

Average Ionospheric Electric Field Morphologies during Geomagnetic Storm Phases

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Key Points:

- Using Principal Component Analysis on SuperDARN data we identify the primary contributing basis convection patterns to ionospheric electric field morphologies during geomagnetic storm times
- The first 6 eigenvectors of the analysis provide over 80% of the total variance, excluding expansions and contractions of the pattern
- The main changes in the electric field that are ordered by storm phase are an enhancement of the convection potential and a motion towards later local times of the dayside convection throat

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Abstract

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Plain Language Summary

During geomagnetic storms we see extreme changes to Earth's magnetic field structure. This is mainly due to an enhancement of electrical currents in geospace. This changes the Earth's magnetic environment, due to which we also see changes in the ionosphere, the layer of charged particles making up the top of the atmosphere where the current systems close. A geomagnetic storm has three phases: the initial phase, which is a precursor to the storm, the main phase where the current systems enhance abruptly, and a recovery phase. In this paper we use a technique commonly used for pattern recognition to radar data to work out the changes to the average ionospheric flows. We find that most of the changes happen on the dayside. We suggest this means the average storm dynamics are driven directly by the solar wind.

1 Introduction

Geomagnetic storms are understood to be enhancements in the Earth's ring current (Akasofu & Chapman, 1961; Gonzalez et al., 1994). This westward-flowing current causes large-scale deviations in the Earth's magnetic field, such that they can be measured on the ground (e.g. Graham, 1724; Chapman & Dyson, 1918; Chapman & Ferraro, 1930; Chapman & Bartels, 1940; Singer, 1957; Daglis et al., 1999). At mid-latitudes, this effect is strongest and registers as a southward deviation in the horizontal north-south magnetometer measurements. These measurements are often combined to give a magnetic index, which can be used to identify storms, such as the Dst index (Sugiura, 1964) or Sym-H index (Iyemori, 1990).

Notable effects of geomagnetic storms not only include changes in the global magnetic field and strengthening of the magnetospheric and ionospheric current systems, but also changes in the ionosphere, such as higher measured densities in the total electron content in the mid-to-low latitudes, which can drift and enhance ionospheric densities at higher latitudes to form storm-enhanced densities (SEDs) and thus also enter the polar cap, forming tongues-of-ionization (TOIs) (e.g. Foster, 1993; Huba et al., 2005; Lin et al., 2005; Mannucci et al., 2008; Thomas et al., 2013; Zou et al., 2013, 2014, and references therein). SEDs in particular have been linked to equatorward expansion of the convection pattern (Zou et al., 2013, 2014) and it is thus important to understand the high-latitude ionospheric electric field as it evolves throughout geomagnetic storms as it will help us understand plasma transport in the ionosphere and magnetosphere.

Whilst ground magnetometer studies can be used to infer the ionospheric electric field (Kamide et al., 1981), direct measurements of plasma convection can also be utilised to build maps of the high-to-mid latitude ionospheric electric fields (e.g. Hairston & Heelis, 1993; Ruohoniemi & Greenwald, 1996). In a previous study, Walach and Grocott (2019) (from here on referred to as WG19) studied ionospheric measurements from the Super Dual Auroral Radar Network (SuperDARN) during the three phases of geomagnetic storms: the initial, main and recovery phase, identified using Sym-H.

WG19 examined the general trends in the SuperDARN data during geomagnetic storms, such as latitudinal expansion of the ionospheric convection maps, data coverage, data availability, cross polar cap potential (i.e. convection strength), in relation to solar wind and geomagnetic conditions. The study also compared statistically the responses

76 of these measured parameters during geomagnetic storm phases, to periods of disturbed
77 geomagnetic activity, irrespective of storm phase, as well as high solar wind driving when
78 no storms occurred. One of the primary results of this paper was that the storm phases,
79 as well as the ionospheric responses measured by SuperDARN are closely tied to the so-
80 lar wind driving of the system, which matches previous results (e.g. Loewe & Prölss, 1997;
81 Gillies et al., 2011): During the main phase of a geomagnetic storm, higher solar wind
82 driving due to southward interplanetary magnetic field (negative B_Z) enhances the cur-
83 rent systems connecting the ionosphere with the magnetosphere. We thus see a higher
84 cross polar cap potential, as well as an enhanced Sym-H index, matching our understand-
85 ing of how the system works (e.g. Milan et al., 2017). WG19 showed that throughout
86 a geomagnetic storm there is some asymmetry in the two-cell convection pattern mea-
87 sured by SuperDARN, with the dusk cell being much stronger than the dawn cell, as well
88 as changes throughout the storms in the location where the fastest flows are measured
89 in the ionosphere: This is primarily on the dayside, though in the initial and recovery
90 phase the fastest flows are primarily measured in the noon to early morning sectors whereas
91 during the main phase of a storm, this is shifted towards the afternoon sectors. WG19
92 also found that the return flow boundary (the latitudinal location where antisunward
93 flows neighbour the sunward flows) and the Heppner-Maynard boundary (Heppner & May-
94 nard, 1987) (the boundary where the high-latitude ionospheric convection pattern ter-
95 minates) move throughout the storm phases, as does the latitudinal distance between
96 them.

97 Other previous studies using SuperDARN data from geomagnetic storm periods
98 have looked at the number of scatter echoes and line-of-sight velocities in relation to sud-
99 den storm commencements (SSC) and sudden commencements (SC) (e.g. Gillies et al.,
100 2012; Kane & Makarevich, 2010), but without a detailed quantitative analysis of iono-
101 spheric convection morphologies. A further statistical study by (Gabrielse et al., 2019)
102 compared the mesoscale flows measured by SuperDARN during the main phases and re-
103 covery phases, as well as coronal mass ejection (CME) and highspeed stream (HSS) storms.
104 Whilst WG19 did not split the data into the exact same categories, the results broadly
105 agree with these previous studies. Here we only focus on the geomagnetic storm phases
106 to learn about the average ionospheric behaviour. Whilst WG19 answers some basic ques-
107 tions on the morphology and latitudinal extent of ionospheric convection during the phases
108 of a geomagnetic storm, we will examine the morphologies of geomagnetic storms in more

109 detail here. In this paper, we will study these data further to answer the following ques-
110 tion: How do ionospheric convection morphologies change throughout the storm phases?

111 We answer this question by utilising an objective method for dimensionality reduc-
112 tion (Principal Component Analysis (e.g. Joliffe, 2002)), which will tell us what the pri-
113 mary morphologies in the data are with respect to storm phase.

114 **2 Data**

115 There are two primary datasets used in this study: The geomagnetic storm list and
116 the SuperDARN data, which we describe in this section.

117 **2.1 Geomagnetic Storms**

118 The geomagnetic storm list is published by WG19 and can be found in their sup-
119plementary material. It is formed by applying an automatic identification algorithm to
120 the Sym-H index, which reflects enhancements in the global ring current (Iyemori, 1990).
121 The algorithm identifies the initial, main and recovery phases of geomagnetic storms, sim-
122ilar to Hutchinson et al. (2011), which allows us to draw conclusions about the phenom-
123ena associated with the progression of storms. In brief, the initial phase of a geomag-
124netic storm is classified by a positive excursion in the Sym-H index, associated with an
125increase in the Ferraro-Chapman currents along the magnetopause, followed by a decrease
126to below -80 nT during the main phase, where the ring current enhances. The minimum
127in Sym-H coincides with the end of the main phase, which is followed by a gradual in-
128crease to normal values, known as the recovery phase. For further detail, the reader is
129referred to WG19.

