation (between 1 second and 60 minutes).
4. Assess the **spatial coherence** of extreme $|dB_H/dt|$, (e.g. between sites at different latitudes) to determine the regional extent of future extreme events.

2: Magnetic Local Time, Latitude, and Seasonal Dependence

Fig. 1 presents the occurrence probability of $|dB_H/dt|$ exceeding the 99.97th percentile ($P_{99.97}$), binned by absolute corrected geomagnetic (CGM) latitude and MLT. The exceedances were declustered to ensure a minimum 12-hours separation. The highest probabilities occur in the auroral zone at 20–24 MLT, which corresponds to the peak likelihood for substorm onsets and expansions. The distribution of peaks in the range 03–12 MLT correspond with a known pattern of Pc5 ULF wave activity (increasing in latitude with later MLT), whilst the highest-latitude events near noon (and predominantly under Northward IMF) may be associated with Region 0 currents into the dayside cusp.

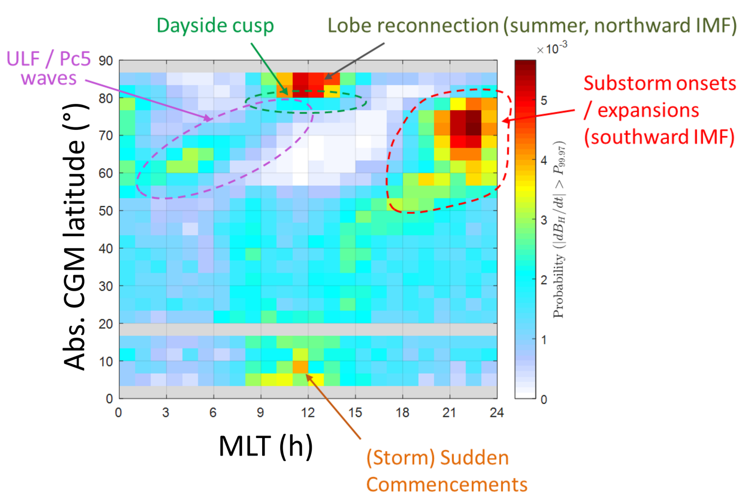

Fig. 1. Probability of $|dB_H/dt|$ exceeding the 99.97th percentile ($P_{99.97}$)

Fig. 2 presents the occurrence likelihood vs. month and MLT for sites within three latitudinal zones of the Northern Hemisphere. For auroral locations (panel b), note the strong equinoctial and secondary winter peak for the MLT 20-24 sector (associated with substorms). In the polar region (panel c) the increased probability of exceedances near noon are clustered in the summer months when the Earth's dipole tilt is greatest.

