Reply to Referee #1

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We thank Referee #1 for constructive comments and agree with almost all of them. Please, see below for our point-by-point replies. The original review is written in *black* and our replies in blue.

The authors present results from large scale geoelectric field modelling during the May 2024 storm in Northern Europe, using the approach after Juusola (2025b) which also works in the absence of ground conductivity models. The ground electric field response (E) is divided into a divergence-free (DF) and curl-free (CF) part, where the DF part represents the large scale geoelectric field and is derived by magnetic field observations only. CF is computed from a ground conductivity model (S-map) and can locally have much larger amplitude and show strong polarization especially valid for GIC in power grids. The authors set out to see if EDF provides a good proxy for GIC, using various data sets (IMAGE, SUPER-MAG, BEAR) for the May 2024 geomagnetic storm. They then present several hypothetical scenarios using the Finnish benchmark power grid to assess potential GIC levels. Then the authors turn to a broader scale looking at model outputs for ionospheric equivalent currents and electric field models for northern Europe for two time-steps during the May 2024 storm 22:29 when the electrojet was exceptionally far south and 22:36 at peak GIC time. A next chapter sees the inclusion of the modelling results for one location in central Europe (observatory NCK) where a 1-D conductivity assumption has been shown to be sufficient. Then SUPER-MAG data are used to model global ionospheric current density, of which the northern hemisphere is shown in several figures for several time-steps.

I find that there is a lot of very interesting content, but that the overall structure of the manuscript is confusing with little introduction and explanation why certain aspects are pulled together. The line of thought is sometimes lost when observational results (what really occurred during the May 2024 storm) is alternated with very speculative aspects (moving the Finnish power grid to the Norwegian coast, and the northwards shift by 1° that is not very well explained). Some of these excursions in the argumentation are very unrealistic and could be omitted to shorten the text and make everything more concise and comprehensible. Maybe data availability to validate the models is a problem, but this isn't discussed. Why was BEAR data used for one site if much newer MT data from across Scandinavia should be available? The example from the Hungarian observatory is also very far-fetched. Continuous electric field observations (including the May 2024 storm) are for example available from GFZ Potsdam for a site in north Germany. The quantification of model performance is also very broad-brush – can the authors give better estimates for the comparison of e.g., GIC derived from EDF or E total?

I would encourage a shortening and restructuring of the manuscript, leaving out the most extreme hypothetical examples and strengthening the introduction and overall flow and argumentation of the text. Some of the figures need improvement and figure captions should be made more comprehensive.

In agreement with these comments, we suggest to add introductory text to the sections and explanations at places where we change aspect. We will shorten the manuscript by removing the section dealing with the shift of the Finnish grid to the Norwegian coast and the Hungarian observatory. We will also clarify the figures and their captions. Please see below for detailed answers to the points raised by the reviewer.

General remarks:

Abstract, line 10: 'compared to 10s geoelectric field' – unclear statement.

We suggest to remove this statement and rewrite the end of the abstract as follows: "We compare the resulting GIC in the Finnish benchmark power grid and conclude that while $\boldsymbol{E}_{DF}$ determines the overall direction and level of GIC activity in the power grid, $\boldsymbol{E}_{CF}$ can produce localized enhancements that can significantly modify the GIC amplitudes at nearby substations for certain directions of the $\boldsymbol{E}_{DF}$. The ionospheric equivalent currents provided by the SECS method yield information on the external drivers of the GIC peaks. The adaptable triangular grid for the SECS method provides a robust tool for optimal analysis of ground-based magnetometer data, scalabale to both regional and global magnetometer distributions."

Line 30: 'Because continuously operating MT networks are not available' – unprecise statement. Large scale MT arrays have been measured in many areas, and this allows the inclusion of the realistic ground conductivity response. Continuous geoelectric field measurements are somewhat rarer, but there are several examples (see Lyon et al., 2025)

We suggest to clarify the text by replacing it with: "Continuously operating magnetotelluric (MT) sites measuring magnetic field and electric field time series are rare, and they do not comprise dense and extensive networks (e.g., Kelbert, 2020; Lyon et al., 2025). An exception was the Baltic Electromagnetic Array Research (BEAR) network (Lahti et al., 2005) in Fennoscandia, and even that operated only for about 1.5 months during June-July 1998. Relatively dense magnetometer networks, on the other hand, operate all the time."

