

Comments from referee #1

The authors describe their work to complete the end to end modelling of GIC flow in the Swedish high voltage power grid using magnetic field measurements, the SMAP conductivity model and the RAISE representation of the power network. They investigate the October 2003 storm and then extend this to a 1-in-100 year storm using magnetic latitudinal bands of different scaling based on a recent statistical analysis of geoelectric fields.

They find the peak geoelectric field to lie between 10-30 V/km in some regions of Sweden. They use the model to identify lines that are expected to be more vulnerable to high current flow, though represented as total integrated voltage along particular lines. They discuss the implications and compare to regions where known outages have occurred before. They have generated two informative movies to illustrate the dynamic nature of the GIC flow.

This is an extremely well written paper and I could not find any issues with the logic, clarity or flow of the manuscript. The figures and tables are excellent and the results are useful for the operator. The authors are to be commended.

We thank the reviewer for the positive and encouraging assessment of our study. Please see below for detailed replies to all comments. The original review is written in black and our replies in red.

My only minor comments are:

1. Why are the values of the line and transformer resistance under national security restrictions? They are available in other countries for example, so are probably similar in Sweden. Average values of resistance per km are given in e.g. Viljanen et al (2012) doi: 10.1051/swsc/2012017 if you wanted to model GIC and use a standard 0.5 Ω for the grounding resistance.

Detailed electrical parameters of transmission networks (e.g., line resistances) are considered sensitive because they allow the reconstruction of high-fidelity power-flow models. Such models can be used to identify critical nodes, simulate contingencies, and design cyber-physical attack scenarios capable of causing temporary or large-scale blackouts.

From a legislative perspective, this type of technical information falls under the protection of critical infrastructure regulations. In the EU, electricity transmission and distribution systems are explicitly classified as “critical entities” (see Annex of Directive (EU) 2022/2557 on the resilience of critical entities). As a result, operators are required to restrict access to operationally sensitive data that could compromise system security.

Available online:

<https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A32022L2557>

We agree that the resistance-per-kilometre values provided in Viljanen et al. (2012) can be used to estimate GICs. For example, Rosenqvist et al. (2025) used 0.5Ω for the grounding resistance and typical line resistances of $0.022 \Omega/\text{km}$ for 200 kV lines and $0.008 \Omega/\text{km}$ for 400 kV lines. Accurate modelling of power-system behaviour requires not only the resistances but also detailed knowledge of network topology and line connectivity. Without this information, the resulting GIC estimates could lead to substantial uncertainties and potentially misleading conclusions about system vulnerability.

2. Why not use Belsk, Brorfelde and Wingst observatories in the analysis to capture variations outside and to the south of Sweden in October 2003?

Thank you for this observation. The main reason we did not use Belsk, Brorfelde, or Wingst is that our analysis relied on magnetic field from stations that provided consistent 10-second data within the IMAGE network. Among the three stations mentioned, only Wingst is part of IMAGE, and its data coverage in IMAGE began in 2015.

We nevertheless examined the data available from all three observatories for the October 2003 event. Each provides 1-minute magnetic field vectors (Belsk in Poland, Brorfelde in Denmark, and Wingst in Germany via INTERMAGNET). In contrast, our modelling uses 10-second resolution data, which is necessary to capture the rapid geomagnetic variations relevant for GIC calculations. Using 1-minute data would introduce temporal smoothing and reduce the accuracy of the derived electric fields.

Comments from referee #2

This is an interesting paper that studies the effects of two possible 1-in-100 years geoelectric field events on the Swedish power grid using the most advanced tools available in Sweden. However, the approach to create the 1-in-100 years geoelectric fields is not convincing at present and needs some reconsideration. The topic is worthwhile, and with some more work this should make a valuable addition to the series of Swedish publications that characterize geomagnetic activity and the power grid response in Sweden.

We thank the reviewer for a critical review and helpful comments. We have done our best to reply to each concern. The original review is written in black and our replies in red. The line numbers refer to the original version of the manuscript.

Major comment:

You create two possible 1-in-100 years events, Case 1 and Case 2, based on magnetic field observations during the Halloween storm. In Case 1, you calculate the geoelectric field based on the magnetic field observations and then scale the resulting values upward in southern Sweden. In Case 2, you assume spatially uniform external magnetic field with an amplitude and time development based on one magnetometer station during storm. The resulting geoelectric field is again scaled similar to Case 1.

I find this approach problematic. Clearly, the reason for the characteristic latitude of the geoelectric field maximum, on which the scaling is based, is due to the external driver. In Case 2, you first create a spatially uniform external driver, but then change the latitude profile of the resulting geoelectric field such that it no longer corresponds to the driver. Nonetheless, you describe Case 2 to represent "an idealized scenario in which the magnetic field time series is spatially uniform" (lines 113-114). This is inconsistent. I suggest that either you drop the scaling or scale the external driver instead of the resulting geoelectric field. The latter also requires changing the way you describe the case.

We thank the referee for this important point. We agree that the original wording for Case 2 scenario is described in an inconsistent way. We have revised the text to make it clearer.

Line 5:

[...] In Case 2, we assume an idealized ionospheric current system in which all stations share the same temporal magnetic field pattern.[...]

Line 105:

[...]. Our motivation for scaling the geoelectric field was that it is the physical driver of GICs. Using real ground-magnetic perturbations as input preserves a realistic ionospheric forcing (rather than relying on a synthetic magnetic-field time series), while the scaling ensures that the resulting geoelectric field reaches the level associated with a 1-in-100-year event from the perspective of the physical driver of GICs. This allows us to generate as many worst-case scenarios as magnetic field inputs are available. However, because ground magnetic perturbations are driven by ionospheric current systems that activate during geomagnetic storms and substorms, we recommend using magnetic-field inputs from previously recorded events that produced the largest geoelectric field response.

To illustrate the range of possible worst-case conditions, we explore two complementary approaches. The first worst-case scenario (Case 1) is intended to remain as realistic as possible, with each geographic location experiencing a different magnetic field perturbation. This is achieved by using as many magnetometers as are available in Sweden, providing a well-resolved ionospheric driver. The second worst-case scenario (Case 2) is intended to represent an idealised case in which every location in Sweden experiences the same magnetic field perturbation (i.e., the frequency content remains identical). This is achieved by using data from a single magnetometer. Such an idealised situation could be produced by a large-scale westward electrojet (WEJ) extending across Fennoscandia. [...]

The text in Line 113, resulted in a revised version that involves Lines 111-114:

[...] As mentioned above, we explore two different scenarios. In Case 1, we use the actual observed magnetic field perturbations, interpolated across the Fennoscandian region using the SECS method. We remind the reader that this approach is intended to represent a realistic situation where signatures of meso- and small-scale magnetosphere–ionosphere currents are represented. In the second case (Case 2), we construct an idealised worst-scenario in which all magnetometer stations experience the same temporal pattern of magnetic field perturbations.

Furthermore, we analyzed your suggestions:

- Drop the scaling: We decided not to follow this suggestion because the unscaled idealized case (Case 2 without scaling) does not attain the 1-in-100-year geoelectric magnitude; it would only represent an idealized event at the Halloween storm’s scale (see Figure 1, unscaled maximum geoelectric field for Case 2).
- Scale the external driver: We decided not to adopt the referee’s suggestion to scale the external magnetic driver, due to several reasons:
 - Scaling the external driver implies rescaling ground B time series and deriving new return-period estimates for B (an extreme-value analysis analogous to Lanabere et al., 2024). That is a separate study on its own and cannot be completed within the present manuscript’s scope and timeline.
 - Scaling the external driver does not guarantee that the geoelectric field reaches a 1-in-100-year level, which is the central part of this study.
 - The paper’s objective is to compare two constructions that produce the same target 1-in-100-year geoelectric level.

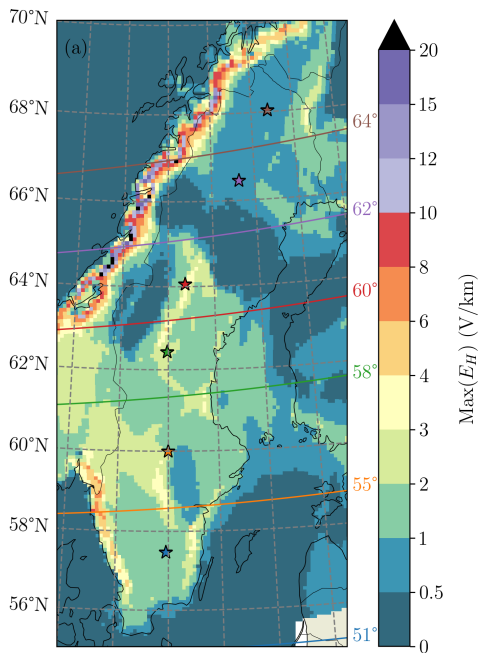


Figure 1: Map of Maximum geoelectric field magnitude during the interval 19:40 to 20:30 UT, for Case 2 without scaling.

