

1 **Why the September 2017 geomagnetic storm was**
2 **stronger at certain locations than the famous**
3 **Halloween event**

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7 **Key Points:**

- 8 • This study compares the extreme geomagnetic storm of 2003 to the less intense
9 but severe storm of September 2017
10 • The 2017 storm caused stronger magnetic variations at high latitudes in the Fennoscan-
11 dian region
12 • Ionospheric current structures and ground conductivity gradients can produce in-
13 tense localized magnetic field enhancements

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Abstract

In this study, we compare two significant geomagnetic storms of the 21st century: the well-known Halloween geomagnetic storm of 2003 (Kp index 9) and a somewhat milder storm of September 2017 (Kp 8). Both events caused exceptionally high values of geomagnetically induced currents (GIC) and earned a place among the top ten with respect to the measured GIC in the Finnish natural gas pipeline. We analyze solar wind and geomagnetic data as well as modeled geoelectric fields during these two events to better understand the drivers behind these strong GIC. We discover certain geographic locations that experienced stronger magnetic field time derivatives during the 2017 storm. This is interesting because in terms of magnetic indices, the 2017 storm was a weaker event. We use equivalent currents to get a view of the ionospheric and induced currents in the Fennoscandian region. We find that the interplay between different structures of ionospheric currents and the three-dimensional ground conductivity leads to a complex behaviour of the geoelectric field. This study improves knowledge in space weather preparedness by identifying location-specific risks for geoelectric hazards, which can create severe problems in the high-voltage power grid.

Plain Language Summary

Intense solar eruptions, known as coronal mass ejections, can have major impact on the near-Earth space and cause geomagnetic storms. These events can cause problems to our satellites and even pose threat to high-voltage power grids on Earth. In this study we compare two major geomagnetic storms of the 21st century: the well-known Halloween event of 2003 and a slightly weaker storm of September 2017. We try to understand why certain geographic locations experienced stronger geomagnetic field variations during the 2017 storm, even though in general terms it was a weaker event. To achieve this, we use physical models to view the ionospheric currents and induced currents in the conducting ground in the Fennoscandian region. We find certain current structures in the ionosphere that can induce intense electric fields in the ground. Also, we discover specific geographic locations that are at a high risk for strong electric fields because they are located near areas with sharp variations in ground conductivity. This study improves knowledge in space weather preparedness by identifying location-specific risks for intense ground electric fields, which can create severe problems in high-voltage power grids.

1 Introduction

Severe geomagnetic storms can make the aurora glow at lower latitudes, but they can also cause unwanted effects such as disruptions in satellite-ground communications and global positioning systems as well as problems in high-voltage power networks. Strong storms can cause voltage fluctuations and damage transformers in electric grids. This is why geomagnetic storms are an important topic not only for space weather research, but also for civil aviation, military and power network operators. Because of these potentially significant issues, several countries, including Finland, have incorporated space weather awareness in their national risk assessment plans in recent years (Pulkkinen et al., 2017; *National risk assessment 2023*, 2023).

Coronal mass ejections (CMEs) are the primary drivers of the most intense magnetic storms, significantly amplifying both the speed of the solar wind and the strength of the magnetic field by several multiples when compared to quiet conditions. These sudden changes in the solar wind rattle the Earth's magnetic field causing ionospheric and magnetospheric currents. These, in combination with conducting properties of the ground, create a geoelectric field. The strength of the field is highly related to the ground conductivity. Conductivity refers to how easily charges can move through a material. In highly conductive materials (like salty sea water or graphite), charges can move more freely. This means that when an electric field is induced in the ground, the charges can redistribute

64 more easily, weakening the strength of the induced electric field. In regions with sharp
 65 contrasts in conductivity, these gradients cause charge accumulation which enhances the
 66 geoelectric field. This field drives geomagnetically induced currents (GIC) in ground-based
 67 conducting systems, such as high-voltage power grids and pipelines.

68 Measurements of the geoelectric field are sporadic and often very noisy. Consequently,
 69 the time derivative of the geomagnetic field ($d\mathbf{B}/dt$ and especially its horizontal part $d\mathbf{H}/dt$)
 70 is often used as a proxy because it is related to the electric field according to Faraday's
 71 law of induction:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (1)$$

72 where \mathbf{E} is the electric field, \mathbf{B} is the magnetic field.

73 Magnetic field recordings are widely available for past events and in near real time,
 74 so it is handy to use them as GIC indicators. However, it is not possible to calculate GIC
 75 directly using the magnetic field or its time derivative. GIC can be calculated if the geo-
 76 electric field and parameters of a technological conductor are known. The geoelectric field
 77 can be modeled by coupling ground conductivity models with the measured magnetic
 78 field (for an extensive review, see Kelbert (2020)). In recent years, there has been a lot
 79 of progress in applying empirical magnetotelluric (MT) impedances (e.g., Bedrosian and
 80 Love (2015)) and using first-principle solutions with complex 3D conductivity models
 81 (e.g., Gao et al. (2021); Marshalko et al. (2021, 2023); Rosenqvist et al. (2022)). When
 82 the geoelectric field is known, calculation of GIC in power grids (Pirjola et al., 2022) or
 83 pipelines (Boteler, 2013) is a straightforward task.

84 As we have seen with past events, the strongest geomagnetic storms are clearly a
 85 key topic in considering GIC impacts on modern infrastructure. The best-known exam-
 86 ple is the Québec blackout in March 1989 affecting millions of people for several hours
 87 (Bolduc, 2002). A geographically more limited incident was the Malmö blackout in south-
 88 ern Sweden in October 2003 (Pulkkinen et al., 2005). Also worth mentioning is the May
 89 1921 storm, which is comparable to the 1859 Carrington event. Although no direct record-
 90 ings are available, GIC was strong enough to cause a destructive fire at a Swedish tele-
 91 phone station (Hapgood, 2019). This example gives a hint that a similar superstorm could
 92 have a serious impact on modern power grids.

93 As discussed above, the ground magnetic field has been a popular quantity in study-
 94 ing space weather events due to the good availability of data. Several recent studies (Schillings
 95 et al. (2022, 2023), Zou et al. (2022), Juusola, Viljanen, Dimmock, et al. (2023)) have
 96 gathered a lot of understanding of characteristics and different drivers of potentially sig-
 97 nificant GIC events. However, there is still a clear need to extend the analysis to the geo-
 98 electric field to have a more explicit connection to GIC. The ground conductivity plays
 99 a central role in terms of the internal contribution to the geoelectric field. In particu-
 100 lar, ground conductivity distributions often have prominent 3D features with lateral gra-
 101 dients which lead to significant enhancement of the geoelectric field in their vicinity. It
 102 also follows that each region of interest requires a dedicated study due to the large vari-
 103 ability in the ground conductivity (cf. Kelbert (2020); Love et al. (2022)).

104 In this study, we will compare two major geomagnetic storm: the Halloween event
 105 on 29-31 Oct 2003 and the event on 7-8 September 2017, to obtain deeper understand-
 106 ing of severe geomagnetic storms and related geoelectric field. The Halloween storm is
 107 one of the largest space weather events of which a lot of instrumental observations are
 108 available (Gopalswamy et al., 2005). It serves as a benchmark to other events thanks to
 109 good availability of different space weather data and many reported impacts on technol-
 110 ogy. The September 2017 event is one of the strongest storms of the previous solar cy-
 111 cle no. 24.