130 **2.2 SuperDARN**

131 SuperDARN consists of high-frequency coherent scatter radars built to study iono-
132spheric convection by means of Doppler-shifted, pulse sequences (e.g. Greenwald et al.,
1331995; Ruohoniemi & Greenwald, 1996; Chisham et al., 2007; Nishitani et al., 2019). Mea-
134surements by this large-scale network of radars are used to construct a high-time res-
135olution picture of high-latitude ionospheric convection (Ruohoniemi & Baker, 1998).

136 With the expansion of the SuperDARN network to mid-latitudes, we are able to
137 study the dynamics of the high-to-mid-latitude ionospheric convection with unprecedented

138 coverage (Nishitani et al., 2019). One of the findings by WG19 was that the high-latitude
139 convection maps which can be produced with SuperDARN data can expand to 40° of
140 geomagnetic latitude during disturbed times, which was not accounted for in previous
141 versions of the SuperDARN Radar Software Toolkit (RST versions < 4.2), which had
142 a cut-off of 50° magnetic latitude. The finding of this expansion matches magnetome-
143 ter and spacecraft measurements from previous studies (e.g. Wilson et al., 2001; Kikuchi
144 et al., 2008).

145 The SuperDARN data used here were therefore processed using the Radar Soft-
146 ware Toolkit (RST) (SuperDARN Data Analysis Working Group et al., 2018), which is
147 specifically designed to accomodate SuperDARN observations down to 40° of magnetic
148 latitude. Typically, to make SuperDARN convection maps several steps of processing have
149 to be followed: 1) Using RST, an autocorrelation function is fitted to the raw radar data.
150 This produces fitacf files, which store the line-of-sight velocity data. 2) The data is then
151 gridded onto an equal area latitude-longitude grid (see equation 1 from Ruohoniemi &
152 Baker, 1998) and split into two minute cadence records. 3) Data from different radars
153 are combined and the spherical harmonic fitting algorithm is performed which fits an elec-
154 trostatic potential in terms of spherical harmonic functions to the data (Ruohoniemi &
155 Greenwald, 1996; Ruohoniemi & Baker, 1998). When this fitting is performed, typically
156 a background model, parameterised by solar wind conditions is used, to infill informa-
157 tion in the case of data gaps (e.g. Thomas & Shepherd, 2018). Alongside this, a Heppner-
158 Maynard boundary (HMB) (Heppner & Maynard, 1987), the low-latitude boundary of
159 the convection pattern where the flows approach zero, can either be specified or be cho-
160 sen using the data. This is to constrain the convection pattern when the spherical har-
161 monic fit is applied (Shepherd & Ruohoniemi, 2000). For typical 2-minute convection
162 maps, it is appropriate to use the data to find a threshold of three radar velocity mea-
163 surements of greater than 100 ms^{-1} for the HMB (Imber et al., 2013).

164 For the purpose of this study, we make 2 minute cadence superposed epoch con-
165 vection maps, where data from the different storms are combined. This differs slightly
166 to the usual steps outlined above and is explained further in the following section.

167 We utilise the same storm list and the same gridded SuperDARN data, spanning
168 from 2010-2016, as published in WG19. We have 54 storms with the median storm du-

169 ration for each storm phase of 19.5 hours for the initial phase, 9.1 hours for the main phase
 170 and 55.8 hours for the recovery phase.

171 **3 Method**

172 In order to study the characteristic ionospheric convection morphologies of the storms
 173 in detail, we make a superposed epoch analysis. Similarly to Hutchinson et al. (2011)
 174 and Wharton et al. (2020), we make a superposed epoch analysis of the storms which
 175 treats each storm phase independently and scales each phase to the beginning and end,
 176 using the median duration. This means that each storm phase duration is scaled to be
 177 the same and we can thus compare average characteristics across storms.

178 We apply our method to the SuperDARN data to make average storm convection
 179 maps, which are parameterised by storm phase and median duration: We use the grid-
 180 ded data from the previous study (WG19), and write new convection maps for each storm
 181 phase, which are thus time-normalised and comprise the data from all storms. In order
 182 to make the convection maps, we write files with all the data and run the map-fitting
 183 procedure using RST v4.2 (SuperDARN Data Analysis Working Group et al., 2018) and
 184 a 8th order spherical harmonic expansion (Ruohoniemi & Greenwald, 1996). This dif-
 185 fers slightly to the usual method described earlier: In order to make the storm maps, no
 186 statistical background model was used, as the data coverage is very good when combin-
 187 ing data from 7 years of geomagnetic storms. As data coverage at lower latitudes can
 188 be sparse, especially during the initial phase, the automatic HMB algorithm can select
 189 unrealistic boundaries. We avoid this by forcing the HMB to match the lower quartile
 190 of the distribution of HMBs from the individual maps per timestep per phase (this is shown
 191 in Fig. 8 in WG19 and the second panel from the top in Figure 4 in this paper). To min-
 192 imize unphysical artefacts dominating the dayside potential, we add padding below the
 193 HMB on the dayside by adding artificial datapoints with line-of-sight velocities which
 194 are equal to zero. We also set all line-of-sight velocities to zero for any backscatter points
 195 on the dayside which lie below the HMB. Before fitting the spherical harmonic expan-
 196 sion, we also merge the line-of-sight data, using the MERGE technique (Cerisier & Se-
 197 nior, 1994; André et al., 1999). This resolves all measurements at a given grid point into
 198 one vector. It is worth noting that despite the padding and merging of vectors, the fit-
 199 ted electrostatic potentials are not forced to be zero below the HMB (due to the fitting

process using a spherical harmonic expansion) and as such, the convection cells do sometimes extend across the HMB.

3.1 Intermediary Maps

Examples of these average convection maps are given in Figure 1, which shows a map from the beginning of each storm phase. All other maps are included in the form of animations as supplementary material or can be downloaded as convection map files from Lancaster University’s research archive (PURE) (Walach, 2020).

From Fig. 1 we see that the convection patterns are different at the beginning of each storm phase: As expected, at the beginning of the initial phase the convection pattern is relatively small and the ionospheric convection velocities are low, whereas at the beginning of the main phase, the familiar two-cell convection pattern (e.g. Ruohoniemi & Greenwald, 1996) is enhanced and expanded, with fast return flows seen on the dusk-side. From examining these convection maps (see also supplementary material), we see that the two-cell pattern stays strong and expanded throughout the main phase. Fig. 1 and the supplementary material shows that this is further enhanced at the beginning of the recovery phase. We see from the supplementary information that the fast flows and expanded pattern stays prevalent long into the recovery phase, but start to decrease after the main phase ends.

