

1 **The impact of century-scale changes in the core magnetic field on external magnetic field**
2 **contributions**

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9

10 **Abstract**

11 The Earth's internal magnetic field controls to a degree the strength, geographic positioning, and
12 structure of currents flowing in the ionosphere and magnetosphere, which produce their own
13 (external) magnetic fields. The secular variation of the Earth's internal magnetic field can therefore
14 lead to long-term changes in the externally produced magnetic field as well. Here we will examine this
15 more closely. First, we obtain scaling relations to describe how the strength of magnetic perturbations
16 associated with various different current systems in the ionosphere and magnetosphere depends on
17 the internal magnetic field intensity. Second, we discuss how changes in the orientation of a simple
18 dipolar magnetic field will affect the current systems. Third, we use model simulations to study how
19 actual changes in the Earth's internal magnetic field between 1908 and 2008 have affected some of
20 the relevant current systems. The influence of the internal magnetic field on low- to mid-latitude
21 currents in the ionosphere is relatively well understood, while the effects on high-latitude current
22 systems and currents in the magnetosphere still pose considerable challenges.

23

24 **Keywords**

25 Magnetic field, magnetosphere, ionosphere, secular variation, current systems

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38 1. Introduction

39 The Earth's core magnetic field plays an important role in the upper atmosphere. It affects the
40 conductivity in the ionosphere, ionospheric plasma transport processes, the geographic locations of
41 the magnetic equator and the auroral zones, and the coupling of the ionosphere-thermosphere
42 system with the solar wind and the magnetosphere. Because of this, the Earth's internal magnetic
43 field controls to a degree the structure and strength of external contributions to the magnetic field
44 that arise from electrical currents flowing in the ionosphere and magnetosphere. While these currents
45 are strongly driven by variable solar wind conditions on short timescales of minutes, hours, and days,
46 on timescales of decades, centuries, and longer, the secular variation of the core magnetic field also
47 has the potential to induce changes in these currents, and therefore the externally induced magnetic
48 field. Such long-term changes in the externally induced magnetic field can be difficult to separate from
49 decadal to centennial-scale changes in the core magnetic field itself. Yet it is important to separate
50 the different sources in order to improve our understanding of the physical processes that generate
51 them.

52 To find out how the secular variation of the core magnetic field could affect the external magnetic
53 field, it is helpful to consider simplified cases first, separating the effects of variations in field strength
54 and orientation in the case of a dipolar magnetic field. Several studies have derived scaling relations
55 to describe how external magnetic field contributions depend on the main geomagnetic dipole
56 moment intensity. Some of these were purely based on theoretical arguments (Siscoe and Chen, 1975;
57 Vogt and Glassmeier, 2001; Glassmeier et al., 2004), while later studies revisited some of the
58 theoretical scaling relations with numerical model simulations (Siscoe et al., 2002; Zieger et al., 2006a,
59 2006b; Cnossen et al., 2011, 2012a). In section 2 we will review and synthesize results from these
60 studies, aiming to derive the most realistic scaling relations currently available for the magnetic
61 perturbations associated with various different current systems. The effects of the orientation and
62 configuration of the main magnetic field on externally induced magnetic fields will be discussed in
63 section 3. These two sections form the basis to examine how more realistic main magnetic field
64 changes, as described by the International Geomagnetic Reference Field (IGRF; Thébaud et al., 2015),
65 have affected the currents in the ionosphere and magnetosphere during the past century. This will be
66 described in section 4, largely based on modelling studies by Cnossen and Richmond (2013) and
67 Cnossen (2014). Implications of these results for modelling the Earth's internal magnetic field are
68 discussed in section 5. We will finish with a brief summary and conclusions in section 6.

69

70 2. Effects of dipole moment intensity variations

71 2.1 Ionospheric conductivity

72 One of the most important effects of a change in dipole moment intensity for currents in the
73 ionosphere-magnetosphere system is its effect on conductivity: the lower the dipole moment, the
74 more freedom ions and electrons have to move, and therefore the larger the conductivity. This is
75 expressed mathematically by the following equations for the ionospheric Pedersen and Hall
76 conductivities (see, e.g., Richmond, 1995):

$$77 \quad \sigma_P = \frac{N_e e}{B} \left(\frac{v_{in} \Omega_i}{v_{in}^2 + \Omega_i^2} + \frac{v_{en\perp} \Omega_e}{v_{en\perp}^2 + \Omega_e^2} \right) \quad (1a)$$

$$78 \quad \sigma_H = \frac{N_e e}{B} \left(\frac{\Omega_e^2}{v_{en\perp}^2 + \Omega_e^2} - \frac{\Omega_i^2}{v_{in}^2 + \Omega_i^2} \right) \quad (1b)$$

79 where σ_P = Pedersen conductivity, σ_H = Hall conductivity, N_e = electron number density, e = magnitude
80 of the electron charge, B = magnitude of the magnetic field, ν_{in} = collision frequency of ions with
81 neutrals, $\nu_{en\perp}$ = collision frequency of electrons with neutrals in the direction perpendicular to the
82 magnetic field, Ω_i = ion gyrofrequency, and Ω_e = electron gyrofrequency. The ion and electron
83 gyrofrequencies are given by:

$$84 \quad \Omega_i = eB/m_i \quad (2a)$$

$$85 \quad \Omega_e = eB/m_e \quad (2b)$$

86 where m_i = ion mass, and m_e = electron mass.

87 The magnitude of the Earth's magnetic field thus affects the Pedersen and Hall conductivities directly
88 via B appearing in the denominator of equations 1a/b, giving larger conductivities for a weaker
89 magnetic field. In addition, the main magnetic field strength affects the ion and electron
90 gyrofrequencies, and thereby the heights at which these equal the ion-neutral and electron-neutral
91 collision frequencies, which influences the vertical profile of the conductivities. A reduction in
92 magnetic field strength causes an upward shift of the peak of the Pedersen conductivity, into a regime
93 where the background electron densities are larger, and broadens the vertical profile of the Hall
94 conductivity (Rishbeth, 1985; Takeda, 1996). The vertically integrated conductivities, i.e., the
95 conductances, therefore also increase with a decreasing main field strength due to these effects.