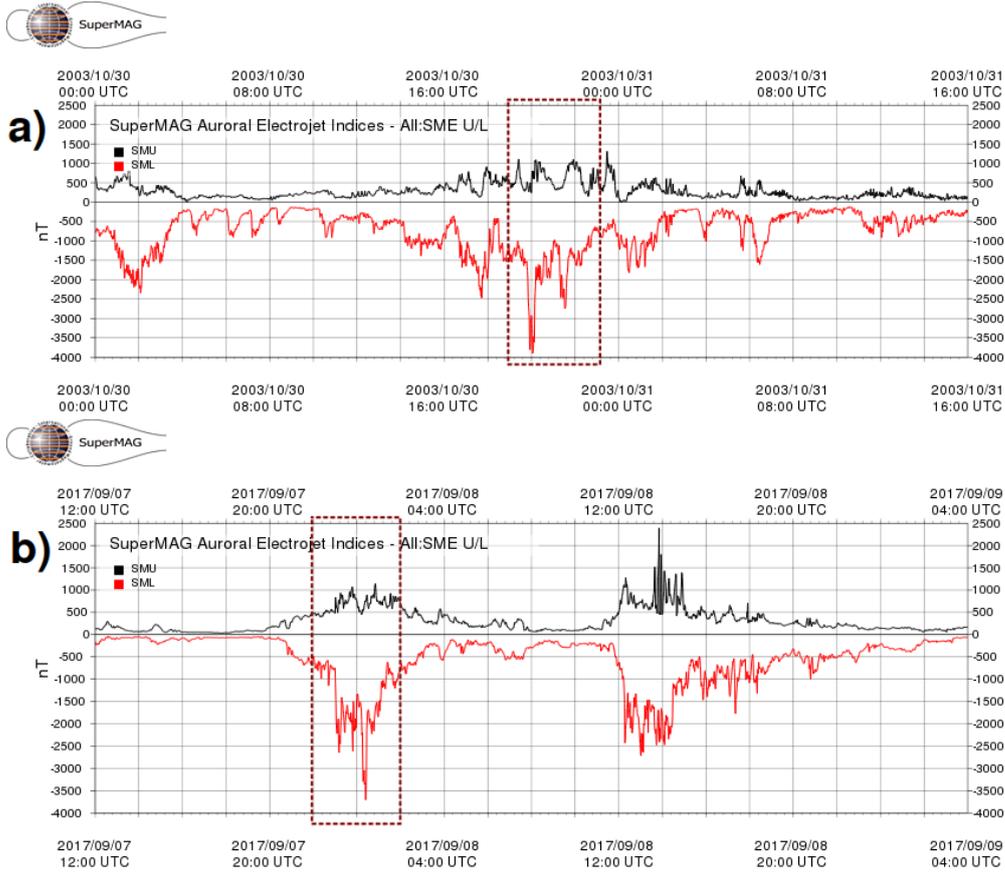


Figure 1. SuperMAG SMU and SML indices during two days of the Halloween geomagnetic storm (a) and two days of the September 2017 geomagnetic storm (b) (Gjerloev, 2012; Newell & Gjerloev, 2011). SMU is shown with black line and SML with red line. The dashed line boxes indicates the periods studied in this paper.

112 An important task is to find a meaningful way to compare events. Traditionally,
 113 magnetic storms are characterized by regional or global activity indices. However, many
 114 classical indices, such as K_p , have a limited range (index values 0-9) or are related to spe-
 115 cific features of activity, such as the D_{st} index, which describes the magnetospheric ring
 116 current. Kappenman (2005) applied the method of morphology-based comparisons of
 117 interpolated and extrapolated ground magnetic field variations to illustrate significant
 118 differences between storms, which may look quite similar if only characterised by activ-
 119 ity indices. We extend this idea with more quantitative analysis including the modeled
 120 geoelectric field.

121 2 Data and methods

122 2.1 Data

123 We use solar wind satellite observations from the OMNIWeb service (King & Pa-
 124 pitashvili, 2020) for assessing the solar wind input to the magnetosphere. We use 10-s
 125 International Monitor for Auroral Geomagnetic Effects (IMAGE) magnetometer data,
 126 which is available via *IMAGE Magnetometer network* (2023). We also use magnetic in-
 127 dices, like K_p , SML and SMU. The K_p index is based on magnetic measurements at mid-

128 latitudes and shows the range of horizontal magnetic field variations during a 3-hr pe-
 129 riod. We use the Potsdam Kp index as defined by Matzka et al. (2021). The SuperMag
 130 SML and SMU indices describe the maximum westward and eastward auroral electro-
 131 jets' strength, respectively. SMU is the upper, and SML is the lower envelope of the north
 132 component for stations between 40° and 80° magnetic north (Newell & Gjerloev, 2011).
 133 Figure 1 shows the values of the SML/U indices during both storms. Other relevant in-
 134 dices are IU and IL. They are similar to SML/U but use data from the IMAGE network,
 135 which is a localized subset of the SuperMag network.

136 During both storms, we focus on 4-hr periods when clear substorms are visible in
 137 the magnetograms (see Fig. 2).

- 138 • For the Halloween event the chosen period is: 2003-10-30 19:00 to 23:00 UT
- 139 • For the September 2017 event: 2017-09-07 22:00 UT to 2017-09-08 02:00 UT

140 **2.1.1 Halloween event**

141 The Halloween event was caused by a series of strong, X-class flares accompanied
 142 by several CMEs on the Earth-facing side of the Sun. The event caused hours long out-
 143 ages in spacecraft measuring solar wind, and many data sets from this period are un-
 144 certain or have long data gaps. In fact, approximately half of the Earth's satellites ex-
 145 perience some problems due to these eruptions (Phillips, 2021). It is estimated that the
 146 CMEs could have had a velocity of over 2200 km s⁻¹ (Skoug et al., 2004). This is ap-
 147 proximately 5 to 6 times higher than during typical slow solar wind conditions, when so-
 148 lar wind speed ranges between 300 and 400 km s⁻¹.

149 These CMEs caused the strongest magnetic storm of the past few decades. The Pots-
 150 dam Kp index reached 9 (extreme) for two consecutive 3-hr periods and D_{st} reached -
 151 400 (Skoug et al., 2004). The SML index peaked at -3600 nT, and IL index at -4500 nT
 152 during the studied period. SML/U indices during the Halloween event are shown in Fig-
 153 ure 1 (a), where the studied period is highlighted. The magnetic north component (X-
 154 component) measurements during the studied period are shown in Figure 2, left panel.
 155 These magnetograms show that there were intense variations observed at all of the shown
 156 magnetometer stations. Record-large GIC, up to 57 A, were measured in the Finnish nat-
 157 ural gas pipeline during the Halloween storm (Tsurutani, Bruce T. & Hajra, Rajkumar,
 158 2021; Dimmock et al., 2019) at 2003-10-29 06:57 UT. The blackout in Malmö (55.6° N)
 159 started on 30 October at 20:07:15 UT (Pulkkinen et al., 2005, Table 2).

160 **2.1.2 September 2017 event**

161 The origin of the 2017 event was, as well, a series of moderate to strong (M to X-
 162 class) solar flares associated with several CMEs. The solar wind speed was measured to
 163 be up to 800 km s⁻¹. The CMEs caused severe geomagnetic disturbances with Kp-index
 164 between 7 to 8 (strong to severe) and D_{st} -150 (Dimmock et al., 2019). The SML index
 165 peaked at -3700 nT, and SMU at 1100 nT. SML/U indices during the September event
 166 are shown in Figure 1 (b), where the studied period is highlighted.

167 SML/U values are similar to those of the Halloween event, but the number of sta-
 168 tions is also higher in 2017 compared to 2003. This is why these indices are not directly
 169 comparable. Regarding the Kp and D_{st}-index, this was clearly a weaker storm, but we
 170 still observed very high GIC values (30.1 A at 00:31 UT, 8 September 2017) at the Mäntsälä
 171 station in Finland (Dimmock et al., 2019). This event made it to the top 10 of highest
 172 measured GIC at Mäntsälä. However, we also note that GIC values of different years are
 173 not fully comparable due to gradual changes in the pipeline network.

174 Although no major power failures are associated with the storm, at 00:29 UT on
 175 8 September 2017, a transformer tripped near Sundsvall, central Sweden (Rosenqvist et

Station	Geo. Lat. [° N]	Geo. Lon. [°E]	CGM Lat. [° N]	CGM Lon.[°E]
Sørøya (SOR)	70.54	22.22	67.34	106.17
Kevo (KEV)	69.76	27.01	66.32	109.24
Ivalo (IVA)	68.56	27.29	65.10	108.57
Muonio (MUO)	68.02	23.53	64.72	105.22
Sodankylä (SOD)	67.37	26.63	63.92	107.26
Pello (PEL)	66.90	24.08	63.55	104.92
Oulujärvi (OUJ)	64.52	27.23	60.99	106.14
Hankasalmi (HAN)	62.25	26.60	58.69	104.54
Nurmijärvi (NUR)	60.50	24.65	56.89	102.18
Tartu (TAR)	58.26	26.46	54.47	102.89

Table 1. Geographic and corrected geomagnetic (CGM, 2001) coordinates of the magnetometer stations mentioned in this study.