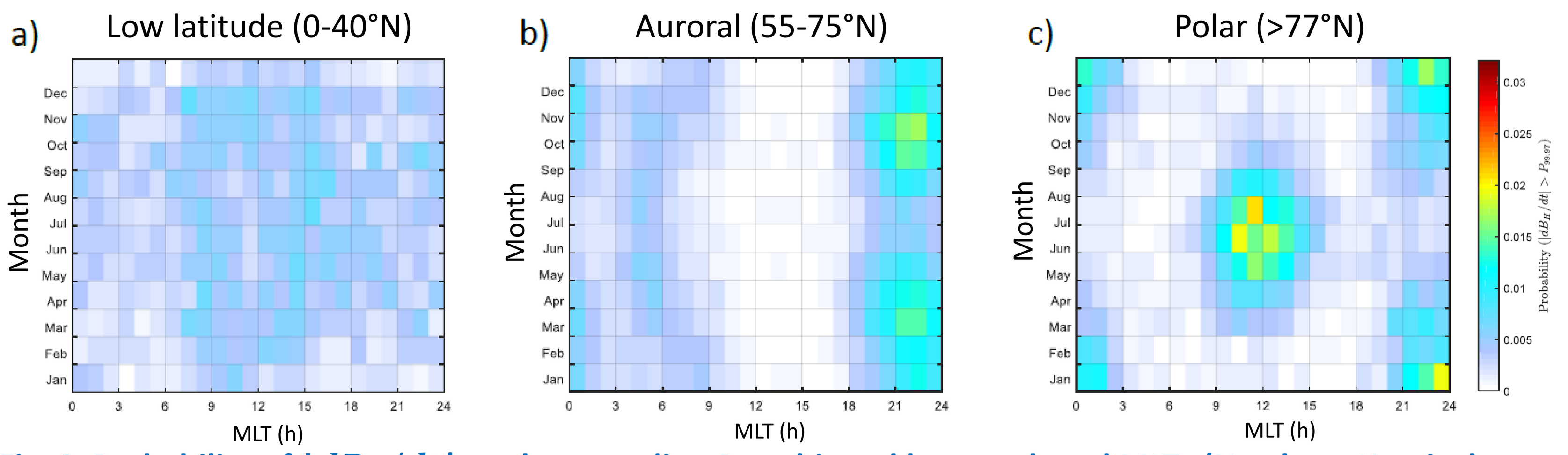

Fig. 2. Probability of $|dB_H/dt|$ peaks exceeding $P_{99.97}$ binned by month and MLT. (Northern Hemisphere sites only.) a) low-latitude, b): auroral zone, c): polar latitudes.

For further information see Rogers et al. 2020a

3: Directional Dependence of Large $|dB_H/dt|$

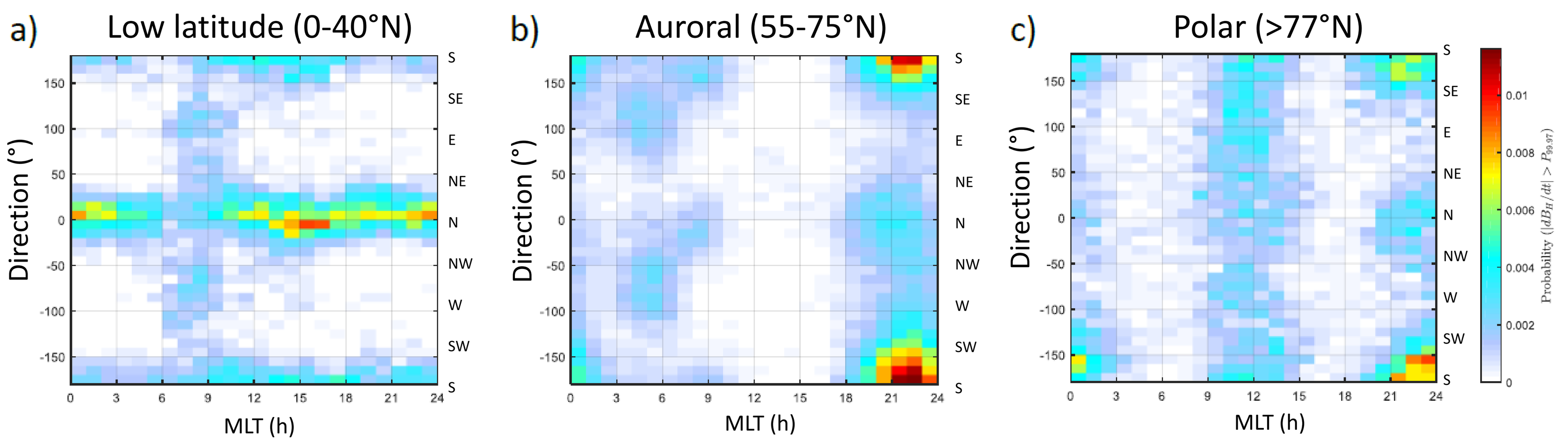

Fig. 3. As Fig. 2, but with vertical axes indicating the compass direction of the large fluctuations, dB_H/dt.

Fig. 3 shows the compass directions of dB_H associated with the large $|dB_H/dt|$ on the vertical axes, and MLT on abscissae. Note the strong northward directional preference for low-latitude stations (panel a) associated with Sudden Commencements, and a strong southward preference for auroral substorm-related peaks (20-24 MLT in panel b), indicating a relation to strong westward auroral electrojet currents. (Electrical currents are approximately 90° rotated w.r.t. the direction of dB_H). The very high latitude events (panel c, near noon) have an isotropic directional distribution.