3.2 Principal Component Analysis

Studying these average maps is useful to observe obvious changes in the convection, such as deviations from the two-cell convection regime, expansions and contractions, or patches of fast flows. In order to quantify changes in the convection morphologies further we now utilise principal component analysis on the data. This is a well-known technique for pattern recognition and is also known under different names, such as empirical orthogonal functions, and has been used successfully for geophysical datasets (see Baker et al., 2003; Cousins et al., 2013, 2015; Milan et al., 2015; Shore et al., 2018; Shi et al., 2020; Kim et al., 2012, and references therein). An alternative method is to use the spherical harmonics to examine changes (e.g. Grocott et al., 2012), but in this case the components are predetermined, which limits their interpretability. In PCA the components are defined by the data which allows us to find the main constituents which make

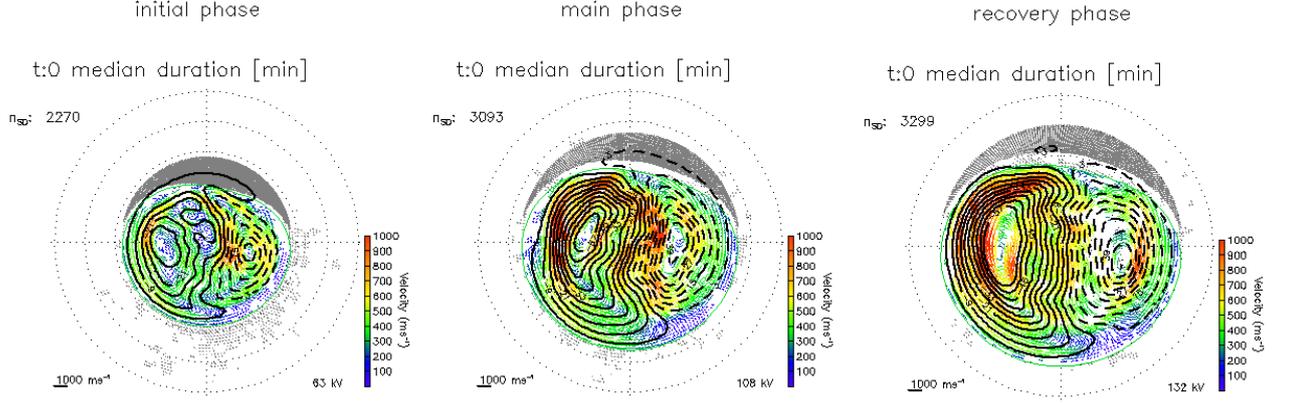


Figure 1. Example SuperDARN convection maps from the Superposed Epoch Analysis showing the first map of the initial (left), main (centre) and recovery phase (right), respectively. Each panel shows a map in the geomagnetic (AACGM) coordinates, whereby noon is towards the top of the page and dusk is towards the left and the grey concentric circles show equal magnetic latitudes of 10° , ranging from $80-40^\circ$. The ionospheric flow vectors are colour coded by magnitude, and the electrostatic potentials are shown as equipotentials at 3 kV steps (in black). The green boundary in each panel indicates the Heppner-Maynard boundary and n_{SD} indicates the number of grid points with measurements (excluding the additional dayside padding vectors).

230 up the patterns. Overall, this allows us to quantify the main components to the patterns
 231 and see how they change over time.

232 The underlying principle is that the dataset can be decomposed into a series of ba-
 233 sis functions which reveal underlying correlations within the data. In our case, the dataset
 234 is made of the electrostatic potential maps, Φ_t (where $t=0, \dots, m$), such that $m = 1266$
 235 (the median storm duration at a time resolution of 2 minutes) and each Φ_t has n -elements,
 236 where n is given by the number of latitude by longitude grid points (2° resolution). All
 237 the observations can be expressed as one $m \times n$ matrix (Φ). The covariance matrix Σ
 238 is then given by $\Sigma = \frac{1}{m} \Phi^T \Phi$, where Φ^T is the transpose of Φ . The data Φ_t can be ex-
 239 pressed (or reconstructed) in terms of eigenvectors, \mathbf{X}_i , of the covariance matrix Σ and
 240 their components, α_i , such that

$$241 \quad \Phi_t = \sum_{i=1}^n \alpha_i \mathbf{X}_i. \quad (1)$$

242 This means components at a given time, α_i , are given by

$$243 \quad \alpha_i = \Phi_t \cdot \mathbf{X}_i. \quad (2)$$

244 Applying this method to the convection maps allows us to quantify and detect mor-
 245 phological changes automatically, as well as determine the primary components which
 246 make up the ionospheric electric field. In order to do this, we first scale all the ionospheric
 247 convection maps, such that they are the same size. This is necessary for the principal
 248 component analysis to work. Using different pattern sizes would involve padding areas
 249 with no data with zeros and result with no correlation between the majority of gridpoints
 250 and thus the principal component analysis method would not work. Whilst changing the
 251 size of the pattern will make the expansions and contractions invisible for the Principal
 252 Component Analysis, this information is kept, so it can be studied in conjunction with
 253 the components later. We discuss this again later in the paper and also address the ex-
 254 pansions and contractions in WG19. We take the electrostatic potential from each map
 255 and resize the potential pattern by scaling by the Heppner-Maynard boundary (Heppner
 256 & Maynard, 1987) at midnight to 50° of magnetic co-latitude. We map the potential to
 257 a 2° latitude by 2° longitude grid which allows us to describe each pattern by a 1-dimensional
 258 4500 line matrix ($n = 4500$). We then calculate the mean for all storm epochs at each
 259 spatial point in the electric potential grid and subtract this from each individual map.
 260 On the remaining dataset we perform the eigen decomposition using the Householder
 261 method of eigen-decomposition (Press et al., 2007). Using only data from geomagnetic
 262 storm times for the principle component analysis means that the only bias is in our event
 263 selection, which was done using the automatic algorithm from WG19 on the Sym-H in-
 264 dex. It is worth noting that whilst selecting by geomagnetic storm times only means we
 265 can analyse the storm-time morphologies specifically, we also impose a selection bias: al-
 266 though we include some quieter times during the recovery phase of the storms, this se-
 267 lection bias results in our mean and eigenvector patterns looking different from analy-
 268 ses done in previous studies (e.g. Cousins et al. (2013) used an interval which had very
 269 little geomagnetic activity and Milan (2015) used all of the available AMPERE data)
 270 and we comment on this further in the discussion section.

271 4 Results

272 By examining the eigenvalues, we can determine the importance of each of the eigen-
 273 vectors (i.e. the component patterns that are added or subtracted together to make the
 274 convection maps). Figure 2 shows the cumulative explained variance, expressed in per-
 275 centages. We see immediately that the curve converges fast: The orange dotted and dashed

276 lines show the i -values closest to $>80\%$ and $>95\%$ cut-off values, respectively. Whilst
 277 we have 4500 eigenvalues and vectors, we see from Fig. 2 that we do not need all these
 278 values to express the majority of the variability in the electric potential patterns. In fact,
 279 the variance converges fast enough that the first 6 eigenvectors explain over 80% of the
 280 variance (this is shown by the green lines). In the following parts of the manuscript we
 281 will thus focus our attention on the first 6 eigenvectors and components and examine these
 282 further.

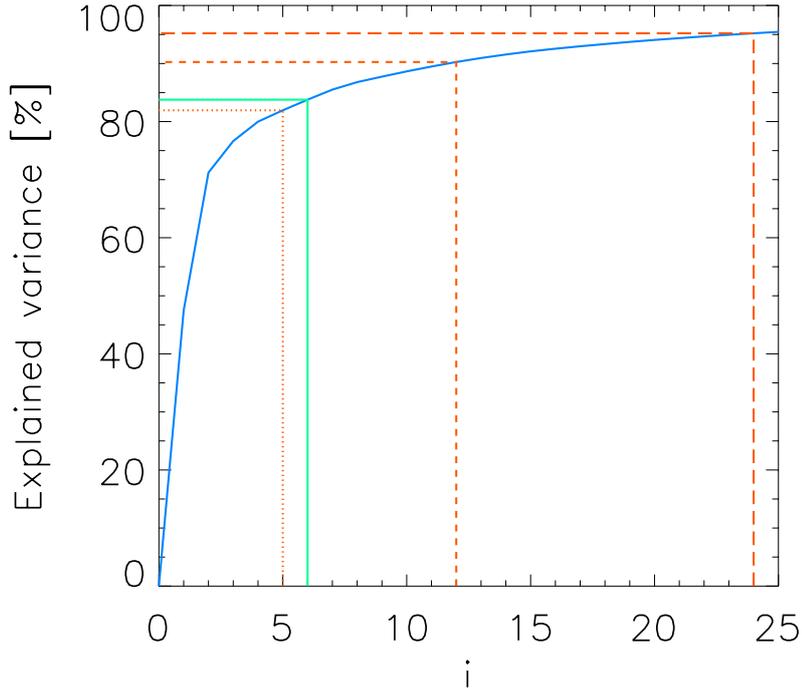


Figure 2. Explained variance (the first 25 eigenvalues) shown cumulatively in % of the total variance. The orange dotted, dashed and long-dashed lines show the i -values closest to 80%, 90% and 95% cut-off values, respectively, whereas the green line shows the cut-off value of the first 6 eigenvalues ($\sim 82\%$).