Line 6: 'Simultaneous magnetic and electric field measurements have been observed' — where?

It is an empirical finding that the geoelectric field has a much larger spatial variability than the geomagnetic field. This is most strikingly demonstrated by synthetic modelling in which the magnetic field is spatially uniform and the electric field is derived from empirical MT-impedances. For example, see Love et al. (2016) (Fig. 1) for wide regions across the United States: the electric field varies within a range of $\sim$0.1–10 $\mathrm{V/km}$, i.e. three orders of magnitude, even at nearby locations.

An example of a sudden storm commencement in China (Ma et al. (2025) (Fig. 4) shows quite a uniform dH/dt vector field, whereas the electric field has a much larger variability in magnitude and orientation across a large area 10^o in latitude and 25^o in longitude.

We suggest to modify the text as follows: "Simultaneous magnetic and electric fields have been observed to exhibit orders of magnitude greater spatial variability in the electric field than in the magnetic field (Love et al., 2016; Kelbert, 2020; Cordell et al., 2025; Ma et al., 2025). Physically, this is understandable as the magnetic field is produced solely by currents (in space and in the conducting subsurface), whereas the electric field is affected also by charges. Due to large lateral gradients in the near-surface conductivity, there can be strong charge accumulation leading to large local enhancement of the electric field."

'Line 79: The structure of the study is as follows...' – here would be a chance to prepare the reader for the journey ahead. Otherwise that sentence is redundant.

We suggest to modify the text as follows: "The structure of the study is as follows: the data and methods are described in Section 2. We will take advantage of the unique BEAR network measurement campaign in 1998 to both illustrate and demonstrate the validity of our methods. The actual results obtained by studying the May 2024 storm are presented in Section 3. In Section 4 we will discuss the recipe for intense GIC production as well the limitations and advantages of out method. The conlusions are summarised in Section 5."

Section 2 Data and Methods: is a very lose listing of all data sets used, without an argument why. Maybe this could be a table.

We considered this, but decided that more explanation is needed than can be fitted into a table. Instead, we suggest to start the section with the following introduction: "In this section, we will first introduce the geomagnetic field and geoelectric field measurements (section 2.1) and then continue with descriptions of the methodology. In section 2.2, we summarize the equivalent current and $\boldsymbol{E}_{DF}$ calculation from magnetometer network observations using the SECS method, in section 2.3, we explain how $\boldsymbol{E}_{CF}$ is estimated from $\boldsymbol{E}_{DF}$, and in section 2.4, we explain what is the Finnish benchmark power grid and how GIC in the grid is calculated from $\boldsymbol{E}$. Finally, in section 2.5, we list other contextual data used in the analysis. Throughout this section, we use one of the geomagnetically most active intervals from the BEAR measurement campaign to illustrate and to demonstrate the validity of our methods. The BEAR data are particularly suitable for this, because they comprise simultaneous geoelectric field measurements and a spatially extensive and dense magnetometer network in Fennoscandia. Also, the geoelectric field and geomagnetic field measurements from BEAR are publically available, contrary to most MT data."

It is never discussed why BEAR data from 1998 was used – it just pops up in the text. There have been many newer MT campaigns in Fennoscandia. Why was the specific time step in June 1998 chosen? What was the geomagnetic activity level then? BEAR timeseries data are not available via the link provided.

Please see our reply to the comment for "Line 30" as well as to the previous point. Also, we suggest to add after line 114: "This is the time of the peak $\boldsymbol{E}_{DF}$ (section 2.3) during one of the most geomagnetically active intervals of the BEAR measurement campaign (Viljanen et al., 2004)."

- Line 98: 'the bottom of the space current region' – do you mean the ionosphere?

Yes, we will modify the text.

Validated geoelectric fields are only point-wise, which are of very limited value for GIC models.