176 al., 2022). Sundsvall is located at a similar latitude as Hankasalmi (HAN) station. Ef-
 177 fects were also seen in the southern hemisphere. A station in southern New Zealand re-
 178 ported enhanced GIC levels on 7-8 September 2017 (Clilverd et al., 2018). At high lat-
 179 itude magnetometer stations in Fennoscandia, we saw larger time derivative values of
 180 the horizontal magnetic field, $d\mathbf{H}/dt$, than during the Halloween event. The magnetic
 181 north component (X-component) measurements during the studied period are shown in
 182 Figure 2, right panel. These magnetograms show that the most intense variations were
 183 observed north of Nurmijärvi (NUR).

184 The original reason for studying the Halloween and 2017 storms specifically, was
 185 an observation that the maximum values of $d\mathbf{B}/dt$ of the September 2017 event exceeded
 186 those of the Halloween storm at high latitudes of the Fennoscandian mainland. This raises
 187 the question of why the September 2017 event did not reach or exceed the magnitude
 188 of the Halloween storm elsewhere.

189 2.2 Methods

190 We utilize solar wind measurements, ground-based magnetometer data, and results
 191 of 3D geoelectric field modeling. We focus on Fennoscandia, where an extensive cover-
 192 age of ground-based magnetometer data of both events (Dimmock et al., 2019; Juusola,
 193 Viljanen, Dimmock, et al., 2023) and detailed ground conductivity models are available
 194 (Korja et al., 2002). Using 3D induction simulations, we have a controlled physical model
 195 providing the geoelectric field related to geomagnetic variations. We analyse magnetic
 196 field variations, their time derivatives, and the geoelectric field to obtain a comprehen-
 197 sive view of the events from the GIC perspective. We apply methods similar to Juusola,
 198 Viljanen, Dimmock, et al. (2023) but as an addition, include the modeled geoelectric field.

199 The Halloween and the September 2017 events are first compared by simply tak-
 200 ing the ratio of the highest values for measured $d\mathbf{H}/dt$ and modeled horizontal geoelec-
 201 tric field. The time derivative of the horizontal geomagnetic field, \mathbf{H} , is given by:

$$d\mathbf{H}/dt = \frac{dB_x}{dt}\hat{\mathbf{e}}_x + \frac{dB_y}{dt}\hat{\mathbf{e}}_y \quad (2)$$

202 where B_x is the northward and B_y is the eastward component of the geomagnetic field.
 203 We also show plots utilizing the 2D Spherical Elementary Current System (SECS) method,
 204 described by Vanhamäki and Juusola (2020). With this method, we can calculate the

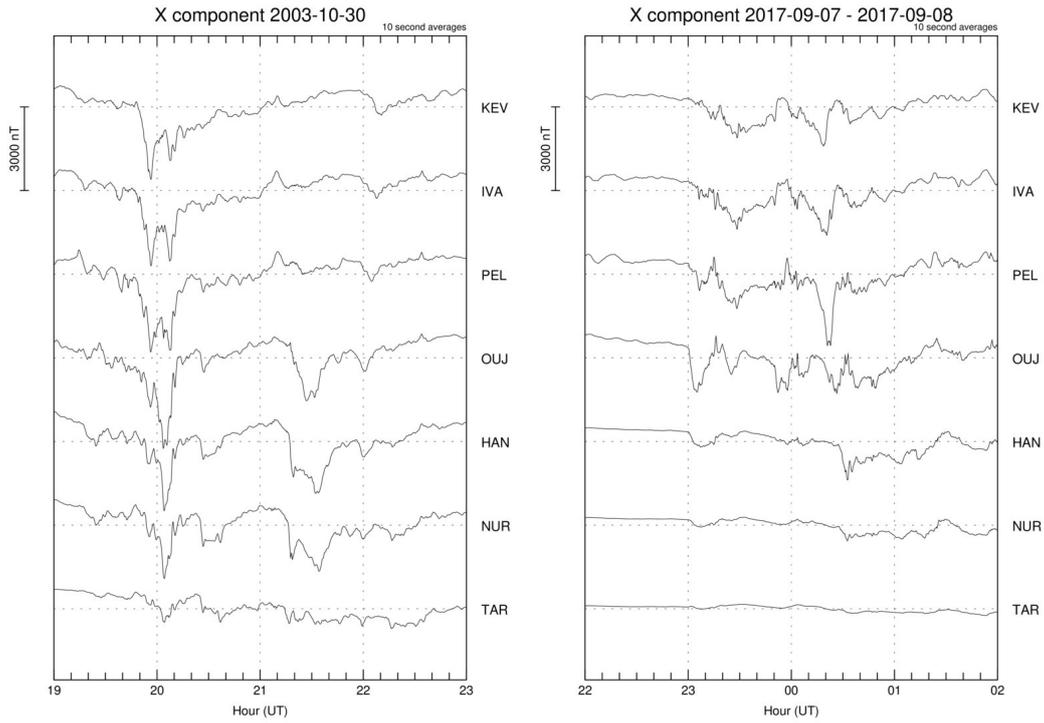


Figure 2. Measured geomagnetic north component (X-component) at seven magnetometer stations during 4 hr of the Halloween event (left panel) and the 2017 storm (right panel). In the 2003 storm we see a dip of almost 4000 nT in the X-component of Oulujärvi (OUJ) station. Also, Tartu (TAR) station shows moderate disturbances. In the case of the 2017 storm, we see a dip of over 2000 nT at Pello station (PEL), but very limited effects in Tartu (TAR) station. Figures retrieved from *IMAGE Magnetometer network* (2023).

205 equivalent external (ionospheric) and internal (telluric) currents and the corresponding
 206 ground magnetic field.

207 The horizontal geoelectric field, \mathbf{E}_h , is given by:

$$\mathbf{E}_h = E_x \hat{\mathbf{e}}_x + E_y \hat{\mathbf{e}}_y \quad (3)$$

208 where E_x and E_y are the north- and eastward components of the geoelectric field, re-
 209 spectively.

210 It is convenient to use the local plane wave approximation, which implies that the
 211 source of the electromagnetic induction is locally spatially uniform, for the geoelectric
 212 field calculation at IMAGE magnetometers' locations. Plane wave assumption allows re-
 213 searchers to relate the surface horizontal frequency-domain geoelectric field with the sur-
 214 face horizontal frequency-domain magnetic field at point \mathbf{r} through an MT impedance
 215 (Berdichevsky & Dmitriev, 2008)

$$\mathbf{E}_h^{pw}(\mathbf{r}, \omega) = \frac{1}{\mu_0} Z(\mathbf{r}, \omega) \mathbf{H}^{pw}(\mathbf{r}, \omega), \quad Z(\mathbf{r}, \omega) = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}, \quad (4)$$

216 where μ_0 is the magnetic permeability of free space.

217 Note that even though in reality the source of the ground electromagnetic field is
 218 always laterally variable, previous studies (Marshalko et al., 2021, 2023) demonstrated
 219 that 3-D electromagnetic modeling in combination with the local plane wave approxi-
 220 mation produces reasonable geoelectric field in the Fennoscandian region.

221 The geoelectric field in this paper is simulated as follows:

- 222 1. 3D electromagnetic forward modeling is carried out via PGIEM2G code with two
 223 (laterally uniform) plane wave sources for the SMAP (Korja et al., 2002) conduc-
 224 tivity model (the variant of the model which was previously used by Marshalko
 225 et al. (2021, 2023); Kruglyakov et al. (2022, 2023)) and an underlying 1D conduc-
 226 tivity profile from Kuvshinov et al. (2021) at fast Fourier Transform (FFT) fre-
 227 quencies ranging between $\frac{1}{L}$ and $\frac{1}{2\Delta t}$, where L is the length of the (input) mag-
 228 netic field time series and Δt is the sampling rate of this time series. 3D MT impedances
 229 $Z(\mathbf{r}, \omega)$ are then calculated for each FFT frequency ω .
- 230 2. Time-varying horizontal magnetic field $\mathbf{H}^{obs}(\mathbf{r}, t)$ observed by magnetometers is
 231 converted from the time to frequency domain using FFT.
- 232 3. Further, the horizontal geoelectric field is calculated for each frequency and each
 233 magnetometer \mathbf{r} as

$$\tilde{\mathbf{E}}_h^{pw}(\mathbf{r}, \omega) = \frac{1}{\mu_0} Z(\mathbf{r}, \omega) \mathbf{H}^{obs}(\mathbf{r}, \omega). \quad (5)$$

- 234 4. Finally, an inverse FFT is performed for the frequency-domain geoelectric field to
 235 obtain the geoelectric field in the time domain.