283 By adding or subtracting factors of \mathbf{X}_i (where $i=1,\dots,4500$) we are able to thus re-
 284 construct the initial maps. These factors as a function of time are given by the compo-
 285 nents, α_i . To simplify the interpretation of what proportion of the CPCP each compo-
 286 nent pattern holds, we have normalised each component pattern by a factor, f_i , such that
 287 terms in equation 2 become $\mathbf{X}_i^* = \mathbf{X}_i/f_i$ and the range of each \mathbf{X}_i^* is approximately
 288 equal to one. We also scale α_i , such that $\alpha_i^* = (\alpha_i \times f_i)$, which represents the approx-

289 imate CPCP each component holds and we can thus analyse this with respect to time
 290 through the storm phase. We now examine these terms ($i = 0..6$) in more detail.

291 Figure 3 shows the primary electrostatic potential pattern components: the panel
 292 in the top left corner shows the mean pattern which was subtracted from all maps be-
 293 fore applying the principal component analysis. The other panels show the first 6 eigen-
 294 vectors (i.e. the most dominant pattern components). The pattern components $\mathbf{X}_{1,\dots,6}^*$
 295 are normalised by their CPCP, such that the colour scale approximately represent a range
 296 of 1. We will refer to this same normalisation factor, f_i , again later, as it will aid the in-
 297 terpretation of Figure 4. Each panel shows the eigenvector as a map in the same coor-
 298 dinate system as Fig. 1, whereby the magnetic pole is in the centre, noon is towards the
 299 top of the page, and dusk towards the left. The concentric dashed circles outline equal
 300 latitudes at 10° separation. As expected, the mean shows that a clear two-cell electric
 301 potential is dominant, with an enhancement in the dusk cell. What is less expected is
 302 that we also see an anti-clockwise rotation of the pattern about the pole. We see that
 303 \mathbf{X}_1^* is able to provide an increase or decrease in the two-cell convection potential with
 304 adding or subtracting the asymmetry from the mean pattern due to the similar rotation
 305 about the pole in the convection throat. \mathbf{X}_2^* provides morphological asymmetry by be-
 306 ing an almost uniformly negative potential, so adding or subtracting this would strengthen
 307 one cell and weaken the other, or vice-versa. \mathbf{X}_1^* and \mathbf{X}_2^* are very similar but one can
 308 primarily strengthen or weaken the dusk cell (\mathbf{X}_1^*) and the other the dawn cell (\mathbf{X}_2^*). $\mathbf{X}_{3,\dots,6}^*$
 309 provide a motion towards earlier or later local times of the throat and other asymme-
 310 tries, such as a variation to potential in the centre of the pattern.

311 The top panel of Figure 4 shows a superposed epoch analysis of the interplanetary
 312 magnetic field components, B_{IMF} , resolved into the GSM (Geocentric Solar Magneto-
 313 spheric) coordinates with X in light green, Y in turquoise, and Z in dark blue. The sec-
 314 ond panel from the top shows the Heppner-Maynard boundary (in black) which the maps
 315 were scaled by, as well as the number of backscatter points per average SuperDARN map
 316 (in rose). This is followed by the median Sym-H and the CPCP (in yellow). Then we
 317 show the first six components of the eigenvectors, all as a function of storm phase-adjusted
 318 time, which are shown in grey. The black lines show the low pass filtered curve, using
 319 a 60-min centred kernel window to show the large scale changes more clearly. The first
 320 vertical dashed blue line marks the end of the initial phase and thus the beginning of the

321 main phase and the second dashed blue line shows the end of the main phase and the
 322 beginning of the recovery phase.

323 We observe that the B_Z component is clearly enhanced, especially during the main
 324 phase of the storm and that the number of backscatter points per SuperDARN map is
 325 high (this can also be seen from the animations MS01-MS03 in the Supporting Informa-
 326 tion).

327 The components can be of positive or negative values. The magnitude of the val-
 328 ues indicate how much the normalised eigenvectors, \mathbf{X}_i^* , have to be amplified by and the
 329 positive or negative indicates whether or not this has to be added to or subtracted from
 330 the mean and the other components to compose the full pattern for this timestep (see
 331 also equations 1 and 2). The benefit of scaling α_i by f_i (i.e. the true range of \mathbf{X}_i), is that
 332 the scaled components α_i^* approximately represent the CPCP of each pattern and thus
 333 aids interpretation.

334 We see immediately that much of the variability in the components is dominated
 335 by what appears to be noise, which we will investigate more quantitatively in the next
 336 section. Focusing on the black curves we see a few clear changes in α_i^* with respect to
 337 the geomagnetic storm phases: α_1^* shows a clear change which mirrors the HMB and Sym-
 338 H closely. At the start of the main phase, this value decreases abruptly, then stays neg-
 339 ative and then starts to increase gradually throughout the recovery phase. α_2^* also de-
 340 creases as we approach end of the main phase but then increases quickly into the first
 341 part of the recovery phase, but then fluctuates about zero from about 10 normalised hours
 342 onwards but remains primarily positive. This is distinctly different to α_1^* which contin-
 343 ues to increase throughout the recovery phase. α_3^* is primarily negative throughout the
 344 initial phase, then increases to a positive value through the main phase and remains pri-
 345 marily positive throughout the recovery phase. α_4^* to α_6^* remain very small and show no
 346 clear deviations from zero with respect to the storm phases.

347 To analyse these changes further with respect to IMF B_Y and B_Z and Sym-H, we
 348 perform a cross-correlation analysis between each of these parameters and the compo-
 349 nents. To highlight the variations over larger timescales, we use the smoothed compo-
 350 nents from Fig. 4. The best correlation coefficient, $|r|$, of each of these and their respec-
 351 tive lag times, t , are given in 1. We also show p for each correlation pair, which is de-

Table 1. t , $|r|$ and p values between Sym-H; B_Y ; B_Z and each component shown in Figure 4 (black smoothed lines).

i	Sym-H:			B_Y :			B_Z :		
	t [min]	$ r $	p	t [min]	$ r $	p	t [min]	$ r $	p
1	0	0.706	0.000	360	0.150	4.803×10^{-14}	40	0.670	0.000
2	338	0.633	0.000	110	0.378	0.000	0	0.648	0.000
3	38	0.440	0.000	174	0.228	1.732×10^{-30}	266	0.207	1.755×10^{-25}
4	150	0.303	0.000	20	0.426	0.000	292	0.433	0.000
5	292	0.322	0.000	138	0.336	0.000	38	0.262	1.287×10^{-39}
6	72	0.427	0.000	0	0.205	6.272×10^{-25}	338	0.327	0.000

352 fined as the significance of the correlation. This is defined by Press et al. (2007) as

$$353 \quad p = \operatorname{erfc} \left(\frac{|r|\sqrt{N}}{\sqrt{2}} \right), \quad (3)$$

354 where erfc is the complementary error function and N is the number of datapoints, which
 355 is, as defined earlier, m . This value expresses the probability that in the null hypoth-
 356 esis of two values being uncorrelated, $|r|$ should be larger than its observed value. A small
 357 value of p (i.e. $p = 0$) thus indicates that the correlation is significant.