We do not aim at modelling GIC. Instead, we try to understand how the geoelectric field is produced by external and internal sources, with special focus on the contribution of subsurface conductivity via $\boldsymbol{E}_{CF}$. Additionally, we inspect the possibility to apply $\boldsymbol{E}_{DF}$ as a proxy for GIC activity. Due to the simple construction of $\boldsymbol{E}_{DF}$ purely from the measured ground magnetic field, it provides, in principle, a proxy applicable in any geographic scale as long as the spatial coverage of geomagnetic data is satisfactory. We suggest to clarify our aim by adding at the end of the first paragraph of the Introduction: "The primary purpose of the present study is to increase understanding on how the geoelectric field that drives GIC is produced by the complex interplay initiated by external drivers in space, and modulated by the conducting subsurface. We will use the May 2024 storm as an example event." We also suggest to add at the end of section 2.3: "Our motivation here is not comprehensive validation of the method, which was done in more detail by Juusola et al. (2025). Instead, we wish to demonstrate that changing the SECS grid from the traditional rectangular grid with uniform resolution in latitude and longitude to the adapted triangular grid still produces reasonable results."

Line 144: 'Furthermore, the measured electric field data is often noisy' — that seems to be an empty argument if it hasn't been tried. Magnetic field observations are noisy as well.

It is empirically known that electric field recordings can be very noisy due to several different reasons as illustrated by Lyon et al. (2025). The noise in magnetometer recordings is much less severe. We suggest to clarify this by modifying the sentence as follows: "Furthermore, the measured electric field data are often noisy due to several different reasons as illustrated by Lyon et al. (2025)."

Line 146: Question about the coordinate system of the BEAR data: should apply to the magnetic field data as well. If this is unclear, then maybe another MT data set should be used.

This is true. However, the BEAR data set is the only one that covers a large region with simultaneous MT recordings in Fennoscandia.

Section 2.5 GIC — not very descriptive section title, do you mean 'GIC modelling framework'?

Yes, we will modify this as suggested.

It is quite unsatisfactory that a very old representation of the Finnish Power grid is used. Why no update?

We suggest to clarify our motivation by adding at the begining of the "GIC modelling framework"-section the following text: "Our purpose is to understand how the geoelectric field that drives GIC is produced by external and internal sources, with special focus on the contribution of subsurface conductivity via $\boldsymbol{E}_{CF}$. Additionally, we inspect the possibility to apply $\boldsymbol{E}_{DF}$ as a proxy for GIC activity. Due to the simple construction of $\boldsymbol{E}_{DF}$ purely from the measured ground magnetic field, it provides, in principle, a proxy applicable in any geographic scale as long as the spatial coverage of geomagnetic data is satisfactory. For these purposes, we use a small but a realistic power grid, whose parameters are publicly available, to demonstrate general features of GIC. In a simple grid, it is easier to understand how different electric field configurations affect GIC, compared to a grid with tens of nodes and lines (as presently in Finland, for example). For accurate GIC modelling in an operational power grid, the optimal approach is that scientists provide the geoelectric field to power grid operators. Then they can, in turn, use up-to-date models of the grid, calculate GIC, and assess possible impacts. We also remark that there are often short- or long-term changes in a real-world grid." We agree that a grid model more closely representing the present grid would be convenient although a grid that has been used previously allows straightforward comparison with previous results. A map of the updated grid could be constructed based on openly available data, but the resistances and other details of substations are not available.

Section 3 Results: requires an introduction on what is to come

We suggest the following introduction: "In this section, we will start by modelling the GIC in the Finnish benchmark power grid during a two-hour interval around the Karlshamn GIC incident (Rosenqvist et al., 2025; Wallner et al., 2026) of the May 2024 geomagnetic storm. Special focus will be given to the contribution to GIC from $\boldsymbol{E}_{DF}$ and $\boldsymbol{E}_{CF}$ as well as the effect of the cadence. After identifying the times of peak GIC, we will continue to examine the external drivers of these peaks."

Line 227: where is substation Rauma? What happened on 4 January 1979?

We suggest to add the following explanation: "The Rauma substation is located a little south of Olkiluoto. It did not yet exist at the time which the benchmark grid model represents. During the March 1991 geomagnetic storm, 175 A (10 s value) was measured at Pirttikoski. Nothing special has been reported concerning the power grid operation at this time. We mention this event, because it includes one of largest measured GIC in Finland and for this event, the benchmark model still gives quite a realistic description of the grid."