96 Cnossen et al. (2011, 2012a) performed simulations with the Coupled Magnetosphere-Ionosphere-
97 Thermosphere (CMIT) model to study how the magnetosphere, ionosphere and thermosphere
98 respond to changes in the main magnetic field strength. The CMIT model (Wang et al., 2004, 2008;
99 Wiltberger et al., 2004) couples the Lyon-Fedder-Mobarry (LFM) magneto-hydrodynamic (MHD)
100 model of the magnetosphere (Lyon et al., 2004) with the Thermosphere-Ionosphere-Electrodynamics
101 General Circulation Model (TIE-GCM; Roble et al., 1988; Richmond et al., 1992). Figure 1 illustrates
102 how the globally averaged Pedersen and Hall conductances depend on the dipole moment intensity,
103 M , based on the CMIT simulations by Cnossen et al. (2012a). Both scale approximately as $M^{-1.5}$. These
104 results represent intermediate solar activity conditions ($F_{10.7} = 150$ solar flux units; sfu) and constant
105 solar wind conditions with a southward directed Interplanetary Magnetic Field (IMF) of 5 nT. The
106 scaling for the Pedersen conductance is slightly dependent on the background solar activity level, with
107 the scaling being stronger for higher solar activity. This arises from an increase in the relative
108 contribution to the Pedersen conductance from the upper part of the ionosphere, which depends
109 more strongly on the dipole moment intensity when solar activity is higher (see Cnossen et al. (2012a)
110 for details).

111

112 [Figure 1: Global mean Pedersen and Hall conductance vs. dipole moment]

113

114 The dependence of the Pedersen and Hall conductances on the dipole moment intensity as shown in
115 figure 1 is dominated by the day-side, where conductivities are generally much larger. This is exactly
116 why models of the main magnetic field normally use night-time measurements: the generally smaller
117 night-time conductivities tend to lead to weaker currents and smaller external magnetic field
118 perturbations. It would therefore be useful to obtain scaling relations for the conductances separately
119 for night-time and day-time.

120 An empirical relationship given by Richmond (1995) suggests that day-time values of the Pedersen and
121 Hall conductances, Σ_P and Σ_H , scale as:

122
$$\Sigma_{P,day} \propto M^{-1.6} \quad (3a)$$

123
$$\Sigma_{H,day} \propto M^{-1.3} \quad (3b)$$

124 Glassmeier et al. (2004) obtained essentially the same scaling for the daytime Hall conductance, based
 125 on theoretical arguments and a simple Chapman layer model of ionospheric electron density.
 126 However, they suggested a considerably weaker scaling for the day-time Pedersen conductance:

127
$$\Sigma_{P,day} \propto M^{-1} \quad (4)$$

128 CMIT model simulations by Cnossen et al. (2011) suggested the following scalings of the day-time
 129 Pedersen and Hall conductances with the dipole moment intensity:

130
$$\Sigma_{P,day} \propto M^{-1.5} \quad (5a)$$

131
$$\Sigma_{H,day} \propto M^{-1.7} \quad (5b)$$

132 The Pedersen conductance scaling indicated by the CMIT model (eq. 5a) agrees very well with the
 133 Richmond (1995) scaling (eq. 3a), which suggests that the Glassmeier et al. (2004) scaling (eq. 4a) is
 134 too weak. On the other hand, the day-time Hall conductance scaling obtained from the model
 135 simulations (eq. 5b) is notably stronger than both the Richmond (1995) and Glassmeier et al. (2004)
 136 estimate (eq. 3b). Still, we suggest that the scalings of eq. 5a and 5b may be the most accurate, as the
 137 CMIT model offers a much more rigorous treatment of the electron densities than the simpler models
 138 underpinning the Richmond (1995) and Glassmeier et al. (2004) scalings. Cnossen et al. (2011) showed
 139 that, primarily because plasma transport processes depend on the magnetic field, the ionospheric
 140 electron density has a dependency on the dipole moment intensity, which further affects the
 141 ionospheric conductivities than already implied by eq. 1a/b.

142 At night-time, the electron density is much harder to predict than during the day, in particular at high
 143 latitudes, where it depends strongly on energetic particle precipitation from the magnetosphere. This
 144 is a much less predictable source of ionization than solar radiation, which is the dominant source of
 145 ionization during the day. This makes it more difficult to derive scaling relations for night-time
 146 conductivities especially within the auroral zone, where particle precipitation is important. Outside of
 147 the auroral zone, conductivities are very small and do not show any dependence on the main magnetic
 148 field strength according to the simulations by Cnossen et al. (2011). Still, understanding the
 149 dependence of the conductivities within the night-time auroral zone is important, because substantial
 150 currents can flow here.

151 Glassmeier et al. (2004) therefore derived a scaling relation to describe the dependence of the night-
 152 time, auroral zone conductances on dipole moment intensity based on theoretical considerations.
 153 Their scaling takes into account that changes in the size of the loss cone, which can be expected to
 154 occur for a change in dipole moment intensity, will affect energetic particle precipitation into the
 155 ionosphere, and thereby the night-time conductance. Glassmeier et al. (2004) argued that this effect
 156 can be described by multiplying a scaling for the day-time Pedersen or Hall conductances with the
 157 factor $M^{3\gamma-3/2}$, where γ takes a value between 0 and $\frac{1}{2}$, depending on the B_z component of the IMF.
 158 Vogt and Glassmeier (2001) suggest that $\gamma = 0$ for strong northward IMF and $\gamma = \frac{1}{2}$ for strong southward
 159 IMF, while traditional scalings for magnetospheric quantities with the dipole moment intensity (e.g.,
 160 Siscoe and Chen, 1975) imply that $\gamma = \frac{1}{3}$. In general form, the multiplication factor suggested by
 161 Glassmeier et al. (2004), combined with the daytime conductance scalings of eq. 5a and 5b, gives:

162
$$\Sigma_{P,night} \propto M^{3(\gamma-1)} \quad (6a)$$

163
$$\Sigma_{H,night} \propto M^{3(\gamma-1)-0.2} \quad (6b)$$

164 These scalings suggest that the conductances in the auroral zone depend at least as strongly on the
 165 dipole moment intensity during the night as during the day (for $\gamma = 1/2$), if not more strongly (for $0 \leq \gamma$
 166 $< 1/2$). This is in contrast to the results obtained by Cnossen et al. (2011) from their CMIT model
 167 simulations, which showed very little dependence of the night-time Pedersen conductance on the
 168 dipole moment intensity, even within the auroral zone, and a dependence of the night-time Hall
 169 conductance within the auroral zone that can be approximately described as:

$$170 \quad \Sigma_{H,night} \propto M^{-0.9} \quad (7)$$

171 This indicates a considerably weaker dependence on the dipole moment intensity than suggested by
 172 eq. 6b, even when one assumes $\gamma = 1/2$ (note that Cnossen et al. (2011) used IMF $B_z = -5$ nT, which is
 173 only moderately southward). However, the version of the CMIT model used by Cnossen et al. (2011)
 174 relied on a particle precipitation parameterization that does not allow for any change in the size of the
 175 loss cone when the dipole moment intensity changes (Wiltberger et al., 2009). Without this effect, the
 176 dependence of the night-time conductances on the dipole moment intensity as found by Cnossen et
 177 al. (2011) may therefore be unrealistically weak. Here we will consider eq. 6a/b to be the best scaling
 178 currently available for night-time conductances within the auroral zone. Zhang et al. (2015) recently
 179 developed a new approach to modelling different kinds of electron precipitation, which can be used
 180 as part of CMIT, but the implications of this new approach for the dependence of energetic particle
 181 precipitation and night-time conductivities on the dipole moment intensity have not been studied yet.

182 Since night-time observations are normally used to minimize the external magnetic field contributions
 183 when creating internal magnetic field models, the uncertainty regarding the potentially strong
 184 dependence of night-time conductances on the main magnetic field strength in the auroral zone is
 185 problematic for the separation of internal and external contributions to the magnetic field on long
 186 timescales. At lower latitudes, ionospheric models such as the CMIT model used by Cnossen et al.
 187 (2011, 2012a) should still give a reasonably good description of the dependence of both day- and
 188 night-time conductivities on the main magnetic field strength.

189

190 *2.2 Sq currents and the equatorial electrojet*

191 Upper atmosphere winds, produced by the daily variation in the absorption of solar radiation, move
 192 the ionospheric plasma through the Earth's magnetic field. This acts as a dynamo, setting up currents
 193 and causing electric polarization charges and electric fields to develop. On the dayside, the ionospheric
 194 wind dynamo produces a regular current pattern, which gives a characteristic daily variation in ground
 195 magnetic perturbations at low- to mid-latitudes, known as the solar quiet (Sq) variation. The
 196 equivalent Sq current system, i.e., the horizontal currents overhead that would produce the observed
 197 magnetic perturbations on the ground, consists of a clockwise current vortex in the Southern
 198 hemisphere and counter-clockwise current vortex in the Northern hemisphere.

199 The Sq Hall current, \mathbf{J}_H , and Pedersen current, \mathbf{J}_P , can be written as:

$$200 \quad \mathbf{J}_H = \sigma_H \mathbf{b} \times (\mathbf{E}_\perp + \mathbf{v} \times \mathbf{B}) \quad (8a)$$

$$201 \quad \mathbf{J}_P = \sigma_P (\mathbf{E}_\perp + \mathbf{v} \times \mathbf{B}) \quad (8b)$$

202 where \mathbf{b} is a unit vector in the direction of the geomagnetic field \mathbf{B} , \mathbf{E}_\perp is the electric field perpendicular
 203 to \mathbf{B} , and \mathbf{v} is the wind velocity. The current associated with the $\mathbf{v} \times \mathbf{B}$ term, also known as the dynamo
 204 electric field, is to first order proportional to the product of the conductivity and the magnetic field
 205 strength (or M). If we use the scalings from eq. 5a and 5b for the daytime Pedersen and Hall
 206 conductances, this would give an approximate scaling of Sq with $M^{-0.5}$ to $M^{-0.7}$. However, the vertical

207 shift in the Pedersen conductivity profile with a changing dipole moment intensity also changes the
 208 altitude regime that needs to be considered for the neutral winds, with winds typically being stronger
 209 at higher altitudes. Since a weaker dipole moment intensity causes an upward shift of the Pedersen
 210 conductivity profile, this leads to a larger conductance as well as stronger winds (see also Takeda,
 211 1996), which should lead to a stronger inverse scaling relation than suggested above. In addition, the
 212 neutral wind structure itself has been shown to change with dipole moment intensity (Cnossen et al.,
 213 2011) and the electrostatic electric field \mathbf{E} also depends on the dipole moment intensity, strengthening
 214 with increasing magnetic field strength (Takeda, 1996). Simply scaling the Sq variation as the product
 215 of the conductance and the dipole moment intensity is therefore an oversimplification.

216 Instead we will rely on results obtained from CMIT simulations carried out by Cnossen et al. (2012a),
 217 which take the effects discussed above into account. These indicate that the daily amplitude of the Sq
 218 magnetic variation at 30° magnetic latitude scales with $M^{-0.85}$ to $M^{-1.06}$ (depending on the component)
 219 under moderate solar activity conditions, as shown in figure 2. Note that the fits exclude the points
 220 for the smallest dipole moment intensity ($M=2 \times 10^{22}$ Am²), because the magnetic perturbations, and
 221 indeed the ionosphere-thermosphere system as a whole, start to behave differently for such a weak
 222 main field strength. At 30° magnetic latitude, the northward component is most strongly dependent
 223 on the dipole moment intensity, but its dependence on M gets weaker for 25° magnetic latitude and
 224 stronger for 35° magnetic latitude. The dependencies of the eastward and downward components on
 225 M are much less sensitive to magnetic latitude.