236 Note that in order to avoid an artificial amplification of the geoelectric field at the
 237 ends of 4-hr time intervals due to the so-called Gibbs effect, we perform geoelectric field
 238 calculation for $L = 8$ hr time intervals (2003-10-30 17:00 - 2003-10-31 01:00 UT, 2017-
 2017-09-07 20:00 - 2017-09-08 - 04:00 UT). The sampling rate of the input magnetic field time
 series is $\Delta t = 10$ s.

239 Usefulness of the modeled geoelectric field is highly dependent on the ground con-
 240 ductivity, which is not perfectly known. This leads to a considerable uncertainty of the
 241 geoelectric field amplitudes, which can vary a lot in short (tens of kilometers) length scales
 242 (Marshalko et al., 2023), whereas the magnetic field changes much less. A possible way

Parameter	Halloween event	2017 event
Solar wind speed [km/s]	2240	820
Kp	9	8
D _{st}	-383	-150
GIC [A]	57.0	30.1
Boundary [° MLAT]	49.4	55.8

Table 2. Geomagnetic and solar wind indices and approximate location of the auroral oval boundary during the peak of the Halloween and the September 2017 geomagnetic storms. Values retrieved from King and Papitashvili (2020), Skoug et al. (2004), Matzka et al. (2021), Hajra et al. (2020).

243 to circumvent this issue is to use relative values, i.e., to perform a comparison with re-
 244 spect to a benchmark event.

To get a visually convenient time series plots of $d\mathbf{H}/dt$ and the electric field, normalization of data for each station was carried out in the following way:

$$f_n(t) = \frac{|f(t)|}{\max(|f(T)|)}, \quad (6)$$

245 where $f(t)$ is a single value of the time series f (e.g. the horizontal geoelectric field, \mathbf{E}_h)
 246 at time t , $f_n(t)$ is the corresponding normalized value, and $\max(|f(T)|)$ is the maximum
 247 value of the whole 4-hr period at a specific station.

One more measure of the strength of a magnetic storm is the extent of the auroral oval. This region is located near the border of the open and closed magnetospheric field lines, and gets the most intense particle precipitation from the magnetosphere. There have been studies, e.g. Xiong et al. (2014) and Blake et al. (2021), that provide estimates of the oval boundaries as a function of the D_{st}-index. Blake et al. (2021) states that the equatorward boundary of the oval is given by:

$$\text{Boundary(MLAT)} = 36.7 - \frac{9400}{D_{st} - 342}, \quad (7)$$

248 where MLAT is the magnetic latitude, and this applies for condition $-1150 < D_{st} <$
 249 0 nT.

250 Maximum values of some indices and parameters of the two storms obtained based
 251 on solar wind data from OMNIweb (King & Papitashvili, 2020), estimates from Skoug
 252 et al. (2004) and the equation above are listed in the Table 2.

253 3 Results

254 Figure 3 shows the comparison of the largest values of the measured $d\mathbf{H}/dt$ and
 255 the modeled horizontal geoelectric field. We see that for higher latitudes both ratios (\mathbf{E}_h
 256 and $d\mathbf{H}/dt$) are larger. The ascending trend is clear for $d\mathbf{H}/dt$, but a bit less obvious
 257 for \mathbf{E}_h . For example, at Kilpisjärvi station (KIL), the ratio of $d\mathbf{H}/dt$ is greater than 1
 258 and the ratio of \mathbf{E}_h is slightly less than 1, meaning that at KIL the 2017 event was ac-
 259 tually stronger with respect to the measured magnetic field time derivative and almost
 260 similar with respect to the magnitude of \mathbf{E}_h . Generally ratios of $d\mathbf{H}/dt$ are larger than
 261 those of \mathbf{E}_h , and the stations Muonio (MUO) and Sørøya (SOR) clearly stand out with

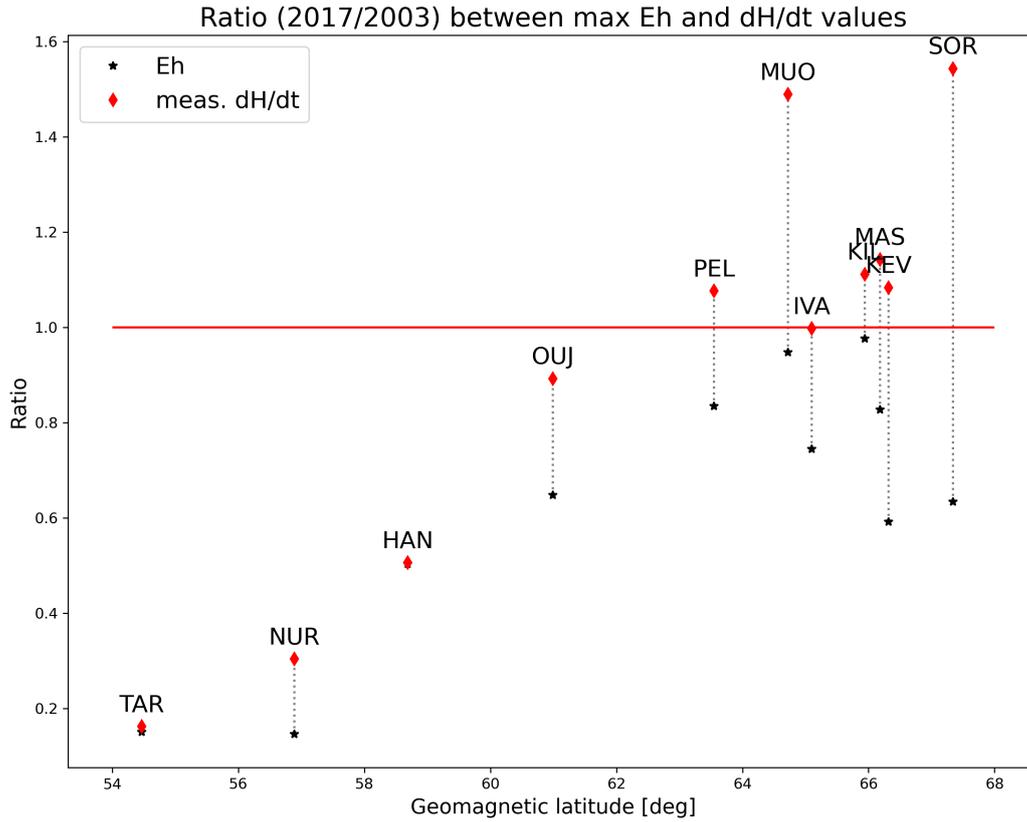


Figure 3. Ratio of the maximum values of the modeled horizontal geoelectric field, E_h (black stars), and measured dH/dt (red diamonds) during the studied periods of the Halloween and September 2017 events. Ratios are shown as functions of the geomagnetic latitude (CGM for year 2001). The red line emphasises ratio equal to unity, i.e. the same magnitude for both events. For visual clarity, black stars and red diamonds corresponding to a specific station are connected by a dotted line.

262 their maximum $d\mathbf{H}/dt$ values. Another interesting feature is the descending ratios of \mathbf{E}_h
 263 at latitudes higher than MUO station (CGM latitude 64.7°).