In Case 1, you note that your analysis fails to explain the observed Malmö blackout. This you explain to be due to the missing magnetometer observations in the key area (lines 237-239). You also note that in northern Sweden the Halloween event is classified as a 1-in-100 years event whereas in southern Sweden it only reached 1-in-10 or 50 years (lines 108-110). Combining these, it rather sounds to me that the Halloween storm might well have been a 1-in-100 years event across Sweden, but the insufficient magnetometer coverage in southern Sweden did not allow full observation of its effects in this area. Thus, the role of the scaling in this case would not be to increase the classification of the storm but to rather correct for missing data. Such a correction should be applied to the driver rather than to the resulting geoelectric field. As this may not be straightforward, I suggest at least discussing the point in the text.

We thank the referee for this comment. We do not agree with the interpretation that the Halloween storm would have been a 1-in-100-year event across all of Sweden but was simply under-observed in the south. Although southern Sweden ($\sim 55^\circ$ Glat) was not included in previous return-value analyses (Lanabere et al., 2024), the dataset did include stations spanning 58.26° Glat (34.5° Mlat) to 68.02° Glat (64.7° Mlat). Across this latitude range, the return-period characterization of the Halloween event shows a clear and robust latitudinal dependence:

- North of $\sim 60^\circ$ MLAT, the Halloween event corresponds to a 1-in-100-year level.
- South of $\sim 60^\circ$ MLAT, the same event corresponds to 1-in-10 to 1-in-50-year levels.

This latitudinal contrast is not an artefact of missing magnetometer coverage but reflects the different tail behaviours of the extreme-value distributions at different latitudes. As shown in Lanabere et al. (2024) and previously in Wintoft et al. (2016):

- Below $\sim 60^\circ$ Mlat, the shape parameter of the Generalized Pareto Distribution (GPD) is positive, indicating a heavy-tailed distribution with no upper bound. In these regions, the maximum observed values during the Halloween storm are not close to the statistical upper tail, and substantially larger events are expected in the future.
- Above $\sim 60^\circ$ Mlat, the shape parameter is often negative (or its confidence interval includes negative values), implying a bounded or weakly heavy-tailed distribution. In these regions, the maximum observed values are already close to the statistical upper limit.

Therefore, the lower return-period classification of the Halloween event in southern Sweden is a statistical property of the extreme-value behaviour, not a consequence of insufficient magnetometer coverage. Even with perfect spatial coverage, the EVT characteristics south of 60° Mlat would still classify the Halloween storm as a substantially less extreme event than in the north.

We have now added a short discussion of this point in Line 110

[...] This latitudinal contrast reflects systematic differences in the tail behaviour of the extreme-value distributions (heavy-tailed with positive shape parameters in the south of 60° MLAT and bounded or weakly heavy-tailed in north of 60° MLAT) as documented in both Lanabere et al. (2024) and Wintoft et al. (2016). These differences arise from the underlying statistics rather than from gaps in magnetometer coverage, and therefore the Halloween event is not expected to represent a 1-in-100-year level in southern Sweden even under complete observational coverage.

Minor comments:

Lines 11-12: "East–west-oriented power lines are especially vulnerable, as they align with the dominant orientation of the induced electric field." Do you mean this statement applies generally? Is the geoelectric field in Sweden typically oriented in the east-west direction? If not, please modify the statement.

We thank the referee for this observation. It is true that, in general, the geoelectric field in Sweden is typically oriented in the east-west direction (Lanabere et al., 2023 Figure 2c). However, we wanted this sentence to emphasize the results found in this study. We have rewritten sentence in line 11-12 to:

[...] East–west-oriented power lines are especially vulnerable, as they are mainly located south of 60° MLAT, where the largest geoelectric fields are calculated.[...]

Line 29: "most commonly" On what is this claim based? Kp is also very widely used.

Thank you for this comment. We changed the statement to “commonly”

Line 43: "(NERC, 2016)" What is NERC?

NERC stands for “North American Electric Reliability Corporation”. We have added this clarification after the citation.

Line 63: "the paper of this paper" Delete "the paper of"?

Done

Lines 67-68: "a once in 100 year event" Shouldn't "year" be "years"? Please check throughout the manuscript.

We thank the referee for noting this. After consulting with native English speakers, we confirm that the correct forms are:

- a 1-in-100-year event
- once in 100 years.

We checked and corrected throughout the manuscript.

Lines 71-80: This section does not describe either data or methods. It could be moved to section 3.

Thank you for the comment. We agree that this paragraph does not describe either data or models, so we have moved it to Section 3 (Line 108) as the first step of the Method. This step now indicates that a previously observed event should be selected as a reference. We have also included it as the first step in the workflow presented in Table 1.

Lines 75-76: What about differences due to 1D and 3D modelling? 3D modelling is expected to give higher geoelectric field amplitudes than 1D due to the effect of lateral conductivity gradients.

Thank you for this comment. We agree that the differences between 1D and 3D are significant mainly in areas with strong lateral conductivity gradients. We have modified the text from lines 75-76 to:

The significantly higher value in Rosenqvist et al. (2025) is attributed to the fact that the maximum was observed near Sweden's west coast, an area not covered in the analysis by (Lanabere et al., 2023), and to the expected higher geoelectric field amplitudes from 3D modelling compared with 1D modelling, due to the effect of lateral conductivity gradients.

Line 86: "external (Bext) produced by", "internal (Bint) produced by" Something is missing here. Do you mean external component and internal component?

Thank you for the observation, we meant “external component” and “internal component”. The text has been updated accordingly.

Line 90: More detailed descriptions of GIC-SMAP and RAISE should be included. For example: What are the inputs and outputs of each model? What are the key principles and assumptions of these models? What are the key sources of uncertainty?

Thank you for pointing this out. We agree that more detailed descriptions of the GIC-SMAP and RAISE models should be included, as this is important for improving the reader's understanding of the models. We have restructured Section 2 and added in line 90 two new subsections: GIC-SMAP model and RAISE model with the following text:

2.2 The GIC-SMAP model

The GIC-SMAP model calculates the horizontal geoelectric field $E_H(\omega) = Z(\omega)\mu_0^{-1}B_H(\omega)$ in the frequency domain by relating the ground impedance tensor $Z(\omega)$ to local magnetic field perturbations $B_H(\omega)$. An inverse Fourier transform is applied then in order to transform into the time domain. In a new version of the model, where the E_H is computed at every point of the grid in Sweden, the magnetic field data is first interpolated using the Spherical Elementary Current System (SECS) method (Amm & Viljanen, 1999) using all available IMAGE stations.

The ground impedance tensor is previously obtained by computing the geoelectric field using a uniform magnetic field variation with unit amplitude, by solving the equations describing the current distribution in the ground in the frequency domain using the commercial software COMSOL Multiphysics for a unit-amplitude ($H_0 = 1$ A/m), uniform magnetic source field applied at 100 km altitude for a fixed set of frequencies (1–100 mHz). See the supporting information (S2) in Dimmock et al., (2019) for a further description of the technical setup (i.e., equations, parameters, domain, etc) and Rosenqvist and Hall (2019) for additional details about the model.

The main source of uncertainty in the GIC-SMAP model arises from the sparse distribution of active IMAGE magnetometers in Sweden used in the SECS method to interpolate the magnetic field onto the model grid. Additional sources of uncertainty arise from the conductivity model (Marshalko et al., 2023). First, the underlying crustal conductivity map for the Fennoscandian Shield (SMAP) (Engels et al., 2002; Korja et al., 2002) is well constrained by extensive magnetotelluric surveys in northern Sweden, whereas large parts of southern Sweden remain sparsely surveyed and rely more heavily on extrapolated conductivity estimates. Second, the calculation of the surface impedance assumes a uniform magnetic field, whereas in reality, the magnetic field exhibits spatial variability. Third, frequencies below 1 mHz may contribute to the amplitude of the geoelectric field when superimposed on the higher frequencies (Wallner et al., 2026).

The model has been validated against GIC measurements in both northern and southern Sweden (Rosenqvist and Hall, 2019; Rosenqvist et al., 2022), indicating that the uniform-source-field assumption performs well during geomagnetically quiet periods, while further validation during geomagnetically active intervals remains pending.