226

227 [Figure 2: Sq amplitude at 30° magnetic latitude vs. dipole moment]

228

229 Close to the magnetic equator, the nearly horizontal magnetic field there, together with a large
 230 difference in Hall and Pedersen conductivity in the lower ionosphere, results in a strongly enhanced
 231 eastward current, known as the equatorial electrojet. The strength of the equatorial electrojet is
 232 dependent on the so-called Cowling conductivity, σ_C , given by (e.g., Richmond, 1995):

$$233 \quad \sigma_C = \sigma_P + \frac{\int \sigma_H ds}{\int \sigma_P ds} \sigma_H \quad (9)$$

234 where the integrals are taken along a magnetic fieldline. In the equatorial region, the fieldlines only
 235 reach the lower part of the ionosphere, where the collision frequencies are larger than the gyro-
 236 frequencies. In this height range, the fieldline-integrated Pedersen conductivity should not depend
 237 much on the main field strength at all, while the dependence of the fieldline-integrated Hall
 238 conductivity should scale close to M^{-1} (see eq. 1/2; also Cnossen et al. (2012a)). This means that the
 239 scaling for the Cowling conductance should be somewhere in between M^0 and M^{-2} , but probably closer
 240 to M^{-2} than M^0 , as the Hall conductivity dominates in the lower ionosphere. This is indirectly confirmed
 241 by the modelling results of Cnossen et al. (2012a). These indicate that the amplitude of the horizontal
 242 component of the daily magnetic variation simulated at the magnetic equator, which we will call
 243 ΔB_{EEJ} , scales as:

$$244 \quad \Delta B_{EEJ} \propto M^{-0.7} \quad (10)$$

245 for M between 6×10^{22} and 10×10^{22} Am². If we assume that this amplitude scales as the product of the
 246 Cowling conductance and the main field strength, this implies that the Cowling conductance scales
 247 approximately as $M^{-1.7}$. This is in excellent agreement with a scaling for the Cowling conductance
 248 previously suggested by Glassmeier et al. (2004).

249

250 *2.3 Polar electrojets*

251 The ground magnetic perturbations associated with the polar electrojets are mainly determined by
 252 the ionospheric Hall currents, because the ground signature of the horizontal Pedersen currents is
 253 cancelled by the signature of the (vertical) field-aligned currents, assuming that the ionospheric
 254 conductivity is spatially uniform (Fukushima, 1976). Although this assumption is not strictly valid in
 255 practice, we can use this to derive a first-order scaling relation for the magnetic perturbation
 256 associated with the polar electrojet, ΔB_{PEJ} , following Glassmeier et al. (2004). They proposed that
 257 $\Delta B_{PEJ} \propto \Sigma_H E_c$, where E_c is the high-latitude electric field driven by magnetospheric convection.
 258 Glassmeier et al. (2004) used further assumptions and theoretical arguments to propose a scaling for
 259 E_c with the dipole moment intensity, arriving at:

$$260 \quad E_c \propto M^{10/3-4\gamma} \quad (11)$$

261 For $\gamma = 1/3$ (moderately southward solar wind conditions) this gives $E_c \propto M^2$. It is also possible to obtain
 262 a scaling relation for E_c from the CMIT model simulations by Cnossen et al. (2012a), which used IMF
 263 $B_z = -5$ nT. To do this, we assume that E_c can be approximated by $\Phi/\cos(\lambda_{pc})$, where Φ is the cross-
 264 polar cap potential and λ_{pc} is the latitude of the polar cap boundary, defined as the boundary between
 265 open and closed magnetic field lines ($\cos(\lambda_{pc})$ is used here as a characteristic length scale for the polar
 266 cap). The simulations by Cnossen et al. (2012a) indicate that the quantity $\Phi/\cos(\lambda_{pc})$ scales almost
 267 linearly with the dipole moment intensity for values of M between 6×10^{22} and 10×10^{22} Am².
 268 However, it can be approximated closely by the following power law scaling (again valid for M between
 269 6×10^{22} and 10×10^{22} Am²), which has the advantage that it is independent of units:

$$270 \quad E_c \propto M^{0.6} \quad (12)$$

271 Zieger et al. (2006a, 2006b) also examined the dependence of the cross-polar cap potential and polar
 272 cap size on the dipole moment intensity, using simulations with the Block Adaptive Tree Solar-wind
 273 Roe Upwind Scheme (BATS-R-US) MHD code (Powell et al., 1999) and the analytical Hill model (Hill et
 274 al., 1976). For the same IMF B_z (-5 nT) they found similar dependencies of $\cos(\lambda_{pc})$ and Φ to Cnossen
 275 et al. (2012a). Both modelling studies thus indicate that the theoretically obtained scaling by
 276 Glassmeier et al. (2004) for E_c (eq. 11) is much too strong. Here we will use eq. 12 as the most suitable
 277 scaling for E_c . Combined with the night-side Hall conductance scaling for the auroral zone given in eq.
 278 6b, this gives:

$$279 \quad \Delta B_{PEJ} \propto M^{3(\gamma-1)+0.4} \quad (13)$$

280 With γ taking values between 0 and $1/2$, this indicates that the magnetic signature of the polar electrojet
 281 strongly decreases with dipole moment intensity, especially for $\gamma = 0$ (strong northward IMF).

282 In principle, it should also be possible to calculate the magnetic signature of the polar electrojet, and
 283 its dependence on the dipole moment intensity, directly from model simulations, such as those carried
 284 out by Zieger et al. (2006a, 2006b) and Cnossen et al. (2012a). However, high-latitude magnetic
 285 perturbations calculated from more realistic CMIT model simulations carried out by Cnossen and
 286 Richmond (2013) have shown rather poor agreement with observed values. We have therefore not
 287 analysed the simulated currents at high-latitudes directly, as this could give misleading results. Zieger
 288 et al. (2006a, 2006b) did not show results for the magnetic signature of the polar electrojets either.

289

290 *2.4 Field-aligned currents*

291 While the contribution of high-latitude field-aligned currents to magnetic perturbations on the ground
 292 may be mostly cancelled by horizontal Pedersen currents, they are still of interest for space-based
 293 observations and because of their role in coupling the ionosphere and magnetosphere. We therefore
 294 briefly discuss them here.

295 In the first instance, field-aligned currents get stronger for increased conductivity. However, unlike
 296 the conductivity, the dependence of the total amount of field-aligned current on the dipole moment
 297 intensity does not follow a straightforward power law scaling (e.g., Zieger et al., 2006a, 2006b;
 298 Cnossen et al., 2012a). This is because a change in dipole moment intensity also affects other aspects
 299 of the magnetosphere-ionosphere system, such as the size of the magnetosphere, which additionally
 300 influence the field-aligned currents. Figure 3 shows how the total field-aligned current (upward +
 301 downward), averaged over the two hemispheres, depends on the dipole moment intensity according
 302 to the CMIT simulations by Cnossen et al. (2012a) under moderate solar activity conditions. This
 303 represents mainly region-1 currents, as the model generates only very weak region-2 currents, due to
 304 a poor representation of the ring current.