264 Figure 4 (a) and (b) show normalized values of the magnitude of the horizontal geo-
 265 electric field at 11 stations. In this plot, we can easily see if the peaks in the horizon-
 266 tal geoelectric field (\mathbf{E}_h) occur at the same times at different locations. For the Halloween
 267 storm (a), we see that the peak values for all stations are concentrated at around 20:00
 268 UT ± 10 min. There is also a secondary peak at HAN, NUR, and TAR stations at 21:20
 269 UT which is not so clearly visible in the northern stations. In the case of the 2017 storm
 270 (b), we see that the \mathbf{E}_h enhancements are more spread out between 23:00 UT and 00:30
 271 UT. Stations OIJ, HAN and TAR show a sharp rise in \mathbf{E}_h at 23:00, but this is not vis-
 272 ible at other stations. In a similar way, Figure 4 (c) and (d) show the normalized values
 273 of the measured horizontal magnetic field time derivative. Maximum value for each
 274 station is marked with a red triangle marker. The behavior of $d\mathbf{H}/dt$ is quite similar to
 275 that of \mathbf{E}_h . The peak values at different stations are more concentrated in the 2003 event
 276 than in the 2017 event. In the next few figures, we focus on the exact moments of these
 277 most intense values and use equivalent currents to visualize the ionospheric and induced
 278 parts of the horizontal magnetic field and currents.

279 Figure 5 shows the temporal development of different magnetic field parameters.
 280 Figures 6-9 demonstrate ionospheric and telluric currents and external/internal magnetic
 281 fields in the Fennoscandian region. All the figures show, side by side, the 2003 and 2017
 282 events at the moment of maximum amplification of each quantity ($d\mathbf{H}/dt$, \mathbf{E}_h) at Muo-
 283 nio (MUO) station for comparison. MUO was one of the stations where the 2017 storm
 284 caused a significantly stronger $d\mathbf{H}/dt$ than the Halloween event (see Figure 4 (c),(d)).

285 Figure 6 shows snapshots of the time derivatives of external currents and horizon-
 286 tal magnetic field at MUO station, for both events, at moments of maximum $d\mathbf{H}/dt$. In
 287 the right panel (2017 storm), we see that there is a strong local intensification of the ex-
 288 ternal current, $d\mathbf{J}/dt$, to the west of MUO station. In terms of intensity, this is about
 289 twice as strong as during the Halloween event. Maximum values are shown in the text
 290 box in the top left corner of each plot. During the Halloween event, the time derivative
 291 of the external current shows intensification in a much wider area south of MUO. Sim-
 292 ilarly, with the internal current in Figure 7 (right panel), we see a very localized pattern
 293 around MUO, PEL and SOD stations, with strong values of the internal $d\mathbf{H}/dt$.

294 Figure 8 shows snapshots of the time derivatives of the external currents and hori-
 295 zontal magnetic field at MUO station, during both of the studied storm periods, at mo-
 296 ments of maximum \mathbf{E}_h . The horizontal geoelectric field values at MUO station were slightly
 297 weaker during the 2017 event. In Figure 8, we see quite similar patterns between the 2003
 298 and 2017 events. The strongest enhancement in the external $d\mathbf{H}/dt$ is seen approximately
 299 between MUO and RAN stations. Figure 9 shows plots of the internal $d\mathbf{J}/dt$ and $d\mathbf{H}/dt$.
 300 There we see again a very localized enhancement near Kevo (KEV) station during the
 301 Halloween event (left panel). During the 2017 snapshot (right panel) the internal cur-
 302 rents have quite a complex structure, with one clear hot spot near KIL station.

303 Finally, we briefly look at the approximate location of the auroral oval during these
 304 two storms. The latitudinal range of the auroral oval also increases with stronger geo-
 305 magnetic activity. According to Xiong et al. (2014), the quiet time ($K_p = 1-2$) range
 306 of the oval is a little less than 10° . During geomagnetic storms ($K_p > 4$), the extent
 307 of the oval is up to 15° in latitude. Based on these estimates, during the studied 4-hr
 308 period, the oval was, on average, located between 54 and 69°N MLAT during the Hal-
 309 loween event, and between 60 and 75°N in MLAT during the 2017 storm. During the
 310 Halloween event, the auroral oval was about 6° closer to the equator than during the Septem-
 311 ber 2017 event.

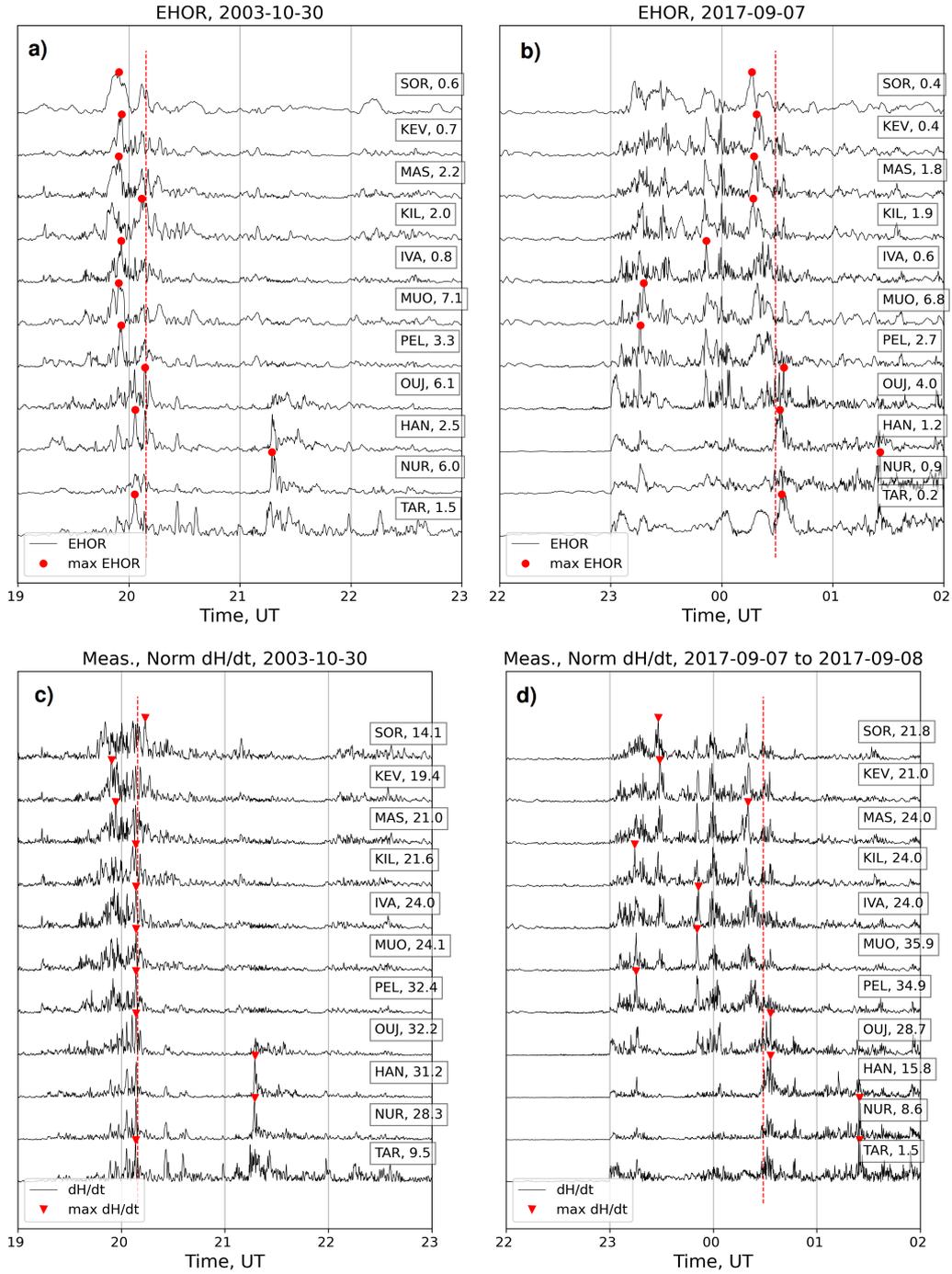


Figure 4. Normalized values of the modeled E_h (a),(b) and measured dH/dt (c),(d) magnitude for 11 stations organized by descending geomagnetic latitude. The left panel shows a 4-hr period of the Halloween event and the right side 4 hr of the September 2017 event. The red markers show the time at which the the maximum value occurred. The vertical red dashed line shows the time of the Malmö blackout during the Halloween event and the power transformer issues reported during the September 2017 storm near Sundsvall, Sweden. The stations' name abbreviations are shown in text boxes on the right in each plot. The text box also shows the maximum value [V/km] in (a),(b) and nT/s in (c),(d) for each station.