2.3 The RAISE model

The recently developed RAISE model (Rymdvädersmodell för Analys av Inducerade Strömmar och Elektriska fält, Swedish for "Space Weather Model for the Analysis of

Induced Currents and Electric Fields"), introduced by Rosenqvist et al. (2025), was employed to analyze the voltages in the Swedish power grid lines. The simplified Swedish power grid representation consists of 194 nodes and 335 transmission lines, of which 49% are 400 kV lines and 51% are 220 kV lines. This model has previously been applied to investigate GIC activity during the April 2023 and May 2024 geomagnetic storms (Dimmock et al., 2024; Rosenqvist et al., 2025). RAISE integrates the GIC-SMAP model (Rosenqvist and Hall., 2019) with a simplified representation of the Swedish high-voltage power grid, assuming constant earthing resistance and fixed line resistances for both 200 kV and 400 kV transmission lines. Due to this simplification in line resistances, the results presented here focus on calculated voltages without explicitly computing the corresponding GICs.

The RAISE model relies on the following assumptions and simplifications:

- Only transmission lines and power stations operated by Svenska kraftnät (SvK) are included. Substations and lines owned by regional or private operators are not part of the dataset.
- Power Stations without verifiable connections are removed. Thus, power stations located more than 650 m from any mapped transmission line are excluded to ensure a topologically consistent network.
- International interconnections are omitted. This implies that all AC and DC links to neighboring countries (Norway, Finland, Denmark, Poland, Lithuania) are removed, and Sweden is treated as an electrically isolated system.
- The curvature of Earth is neglected, assuming that the distance between the nodes of the transmission line is of the order of hundreds of kilometers, much less than the Earth radius.
- The earthing resistance is considered constant, and the transmission lines are assumed to have a constant resistance per unit length depending on the transmission voltage level.

Line 102: Please check the style of references throughout the text.

The reference style has been checked and corrected.

Lines 104-105: "amplitude of the EH reaches an amplitude" Maybe write "amplitude of EH reaches a level" to avoid repetition?

Revised as suggested.

Table 1: Should you add Lanabere et al. (2023, 2024) and Rosenqvist et al. (2025) as references to step 1 (cf. lines 71-80 and 108-110)?

Thank you for the suggestion. We included the references in the new Step 1 related to the identification of the event with the largest E_H .

Lines 118-120: Please explain this in more detail. Does GIC-SMAP expect B_{tot} or B_{ext} as input? I would have expected a first-principles model to take B_{ext} as input and return B_{tot} as output, but apparently this is not the case?

We have now included more information about the GIC-SMAP model in section 2. (see comment before). There we say that:

The GIC-SMAP model calculates the horizontal geoelectric field $E_H(\omega) = Z(\omega)\mu_0^{-1}B_H(\omega)$ in the frequency domain by relating the ground impedance tensor $Z(\omega)$ to local magnetic field perturbations $B_H(\omega)$. [...]

The GIC-SMAP should use the total magnetic field. However, the GIC-SMAP model can be used with either B_{tot} or B_{ext} , and the output is the geoelectric field associated with the total magnetic field (including the internal source produced by the induced telluric currents in the ground and the external part produced by currents in the ionosphere and magnetosphere) or external magnetic field (produced by currents in the ionosphere and magnetosphere) respectively.

Figure 1: What are the arrows in panel (a)?

More information is added in the label of Figure 1, panel (a).

Interpolated magnitude (shaded) and direction (arrows) of the horizontal magnetic field (B_H) at 20:04 UT, the time when most stations recorded their maximum B_H .

The following text is included for clarification:

The colored stars in panel (a) mark the sites where time series data were extracted.

Figure 2: "specific sites" Are these the same locations as the stars in Fig. 1a?

We changed the relevant sentence to:

Colored stars mark the same sites as in Figure 1a, where the temporal dB_H/dt and E_H profiles were extracted and shown in the panels (b) and (c) respectively.

Figure 3: "Magnetic field perturbations ($dB_{H,ext}/dt$) at the magnetic stations along 25.42oE (solid line) and in Sweden (dashed line)." Please clarify this sentence. The stations in Finland and Estonia do not have a constant longitude. What are the arrows in panel (a)?

We include in the description of Figure 3 panel (a) the following clarification:

(a) Ionospheric equivalent current (J_{eq}) magnitude (shaded) and direction (arrows) [...]

And we clarified the sentence related with panel (c)

(c) Magnetic field perturbations ($dB_{H,ext}/dt$) at the magnetic stations along Finland and Estonia (solid line) and in Sweden (dashed line).

Line 193: "the induced electric field response is greater at HAN." Do you really mean that the induced electric field was calculated at HAN? (I understand this to mean the true location of

HAN.) Or do you mean that the induced electric fields calculated using Bext from HAN at the locations marked with stars in Fig. 3a were greater than those calculated using Bext from OUJ?

Thank you for pointing this out. The correct statement is “the induced geoelectric fields calculated using Bext from HAN at the locations marked with stars in Fig. 3a were greater than those calculated using Bext from OUJ”. We changed the old statement to:

[...]; however, the induced geoelectric fields calculated using $B_{H,ext}$ from HAN at the locations marked with stars in Figure 1a were greater than those calculated using $B_{H,ext}$ from OUJ.

Lines 194-197: I do not understand this reference. Dimmock et al. (2024, Figure 4) concerns a different event (23 Apr 2023) and they do not show the geoelectric field.

Thank you for checking this. The correct reference was to Figure 9 in Dimmock et al. (2024). In this example, dB/dt and E are shown for the 23 April 2023 event, and we aim to highlight that the largest peak in dB/dt does not necessarily correspond to the largest peak in E.

Line 211: "and the similarly response at the OUJ station" Please explain what this means.

We improved the description in 210 with the following text:

Between 58° and 62° MLAT, the differences are minimal because the magnetic field input in Case 1 at these latitudes is mainly dominated by the observations in HAN and OUJ, which are very similar to the input used in Case 2.

Figure 5: What are the arrows?

We have updated the caption of Figure 5 to clarify what the arrows represent.

Line 223: "3 V/km"

Line 225: "1 V/km" Why were these threshold values selected?

Thank you for making this important observation. The thresholds of 1 V/km and 3 V/km were selected to represent low and high maximum voltage per km during the substorm event. To better define these limits, we used the 20th and 80th percentiles (P(20) and P(80) respectively) of the maximum voltage per km in each case:

Case 1: P(20) = 1.17 V/km; P(80) = 3.34 V/km

Case 2: P(20) = 0.75 V/km; P(80) = 2.76 V/km

Panels (b, c, d and e) in Figure 6 and Figure 7 have been updated together with the caption.

Caption of Figure 6: *[...] (e) Power lines exceeding the 80th percentile of the maximum voltage per km during the whole period (3.34 V/km, in red), and power lines that remained below the 20th percentile (1.17~V/km, in black).*

Caption of Figure 7: *[...] (e) Power lines exceeding the 80th percentile of the maximum voltage per km during the whole period (2.76 V/km, in red), and power lines that remained below the 20th percentile (0.75~V/km, in black).*

We adapted also the text in line 223:

[...] Around these areas, the maximum power line voltage per km exceeded 3.34~V/km (red lines in Figure 6b), which corresponds to the 80th percentile of the maximum voltage per km across all lines. Power lines that exceeded 3.34~V/km are typically short east–west oriented, [...]

We adapted also the text in line 225:

[...] In contrast, power lines with voltages per km below the 20th-percentile maximum voltage per km (1.17 V/km) throughout the storm (black lines) are mainly [...]

We adapted also the text in line 230-231:

[...]Consequently, power lines exceeding the 80th percentile of the maximum voltage per km across all lines for Case 2 (2.76~V/km) appear even at lower latitudes in Figure 7e.

In both cases, the lines that did not exceed the 20th percentile maximum voltage per km (0.75~V/km) [..]

We adopted the text in lines 358-361

- Voltage per km larger than the 80th percentile of maximum voltage per km across all lines (3.34~V/km for Case 1 and 2.76 V/km for Case 2) are concentrated near [...]

- In western Sweden, several power lines exhibit voltage per km larger than 3.34~V/km for Case 1 and 2.76 V/km for Case 2 even when oriented northwest–southeast, primarily due to localized conductivity structures. In eastern Sweden, for Case 1, the power lines exceeding the 80th percentile of maximum voltage between Vittersjö [...]

Section 4: Due to the limitations of the power grid model you use, the analysis is limited to estimating voltages in separate transmission lines. Such an approach does not consider the power grid as an entity as proper GIC estimation would do, and hence does not provide a full picture of the response. The limitations of the chosen approach in this respect should be discussed. For example, the most intense GIC are typically observed at substations located at the edges of the power grid (<https://doi.org/10.1051/swsc/2012017>). According to your power grid map, both Malmö and Karlshamn appear to be located at the southern edge of the Swedish power grid. Even without exact values for the resistances, more useful results would probably be gained by estimating the GIC instead of analyzing the separate line voltages. Of course, in order to explain actual impacts, such as the Malmö blackout, you would also need to know the true grid geometry at the time of the event.