305 [Figure 3: Total FAC vs. dipole moment]

306

307 2.5 Ring current

308 The surface magnetic field associated with the ring current, ΔB_{RC} , is proportional to the energy of the
 309 ring current particles, E_{rc} , divided by the dipole moment intensity, M (e.g., Kivelson and Russell, 1995):

$$310 \quad \Delta B_{RC} \propto \frac{E_{rc}}{M} \quad (14)$$

311 Siscoe and Chen (1975) reasoned that the energy of ring current particles can be expected to scale in
 312 the same way as the total energy input to the magnetosphere, which should be proportional to the
 313 cross-sectional area of the magnetosphere tail, R_T^2 . If the magnetosphere retains its shape (i.e.,
 314 remains self-similar), R_T^2 is proportional to R_{MP}^2 , where R_{MP} is the magnetopause stand-off distance.
 315 From a simple pressure balance at the magnetopause between the solar wind dynamic pressure and
 316 the magnetic pressure from the Earth's magnetic field, it follows that R_{mp} scales to first order as $M^{1/3}$
 317 (e.g., Kivelson and Russell, 1995). This then gives:

$$318 \quad \Delta B_{RC} \propto \frac{R_T^2}{M} \propto M^{-1/3} \quad (15)$$

319 Vogt and Glassmeier (2001) relaxed the assumption of self-similarity, suggesting that the tail radius R_T
 320 should scale as M^γ . This is where the factor γ , first introduced in section 2.1, comes from. Further,
 321 Glassmeier et al. (2004) argued that it is not only the cross-section of the tail of the magnetosphere
 322 that matters for the energy of the ring current particles, but also the volume of the part of the
 323 magnetosphere where particle trapping is important, V_{rc} . Assuming that this volume scales with M ,
 324 they proposed the following scaling for ΔB_{RC} :

$$325 \quad \Delta B_{RC} \propto \frac{R_T^2 V_{rc}}{M} \propto M^{2\gamma} \quad (16)$$

326 Unlike eq. 14, the Glassmeier et al. (2004) scaling (eq. 16) indicates a decrease in ΔB_{RC} with decreasing
 327 dipole moment intensity. This is much more reasonable in the limit of a vanishing main field and is
 328 also supported by observations in Mercury's magnetosphere, which indicate that its small magnetic
 329 field does not support a large ring current. Having said that, it is still uncertain whether eq. 16
 330 describes accurately how strongly we can expect ΔB_{RC} to decrease with decreasing dipole moment
 331 intensity. Modelling studies that have been carried out so far to examine effects of changes in dipole

332 moment intensity on the magnetosphere-ionosphere system (e.g., Zieger et al., 2006a, 2006b;
333 Cnossen et al., 2011, 2012a) did not examine the effects on ΔB_{RC} , because the ring current is not well
334 described by the models they used. Effects of changes in dipole moment intensity on other
335 magnetospheric currents, such as tail and magnetopause currents, have not yet been studied either.

336

337 **3. Effects of changes in dipole moment orientation**

338 In this section we consider again first the simplified case of a dipolar magnetic field, but this time we
339 discuss effects of the orientation of that dipole. The orientation of the dipole determines the mapping
340 between geographic and magnetic coordinates, and therefore the geographic positioning of important
341 features, such as the magnetic poles, the auroral oval, and the magnetic equator (e.g., Siscoe and
342 Christopher, 1975; Cnossen and Richmond, 2012). When the dipole orientation changes, these
343 features move in a geographic reference frame, and current systems that are tied to them move along.
344 However, much more than a simple shift of current systems occurs.

345 First, a change in the geographic location of a current system, in particular the geographic latitude,
346 affects the background conductivity arising from solar extreme ultraviolet (EUV) radiation. Movement
347 to a lower geographic latitude results on average in a higher conductivity, and hence stronger currents.
348 Second, the dynamo electric field, $\mathbf{v} \times \mathbf{B}$, is naturally affected by changes in the direction of the magnetic
349 field, which consequently affects the currents. Further, also the neutral wind can be influenced by a
350 different orientation of the magnetic field, because the ion-drag force on the neutral wind depends
351 on the magnetic field orientation (e.g., Cnossen and Richmond, 2008). In addition, the magnetic field
352 orientation affects plasma transport processes, and therefore the plasma distribution and
353 conductivity, additionally influencing the currents.

354 The effects described above drive asymmetries in conductivities and winds between the Northern and
355 Southern hemisphere when the dipole is not aligned with the Earth's rotation axis, which add to any
356 North-South asymmetries already present due to seasonal variations. Hemispheric asymmetries in
357 conductivities and winds lead to asymmetries in electric potential, which tend to be quickly shorted
358 out by inter-hemispheric currents flowing along the magnetic field at low- to mid-latitudes, due to the
359 high conductivity parallel to the magnetic field. During solstice, inter-hemispheric field-aligned
360 currents flow mainly from the summer to the winter hemisphere at dawn and vice versa around noon
361 (Takeda, 1982; Park et al., 2011). The orientation of the magnetic field determines in part how strong
362 these interhemispheric field-aligned currents and the magnetic perturbations associated with them
363 are.

364 In addition to the average structure and strength of ionospheric current systems, the orientation of
365 the magnetic field also affects their temporal variations. When the dipole is not aligned with the
366 rotation axis, its daily precession about the rotational axis creates a UT dependence in the ionosphere.
367 The larger the dipole tilt, by which we mean here the angle between the magnetic dipole axis and the
368 Earth's rotation axis, the larger this daily variation becomes. Seasonal variations are similarly modified
369 by the orientation of the dipole axis. Further discussions of these effects are given by, e.g., Walton
370 and Bowhill (1979), Wagner et al. (1980), Richmond and Roble (1987), and more recently Cnossen and
371 Richmond (2012).

372 Hurtaud et al. (2007) examined how high-latitude region-2 field-aligned currents depend on the dipole
373 orientation, studying three different cases: a) a dipole aligned with the Earth's rotation axis, b) a dipole
374 tilted with respect to the rotation axis, and c) a dipole that is additionally offset from the centre of the
375 Earth. Simulations with the Ionosphere Magnetosphere Model (Peymirat and Fontaine, 1994) showed

376 that the introduction of a dipole tilt causes stronger diurnal and seasonal variations in region-2 field-
377 aligned currents, due to increased diurnal and seasonal variations in ionospheric conductivity, as
378 expected. The offset from the centre of the Earth reduced the variations in one hemisphere (where
379 the magnetic pole was closer to the geographic pole), while enhancing them in the other. This effect
380 is also described by Laundal et al. (2016, accepted) in the context of North-South hemispheric
381 differences.