For further information see Rogers et al. 2020a

4: Return Level Estimates for Directionally Anisotropic dB_H/dt

Return level (RL) models that take into account direction of dB_H may yield more accurate results since, by setting tail thresholds that vary with direction, they explain more of the variability in the data. Following a technique developed for extreme ocean wave height analysis (MacKay et al. 2010) we fitted Generalised Pareto (GP) distributions in eight discrete directional sectors of 45° width and reconstructed an "omnidirectional" RL using a weighted sum of complementary GP distributions from all sectors. **Fig. 4** presents estimated return periods *vs* RLs at a low-latitude magnetometer. The solid blue line is the maximum likelihood estimate (MLE) using the omnidirectional method and for most return periods this is smaller than that obtained with no directional sectoring (magenta dashed line). However, the method is associated with larger confidence intervals (shaded regions). 100-year RLs for both methods are presented in **Fig. 5a** as a function of absolute CGM latitude and the differences are shown in **Fig. 5b**. For latitudes below 40° there is a decrease in RL estimate, but for higher latitudes the method often predicts larger RLs.

See Rogers et al. 2020b for more details.

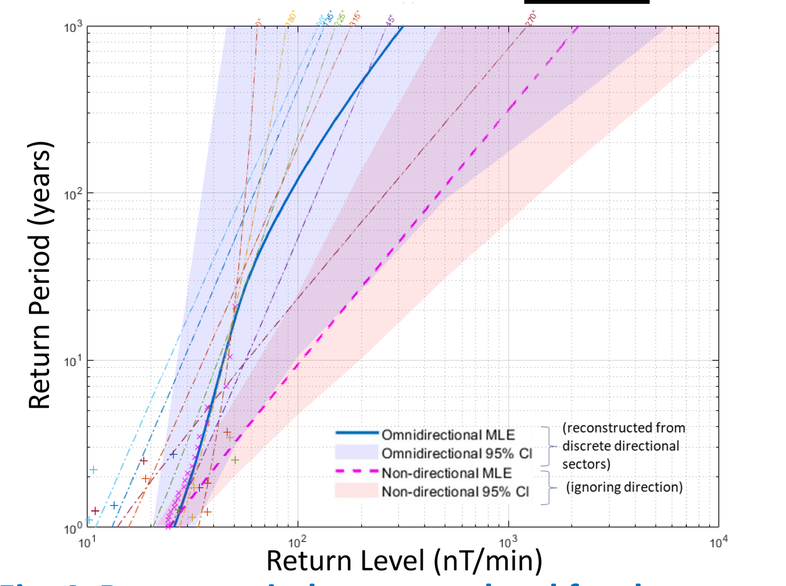

Fig. 4. Return period *vs.* return level for the Ascension I. (ASC) magnetometer

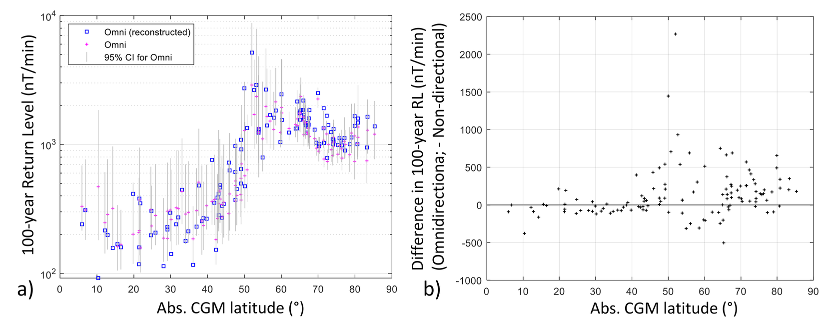

Fig. 5. 100-year RL vs. CGM latitude. a) Values (MLEs) for the two methods, b) differences in MLEs.

5: Timescale (or Frequency) Dependence

To better understand the full spectrum of geomagnetic fluctuations (and associated geoelectric fields) we modelled the climatological statistics of magnetic field fluctuations over timescales, τ, from 1 to 60 min, both as ramp changes (first differences of the field) and as root-mean-square variations over those timescales. Return levels were calculated over periods from 5 to 500 years. **Fig. 6** presents a) the 99.97th percentiles and b) 100-year RLs of ramp changes as a function of frequency ($1/\tau$) with colours indicating CGM latitude. We found that these curves were well modelled by fitting quadratic functions whose three coefficients change smoothly with latitude (shown in **Fig. 7**).