358 Table 1 shows that p is generally low, and $p = 0$ for the cross-correlation between
 359 the first 6 components and Sym-H. This means these correlations are statistically sig-
 360 nificant. We see that the first component in particular is highly correlated with both Sym-
 361 H and B_Z , with a time lag, $t = 0$. This means that changes in this component are cor-
 362 related with changes in Sym-H (i.e. the storm phases) and B_Z (i.e. solar wind driving).
 363 As i increases, $|r|$ tends to decrease. The correlational pairs with B_Y are in general lower
 364 than the correlations with B_Z , which means the time variability we see in the compo-
 365 nents tend to correlate better with B_Z than B_Y . The notable exceptions here are α_3^* ,
 366 and α_5^* , which are the only components where the correlations with B_Y are marginally
 367 higher than the correlations with B_Z .

368 The time lags are more difficult to interpret but indicate several patterns: The ma-
 369 jority of the convection pattern (i.e. α_1^* , which holds almost 50% of the variance) shows
 370 its best correlation at $t = 0$, which means this component's contribution is mostly re-

371 lated to Sym-H as this is how the storm phases are defined. We further note, that for
 372 any pairs where $|r|$ is very low (<0.3), t tends to be > 1 hour, which we interpret to not
 373 be meaningful and thus do not comment further on these.

374 5 Discussion

375 In Fig. 4 we show that, on average, the Heppner-Maynard boundary expands to
 376 $<50^\circ$ magnetic latitude approaching the main phase and stays expanded, well into the
 377 recovery phase when considering the lower quartile of the distribution shown in WG19.
 378 It is possible that in reality, this expansion moves to lower latitudes than 40° for indi-
 379 vidual storms but our observations are limited by the geographical location of the Su-
 380 perDARN radars and our choice of the HMB. This expansion is coincident with the IMF
 381 B_Z component becoming more southward, leading to a higher dayside reconnection rate
 382 and thus more rapid opening of magnetic flux (Siscoe & Huang, 1985; Cowley & Lock-
 383 wood, 1992; Milan et al., 2012; Walach et al., 2017). This means an expansion of the open-
 384 closed field line boundary occurs, which happens in tandem with the expansion of the
 385 convection pattern observed here (see also WG19). The high-latitude ionospheric elec-
 386 tric field and thus convection pattern is an important mechanism for plasma transport
 387 and thus its expansion will mean the circulation of plasma at lower latitudes than was
 388 previously circulated by the high-latitude convection pattern. Zou et al. (2013) also showed
 389 that the convection pattern expanding during geomagnetic storms plays an important
 390 role in the generation and propagation of storm-enhanced densities (SEDs) seen on the
 391 dayside at mid-latitudes: Zou et al. (2013) found that there are two parts to SEDs, with
 392 the equatorward expansion of the convection pattern being the primary driver for the
 393 SED formation.

394 We find that the first six eigenvalues hold $>80\%$ of the variability in the scaled iono-
 395 spheric electric potential during storms (see Fig. 2). As the potential patterns which are
 396 analysed using the Principal Component Analysis are scaled by the HMB, this variabil-
 397 ity does not include the expansion or contraction of the pattern, which happens in ad-
 398 dition to the morphological changes analysed here. The first and second eigenvectors (see
 399 \mathbf{X}_1^* and \mathbf{X}_2^* in Fig. 3) represent a dual-cell convection pattern, associated with the Dungey-
 400 cycle (e.g. Dungey, 1961, 1963; Milan, 2015; Walach et al., 2017); when α_1^* and α_2^* are
 401 negative \mathbf{X}_1^* and \mathbf{X}_2^* are subtracted from the mean, producing a more enhanced dual-
 402 cell convection pattern. We see from Fig. 4 that this is the case throughout the main phase

403 of the storm, subsiding in the recovery phase and peaking towards the end of the main
 404 phase, when solar wind driving is highest. This matches the findings of WG19, which
 405 showed that this is also when the cross polar cap potential is highest. We see from Fig.
 406 4 that the CPCP addition from the first component changes from ~ 20 kV in the initial
 407 phase to ~ -40 during the main phase, which is a step change of 60 kV and slightly higher
 408 than the 40 kV step change in CPCP that was seen in WG19. This highlights that whilst
 409 this component drives a lot of the storm phase change related variability, more compo-
 410 nents need to be added to get an accurate representation of the CPCP. The second com-
 411 ponent also adds to the potential, in particular during the main phase, where its con-
 412 tribution reaches ~ 20 kV. The first component primarily enhances or decreases the dusk-
 413 side of the potentials, whereas the second component primarily enhances or decreases
 414 the dawnside potential cell. During the main phase of the storm, when they are both neg-
 415 ative, the convection pattern is enhanced and the two cells both increase. A few hours
 416 into the recovery phase however, when α_1^* is still negative and α_2^* is positive (both are
 417 at ~ 20 kV magnitude), the electric potential increases on the dusk side but decreases
 418 on the dawn side, which means the dusk cell is noticeably larger than the dawn cell. We
 419 see from Fig. 4 that the following components contain slightly lower magnitudes of the
 420 potential, and decrease with each component.

421 The third, fourth, fifth and sixth components only add up to ~ 10 kV to the con-
 422 vention pattern at their peak, which is minimal in the context of a CPCP between 50
 423 to 120 kV. It is confirmed by table 1 that what looks like noise in Fig. 4 in some of the
 424 higher order components (α_4^* and α_5^*), is indeed very weakly correlated with Sym-H, which
 425 means these changes are not related to the storm phases. Whilst α_6^* shows a higher cor-
 426 relation ($|r|=0.427$), it adds however less to the total CPCP and is thus less impor-
 427 tant. We see that the correlation between α_1^* and Sym-H is on the other hand very high
 428 ($|r|=0.706$) and significant ($p=0.00$), which means this component is clearly correlated
 429 with the storm phases. This component is also highly correlated with B_Z , which is no
 430 surprise, given the high levels of solar wind driving seen during geomagnetic storms.

431 The third eigenvector (\mathbf{X}_3^*) resembles the classic dual cell convection pattern but
 432 with a 90° rotation about the pole towards dawn. This component is therefore able to
 433 add asymmetry to the dual cell pattern in an unconventional way: its addition can move
 434 the dayside throat to earlier local times. The fourth and fifth eigenvectors (\mathbf{X}_4^* and \mathbf{X}_5^*
 435 in Fig. 3) represent asymmetric dawn-dusk changes to the patterns, which appear to mainly

436 rotate the convection throat on the dayside, though can rotate the nightside convection
 437 throat as well. The sixth eigenvector (\mathbf{X}_6^*) is very symmetrical and closely resembles the
 438 second order and degree spherical harmonic pattern (e.g. see Figure 2 from Grocott et
 439 al. (2012)).

440 We see from Figs. 3 and 4 that the main changes with respect to storm phase which
 441 we see are primarily related to the dawn and dusk cells enhancing or decreasing. We see
 442 from Fig. 4 that the third component is primarily negative during the initial phase. Then,
 443 going into the main phase of the storm, the third component increases steadily until a
 444 change in polarity is seen in this component, right before the end of the main phase. This
 445 will not only change the cross polar cap potential, increasing it during main and recov-
 446 ery phases and decreasing it during the initial phase, but it will also change the location
 447 of the dayside throat. It indicates that the convection throat on the dayside reaches across
 448 the midnight-noon meridian towards dawn and becomes more noon aligned as the main
 449 phase progresses but then jumps back to be more dusk-aligned before the end of the re-
 450 covery phase. For the rest of the storm time, we see this component varying slightly be-
 451 tween positive and negative values, but primarily staying positive, meaning that the day-
 452 side throat has a tendency to be noon-aligned.