Thank you for this important point. We agree that we should include a discussion of the limitations of our approach. We included the following paragraph in Line 219

The impact on the Swedish power grid is limited to the analysis of the induced voltages in the transmission lines, calculated by integrating the geoelectric field along the power lines under two 1-in-100-year event scenarios. To complement the total induced voltage, we also compute the voltage per kilometre, which corresponds to the line-averaged geoelectric field projected along the transmission line direction. This provides a measure of the effective

geolectric driving experienced by each line, independent of its length. We acknowledge that this does not represent the full behaviour of the Swedish power grid as a connected network. However, large induced voltages (Voltages > 100 V) have been related to several issues during the March 1989 geomagnetic storm (Lucas et al., 2018).

A proper GIC assessment would require detailed and time-accurate information on grid topology, transformer resistances, grounding configurations, and relay-protection settings. These engineering parameters are not publicly available at the level of detail required for reliable modelling the power grid. For this reason, it is not currently feasible to determine what would constitute a true worst-case scenario for the power grid itself, nor to model specific impacts such as transformer saturation or protection-system behaviour. Our study therefore focuses deliberately on the geoelectric field forcing, consistent with how Svenska kraftnät defines extreme events (based on the physical NOAA G-scale rather than grid-hardware responses). Moreover, large global geomagnetic disturbances, typically associated with locally enhanced geoelectric fields, are known to increase the likelihood of power-grid disturbances (Rosenqvist et al., 2025).

Lines 263-265: Is the number of power lines with the 100 V threshold exceeded really a relevant problem? It does not mean that there would be large GIC at the ends of all these power lines. Large GIC would be expected at the substations located at the edges of the power grid (see the point above).

Thank you for this comment. We agree that the number of power lines with the 100 V threshold is not always a relevant problem. However, large induced voltages (> 100 V) have been related to several issues during the March 1989 geomagnetic storm (Lucas et al., 2018).

We have removed the text in Lines 263-265 and incorporated a discussion of this observation into Subsection 5.2 Power grid implications, within the conclusion section. Line 318 now reads:

[...] We have shown that during intervals of very active ionospheric current variations, particularly during substorm activity, large dB/dt and E_H values were estimated at latitudes below 60° MLAT. As a consequence, several power lines exceeded high voltage thresholds (e.g., approximately 100 power lines experienced induced voltages exceeding 50 V at several times during the substorm period). For comparison, Lucas et al. (2018) reported that 62 transmission lines exceeded 100 V during the March 1989 geomagnetic storm, which triggered a major blackout in the Hydro-Québec power system. Although power-grid disturbances do not always coincide with the time of peak voltage or geoelectric field (Dimmock et al, 2024, Wallner et al, 2025), or with peak GICs (Pulkkinen et al., 2005), intervals of high induced voltages still imply larger voltage variations.

Lines 345-346: "How do small-scale ionospheric currents during extreme storms influence the spatial variability of geoelectric fields and GICs?" What do you mean by small-scale? Due to the ~100 km distance between the ground and the ionosphere, magnetic field perturbations due to ionospheric current structures smaller than about 100 km in scale size are significantly attenuated before reaching the ground.

We thank the referee for this clarification. Our intention with the term small-scale was not to imply ionospheric current structures below ~100 km, which indeed become strongly attenuated before reaching the ground. In the GIC literature, small-scale typically refers to rapid, localized current systems with spatial scales up to several hundred kilometres, which can still produce localized strong dB/dt signatures. Such structures are often associated with vortex-like structures embedded within the large-scale auroral electrojet (Viljanen et al., 2001; Belakhovsky et al., 2019). Although the term is not sharply defined, in this context it refers to current features with scales < ~1000 km.

We improved Lines 345-346 by specifying our intended scale and now write:

[...] How do small-scale ionospheric currents (< 1000 km) during major geomagnetic storms influence the spatial variability of geoelectric fields and GICs?

Lines 354-355: "The largest scaled EH are found within the 55° –58° MLAT band" This is a circular conclusion since you have artificially scaled the geoelectric field amplitude up particularly in this latitude band.

We agree that the original wording could be interpreted as a circular conclusion. We have therefore rewritten this bullet point as:

The largest scaled EH values are found in localized areas with pronounced lateral conductivity gradients, reaching up to 12 V/km, and in the western part of the 55°–58° MLAT band where conductance is particularly low.

Line 356-357: "due to the prevailing orientation of the horizontal electric field" This conclusion sounds far more general than is probably intended or can be drawn based on your results. Please modify. (See also the similar comment on the abstract.)

Thank you for this comment. We have therefore rewritten this bullet point as:

North-South-oriented power lines experience larger total induced voltages because their overall length is greater than that of East-West lines. However, East-West lines show larger voltages per kilometre, mainly because they are located south of 60° MLAT, where the largest geoelectric fields are calculated.

Lines 365-366: "limited magnetometer coverage in southern Sweden" How accurate is the conductivity model in this area? Inaccuracies in the conductivity model can be a significant source of error for the modeled geoelectric field (<https://doi.org/10.1029/2022SW003370>).

We completely agree with this comment. The modeled geoelectric field in Southern Sweden has two main sources of inaccuracies. First, the limited coverage of magnetic field observations. Second, the number of magnetotelluric surveys used to build the conductivity maps.

We have therefore rewritten this bullet point as:

[...] is likely due to limited magnetometer coverage in southern Sweden (MLAT<55°) and to the inaccuracies in the regional conductivity model, [...]

Lines 368-370: This sentence is very long and difficult to follow. Please divide it into two or more shorter sentences. What is "sudden weakening of worst-case scenarios"?

We agree that the original sentence was long and difficult to follow, and that the phrase "sudden weakening of worst-case scenarios" was unclear.

We have therefore rewritten it as:

"During the WEJ peaks and sudden weakening in the worst-case scenarios, around 100 power lines exceeded 50 V multiple times during the substorm. At the moment of the WEJ weakening, close to the time of maximum dBH/dt , about 100 lines exceeded 100 V."

Comments from referee #3

This ambitious paper sets out to assess the exposure of the Swedish power network to an extreme geomagnetic disturbance (GMD). The paper describes an approach to making the assessment and discusses the outcomes.

The analysis is based on a single storm model, a 50-min substorm of the Halloween storm of 2003. Variability within the class of extreme events has been modelled by two cases generated from this one event. The first case is generated by scaling upwards the magnitudes of the disturbance. The second case is generated by extending the most intense sub-region over the whole geographic region of study. Neglecting the practical limitation of the physical disturbance that these approaches represent, the results of the simulations are presented and analysed in detail that might not be evident in a real power system response.

We thank the reviewer for a critical review and helpful comments. We have done our best to reply to each concern. The original review is written in black and our replies in red. The line numbers refer to the original version of the manuscript.

In my opinion, the paper falls short of its objective because of the lack of rigour in matching the assumptions to reality. Maybe, it is impossible to do so. Nevertheless, the paper exposes an important aspect underlying the approach – how to model the physical form and characteristics of a 1-in-100-year extreme GMD. Although this issue is not addressed directly, the paper has value in its clear description of the approach to the study of a large region and the patterns and discussion of some simulation results.

Specific comments: Individual scientific questions/issues

Extreme space weather events are characterised by the Dst index (-400 to beyond -1000 nT) or the maximum amplitude of EH at some time resolution, and the authors recognise that whether an event occurs during the day or night makes a difference. In this paper, a 1-in-100-years extreme event has been characterised using sparse data (one event), apparently without reference to the practical effects of the disturbances on power systems.

We thank the reviewer for this comment. We emphasise that a “worst-case scenario” in our study refers only to the 1-in-100-year geoelectric-field amplitude, which is the physical driver of GICs, and not to a worst-case scenario for the power grid itself. We would like to point out that although we use one event to characterize the spatial distribution of the perturbations for Case 1, the thresholds that we used are based on decades of data.

We recognise a vast number of extreme geoelectric field scenarios exist and we only use one event. However, the goal of the study is to understand the implications of the impact on the Swedish power grid if a previously recorded event would have reached a 1-in-100-year geoelectric field level. In our approach we made the logical choice to use the event with the strongest geoelectric field (Halloween event).

Using a simplified power-grid representation, we convert this extreme E_H value into line-average geoelectric fields (voltage per km) to map physical exposure, not operational impact. Although the 1-in-100-year geoelectric field is not tied to power systems

disturbances, such large geoelectric fields typically occur during strong geomagnetic activity, which also increases the likelihood of power-grid disturbances. This is consistent with Rosenqvist et al. (2025), where most recorded grid disturbances occur during elevated Kp conditions.

We have included additional text at the beginning of the Method section, in line 105.