For three UK sites, we extended this to 1-s timescales and calculated the return levels for geoelectric fields over a wide frequency range using measured magnetotelluric functions.

For details, please see Rogers et al. 2021 (*Space Weather*, in press).

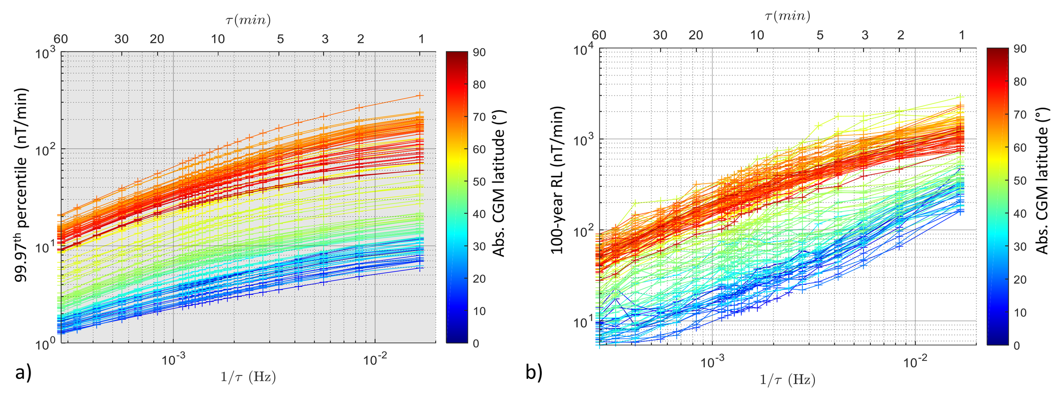

Fig 6. a) 99.97th percentiles and b) 100-year RLs of $|dB_H/dt|$ for 125 magnetometers, as a function of sampling frequency, $1/\tau$, and coloured according to absolute CGM latitude.

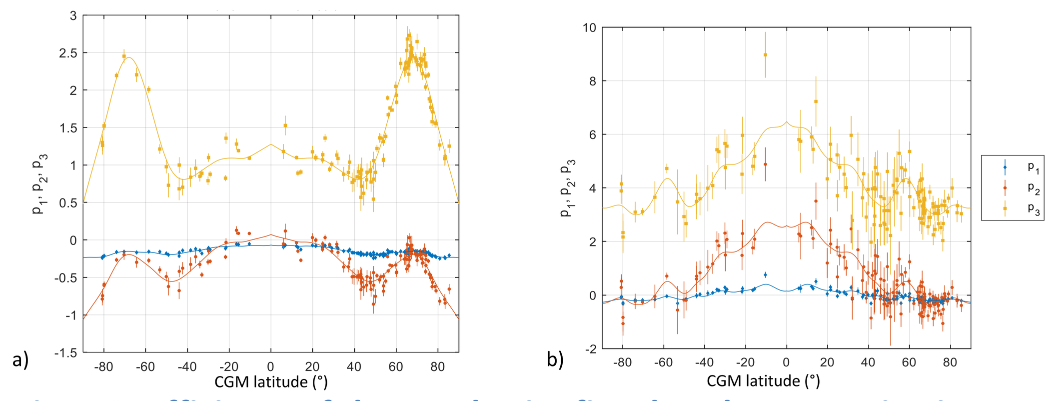

Fig 7. Coefficients of the quadratics fitted to the curves in Fig 6. as a function of CGM latitude. Error bars are 95% CIs. Solid lines are smoothed spline fits.

6: Spatial Coherence of Extreme $|dB_H/dt|$

Comparing daily maxima of $|dB_H/dt|$ for each pair of magnetometers we found large correlations between sites below 55° CGM latitude and with those above 80° (see **Fig. 8a**). Auroral sites exhibit strong correlation only where closely spaced in magnetic latitude or conjugate latitude.