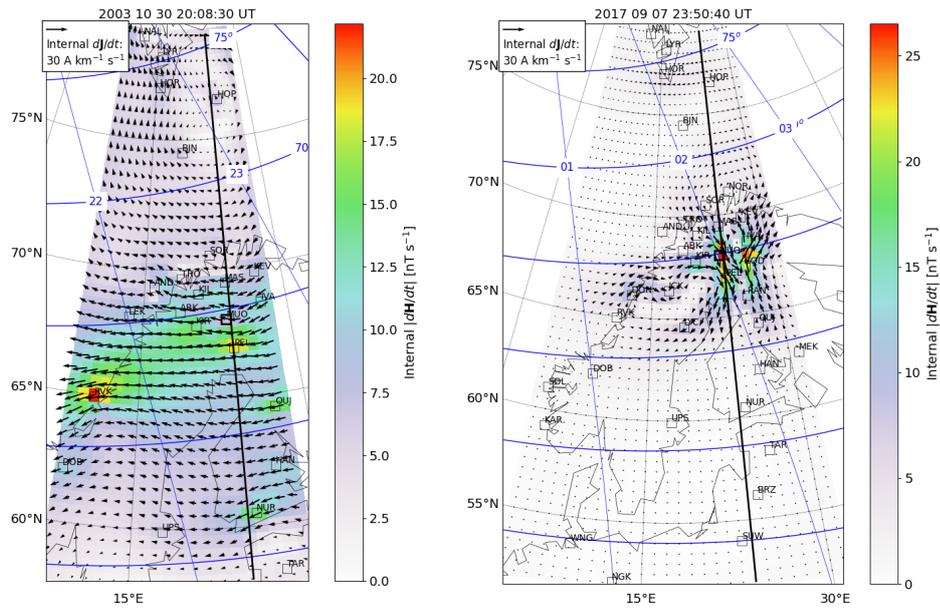


Figure 7. The same as Figure 6 except that the arrows show the time derivative of the induced (internal) equivalent current density instead of the ionospheric equivalent current density and the color scale shows the time derivative of the internal part of the horizontal ground magnetic field.

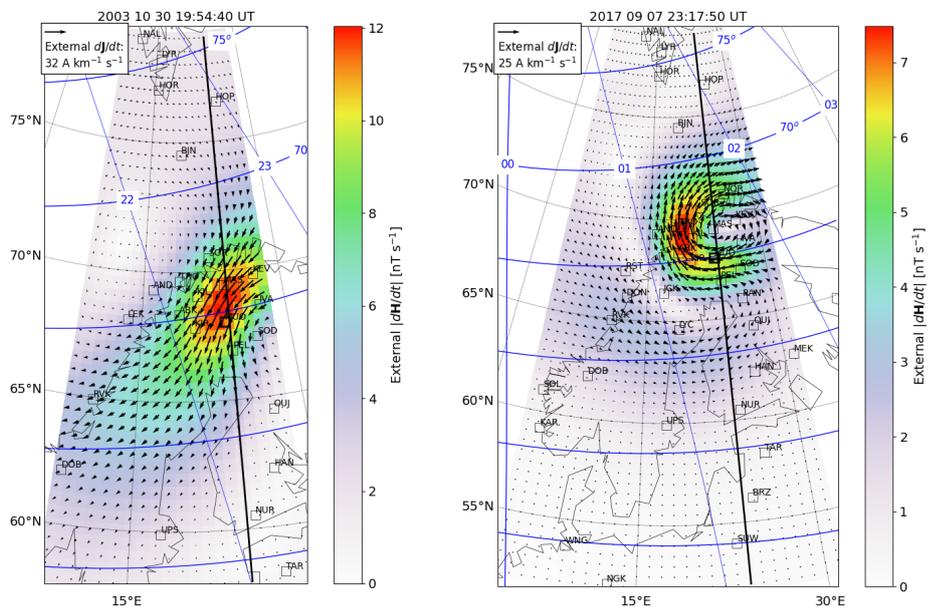


Figure 8. The same as Figure 6 except for the time of the \mathbf{E}_h peak at MUO instead of the time of the $d\mathbf{H}/dt$ peak.

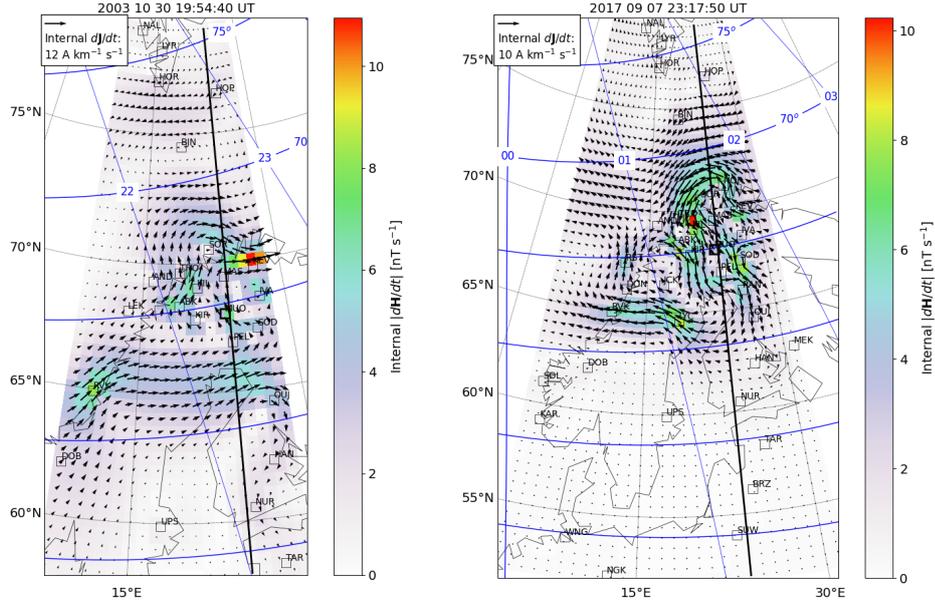


Figure 9. The same as Figure 7 except for the time of the \mathbf{E}_h peak at MUO instead of the time of the $d\mathbf{H}/dt$ peak.

4 Discussion

In this study, we compared 4-hr periods of the extreme Halloween storm and the severe September 2017 storm. With regards to solar wind parameters and magnetic indices, the Halloween event was clearly stronger. However, comparison of the ground based magnetometer measurements shows that the 2017 storm was stronger at high latitudes and produced very high GICs. We observed station-specific enhancements in the electric and magnetic field magnitudes, and we used equivalent currents and ground conductivity mapping to help explain the ionospheric and telluric sources for these very localized enhancements. We start the discussion with the ionospheric sources.

The latitudinal extension of the auroral oval is related to the strength of magnetospheric disturbance. Based on estimates of Blake et al. (2021) and Table 2, we conclude that the auroral oval was around 6 degrees lower in latitude during the Halloween storm. Also, in Figure 5 (left panel, second plot from the top) we see that the enhancement of the external \mathbf{H} during the Halloween storm begins in the north (north of MUO station) and then moves equatorward (from 70 to 60° N) during the next tens of minutes. In Figure 5 (right panel, second plot from top) we see that the enhancement during the 2017 storm remains at high latitude, between 65 to 70° N. These observations indicate that the strongest ionospheric currents during the Halloween storm were located south of the stations where we saw the largest $d\mathbf{H}/dt$ values in the 2017 storm.