[...] Our motivation for scaling the geoelectric field was that it is the physical driver of GICs. Using real ground magnetic perturbations as input preserves a realistic ionospheric forcing (rather than relying on a synthetic magnetic field time series), while the scaling ensures that the resulting geoelectric field reaches the level associated with a 1-in-100-year event from the perspective of the physical driver of GICs. This allows us to generate as many worst-case scenarios as magnetic field inputs are available. However, because ground magnetic perturbations are driven by ionospheric current systems that activate during geomagnetic storms and substorms, we recommend using magnetic field inputs from previously recorded events that produced the largest geoelectric field response.

It has been postulated by others that ‘failure’ due to GMDs occurs by a process of transformer insulation degradation (such as at Salem in 1989, though even that damage did not lead to an immediate fault), by power system collapse (such as in Quebec in 1989, though that collapse was initiated by protection relay operation removing SVCs from service), or by protection relay maloperation not traced to equipment damage (such as at Malmö in 2003 and Bandsjö in 2017 and 2023). The effect of GMDs on power systems is not a simple relationship between peak measurements of geomagnetic or geoelectrical parameters and power system degradation. The relationship to simulated parameters of artificial GMDs is probably even weaker.

We thank the reviewer for this very interesting point. We agree with the reviewer that the mechanisms leading to power-system failures during geomagnetic disturbances are complex and that the effect of the physical driver on power systems is not a simple relationship between the peak measurements of geoelectric fields and power system degradation.

We included the following text in line 330:

[...] Understanding which combinations of geoelectric field, induced voltage, network configuration, and system state lead to real incidents remains an open problem and requires further investigation. Such studies will soon be possible with the recently installed GIC monitoring device in Karlshamn, connected to the transformer neutral-to-earth point and deployed by the Swedish transmission system operator, Svenska Kraftnät.

Therefore, my first question is whether the authors can justify their decision to base an ‘extreme event’ on a 10 s EH threshold (line 118) and apparently arbitrary line voltage thresholds of 100 or 200 V (line 255) using the base parameters of a single event? Even with the power utilities’ addition of line resistances to the calculated line voltages, is the resultant peak GIC the most useful and reliable metric of system stress likely to initiate outages?

We thank the reviewer for raising this question. Our worst-case scenario event (Case 1) represents an extreme geoelectric-field event, specifically illustrating how the geoelectric field during the Halloween storm in Sweden would have appeared if it had reached a 1-in-100-year level. This is only one possible scenario, reconstructed from the past event that has resulted in the largest geoelectric field.

The 10-s EH threshold represents the 1-in-100-year extreme geoelectric-field amplitude, which is the physical driver of GICs, not a proxy for power-system failure. We do not use line voltage as a proxy for GIC either; we simply integrate the extreme electric field along each line to show how such an external driver would map into line-average geoelectric fields. This represents an extreme event from the external forcing, not an extreme event for the power grid itself.

The authors generate two 'plausible' cases of GIC events using different assumptions and scaling the parameters of the Halloween storm.

We are not generating two plausible cases of GIC events, we are generating two plausible extreme geoelectric field events.

An important issue is summed up at line 108: "The EH reached during this event has been classified as having an estimated recurrence of 1-in-100-year event in northern Sweden, but only a 1-in-10- to 1-in-50-year event in southern Sweden". This leads to a question that is not identified in the paper: Would the ionospheric structures retain their physical shape with scaling to higher intensities: case 1: "the actual observed magnetic field perturbation extrapolated to the whole Fennoscandian region", or case 2: "the magnetic field time series is spatially uniform across all magnetometer stations"?

We thank the referee for this comment. The purpose of our two cases is not to reproduce an extreme ionospheric current system or to simulate how ionospheric structures would scale under higher intensities. Instead, the cases illustrate two different ways in which an extreme geoelectric-field amplitude (the 1-in-100-year E_H value) could map onto Sweden, depending on the assumed spatial pattern.

To make it clearer we have added a few sentences at the beginning of the Method section, and after the response to your previous comment in line 105:

[...] To illustrate the range of possible worst-case conditions, we explore two complementary approaches. The first worst-case scenario (Case 1) is intended to remain as realistic as possible, with each geographic location experiencing a different magnetic field perturbation. This is achieved by using as many magnetometers as are available in Sweden, providing a well-resolved ionospheric driver. The second worst-case scenario (Case 2) is intended to represent an idealised case in which every location in Sweden experiences the same magnetic field perturbation (i.e., the frequency content remains identical). This is achieved by using data from a single magnetometer. Such an idealised situation could be produced by a large-scale westward electrojet (WEJ) extending across Fennoscandia.

The results of the simulations are described in detail. The basis of the scaling is consistent with approaches by others to similar modelling of the Swedish E-field profiles, so it is not surprising that the results are generally consistent with other published results. The observations are detailed but not especially novel. For example, at line 195, reference is

made to 'the transformer trip event', a detail that has not yet been introduced and, relevant to line 196, several papers have shown the relationships between frequency components of the B-field, E-field, and GICs. The difference between the results of the two cases, as depicted in Figure 5(c) surely depends on the way the cases were constructed. To what extent do the simulation results represent plausible GMD events of 1-in-100-years severity?

Thank you for this question. Our answer is that we do not know, and determining how 1-in-100-year geoelectric-field values relate to plausible 1-in-100 year GMD is outside the scope of this study. Analyses of 1-in-100 year GMD and 1-in-100 year GIC scenarios are planned for future work, where comparison between the different worst-case scenarios could be carried out.

The discussion of the modelled results, and the explanations in section 4, appear to support and validate the simulations. However, the focus on voltages and voltage increase with line length (line 253) fails to mention that the line resistance also increases with length, such that longer lines might not contribute significantly higher induced currents. Further, the comments about Malmö (line 237) and Karlshamn (line 241) suggest high susceptibility to GICs even in the south.

Thank you for pointing this out. We have updated the text in line 253. not it reads:

[...] In general, the voltage in the line increases with length as shown in Figure 8c; however, because line resistance also increases with length, longer lines might not contribute significantly higher induced currents.

In relation to the high susceptibility in Malmö and Kalshamn, we have included the following text in Line 242:

[...] As with Malmö, this behaviour may be influenced by sparse magnetometer coverage in southern Sweden and by limitations in the conductivity model. In addition, the most intense GICs are often observed at substations located near the edges of a power-grid network (Viljanen et al., 2012). Both Malmö and Karlshamn lie along the southern boundary of the Swedish transmission system, which may enhance their vulnerability. These examples highlights how local grid topology and substation characteristics may influence vulnerability independently of regional E_H strength.

Figure 9 is interesting. A related paper [Rosenqvist et al., 2025] provides details of three GIC incidents during the Halloween storm period used in these simulations. They occurred at 19:55, 20:03, and 20:07. Two of the three did not coincide with the peaks of the number of lines exceeding the various voltage thresholds. From these records, it appears that the GIC effect that caused incidents was not necessarily a peak line voltage. This information raises questions about the validity of the presumed relationship between voltage stress and power system response.

We thank the reviewer for this important observation. We agree that line-voltage peaks do not necessarily coincide with GIC peaks or with the timing of power-grid disturbances. Our results are consistent with this: extreme geoelectric-field values tend to occur during very active geomagnetic conditions, but the resulting GIC impacts do not align in a simple or direct way with the maximum induced voltages. This has also been observed in other recent events, such as the May 2024 storm (see Figure 5 in Wallner et al., 2025; Figure 9 in

Dimmock et al., 2024), where disturbances did not occur at the time of the largest E_H or line-voltage values.

Understanding the detailed relationship between voltage stress, GICs, and power-system response is a key point, but outside the scope of this paper. At present, we do not know the exact relationship between line-voltage exceedances and the timing of power-system incidents. A more complete assessment would require modelling of the full power-system response, including line resistances, grounding, and network topology. We are actively exploring how to better connect geoelectric field driven voltages with observed disturbances.

In the revised manuscript, Lines 263-265 have been removed and we included the following text in Line 318:

[...] We have shown that during intervals of very active ionospheric current variations, particularly during substorm activity, large dB/dt and E_H values were estimated at latitudes below 60° MLAT. As a consequence, several power lines exceeded high voltage thresholds (e.g., approximately 100 power lines experienced induced voltages exceeding 50 V at several times during the substorm period). For comparison, Lucas et al., (2018) reported that 62 transmission lines exceeded 100 V during the March 1989 geomagnetic storm, which triggered a major blackout in the Hydro-Québec power system. Although power grid disturbances do not always coincide with the time of peak voltage or geoelectric field (Dimmock et al, 2024, Wallner et. al., 2025), or with peak GICs (Pulkkinen et al., 2005), intervals of high induced voltages still imply larger voltage variations.