To examine spatial dependence in the extremes, we took quantiles U and V of daily max. dB_H/dt at each pair of magnetometer sites, set a high threshold, u, and defined a tail dependence parameter as

$$\chi = \lim_{u \to 1} \mathbb{P}[V > u \mid U > u]$$

The values of $\mathbb{P}[V > u \mid U > u]$ for $u = 0.99$ are presented in **Fig. 8b.** We found that sites < 55° CGM latitude tend towards asymptotic dependence, whilst auroral sites (55-80°) exhibited asymptotic independence.

For further information please see Rogers et al. 2020b and Farrell, 2019.

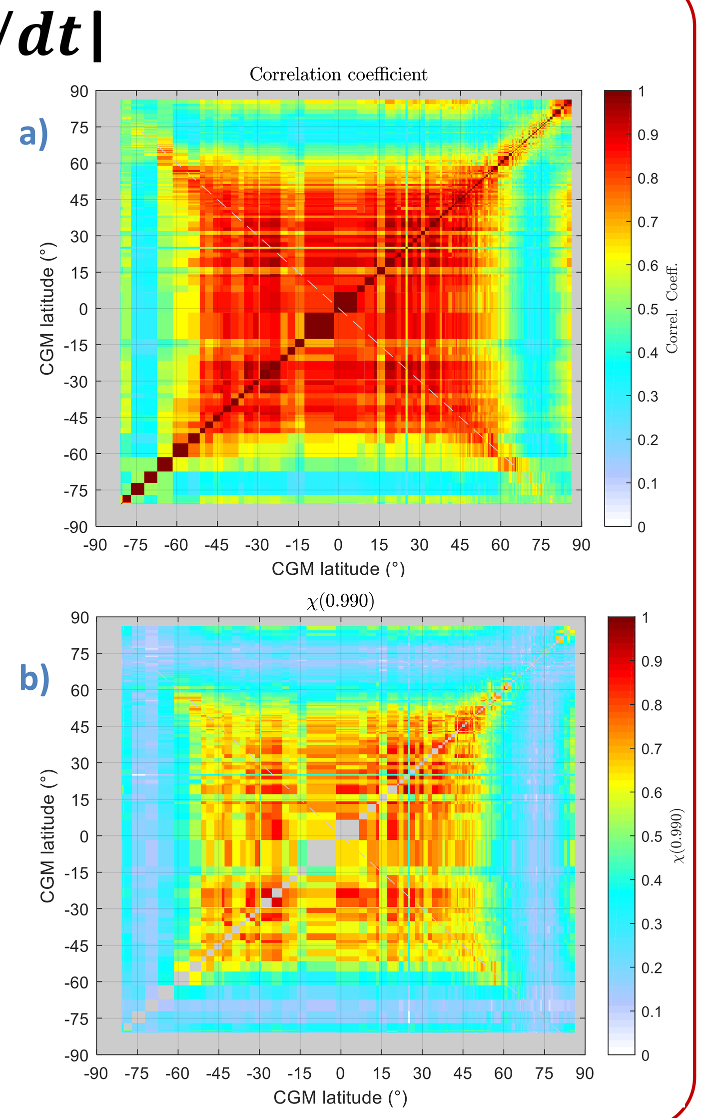

Fig. 8. a) Correlation coefficients, and b) tail dependence parameters for daily max. $|dB_H/dt|$, vs. CGM latitudes for each site pair.

7: Conclusions

- As part of the SWIGS programme we have developed global climatological statistical models of extreme rates of change of the geomagnetic field, dB_H/dt, that are important for analysing GIC risk.
- The probability of $|dB_H/dt|$ exceeding a high threshold has been modelled as functions of magnetic latitude, MLT, month, and the compass direction of dB_H.
- These occurrence patterns have been explained by reference to known patterns of auroral substorms, large ULF waves, and Sudden Commencements (Chapman-Ferraro currents).
- Return levels were modelled for return periods between 5 and 500 years by fitting Generalised Pareto (GP) distributions and modelling their variation with latitude for timescales from 1s to 60 min.
- Reconstructing RLs from GPs fitted in discrete directional sectors (using variable thresholds) predicted RLs that were lower at latitudes below 40°, but higher at higher latitudes.
- Examine spatial coherence in daily maxima, we found that pairs of sites below 55° CGM latitude exhibited asymptotic dependence in the extremes of $|dB_H/dt|$, whilst those at auroral latitudes showed asymptotic independence.

References

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