Another observation we made regarding the latitudinal differences is related to Figure 3. There was a clear ascending trend in the ratios of the parameters up until MUO station (CGM latitude 64.7°), meaning that with increasing latitude, the ratios of $d\mathbf{H}/dt$ and \mathbf{E}_h seemed to grow stronger in favour of the 2017 event. This is expected since the large-scale ionospheric currents were located at higher latitudes in the 2017 event. At stations IVA, MAS, KEV, and SOR something more complicated happens. The ratios of the two parameters start to drift apart, so that $d\mathbf{H}/dt$ keeps increasing but \mathbf{E}_h begins to decrease. In other words, the geoelectric field at high latitudes, at most stations,

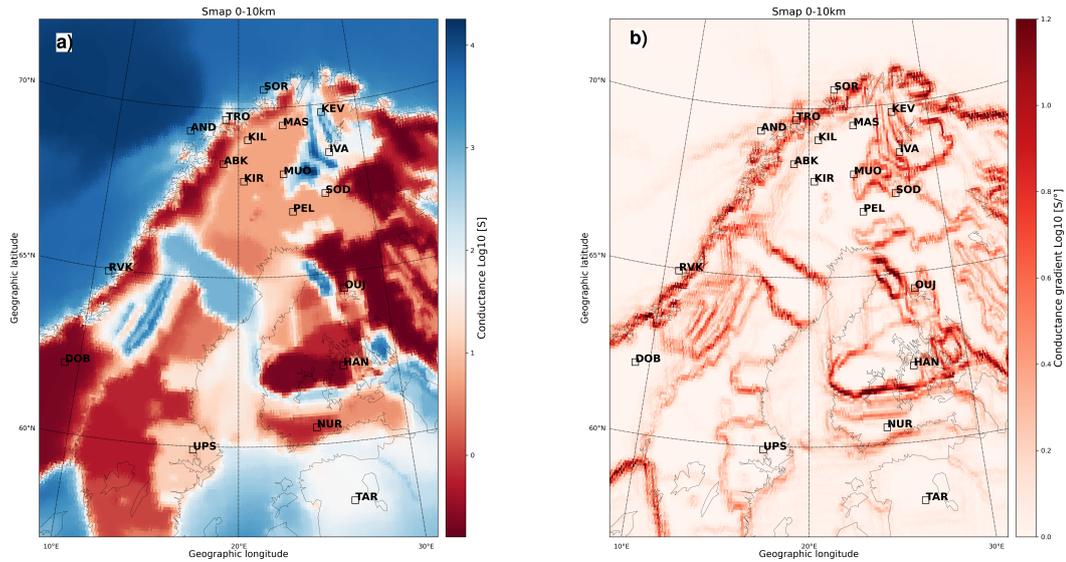


Figure 10. (a) Ground conductance based on SMAP 0-10 km data (Korja et al., 2002). Conductance is higher in the sea but also in some land areas, like the Finnish Lapland. A few IMAGE station locations and name abbreviations are marked on the map. (b) Horizontal gradient of the ground conductance based on SMAP 0-10 km data. Sharp gradients are visible along the Norwegian coastline but also inland. Several Finnish stations, e.g. SOD, MUO and KEV, are located on top of strong horizontal conductance gradients.

339 is weaker during the 2017 event, even though it has a stronger ionospheric driver. The
 340 explanation may be related to the conductivity structures of the ground and the orientation
 341 of the ionospheric currents.

342 The geoelectric field is enhanced or weakened depending on the orientation of the
 343 ground conductivity gradients in relation to the ionospheric currents. The stations SOR,
 344 KEV, and MUO, which stood out in the Figure 3, are located near areas of high con-
 345 ductivity or quite sharp conductivity gradients. Figure 10 demonstrates the distribution
 346 of conductance (depth-integrated conductivity) and the horizontal conductance gradi-
 347 ent in the upper layer of the SMAP model. Different kind of behavior of the geoelectric
 348 field at stations SOR and KEV is probably related to the higher ground conductivity
 349 which is able to dissipate the charges quicker. This weakens the geoelectric field in the
 350 region. The case of MUO station is a bit different. The behavior of \mathbf{E}_h at this location
 351 can be related to the nearby sharp conductivity gradient. It may be optimal in creat-
 352 ing a localized accumulation of charges which amplifies the geoelectric field together with
 353 ionospheric currents during the 2017 event. Also, if we look at the maximum absolute
 354 \mathbf{E}_h values at MUO station during both events (7.1 V/km in 2003 and 6.8 V/km in 2017,
 355 Figure 4 (a),(b)), the station clearly has the highest values compared to all other sta-
 356 tions.

357 Lastly, we experimented with different conductivity models effect on the simulated
 358 \mathbf{E}_h . We compared geoelectric fields calculated using 3D and 1D MT impedances. In 1D
 359 simulations, the Earth's crust is considered to have uniform electrical properties hori-
 360 zontally, and its properties change only in vertical direction. For each magnetometer lo-
 361 cation, we used corresponding 1D conductivity profiles from the 3D model of Fennoscandia
 362 to calculate local 1D MT impedances using a recursive formula for surface impedance
 363 (see, e.g., Trichtchenko and Boteler (2002) for more information). Results are shown in

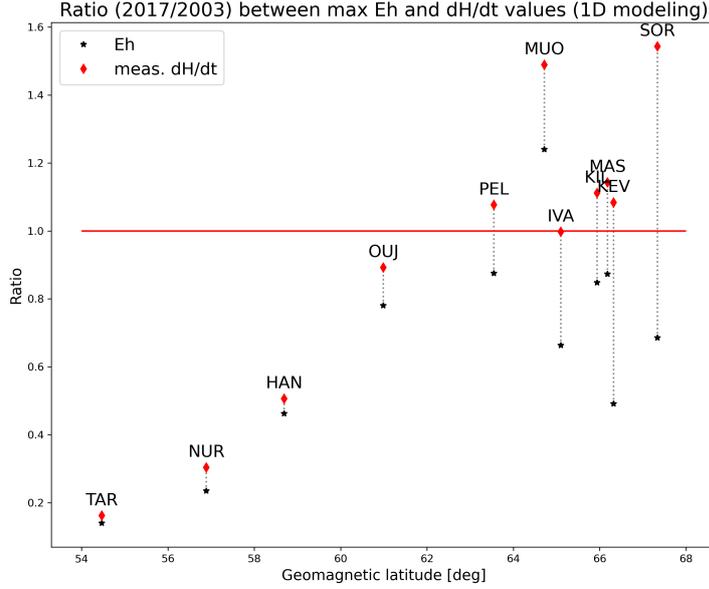


Figure 11. Same as Figure 3 but the geoelectric field modeling results are obtained using 1D MT impedances.

364 Figure 11. We found that there was no significant difference between ratios acquired using
 365 using 3D and 1D MT impedances for considered locations. The largest difference was discovered
 366 discovered for MUO station, which showed much larger \mathbf{E}_h values for the 2017 event. This
 367 supports the hypothesis of significance of the ground conductivity gradient alongside with
 368 optimally oriented ionospheric currents. To summarize, we believe that the generally smaller
 369 \mathbf{E}_h values at high latitudes are related to higher ground conductivity. MUO station is
 370 different because of the sharp conductivity gradient. We think that this is an interesting
 371 discovery and would like to analyse it more in future studies. Next we discuss the
 372 peaks in the normalized $d\mathbf{H}/dt$ plots and use the 2D SECS plots of the external and internal
 373 currents to explain these peaks.

374 Strong external $d\mathbf{H}/dt$ tend to occur when there is an intense ionospheric current
 375 that is abruptly modified (Juusola, Viljanen, Dimmock, et al., 2023). During the Hal-
 376 loween event $d\mathbf{H}/dt$ peak (Figure 4 (c), at 20:08:30 UT), an intense, latitudinally extended
 377 westward electrojet (WEJ), disappeared. The $d\mathbf{J}_{eq}/dt$ pattern (see Figure 6, left panel)
 378 describes the abrupt stopping of the WEJ current. During the 2017 storm, $d\mathbf{H}/dt$ peak
 379 (23:50:40 UT), there is a localized $d\mathbf{J}_{eq}/dt$ pattern caused by an eastward drifting chan-
 380 nel of northward equivalent current.

381 The differences in the external $d\mathbf{H}/dt$ at MUO during the 2003 and 2017 peaks were
 382 small, only a few nT/s (Figure 6). The most significant difference was in the internal $d\mathbf{H}/dt$,
 383 which was much stronger in the case of the 2017 event (Figure 7). The external $d\mathbf{J}_{eq}/dt$
 384 pattern over MUO was east-west oriented in the 2003 event and north-south oriented
 385 in the 2017 event (Figure 6). Clearly, the north-south orientation was optimal for induc-
 386 ing strong currents in the local north-south aligned conductivity structure (Figures 7,10).
 387 Thus, the reason why the 2017 event was stronger than the 2003 event at MUO was an
 388 intense time derivative of the external magnetic field that was optimally oriented to in-
 389 duce strong telluric currents in the local conductivity structure. The reason why intense
 390 $d\mathbf{H}/dt$ disturbances were not observed at the lower latitude IMAGE stations in 2017,
 391 was that the ionospheric currents did not expand that far while in 2003 they did. Next
 392 we focus on the normalized \mathbf{E}_h plots.