Have the authors adequately considered the possibility that the differences between the two constructed simulations may be less significant than the types and settings of the relays that initiated tripping in the several GIC-related incidents identified in Rosenqvist's paper? Perhaps the detailed comparison of the two case studies is misleading and could be reduced, with advantage to the overall clarity of the paper. What truly significant conclusions can be drawn from the simulations?

We thank the reviewer for these thoughtful questions. We hope that the justification for including the two worst-case scenarios is now clearer based on our previous responses.

From the two constructed scenarios, we have obtained an estimation of the expected geoelectric field values across Sweden in a worst-case scenario. We have identified where the strongest geoelectric fields occur, and validated these magnitudes against previously recorded or estimated extreme geoelectric field values. This allowed us to determine which power lines are most likely to experience the largest induced voltages per kilometre. From the perspective of the Swedish Power Grid operators, the identification of vulnerable regions due to the external driver (geoelectric field) is very valuable. These results provide essential boundary conditions for future work that will explicitly assess worst-case impacts from a power-grid perspective.

The discussion of power grid implications (section 5.2, starting at line 308) could have been used to define the extreme event parameters before the modelling started. It appears that the argument follows the structure of:

Extreme space weather events are linked with transformer damage. No references are given, but the examples are generally the Salem, USA transformers in March

and November 1989; several Eskom generator transformers at different power stations following the GMDs of 2001-2003, and one or more transformers in New Zealand.

In the introduction we had included examples of extreme space weather events linked to problems for power systems. The included references were Bolduc 2002 (13 March 1989 event) and Pulkkinen et al., 2005 (29-31 October 2003 event). In the revised version, we have also included the reference Girgis et al., 2012 where the authors present the GIC current at Salem Generating station in 1989.

R. Girgis and K. Vedante, "Effects of GIC on power transformers and power systems," PES T&D 2012, Orlando, FL, USA, 2012, pp. 1-8, doi: 10.1109/TDC.2012.6281595.

The records indicate that only one New Zealand transformer failed during a severe or extreme GMD, all the remainder failed or were removed from service several days, weeks or months after the GMD although techniques like oil analysis can show that the degradation was linked to GMD events. Therefore, simultaneous transformer tripping due to physical damage appears unlikely during a 1-in-100-year event. Transformer tripping by relays responding to waveform distortion or other parameters could cause multiple unit tripping – this is a relay/protection problem. Apart from the ambiguity in the reported new specification for Swedish transformers to withstand GIC, it is not evident that the thermal stress is directly linked to peak exposure to line voltages. High geoelectric voltages on lines are given significance in this paper. However, it was not a line voltage that initiated collapse (blackout) of the Hydro Quebec system in 1989; it was a relay response to harmonics. It is unclear whether any voltage collapse blackouts have been initiated purely by geoelectric voltages or GICs.

We agree that transformer tripping due to physical damage is unlikely during a 1-in-100-year event. Our analysis of transformer GIC-withstand requirements led us to the same conclusion. However, previous studies have shown that power grid disturbances can coincide with intervals of peak geoelectric field (see Fig. 4d in Rosenqvist et al., 2025), and therefore we do not dismiss the relevance of analysing peak induced voltages.

The authors suggest high geoelectric voltages could “pose a significant risk to protection relays” (line 326). However, the mechanism of risk is not identified. Considering the timing of actual relay events (see above) the problem is possibly that inappropriate relays (such as one measuring a non-physical quantity or lacking immunity to harmonics), or inappropriate relay settings, or, possibly, faulty relays or relay systems might cause ‘unnecessary’ tripping. Collapse might be initiated by one or multiple coincident relay maloperations, each of which might remove a transformer or line circuit for several hours while its integrity is checked. Based on Figure 9, such relay events might not occur as a direct result of high or maximum voltage but at high or changing rates of change of voltage.

We thank the reviewer for this very important point. We modified the text in line 326, now reads:

[...] The large number of power lines subjected to high induced voltages in our scenario could lead to elevated GICs, which in turn may affect protection relays. Relay misoperations are often linked to harmonics, inappropriate relay types or settings, or faulty relay systems, rather than to the voltage magnitude itself. Collapse can be initiated by one or several coincident relay misoperations, each removing a transformer or line from service while its integrity is verified. Based on this, relay actions may occur during intervals of high or rapidly changing rates of change voltage rather than strictly at maximum voltage.

Understanding which combinations of geoelectric field, induced voltage, network configuration, and system state lead to real incidents remains an open problem and requires further investigation. Such studies will soon be possible with the recently installed GIC monitoring device in Karlshamn, connected to the transformer neutral-to-earth point and deployed by the Swedish transmission system operator, Svenska Kraftnät.

What is it, then, that defines an extreme event from the perspective of the electricity system owner and operator? Does it cause threshold maximum conditions throughout the region, could there be 'hot spots' of intense stress, and how big is a region? For electricity utilities, an extreme event might focus on geomagnetic and geoelectric conditions that stress different items of the utilities' equipment, rather than on peak (10 s) values. (Other infrastructure, such as pipelines, might see extreme events differently.) Would simulations directed towards identifying such conditions be more consequential?

Thank you for these insightful questions. They raise exactly the kinds of considerations that are essential for advancing the perspective of the electricity system owner and operator. Defining what constitutes an "extreme event" for the power-grid operator has been included as an open question in Line 349.

Though this paper does not answer these basic questions, it makes an important contribution to the field simply by its clear description of the approach that exposes these other aspects.

We thank the reviewer for raising these fundamental questions, which are indeed highly relevant for future studies that aim to adopt the perspective of electricity-system owners and operators.

Addressing an extreme event from that operational point of view lies beyond the scope of the present study. Our aim here is to generate worst-case scenarios from the perspective of the external physical driver, independent of the internal power-system response.

We appreciate that the approach presented here helps expose these broader issues, and we see this study as a necessary step toward future investigations that integrate both the physical driver and the power-system response.

Technical corrections: spelling, grammar, etc

In line 204, correct 'factos' to factors.

Done

At line 243, the word 'drive' suggests the vulnerability is directly caused by the topology or substation independently from the geoelectric voltage. I suggest instead that '... grid topology and substation characteristics may influence vulnerability as much as does the regional EH strength' – or similar.

Done

At line 252, would 'dominant' be more suitable than 'preferred'?

Done

At line 267, it appears MLT should be MLAT.

We refer to MLT sector (nightside) as the region where the largest magnetic activity typically occurs at high latitudes. We changed the sentence to:

This study presents the first assessment of a worst-case scenario for the entire Swedish power grid using real data during the development of a premidnight substorm event.

At line 311, the units of line resistance are probably ohm/km values, not simply ohms.

Done

The details of many references are incorrect. Many take the form of <https://doi.org/https://doi.org/10.1029/2022SW003304> (line 395). Another does not return a page.

All references have been reviewed

Comments from referee #4

General Comments

This paper extends previous investigations into understanding the impacts of induced electric fields and GICs on Sweden's power grid for extreme geomagnetic storm scenarios. The study utilises results generated from models described and published in previous works. The text and figures are generally of high standard, however, given the reliance of models cited in previous works, the paper could benefit from a little more detail regarding these to make this paper more self-contained. There are also some statements/concepts that require further qualification and/or clarification. The following general comments are followed by specific comments that should be considered by the authors to improve the overall readability.

We thank the reviewer for a critical review and helpful comments. We have done our best to reply to each concern. The original review is written in black and our replies in red. The line numbers refer to the original version of the manuscript.

Although the authors do state the following with regards to Case 2, "*In the second case (Case 2), we construct an idealized scenario in which the magnetic field time series is spatially uniform across all magnetometer stations.*", the paper could benefit from a little more qualification early in the paper of why this approach was taken. It is acknowledged that the benefit becomes apparent later in the paper, particularly for southern Sweden, however, early qualification would improve the readability.

We thank the referee for this comment. We agree that an early qualification would improve readability. We have added a few sentences at the beginning of the Method section, in line 105:

Our motivation for scaling the geoelectric field was that it is the physical driver of GICs. Using real ground-magnetic perturbations as input preserves a realistic ionospheric forcing (rather than relying on a synthetic magnetic-field time series), while the scaling ensures that the resulting electric field reaches the level associated with a 1-in-100-year event from the perspective of the physical driver of GICs. This allows us to generate as many worst-case scenarios as magnetic field inputs are available. However, because ground magnetic perturbations are driven by ionospheric current systems that activate during geomagnetic storms and substorms, we recommend using magnetic-field inputs from previously recorded events that produced the largest geoelectric field response.