382 Currents in the wider magnetosphere may also show some dependence on dipole orientation,
383 because this determines in part the geometry between the Earth's magnetic field and the solar wind
384 and the IMF, which can affect the solar wind-magnetosphere coupling efficiency (e.g., Cnossen et al.,
385 2012b). However, little is known about the effects of this on magnetospheric current systems. In
386 principle, naturally occurring diurnal and seasonal variations in the orientation of the main dipole
387 component of the Earth's present-day magnetic field with respect to the solar wind and IMF could
388 provide some information, but in practice these effects tend to be swamped by the large variability in
389 solar wind IMF conditions. A modelling study by Zieger et al. (2004) of a rather extreme change in
390 dipole orientation does offer some insights. They adapted the BATS-R-US model to simulate the
391 magnetosphere under the condition of a dipole that is oriented perpendicular to the Earth's rotation
392 axis. This resulted in dramatic daily variations in the magnetopause currents and tail current sheet.
393 However, they stressed that bowshock and magnetosheath currents remained more or less the same,
394 as these are controlled by the IMF orientation.

395 When we move away from a simple dipolar magnetic field structure, it becomes more complicated to
396 describe what happens to current systems in the ionosphere and magnetosphere. For the
397 magnetosphere, the non-dipolar contributions to the magnetic field are less important as these
398 contributions diminish quickly with distance from the Earth. However, in the ionosphere there are
399 notable regional variations that are associated with non-dipolar structures of the magnetic field. Some
400 of the effects of non-dipole components on low-latitude currents were discussed by Walton and
401 Bowhill (1979), while Siscoe and Sibeck (1980) described effects on the auroral zone. Gasda and
402 Richmond (1998) discussed the influence of non-dipolar structures on auroral electrodynamics in
403 further detail, including implications for the auroral electrojets and field-aligned currents. They
404 predicted considerable longitudinal variations in electrojet current densities, with differences
405 between local maxima and minima of about 40% in the Northern hemisphere. Le Sager and Huang
406 (2002) used model simulations to study how the Sq current system changes when the full IGRF
407 magnetic field structure is used to define the main field, as opposed to an aligned or tilted dipole. A
408 realistic magnetic field resulted in considerably different horizontal and field-aligned low- to mid-
409 latitude currents, while some features were not simulated at all with the dipole approximations. For
410 instance, a time lag of ~1 hour between the horizontal current foci in the Northern and Southern
411 hemispheres at equinox, which had previously been found in observations, could only be
412 (approximately) reproduced with the full IGRF.

413

414 **4. Effects of realistic magnetic field changes in the past ~100 years**

415 In this section we will examine the effects of changes in the actual magnetic field between 1908 and
416 2008, based on CMIT simulations carried out by Cnossen and Richmond (2013) and similarly set up
417 TIE-GCM simulations by Cnossen (2014). All of these simulations were run with background
418 geophysical conditions of 2008, when solar and geomagnetic activity were generally low. Figure 4a
419 illustrates how the magnetic field intensity changed between 1908 and 2008, according to the IGRF.
420 The main dipole component decreased in intensity from $\sim 8.3 \times 10^{22} \text{ Am}^2$ in 1908 to $\sim 7.7 \times 10^{22} \text{ Am}^2$ in

421 2008, i.e., a very small change in comparison to the large range of values explored in section 2.
422 However, the changes in magnetic field strength are far from globally uniform and are still rather large
423 (up to nearly 40%) in some regions, such as South America and the southern Atlantic Ocean. This
424 relates to the expansion of the South Atlantic Anomaly region. Figure 4b shows the movement of some
425 of the key features of the magnetic field, such as the magnetic dip equator, the magnetic dip poles,
426 and several constant inclination contours in between. Again, the strongest changes have occurred
427 over the Atlantic Ocean.

428

429 [Figures 4a/4b: IGRF magnetic field changes between 1908 and 2008]

430

431 The effects of these changes in the magnetic field on the ionospheric Pedersen conductance, as
432 simulated by Cnossen (2014) with the TIE-GCM, are illustrated in figure 5. Two different UTs are
433 shown. At 0 UT it is night-time in the region where the magnetic field has changed the most, which
434 results in much smaller changes in Pedersen conductance at low to mid-latitudes than at 12 UT, when
435 it is day-time in this region. The low- to mid-latitude changes in day-time Pedersen conductivity appear
436 to be caused primarily by changes in the main field strength, as they are in good agreement with the
437 scaling relation of equation 5a. At high latitudes, the changes in Pedersen conductance are much less
438 dependent on local time, although they appear slightly stronger at night than during the day between
439 $\sim 90^\circ\text{W}$ and 60°E . Similar spatial patterns of change and local time dependencies can be found for the
440 Hall conductance (not shown).

441

442 [Figures 5a/5b: Pedersen conductance at 0 and 12 UT for 2008 and 2008-1908]

443

444 The Sq current system is affected by changes in the ionospheric conductivities, but also by the change
445 in the geographic positioning of the magnetic equator and other magnetic structures. This effect is
446 clearly seen in the equivalent current function, shown in figure 6 (shown for 12 UT only). The contours
447 of the equivalent current function correspond to flow lines of the equivalent current system. Changes
448 in the Sq currents further lead to changes in the associated ground magnetic perturbations, shown in
449 figure 7 (for 0 and 12 UT). Because the Sq system is a daytime phenomenon, changes are again more
450 prominent around 12 UT than around 0 UT. Over South America, the Atlantic Ocean, and Africa,
451 changes are particularly large: magnetic perturbations in all three directions are easily a factor 2
452 different between 1908 and 2008, and locally this can be even more.