453 This may appear to be a result of solar wind driving and a change in the IMF B_Y
 454 component, which can move the dayside convection throat (e.g. Cowley & Lockwood,
 455 1992; Thomas & Shepherd, 2018). This would be further evidenced as α_4^* shows a mild
 456 correlation (0.426) with the IMF B_Y component, but this component adds a minor amount
 457 of electric potential and α_3^* is much less correlated with B_Y (0.228) than Sym-H (0.440).
 458 We see however from the top panel in Fig. 4 that the average IMF B_Y component is near
 459 zero for these storms. In fact, 37% of the time the IMF B_Y component is positive for
 460 these storms, 38% of the time the IMF B_Y component is negative and it is zero the rest
 461 of the time. We see that it is the IMF B_Z component, which is enhanced during the main
 462 phase of the storm. That the average storm does thus not have a strong dusk-dawn com-
 463 ponent modulating the dayside flows (i.e. neither positive B_Y , nor negative B_Y are con-
 464 sistent dominant) is also shown in Figure 2 (panel j) in WG19, which shows that dur-
 465 ing the main phase of the storm, the IMF is overwhelmingly southward for all storms
 466 considered here. Usually when SuperDARN maps are created, base-models, which are
 467 in part parameterised by the solar wind are used (e.g. Thomas & Shepherd, 2018) such
 468 that datagaps are overcome. In this study however, no solar wind inputs were used at

469 all as the data coverage is very good when combining data from 7 years of geomagnetic
 470 storms. We conclude that some of this rotation in the dayside throat may be due to an
 471 IMF B_Y component, but we speculate that there are other mechanisms at play due to
 472 the inconsistency in the directionality of the B_Y component.

473 We theorize that some of the control in the dayside throat moving towards later
 474 local times could be due to a number of factors (or combination thereof): higher solar
 475 wind driving and the dayside reconnection rate increasing, or due to feedback through
 476 other means (e.g. thermospheric winds (Billett et al., 2018) and/or SEDs modulating
 477 the location of the throat (Zou et al., 2013, 2014) and/or the plasmaspheric plume im-
 478 pacting the magnetopause reconnection rate post-noon). Further evidence for the plas-
 479 maspheric plume being responsible for this moving of the dayside convection throat is
 480 available from comparing our results to those of Wharton et al. (2020): In their paper,
 481 Wharton et al. (2020) looked at the eigenfrequencies in ground magnetometer variations
 482 on the dayside during the same storm phases as ours. They found that that at L-shells
 483 < 4 , the eigenfrequencies in magnetometer measurements increase during the main phase
 484 of geomagnetic storms, which is due to the decrease in the plasma mass density caused
 485 by plasmaspheric erosion. This approximately corresponds to a geomagnetic latitude of
 486 60° or less (see table 1 in Wharton et al. (2020)), which corresponds to the dayside throat
 487 location we see during the main phase of the storm. Wharton et al. (2020) find that at
 488 $L > 4$ (which maps to higher latitudes and thus inside the convection pattern on the day-
 489 side), the eigenfrequencies decrease by $\sim 50\%$ during the main phase, due to a weaker
 490 magnetic field and an enhanced plasma mass density. This may be further evidence of
 491 the plasmaspheric plume. Overall however, to find a conclusive answer for the moving
 492 of the dayside throat, further studies are needed.

493 Morphological changes on the nightside are more difficult to analyse and less likely
 494 to yield great insight due to the time-averaging that we have done: We know (see Ta-
 495 ble S1 in WG19) that the minimum and maximum durations of each storm phase can
 496 vary vastly (e.g. the recovery phase can be anything from ~ 6 to ~ 163 hours). By com-
 497 bining the data, such that the average convection maps match the median storm phases,
 498 we time-shift the data. Whilst the majority of storms are of similar length, it provides
 499 a good framework for studying the average storm-time responses, however other time-
 500 dependent phenomena, such as substorms are averaged out. It is well known that sub-
 501 storms occur frequently during geomagnetic storms and are important for the energisa-

502 tion of the ring current (e.g. Daglis, 2006; Sandhu et al., 2019), but Grocott et al. (2009)
503 showed that substorms primarily produce a response in the high-latitude ionospheric con-
504 vection pattern on the nightside and that ordering by onset location is important when
505 trying to gain insight from the average convection pattern. It thus follows that although
506 substorms commonly occur during geomagnetic storms, we do not see their signatures.
507 We therefore cannot say if there is any substorm ordering by storm phase or time through-
508 out the storm phases as no clear substorm signatures are seen in the average maps.

509 Gillies et al. (2011) studied line-of-sight SuperDARN velocity measurements dur-
510 ing geomagnetic storms and found that an increase in IMF B_Z is accompanied by a speed
511 increase measured with SuperDARN in the noon sector (9 to 15 MLT) and midnight sec-
512 tor (21 to 3 MLT) during the main phase. Gillies et al. (2011) also found a reduction
513 in the measured plasma drift early in the main phase for intense storms, and speculated
514 this either to be due to a reduction in the plasma drift speed or a change in the direc-
515 tion of the drift relative to the SuperDARN radar beam. In this study we have shown
516 (see Fig. 4), that the addition to the convection potential increases during this time (due
517 to the first, second and third components), which means that the convection potential
518 increases and thus ionospheric convection velocities are likely to be also increasing. This
519 is supported by our previous analysis (WG19) which showed that the cross polar cap po-
520 tential increases during this time and thus the convection should also increase. This pro-
521 vides further evidence that the decrease in the plasma drifts seen by Gillies et al. (2011)
522 during the main phase is due to the change in the direction of the flows relative to the
523 SuperDARN radar beam (i.e. the second of their two theories).

524 Cousins et al. (2015) and Shi et al. (2020) used Empirical Orthogonal Function anal-
525 ysis to describe the modes of the Field Aligned Currents. Shi et al. (2020) split the data
526 according to different solar wind drivers, including High Speed Streams (HSS) and tran-
527 sient flows related to coronal mass ejections (CMEs), both of which can be drivers of ge-
528 omagnetic storms. Their patterns reflect the prevalence of the dual cell electrostatic pat-
529 tern that we also see, but due to different data binning, their modes are different, mak-
530 ing a direct comparison difficult. Overall, Shi et al. (2020) found that Sym-H is highly
531 correlated with the modes in the transient flow category, indicating that strong geomag-
532 netic storm activity dominates this category, which gives a strong dual cell convection
533 pattern, as well as expansions and contractions. Both their HSS and transient categories
534 show a mode which gives a strong asymmetry on the dayside (and would result in a sim-