To illustrate the range of possible worst-case conditions, we explore two complementary approaches. The first worst-case scenario (Case 1) is intended to remain as realistic as possible, with each geographic location experiencing a different magnetic field perturbation. This is achieved by using as many magnetometers as are available in Sweden, providing a well-resolved ionospheric driver. The second worst-case scenario (Case 2) is intended to represent an idealised case in which every location in Sweden experiences the same magnetic field perturbation (i.e., the frequency content remains identical). This is achieved by using data from a single magnetometer. Such an idealised situation could be produced by a large-scale westward electrojet (WEJ) extending across Fennoscandia.

The authors use multiple terminology for storms as "strong", "intense", "severe", and "extreme". When using these different terms it should be made clear that it is with respect to a particular metric, or alternatively, use consistent terminology throughout the paper. Although there is no consistent international standard definition of "extreme" storms, as noted by the authors in lines 272-273, the terms should be applied with a consistent approach within the paper.

We thank the reviewer for pointing out the inconsistent terminology. We have now adopted a consistent scheme throughout the manuscript and clarified this in Line 28:

*In this paper, we use the term **extreme** exclusively for 1-in-100-year events. All other impactful events (e.g., strong, intense, or severe) are referred to as **major** events.*

Specific Comments

Lines 7-8 and throughout: The term "electric field" is used and then interchanged with the term "gEOelectric field". Perhaps better to be consistent.

Thank you for checking this. We selected "gEOelectric field" to be used throughout the manuscript.

Line 8: Suggest removing "s" from "lines".

Done

Line 31: Is the ordering of references alphabetical or chronological? A consistent approach should be used.

A chronological order is used throughout the manuscript. We have corrected the citation and reviewed the full text for consistency.

Line 33: Suggest moving the "Bergin" reference to after "May 1921 storm".

Done

Lines 37-40: As per general comment, the Halloween storm (Dst minimum = -383nT) is referred to as an "extreme" storm whereas the May 2024 storm (Dst = -412nT) is referred to as "severe". Consistent terminology should be used as much as possible.

Thank you for pointing this out. We have updated the terminology to ensure consistency with our definitions earlier in the manuscript. The terms "extreme" and "severe" have been replaced accordingly. Lines 37-40 now read:

The first well-recorded major geomagnetic storm was the Halloween event of 29–30 October 2003, which reached a minimum Dst of approximately -400 nT. More recently, the major storm of 10–12 May 2024 reached a minimum Dst of about -412 nT, making it the largest geomagnetic storm since the Halloween storms of 2003 and the second largest event after the 13 March 1989 storm.

Line 58: Suggest adding "at high latitudes" after "attributed to substorms" and replace "of" with "for".

Done

Lines 73-73: Please clarify if this is electric field calculated using 1D or 3D conductivity structures.

Thank you for this observation. Lines 73-74 now reads:

[...] the event producing the largest geoelectric field in Sweden during the last two solar cycles when derived using a 1D ground conductivity model ($E_H=2.73$ V/km). This result was later confirmed by Rosenqvist et al., 2025, who reported the largest geoelectric field derived using a 3D ground conductivity model ($E_H=22.4$ V/km) for the same event over the same period. [...]

Lines 76-78: As per general comment regarding the use of multiple terminology for storms as "strong", "intense", "severe", and "extreme".

We have updated the manuscript. In the new version, Lines 76-78 now reads:

[...] This was also the first major and well-recorded geomagnetic storm [...]

Line 102: Suggest citing reference as "Rosenqvist and Hall (2019)".

Done

Lines 111-112: Can the authors provide some detail as to the extrapolation/interpolation technique used for Case 1?

We included more information about the GIC-SMAP model in section 2.2. Furthermore, we added the following clarification in line 111:

[...] we use the actual observed magnetic field perturbation interpolated using the SECS method to the whole Fennoscandian region.

Line 116: The "SECS" acronym should be defined in the paper.

Thank you for this observation. It is now included in the new paragraph describing the GIC-SMAP model in Section 2.

Lines 120-121: "However, using the external field allows estimation at locations where measurements were not collected, since it is independent of the ground conductivity." This statement needs more qualification as the paper suggests the interpolation/extrapolation is used for Case 1 and Case 2 to provide time series where measurements are not collected. What are the measurements being referred to?

Thank you for pointing this out. After reviewing the sentence in context, we concluded that it did not add meaningful information and have therefore been removed from the manuscript.

Lines 123-125: These sentences to explain "plausible" are somewhat confusing. Please consider rewording.

The new sentence in lines 123-125 now reads:

By "plausible," we refer to a geoelectric field whose magnitude peaks near the characteristic geomagnetic latitude threshold where extreme driving is expected.

Line 144: "The magnetic field components B_x and B_y time series are presented in Figure 1b,c." Although the caption of Figure 1 indicates the interpolated time series are for the locations indicated by stars, this is not obvious in the text. Please indicate this in the text to assist the readability.

We have updated the text. Line 144 now reads:

The magnetic field components B_x and B_y time series at the locations indicated by a star in Figure 1a are presented in Figure 1b,c.

Line 146: Insert spacing prior to hyphen in "20:02:00– 20:08:40 UT".

Done

Line 149: Insert "a" before "few".

Done

Line 153: Insert "in" before "Figure" and remove "s" from "occurs".

Done

Line 164: Suggest replacing "is illustrated" with "are provided".

Done

Figure 1a: The brown star is heavily obscured.

We changed Figure 1a to make the brown star more visible by moving the KIR label southward.

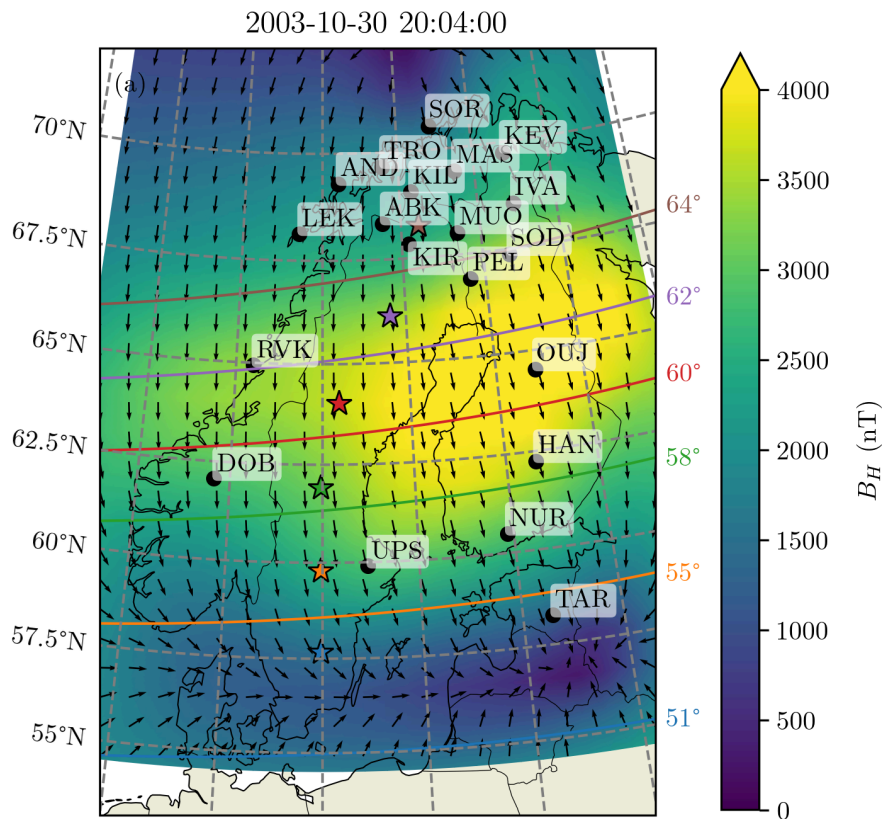


Figure 1 caption, second line: Insert "Interpolated" before "Time series"?

Done

Lines 180-181: This sentence, and the time series plots of Figure 3b (and their max values indicated by black dashed lines), are somewhat inconsistent with the statement in lines 113-114, "In the second case (Case 2), we construct an idealized scenario in which the magnetic field time series is spatially uniform across all magnetometer stations". Please clarify and/or qualify with respect to lines 113-114.

Thank you for making this important point. We agree that there was an inconsistency with the statements in lines 113-114. After reviewing the surrounding text, we found that the inconsistency originated from the preceding sentences. We have therefore revised lines 177-179 to read:

[...] In Case 2, we assume that a large-scale ionospheric current covers all Fennoscandia. The ionospheric equivalent current shown in Figure 2a confirms that a current system was indeed present, but was limited to northern and central Fennoscandia, with a maximum between Finland and Sweden. [...]

This should be later complemented with the already existing sentence in line 183-185

[...] Due to the latitudinal differences in the waveforms, we had to determine which one was most representative of the current system to later apply it across the entire region. [...]