453

454 [Figure 6: equivalent current function at 12 UT for 1908 and 2008]

455 [Figure 7: magnetic perturbations at 0 and 12 UT for 2008 and 2008-1908]

456

457 Figure 8 further illustrates the effects of changes in the main magnetic field on the daily magnetic
458 variation at three example locations, which experienced different types of main magnetic field
459 changes (see figure 4). At Apia (13.8°S , 171.8°W) there have only been small changes in the main field
460 strength ($\sim 5\%$ decrease) and field orientation ($\sim 2^\circ$ in inclination and declination), which produced no
461 significant change in the daily Sq variation. At Huancayo (12.0°S , 75.3°W) there has been a much larger
462 decrease in the main field strength (15-20%), combined with little change in inclination. The changes

463 in Sq variation at Huancayo shown in figure 8 can therefore be attributed mainly to the decrease in
464 the main field strength, although the local time shift in the daily variation of the eastward component
465 is probably associated with a substantial change in declination ($\sim 10^\circ$). In contrast, at Ascension Island
466 (7.9°S , 14.4°W) the decrease in the main field strength is small ($\sim 5\%$), while the inclination angle has
467 changed by more than a factor 2 as the magnetic equator has moved away from this location since
468 1908. This movement of the magnetic equator is primarily responsible for the changes in Sq variation
469 we find at Ascension Island. Observational studies have also found evidence for long-term trends in
470 Sq variation, which to some degree, depending on location, have been attributed to main magnetic
471 field changes (Elias et al., 2010; De Haro Barbas et al., 2013).

472

473 [Figure 8: Daily magnetic variations at three example locations for 1908 and 2008]

474

475 We note that figure 7 also shows fairly large changes in magnetic perturbations at high latitudes, which
476 appear significant. However, the TIE-GCM does not fully represent the high-latitude current systems
477 that contribute to magnetic perturbations in these regions, so that this result is much less reliable than
478 the results for low- and mid-latitudes. The CMIT model should be able to capture some of the high-
479 latitude current systems somewhat better than the TIE-GCM can, because it includes a representation
480 of the magnetosphere, but as noted before, the high-latitude currents are still challenging to simulate
481 correctly.

482 CMIT simulations similar to the TIE-GCM simulations discussed above indicate that there is no
483 significant difference in the total field-aligned current between 1908 and 2008 for either the Northern
484 or Southern hemisphere. In terms of spatial structure, there are no significant differences either when
485 viewed in magnetic coordinates, but when transformed to geographic coordinates, differences do
486 appear due to the movement of the magnetic poles. This is illustrated in figure 9 for 0 UT. Especially
487 in the Northern hemisphere there has been a clear shift in the average field-aligned current pattern
488 from 1908 and 2008. Similar shifts are seen for other UTs.

489

490 [Figure 9: FAC patterns for 1908 and 2008 in the NH and SH at 0 UT]

491

492 **5. Implications for internal magnetic field modelling**

493 The previous sections have shown that the secular variation of the internal magnetic field causes
494 changes in the currents flowing in the magnetosphere and ionosphere, thereby inducing a long-term
495 change in the externally produced magnetic field. This poses a problem for internal magnetic field
496 modellers who seek to model the secular variation of the internal magnetic field, as the observed
497 magnetic field contains contributions from both internal and external sources. How long-term changes
498 in ionospheric and magnetospheric current systems affect the modelling of the secular variation has
499 not been studied before. However, the previous sections indicate that the degree to which long-term
500 changes in the externally induced magnetic field can leak into models of the secular variation of the
501 internal magnetic field depends on the current system in question as well as the approach taken to
502 model the internal magnetic field, in particular the data selection criteria used. Some strategies to
503 minimize effects of long-term changes in external currents associated with main magnetic field
504 changes in internal magnetic field modelling are discussed below.

505 The Sq current system is primarily important during the day-time, and therefore the impact of any
506 long-term changes in the magnetic perturbations associated with this current system will be small
507 when only night-time data are used to construct an internal magnetic field model. This is the approach
508 taken for the majority of internal magnetic field models (see Finlay et al., this volume, 2016). However,
509 if day-time data are included, as is done, for example, in the Comprehensive Model (CM) series
510 (Sabaka et al., 2002, 2004), long-term changes in the Sq current system will be relevant. Fortunately,
511 it should be relatively straightforward to account for this effect as part of the model. The CM series
512 includes a model of the Sq current system in quasi-dipole coordinates, so that the influence of any
513 changes in the positioning of the magnetic equator will automatically be taken into account. The
514 influence of any long-term change in the main field strength is currently not included, but could be
515 considered using scaling relations between the magnetic signatures of the Sq current system and the
516 main field intensity as shown in figure 2.

517 The sensitivity of the magnetic perturbations associated with the ring current and the polar electrojets
518 to main magnetic field changes is dependent not only on whether it is day- or night-time, but also on
519 the solar wind conditions, as expressed through the factor γ in the scaling relations derived in section
520 2. Since these current systems also depend on solar wind conditions on short timescales, some internal
521 magnetic field models already employ data selection criteria based on the B_y and B_z component of the
522 IMF to minimize their influence (e.g., Finlay et al., this volume, 2016). When only data for northward
523 IMF are used, eq. 16 (with $\gamma = 0$) indicates that the contribution of the ring current should not be
524 sensitive to any change in the main dipole moment intensity, so this appears to be an effective way to
525 minimize contamination of both the instantaneous internal magnetic field and its secular variation by
526 the ring current contribution. In contrast, eq. 13 suggests that the magnetic signature of the polar
527 electrojet is strongly dependent on the main dipole moment intensity for northward IMF. With $\gamma = 0$
528 we obtain $\Delta B_{PEJ} \propto M^{-2.6}$, which gives a $\sim 30\%$ increase in the polar electrojet signature for a 10%
529 decrease in the main field strength. Given that magnetic perturbations associated with the polar
530 electrojets are already very hard to model and separate from the internal magnetic field (Finlay et al.,
531 this volume, 2016) avoiding leakage of this external magnetic field contribution into the secular
532 variation of the main field will be extremely challenging.

533

534

535 **6. Summary and conclusions**

536 We have obtained scaling relations to describe how various external magnetic field contributions
537 depend on the internal magnetic field strength, based on theoretical arguments in combination with
538 modelling studies. Scaling relations for the daytime Pedersen and Hall conductances (see eq. 5a/b)
539 can be considered fairly reliable, but night-time scalings in the auroral zone (eq. 6a/b) are more
540 uncertain. This is because the night-time conductances in the auroral zone depend strongly on
541 energetic particle precipitation from the magnetosphere, and it is still not well understood how the
542 flux and energy of these particles might change under the influence of a changing main magnetic field.
543 This problem also feeds into the scaling for the magnetic perturbations associated with the polar
544 electrojets (eq. 13) and estimates of changes in field-aligned currents with a changing dipole moment
545 intensity (figure 3).