535 ilar movement of the dayside throat that we see), which are highly correlated with Sym-
 536 H activity, but also the IMF B_Y and B_X components, and AE and solar wind temper-
 537 ature. Whilst the data presented by Cousins et al. (2015) did not contain any consid-
 538 erable geomagnetic storm activity, their results generally agree with the results from Shi
 539 et al. (2020). What does stand out when comparing results however, is that their first
 540 mode shows, similar to Shi et al. (2020), a strengthening of the pattern, which is highly
 541 correlated with AE and the IMF B_Z component. This is followed by a mode describing
 542 the expansions and contractions, which is correlated with B_Y , AE and Sym-H. The third
 543 mode from Cousins et al. (2015), describes the cusp shaping, which is also correlated with
 544 B_Y , AE and tilt, but not Sym-H. It is worth noting that Cousins et al. (2015) only showed
 545 the first few modes, and their chosen time period contains little geomagnetic activity.
 546 Cousins et al. (2013) on the other hand, used the EOF analysis to study SuperDARN
 547 data. They analysed 20 months of plasma drift data to study electric field variability and
 548 found that the first component accounted for $\sim 50\%$ of the observed total squared elec-
 549 tric field (which is as a proxy for the electrostatic energy per unit volume) and is pri-
 550 marily responsible for variations on long timescales (~ 1 hr). It is worth noting that their
 551 components look different to ours as they used a different dataset (i.e. their K_p median
 552 was 1, so they used a non-storm time dataset) for input but in general find the two-cell
 553 convection pattern to be dominant as well. Comparison between our data, Shi et al. (2020),
 554 Cousins et al. (2013) and Cousins et al. (2015) shows that using different data brings out
 555 different modes with different properties: the primary EOF in Cousins et al. (2015) strength-
 556 ens the convection pattern, whereas the secondary component has a shaping function,
 557 followed by expanding and rotating modes. They further find that their top correlation
 558 for the first component is at 0.44 for the AE index, which is considerably lower than our
 559 top correlation (0.706) coefficient between Sym-H and the first component. The dayside
 560 throat in the patterns (mean and components) shown by Cousins et al. (2013) show no
 561 movement: their mean is perfectly aligned with noon, which we attribute to the fact that
 562 their input data is on average from both positive and negative B_Y with no storm effects.
 563 Conversely, the mean pattern from Milan (2015), where they applied the principal com-
 564 ponent analysis to a much larger dataset of the Birkeland currents inferred by AMPERE,
 565 showed the throat aligned with 11 and 23 MLT. This is comparable to the average con-
 566 ditions, also when studying SuperDARN data (e.g. Thomas & Shepherd, 2018) and in-
 567 dicates that the mean and the components are sensitive to the choice of input data.

568 As part of this study we have provided a first analysis of how the dayside throat
 569 responds to geomagnetic storms (i.e. internal magnetospheric dynamics), versus IMF B_Y
 570 conditions (i.e. external magnetospheric dynamics) and studied the timescales of day-
 571 side throat changes with respect to geomagnetic storms. In order to understand this fully,
 572 requires further study. If the dayside throat is rotated due to the plasmaspheric plume
 573 mechanism, we would expect to see the same movement in the throat (away from dusk)
 574 in the southern hemisphere, but we would expect to see it moving in the opposite sense
 575 in the southern hemisphere for any IMF B_Y related effect. We have provided a first or-
 576 der analysis of this and discussed potential mechanisms here but in order to find a more
 577 definitive answer, southern hemisphere data will be investigated in more detail in a fu-
 578 ture study.

579 6 Summary

580 We have utilised SuperDARN line-of-sight ionospheric plasma measurements to study
 581 ionospheric electric potential morphologies during geomagnetic storm time and specif-
 582 ically geomagnetic storm phases. We applied a principal component analysis to average
 583 ionospheric convection maps to examine the primary morphological features for the first
 584 time and using eigenvalue decomposition, we see how dominant patterns change over time
 585 (i.e. through the storm phases). The main dynamics in the morphologies that we have
 586 uncovered are happening to the ionospheric electric potential pattern on a large scale:
 587 the electric potential pattern expands and contracts; the potentials increase and decrease
 588 in strength; and the dayside convection throat rotates. We speculate that all these changes
 589 are due to the IMF B_Z component of the solar wind increasing during the main phase
 590 of the storm.

591 We find that

- 592 1. the first 6 eigenvectors describe over $\sim 80\%$ of variance.
- 593 2. the two-cell convection pattern is dominant as is expected due to an expected high
 594 level of solar wind driving.
- 595 3. the first eigenvector, \mathbf{X}_1^* , provides an increase or decrease to the dusk-cell and is
 596 highly correlated with Sym-H ($|r|=0.706$).
- 597 4. \mathbf{X}_2^* provides a way to increase/decrease the dawn cell and also shows a correla-
 598 tion with Sym-H ($|r|=0.633$).

- 599 5. \mathbf{X}_3^* provides a motion towards earlier or later local times of the dayside convec-
600 tion throat.
- 601 6. \mathbf{X}_4^* to \mathbf{X}_6^* provide further ways of adding asymmetry and changes to the dual-cell
602 convection pattern, but these are less significant (<20 kV)
- 603 7. the electric potential increases through the main phase and then decreases as soon
604 as the recovery phase is reached.
- 605 8. the dayside convection throat points towards afternoon sector before the main phase
606 and then as the electric potential increases, the dayside throat rotates towards noon.
- 607 9. the dusk cell is generally larger than the dawn cell but during the main phase both
608 are enhanced.

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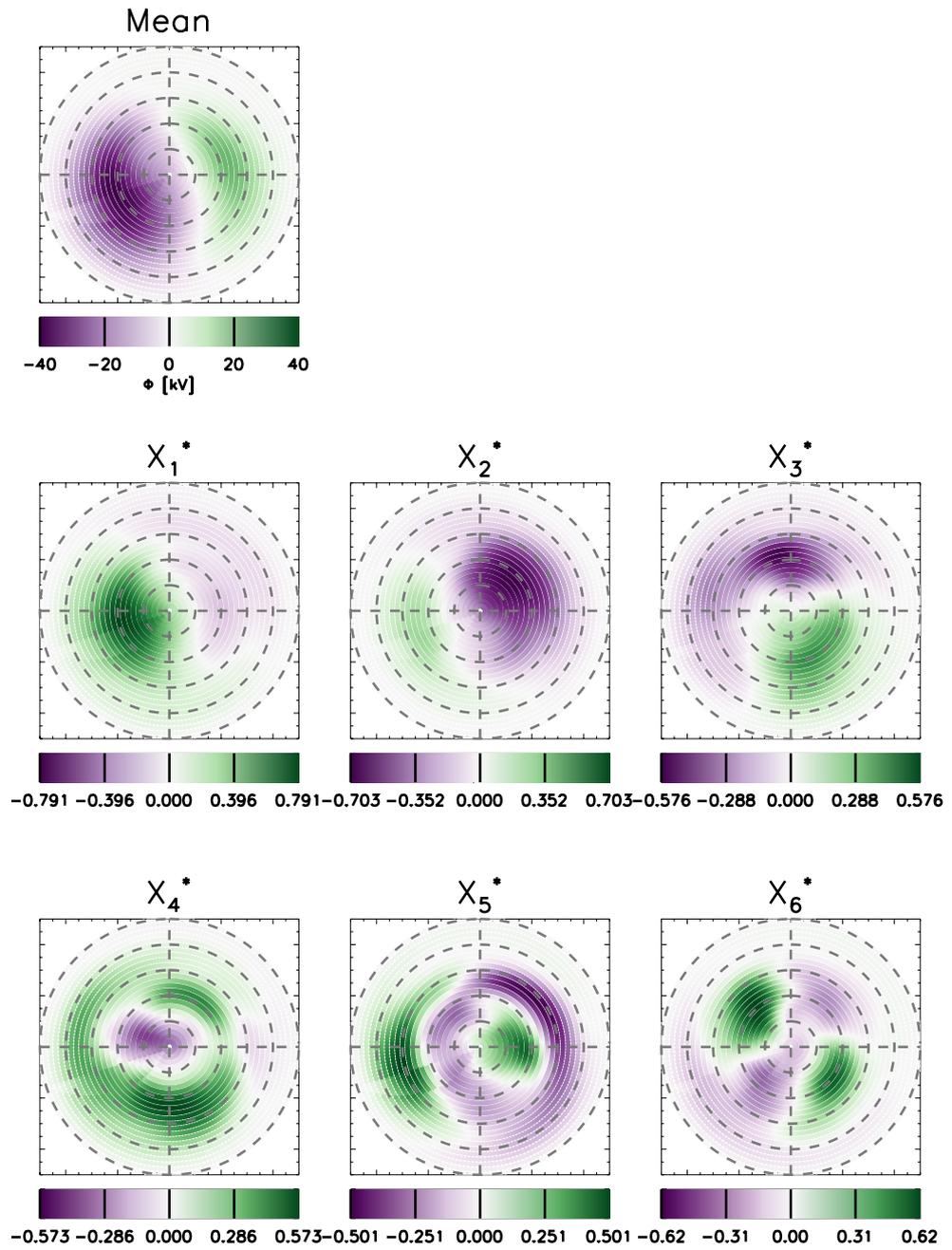