Lines 183-185: Same comment as for 180-181, "Due to the latitudinal differences....". Please clarify and/or qualify with respect to lines 113-114.

Thank you for this comment. We consider that this sentence is now placed in a better context after the revisions made in response to the previous comment.

Line 204: "factos" should be "factors".

Done

Figure 4 caption: Is the term "ground-based observations" correct? The paper states that Case 2 uses B_{ext} from the SECS method which suggests its not directly an observation. Please clarify.

The referee is correct. We have revised the figure caption to avoid implying that Case 2 relies on direct ground-based observations. The updated caption now reads:

Case 2: Estimated 3D horizontal geoelectric field during 30 October geomagnetic storm using two different magnetic field waveform inputs. (a, d) Magnitude of the external component of the horizontal magnetic field (B_{ext}) from the OUJ and HAN stations, respectively. (b, e) magnetic field perturbations. (c, f) horizontal geoelectric field time series at the fixed locations shown with stars in Figure 1a.

Line 211: "similarly"?

This was changed due to the comment of another reviewer to:

[...] mainly dominated by the observations in HAN and OUJ, which are very similar to the input used in Case 2. [...]

Figure 5 caption, second line: "Shows" should be "shows"?

Done

Line 224 and throughout: The power line voltage is described as voltage per km which is effectively electric field. Is this the average electric field over the length of the power line? Some information regarding how this is calculated would help with readability. Further, how were the thresholds of 1 V/km and 3 V/km determined to indicate hazardous conditions?

Thank you for this valuable comment. We have added clarification about these two parameters in Line 220:

The impact on the Swedish power grid is limited to the analysis of the induced voltages in the transmission lines, calculated by integrating the geoelectric field along the power lines under the two 1-in-100-year scenarios. To complement the total induced voltage, we also compute the voltage per kilometre, which corresponds to the line-averaged geoelectric field projected along the transmission line direction. This provides a measure of the effective geoelectric driving experienced by each line, independent of its length. We acknowledge that this does not represent the full behaviour of the Swedish power grid as a connected network. However, large induced voltages (Voltages > 100 V) have been related to several issues during the March 1989 geomagnetic storm (Lucas et al., 2018).

With respect to the thresholds 1 V/km and 3 V/km, these were initially selected to represent low and high maximum voltage per km during the substorm event. To better define these limits, we used the 20th and 80th percentiles of the maximum voltage per km in each case:

Case 1: $P(20) = 1.17$ V/km; $P(80) = 3.34$ V/km

Case 2: $P(20) = 0.75$ V/km; $P(80) = 2.76$ V/km

All text and figures related to these thresholds have been updated in the new version of the manuscript.

Figures 6c and 7c: The figures appear to omit lines between 1-3 V/km? Is this correct? Would it have been better to use a different colour for lines between these thresholds?

Thank you for this comment. The omission of lines with maximum values between 1 V/km and 3 V/km (now 20th and 80th percentiles) is intentional. Our aim in Figures 6c and 7c was to highlight only the transmission lines experiencing the lowest and highest levels of line-averaged geoelectric field (voltage per km) under the worst-case scenarios. Showing only lines below 20th percentile and above 80th percentile allows us to emphasize the extremes in the system without visually overloading the figures.

Lines 241-244: This needs a little more qualification here by referring to Figures 6 and 7. The results of this paper suggest that Karlshamn is not vulnerable to the extreme scenario in Case 1 and appears to be missing from Case 2, perhaps as per the previous comment. It is acknowledged that these statements are somewhat qualified later in the paper (lines 363-364) but qualification here would help with readability.

We thank the reviewer for this valuable comment. We have extended our interpretation about the situation in Malmö and Karlshamn substations. Lines 237-244 reads now:

Interestingly, Malmö, which experienced a GIC-induced blackout in 2003, does not appear as a major hotspot in the Case 1 results. This may be attributed to the limited magnetometer coverage in southern Sweden ($MLAT < 55^\circ$) during the Halloween event, as well as uncertainties in the regional conductivity model. Notably, Malmö is identified as vulnerable under Case 2, when a large-scale ionospheric current system is assumed.

A particularly noteworthy case is Karlshamn, which appears susceptible to GICs even under relatively low E_H values, between 0.42~V/km and 0.75~V/km, according to Table 1 in Rosenqvist et al., (2025). As with Malmö, this behaviour may be influenced by sparse magnetometer coverage in southern Sweden and by limitations in the conductivity model. In addition, the most intense GICs are often observed at substations located near the edges of a power-grid network (Viljanen et al., 2012). Both Malmö and Karlshamn lie along the southern boundary of the Swedish transmission system, which may enhance their vulnerability. These examples highlights how local grid topology and substation characteristics may influence vulnerability independently of regional E_H strength.

Figure 7 caption: Should be "(b-d)"?

Done

Lines 263-265: The authors acknowledge that other parameters are needed to convert the estimated voltages to current flowing through the transmission lines and transformer windings in the network to understand the impact of GICs. Although the estimation of voltages is of value, longer lines in general will have higher total resistances (an analogous plot to Figure 8c of line length to total resistance would be similarly linear). The nominal operating voltage of these lines are hundreds of kV with operating tolerances typically of 5-10%. Statements such as those in lines 263-265 and lines 326-327 should be qualified more definitively using industry standards in terms of line tripping and network impact.

We thank the reviewer for these very important points. In the revised manuscript, Lines 263-265 have been removed and we included the following text in Line 318:

[...] We have shown that during intervals of very active ionospheric current variations, particularly during substorm activity, large dB/dt and E_H values were estimated at latitudes below 60° MLAT. As a consequence, several power lines exceeded high voltage thresholds (e.g., approximately 100 power lines experienced induced voltages exceeding 50 V at several times during the substorm period). For comparison, Lucas et al., (2018) reported that 62 transmission lines exceeded 100 V during the March 1989 geomagnetic storm, which triggered a major blackout in the Hydro-Québec power system. Although power grid disturbances do not always coincide with the time of peak voltage or geoelectric field (Dimmock et al, 2024, Wallner et. al., 2025), or with peak GICs (Pulkkinen et al., 2005), intervals of high induced voltages still imply larger voltage variations.

We modified the text in line 326, now reads:

[...] The large number of power lines subjected to high induced voltages in our scenario could lead to elevated GICs, which in turn may affect protection relays. Relay misoperations are often linked to harmonics, inappropriate relay types or settings, or faulty relay systems, rather than to the voltage magnitude itself. Collapse can be initiated by one or several coincident relay misoperations, each removing a transformer or line from service while its integrity is verified. Based on this, relay actions may occur during intervals of high or rapidly changing rates of change voltage rather than strictly at maximum voltage.

Understanding which combinations of geoelectric field, induced voltage, network configuration, and system state lead to real incidents remains an open problem and requires further investigation. Such studies will soon be possible with the recently installed GIC monitoring device in Karlshamn, connected to the transformer neutral-to-earth point and deployed by the Swedish transmission system operator, Svenska Kraftnät.

Line 291: Suggest replacing "area" with "range".

Done

Line 294: Suggest using "cables" or inserting "the" before "telecommunication".

We have used cables.

Line 301: Although the MLAT threshold for the Pulkkinen et al study was provided early in the paper, perhaps it would be useful to provide again for context here.

We agree with this comment. We included the following clarification in line 301

MLAT threshold (i.e., the magnetic latitude where maximum geomagnetic disturbances and geoelectric fields typically occur)

Lines 310-313: The numbers appear to be quoted as resistances in Ohms but their low values would suggest they are resistivity. Please clarify. If they are resistance values then it would not seem appropriate to apply for all transmission lines as their resistance is a function of resistivity, length and area. Are these values used in the RAISE model or are they determined from applying these resistance values to the obtained voltages? Please provide more information on how the currents were calculated to qualify the estimates of 200 A.

Thank you for pointing this out. The values in Line 311 refer to line resistances per unit length $r_{L,220}=0.022 \text{ } \Omega/\text{km}$ and $r_{L,400}=0.008 \text{ } \Omega/\text{km}$ have been corrected. These values have been used by Viljanen et al., (2012) and later implemented in the RAISE model (Rosenqvist et al, 2025).

The value of 200 A mentioned in the manuscript is not derived from our voltage estimates. Instead, it reflects an operational guideline communicated privately by Svenska kraftnät regarding the GIC levels that can be of concern for transformer performance in the Swedish grid.

Lines 365-367: Should this statement be clarified for Case 1 as Case 2 does suggest Malmo is vulnerable?

Thank you for this comment. We have clarified that that statement is for Case 1.

Line 372: Should the reference citation be "Vanhamaki and Juusola, (2020)"?

Yes, the citation was corrected.

References: Some reference titles use capitalisation and others don't. Should this be consistent?

All references have been reviewed to be consistent.