393 The 2003 \mathbf{E}_h peak (19:54:40 UT) seems to be caused by a southward drifting WEJ
 394 (Figure 8). The peak occurs when the center of the WEJ passes the station. This ap-
 395 proximately north-east to south-west oriented enhancement together with roughly par-
 396 allel conductivity gradient seems to be optimal in creating strong \mathbf{E}_h . The 2017 \mathbf{E}_h peak
 397 (Figure 4 (b), 23:17:50 UT) is caused by a southward drifting WEJ with a vortical $d\mathbf{J}_{eq}/dt$
 398 pattern (Figure 8). The peak occurred when the center of the WEJ passed the station,
 399 i.e., the station was located approximately at the center of the $d\mathbf{J}_{eq}/dt$ vortex. The vor-
 400 tical $d\mathbf{J}_{eq}/dt$ pattern was caused by the drift: it describes how the WEJ current weak-
 401 ens at the northward flank of the WEJ and intensifies at the southward flank.

402 Both the external and internal $d\mathbf{H}/dt$ amplitudes were clearly weaker during the
 403 \mathbf{E}_h peaks than during the $d\mathbf{H}/dt$ peaks (Figures 6-9). The north-east to south-west ori-
 404 entation of the $d\mathbf{J}_{eq}/dt$ together with the approximately parallel ground conductivity
 405 structure seems to enhance \mathbf{E}_h . Also, the vortical $d\mathbf{J}_{eq}/dt$ pattern that occurred dur-
 406 ing the 2017 \mathbf{E}_h peak may be optimal for creating intense \mathbf{E}_h . This happens due to the
 407 intense dB_z/dt at the center of the vortex that creates a strong induced divergence-free
 408 geoelectric field around it, for which $d\mathbf{H}/dt$ is a proxy (see Eq. 1). Such patterns also
 409 occur at substorm onsets (Juusola, Viljanen, Partamies, et al., 2023). To summarize our
 410 observations of the 2D SECS plot, we discovered that the ionospheric current structures
 411 were very different during the two magnetic storm. Still they caused geomagnetic and
 412 geoelectric disturbances of similar magnitude. This emphasizes the complicated inter-
 413 action of the ionospheric currents and the ground conductivity. The ionospheric currents
 414 alone can not explain the localized peaks in the geoelectric field.

415 Another relevant study on the September 2017 storm was published by Wawrzaszek
 416 et al. (2023). They use IMAGE magnetometer data to calculate the geoelectric field with
 417 1D ground conductivity models and utilize the GeoElectric Dynamic Mapping (GEDMap)
 418 to construct a spatial map of the geoelectric field. Their results on \mathbf{E}_h modeling are in
 419 agreement with our study, despite some differences in the peak \mathbf{E}_h time and magnitude.
 420 These differences are to be expected considering the different methods used. Next, we
 421 briefly describe the main sources of error in this study.

422 The main sources of error come from the SECS analysis and uncertainties in the
 423 geoelectric field modeling. The ground conductivity model used for the geoelectric field
 424 simulation is imperfect and could be improved, as stated by Kruglyakov et al. (2022).
 425 There is considerable uncertainty of the geoelectric field amplitudes, which can vary a
 426 lot in short (tens of kilometers) length scales (Marshalko et al., 2023). A possible way
 427 to circumvent this issue is to use relative values, i.e., comparison with respect to a bench-
 428 mark event. We have used a ratio of the maximum \mathbf{E}_h values (Figure 3), to minimize
 429 the effect of the uncertainty of the absolute values. However, assessing the amplitude un-
 430 certainty is difficult. This aspect is something to keep in mind when interpreting the re-
 431 sults. For the purposes of our study, the timing of the \mathbf{E}_h peaks is more relevant. Com-
 432 paring with the study of Wawrzaszek et al. (2023), our modeled \mathbf{E}_h time series look quite
 433 similar. Uncertainties associated with the SECS method are thoroughly discussed and
 434 deemed small in previous studies (Juusola et al. (2020), Kellinsalmi et al. (2022)).

435 Our study considered two major geomagnetic storms, but its results are not lim-
 436 ited to these events. The ionospheric drivers are similar at equal geomagnetic latitudes
 437 (Juusola, Viljanen, Dimmock, et al., 2023). Balan et al. (2021) also found an UT-dependence
 438 of geomagnetic storms. So, our results can be extrapolated to apply for a wider set of
 439 space weather events. On the other hand, the geoelectric field depends strongly on the
 440 ground conductivity, leading to very different configurations at different regions even if
 441 the ionospheric sources are identical. Areas of sharp ground conductivity gradients (e.g.
 442 coastline) seem especially vulnerable to GIC, as also noted by Love et al. (2022) in the
 443 case of North-America. In Finland, the ground is also highly heterogeneous (Korja et
 444 al., 2002). This makes certain in-land areas more susceptible to geoelectric hazards. Over-
 445 all, this gives an idea for further investigation of the variability of the geoelectric field

446 at a given location under the influence of different ionospheric drivers. One future re-
447 search idea is to extend these results to a deeper analysis of a larger set of storms. For
448 an end-user, such as a power grid operator, it could be quite useful to know how much
449 larger or smaller a given event is compared to a benchmark. This can be figured out, for
450 example, by comparing the maximum geoelectric field values. However, it may also be
451 relevant to know whether there are only a few large geoelectric field spikes or more mod-
452 erate but longer-term enhancement of the field, possibly leading to different impacts (see,
453 e.g., Lewis et al. (2022); Reiter et al. (2021)). Another idea is to study the effects of lo-
454 cation using one ionospheric driver and placing it at slightly different locations above the
455 region under investigation. This way we could understand how much the geoelectric field
456 varies at selected points when the location of the external source changes. This is a fun-
457 damental question of practical significance concerning GIC forecasts.

458 5 Conclusions

459 Our study compares two major geomagnetic storms caused by strong Earth-directed
460 CMEs. This study reveals station-specific differences in the intensity of the magnetic field
461 and geoelectric field variations. We observed localized magnetic and geoelectric field en-
462 hancements at high latitudes in the Fennoscandian region during the 2017 event, which
463 exceeded (in the case of magnetic field time derivative) or were similar (in the case of
464 the geoelectric field) to the values observed during the Halloween event. This is inter-
465 esting because in general terms, e.g. magnetic indices, the Halloween event was clearly
466 stronger.

467 The differences between the effects of these two storms at high latitudes are mostly
468 explained by the ionospheric response to the CME arrival. For example, the location of
469 the auroral oval and the abrupt changes in the ionospheric currents and vortical current
470 structures can explain some of the local enhancements. Also the ground conductivity struc-
471 ture has a major impact on the local geomagnetic response, especially in the very het-
472 erogeneous structure in Finland. These findings help in explaining the localized peaks
473 in $d\mathbf{H}/dt$ and \mathbf{E}_h . Our results give an estimate of other similar storm impacts on the
474 geoelectric field and ultimately help to understand the very localized nature of GIC. These
475 results also assist in understanding and making local risk assessments of induced cur-
476 rents. This study is yet another step towards better space weather preparedness.

6 Open Research

Data of geomagnetic field components and geomagnetic indices are from <http://space.fmi.fi/image/> and <https://wdc.kugi.kyoto-u.ac.jp/dst/dir/>. Geomagnetic indices are available at <https://supermag.jhuapl.edu/indices>. The solar wind satellite observations are from the OMNIWeb service (King & Papitashvili, 2020). The SMAP model (Korja et al., 2002) is available at the European Plate Observing System (EPOS) portal via EPOS (2019) (stored in JSON format and compressed with bzip2) under CC BY-NC 4.0. PGIEM2G 3-D EM forward modeling code is developed openly at Gitlab and available at Kruglyakov (2022) under GPLv2. GIC data are available at the website of the Space and Earth Observation Centre of the Finnish Meteorological Institute (FMI) via FMI (2023) under CC BY 4.0.

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