Line 234: ' power grid geometry is different for the two substations' — I would assume that the geometry is the same, just the numbers of connections is different?

Yes, we will correct this as suggested.

Unclear why geoelectric field observations from Hungary are used. How is this significant for Scandinavia where 1-D conditions are almost certainly always violated? Remove this section

We will remove this section.

GIC modelling is quite simplistic. Overall GIC will travel in the network and enter transformers/grounding points due to local ground resistances, so can have overall large effects, not just localized electric field effects. The Finnish benchmark grid is very old, does not contain realistic line pathways and is overly simplistic in other grid topology parameters. How valid is it for the current state of the Finnish power grid?

Please see our reply to the comment concerning the power grid model.

The relocation of the Finnish power grid is very abruptly done in the manuscript without explanation or detail (e.g., how does the geoelectric field look like north of 67 °? Are some substations now located in the Baltic sea? This is a very unrealistic and confusing excursion. Why would ECF (the ground conductivity contribution) not play a role here?

We will remove this example.

Line 332: mentioning the k coefficients here for this specific location is not necessary

We will remove this section.

The last paragraph ('Thus, we can conclude. . . ') in section 3.2 is very disjointed from the previous analysis – I think the authors showed that the local geoelectric field ECF is very much driving the largest GICs in the Finnish grid, although the grid geometry plays an even more crucial role.

Yes, this paragraph represents a more general finding than just the Norwegian example. We suggest to remove the Norwegian example and modify the text accordingly.

Korja et al. (2002) doesn't describe the BEAR MT data, maybe better to refer to: Lahti, T. Korja, P. Kaikkonen, K. Vaittinen, Decomposition analysis of the BEAR magnetotelluric data: implications for the upper mantle conductivity in the Fennoscandian Shield, Gephysical Journal International, Volume 163, Issue 3, December 2005, Pages 900–914, https://doi.org/10.1111/j.1365-246X.2005.02744.x

We will add the reference.

Figures: all polar plots could do with longitudinal labels to improve readability (Fig1)

We will add the labels.

Figure 5: the greyscale is not very readable – if grey scale is preferred, maybe less bins would improve

We will adjust the scale.

Figure 7: use larger circles to indicate the GIC amplitudes as reading the numbers is difficult to get a regional view?

We will increase the size of the circles.

Fig 8: Figure captions aren't very comprehensive, b) and d) should have the same y axis

We will change the y axis as suggested and change the figure caption to: "(a): Time series of the sum of absolute values of GIC at all substations of the power grid from 10 May 2024 21:30:00 to 23:30:00 UT. The GIC are calculated using the total geoelectric field and the DF component of the geoelectric field estimated from 10 s IMAGE observations and from 1 min averaged IMAGE observations. The peak values and their amplitudes are indicated by the labeled vertical lines. (b): The same as (a) except that the power grid has been shifted 0.5^o northward in latitude and the 1 min curve is not shown. The motivation for this shift is to demonstrate how moving the power grid away from the region of intense geoelectric field in southern Finland removes the difference from the GIC sum calculated from $\boldsymbol{E}_{DF}$ and $\boldsymbol{E}$, which is prominent in panel (a). (c): Relative GIC sum calculated using $\boldsymbol{E}$ and $\boldsymbol{E}_{DF}$ as a function of average $\boldsymbol{E}_{DF}$ direction in the network area. The directon angle 0^o means southward $\boldsymbol{E}_{DF}$ and 90^o means eastward $\boldsymbol{E}_{DF}$. (d): Otherwise the same as (c) except for the power grid that has been shifted 0.5^o northward in latitude. Compared to panel (c), the dependence of the GIC sum calculated from $\boldsymbol{E}$ and $\boldsymbol{E}_{DF}$ on the direction of $\boldsymbol{E}_{DF}$ is now much weaker, because the critical area in southern Finland no longer playes a role." We also noticed that we had made an error in the original text: The grid had been shifted by 0.5^o, not by 1^o. We will correct this.

Figure 9: Caption is not complete. Unclear statement 'The same as Fig. 7 except for Olkiluoto substation, instead of Inkoo.'

This figure will be deleted.

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