546 Changes in the orientation of a dipolar magnetic field affect the mapping between magnetic and
547 geographic coordinates, and therefore the interaction between processes that are mainly organized
548 in a magnetic reference frame (e.g., magnetosphere-ionosphere coupling, ion drag) and processes

549 that are mainly organized in a geographic reference frame (e.g., solar EUV-driven ionization and
550 heating). When the geographic and dipole axes are not aligned, this further introduces longitudinal
551 and UT variations in the ionosphere and produces asymmetries between the Northern and Southern
552 hemisphere which lead to interhemispheric currents flowing at low- to mid-latitudes.

553 Departures from a simple dipolar structure cause more complex changes to ionospheric currents. This
554 is illustrated by the simulated changes in the Sq current system due to main magnetic field changes
555 between 1908 and 2008. Locally large decreases in main field strength over South America and the
556 southern Atlantic Ocean, as well as the shift of the magnetic equator in the Atlantic sector, have
557 caused substantial changes in the daily magnetic variation, in particular during daytime, while in other
558 parts of the world there is little difference between 1908 and 2008. At night the simulated differences
559 in magnetic perturbations are generally quite small, also in regions where the magnetic field has
560 changed considerably, although they may still be statistically significant.

561 Further work is needed to improve model estimates of magnetic perturbations at high-latitudes, in
562 particular at night-time. This is not only important for the long-term variations we have focused on
563 here, but also to account for external magnetic field variations on shorter timescales. Improvements
564 to the treatment of energetic particle precipitation (e.g., Zhang et al., 2015) in models will likely help
565 with this. Enhanced resolution and coupling a model such as the LFM or CMIT to a model of the ring
566 current, can also substantially improve the representation of field-aligned currents (e.g., Korth et al.,
567 2004; Wiltberger et al., 2016, accepted). Future studies should test whether with such improvements
568 it is possible to obtain better agreement between observed and simulated magnetic perturbations at
569 high latitudes.

570

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575

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692

693 **Figure captions**

694 Figure 1. Dependence of the global mean Pedersen (Σ_P) and Hall (Σ_H) conductance on dipole moment
695 intensity for intermediate solar activity (F10.7 = 150 sfu) based on CMIT simulations by Cnossen et al.
696 (2012a). Each marker represents a 24-hour average under constant solar wind conditions
697 (Interplanetary Magnetic Field (IMF) $B_x=B_y=0$; $B_z=-5$ nT; solar wind speed $V_x=-400$ km/s; $V_y=V_z=0$), with
698 error bars indicating the standard deviation. The dashed lines indicate the fit to the indicated scaling
699 functions. Note that the standard deviations are very small, so that the error bars are very small too
700 and somewhat hard to see.

701 Figure 2. Dependence of the amplitude of the northward, eastward, and downward components of
702 the daily variation in the Sq magnetic field at 30° magnetic latitude on the dipole moment intensity
703 for intermediate solar activity (F10.7 = 150 sfu) based on CMIT simulations by Cnossen et al. (2012a).
704 Each marker represents a longitudinal average, with error bars indicating the standard deviation.
705 Dashed lines indicate the best fit to the simulation results for $M \geq 4 \times 10^{22}$ Am².

706 Figure 3. Dependence of the total field-aligned current (upward + downward), averaged over the two
707 hemispheres, on the dipole moment intensity for intermediate solar activity (F10.7 = 150 sfu) based
708 on CMIT simulations by Cnossen et al. (2012a). Each marker represents a 24-hour average under
709 constant solar wind conditions (Interplanetary Magnetic Field (IMF) $B_x=B_y=0$; $B_z=-5$ nT; solar wind
710 speed $V_x=-400$ km/s; $V_y=V_z=0$), with error bars indicating the standard deviation.

711 Figure 4a. Main magnetic field intensity (nT) in 2008 (top) and the percentage difference between
712 2008 and 1908 (bottom) according to the IGRF. Magenta markers indicate the locations of Apia
713 (triangle), Huancayo (circle) and Ascension Island (square), which will be discussed later in the text.

714 Figure 4b. Contours of constant magnetic field inclination ($^{\circ}$) for 2008 (solid lines) and 1908 (dashed
715 lines). The positions of the magnetic dip poles are indicated by solid black (2008) and open (1908)
716 circles. Magenta markers indicate the locations of Apia (triangle), Huancayo (circle) and Ascension
717 Island (square), which will be discussed later in the text.

718 Figure 5a. Average Pedersen conductance (S) for 2008 (top) and the difference with 1908 (2008-1908;
719 bottom) at 0 UT for equinox conditions, based on TIE-GCM simulations by Cnossen (2014). Light (dark)
720 shading indicates where differences are statistically significant at the 95% (99%) level according to a
721 two-sided t -test.

722 Figure 5b. Same as figure 5a, but for 12 UT.

723 Figure 6. Average equivalent current function (kA) for 2008 (solid lines) and 1908 (dashed lines) at 12
724 UT for equinox conditions, based on TIE-GCM simulations by Cnossen (2014).

725 Figure 7a. Average ground magnetic perturbations (nT) in the northward (left), eastward (middle) and
726 downward (right) components for 2008 (top) and the difference with 1908 (2008-1908; bottom) at 0
727 UT for equinox conditions, based on TIE-GCM simulations by Cnossen (2014). Light (dark) shading
728 indicates where differences are statistically significant at the 95% (99%) level according to a two-sided
729 t -test.

730 Figure 7b. Same as figure 7a, but for 12 UT.

731 Figure 8. Average daily magnetic perturbations in the northward (top), eastward (middle) and
732 downward (bottom) components for 2008 (solid lines) and 1908 (dashed lines) at Huancayo (black),
733 Apia (red), and Ascension Island (blue), based on TIE-GCM simulations by Cnossen (2014). Shading in
734 corresponding colour tones indicates the 95% confidence interval.

735 Figure 9. Average field-aligned current patterns ($\mu\text{A}/\text{m}^2$) in the Northern hemisphere (left) and
736 Southern hemisphere (right) for 2008 (solid lines) and 1908 (dashed lines) at 0 UT, based on CMIT
737 simulations as set up by Cnossen and Richmond (2013), but extended to a total of 28 days surrounding
738 March equinox. Contour level spacing is $0.05 \mu\text{A}/\text{m}^2$.