Figure 3. Ionospheric electric field component patterns showing the mean for geomagnetic storms (top left), followed by the patterns corresponding to the first 6 eigenvectors of the Principal Component Analysis. Each pattern is centred on the geomagnetic pole, with 12:00 magnetic local time pointing towards the top of the page, and dusk towards the left. Lines of geomagnetic latitudes are indicated from 40° to 90° by the dashed grey circles.

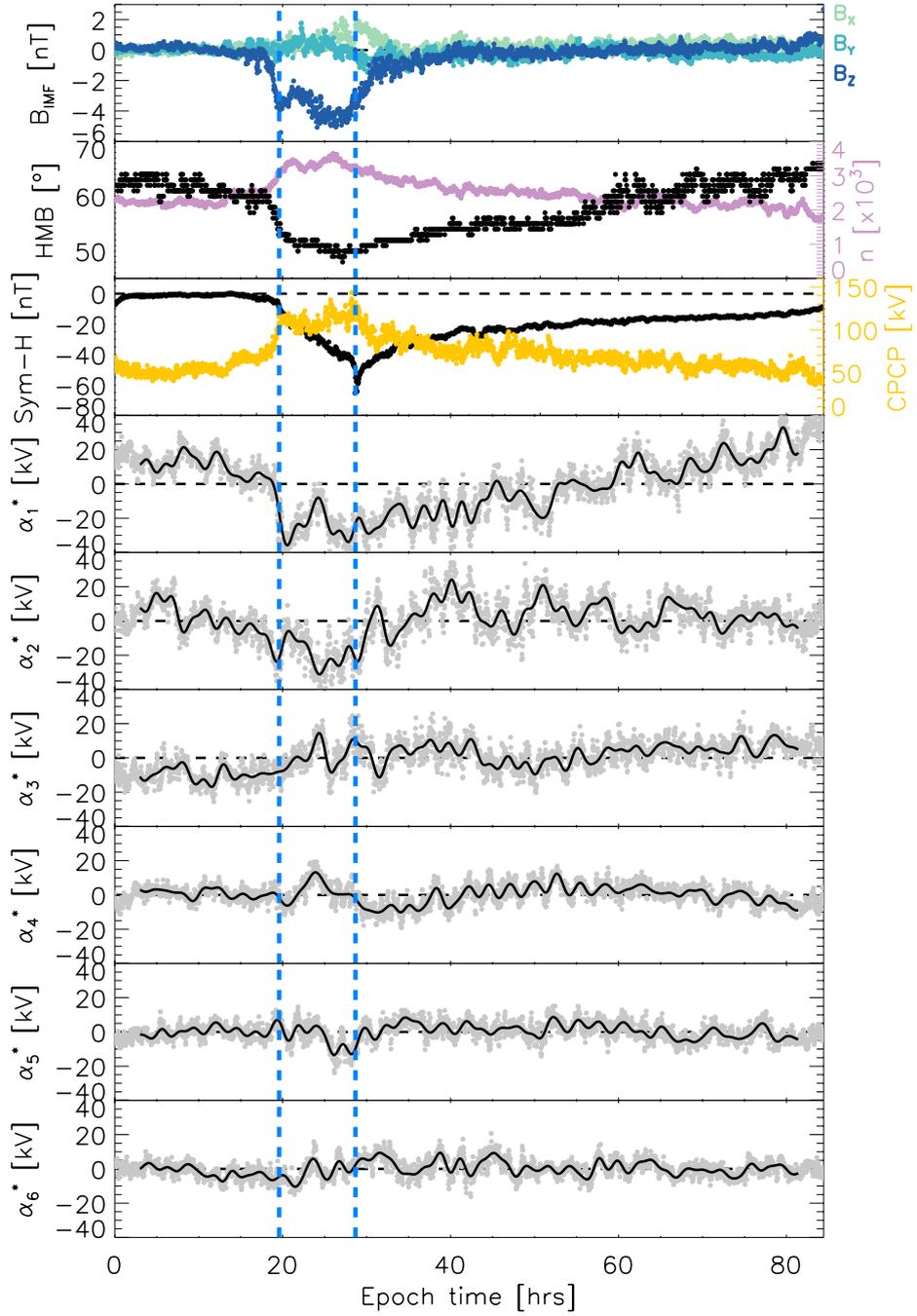


Figure 4. Panels showing the average (median) interplanetary magnetic field, B_{IMF} (top panel), where the light green is B_X , turquoise is B_Y and the dark blue is B_Z ; the Heppner Maynard Boundary and the number of backscatter points per average SuperDARN map (in rose) (second panel from the top); followed by the median Sym-H index and the CPCP (yellow). The panels showing α_1^* to α_6^* show the first 6 normalised components of the Principal Component Analysis with respect to time through the storm phases. The components are shown in grey and the black lines shows them with a 60-minute low pass filter applied. The boundaries between the initial and main, and the main and recovery phases are shown by the dashed blue vertical lines.

Supporting Information for ”Average Ionospheric Electric Field Morphologies during Geomagnetic Storm Phases”

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Contents of this file

1. Captions for Movies S1 to S3

Additional Supporting Information (Files uploaded separately)

1. Movies S1 to S3

Introduction The data accompanying the main manuscript are three animations in gif format, which contain the individual SuperDARN convection map files used for the principal component analysis for the main analysis. Each animation contains the convection maps for one of the storm phases: initial, main and recovery phase. The maps are time-normalized superposed epoch analyses, such that the duration of each phase matches the median duration of each phase (this is explained in the main manuscript), using a 2-minute cadence. The maps were created using the Radar Software Toolkit version 4.2

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(SuperDARN Data Analysis Working Group et al., 2018) (see main manuscript for more detail). Each map shows the gridded and fitted radar data with respect to the geomagnetic pole, where noon is towards the top, midnight towards the bottom, dusk towards the left and dawn towards the right. The dotted circles show lines of equal geomagnetic latitude, which are 10° apart. The thick black (dashed and non-dashed) lines show the electrostatic potential contours, which were obtained by performing a spherical harmonic analysis of the 8th order (Ruohoniemi & Greenwald, 1996). All line of sight data has been merged before the fitting was applied and zero velocity vectors were artificially added on the dayside below the HMB.

Movie S1. Animation of the convection maps for the initial phase. **Movie S2.** Animation of the convection maps for the main phase. **Movie S3.** Animation of the convection maps for the recovery phase.

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