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Mound, JE, Davies, C and Coimbra e Silva, L (2015) Inner Core Translation and the Hemispheric Balance of the Geomagnetic Field. *Earth and Planetary Science Letters*, 424. 148 - 157. ISSN: 0012-821X

<https://doi.org/10.1016/j.epsl.2015.05.028>

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1 Inner Core Translation and the Hemispheric Balance of
2 the Geomagnetic Field

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8 **Abstract**

9 Bulk translation of the Earth's inner core has been proposed as an ex-
10 planation of observed quasi-hemispheric seismic structure. An important
11 consequence of inner core translation would be the generation of a spherical
12 harmonic degree one heat flow anomaly at the inner core boundary (ICB) that
13 would provide an inhomogeneous forcing for outer core convection. We use
14 geodynamo simulations to investigate the geomagnetic signature of such het-
15 erogeneity. Strong hemispheric heterogeneity at the ICB is found to produce
16 a hemispheric signature in both the morphology of the magnetic field and
17 its secular variation; in particular, we note the formation of high-intensity
18 flux patches at high-latitudes and American longitudes in our model with
19 strong ICB heterogeneity. In our simulations, this model provides the best
20 match to the Earth's field over the past 400 years according to previously
21 proposed measures of field structure. However, these criteria do not include
22 the hemispheric balance of the field. We propose new criteria to measure this
23 balance and find that our model with strong ICB heterogeneity produces the
24 poorest match to the hemispheric balance of the historical geomagnetic field.

25 Resolution of the hemispheric balance of the magnetic field throughout the
26 Holocene would provide a strong test of any proposal of rapid inner core
27 translation.

28 *Keywords:* Geomagnetic field, Geodynamo, Inner core translation

29 **1. Introduction**

30 Hemispheric variations in the seismic properties of Earth's inner core (e.g.
31 Tanaka and Hamaguchi, 1997; Niu and Wen, 2001; Waszek and Deuss, 2011;
32 Miller et al., 2013) have been suggested to result from its bulk translation
33 from west to east (Monnereau et al., 2010; Alboussière et al., 2010). In this
34 scenario, the inner core melts on the leading eastern side, absorbing latent
35 heat and producing a dense iron-rich fluid, and crystallises on the trailing
36 western side, releasing latent heat and light elements into the overlying outer
37 core. This translation represents a spherical harmonic degree one convective
38 instability (Deguen et al., 2013). New estimates of the thermal conductiv-
39 ity of the solid, inner core (Pozzo et al., 2014) imply that purely thermal
40 convection within the inner core is unlikely. Convection may still arise due
41 to compositional density variations, although it is unclear whether the in-
42 stability would persist to the present day (Gubbins et al., 2013; Labrosse,
43 2014).

44 If inner core translation does occur, the resultant melting-crystallising
45 dichotomy at the inner-core boundary (ICB) will impose a heterogenous flux
46 boundary condition on convection in the outer core. Recent studies have
47 investigated the impact of heterogenous ICB heat flux on convection in the
48 Earth's outer core (Davies et al., 2013; Sasaki et al., 2013) and suggested

49 that the influence of inner core translation may be required to explain fea-
50 tures such as quiet Pacific secular variation (SV) (Aubert et al., 2013) and
51 persistent eccentricity of the geomagnetic dipole (Olson and Deguen, 2012).
52 The seismic observation of inner core heterogeneity has not been definitively
53 linked to a causal mechanism, and it is possible to explain the pattern with
54 inner core translation in either direction (Monnereau et al., 2010; Cormier
55 et al., 2011). In particular, Aubert et al. (2013) argue that explaining the
56 observed patterns of SV requires a dynamo controlled from the ICB due
57 to a combination of inner core translation (to provide the flux heterogene-
58 ity), gravitational coupling between the inner core and mantle (to maintain
59 the orientation of the pattern), and an east to west translation (to promote
60 geomagnetic westward drift in the Atlantic hemisphere). An east-west hemi-
61 spheric difference in core flow, and hence the geomagnetic field, that persists
62 over long times may represent a signature of inner core translation; in this
63 work we consider the characteristics of such a signature.

64 In order to have an observable impact on the planet’s magnetic field the
65 inner core translation must be able to influence flow throughout the outer
66 core, including near the core-mantle boundary (CMB). Seismic anomalies at
67 the base of the mantle arise due to both chemical and thermal variations.
68 Previous geodynamo simulations have shown that heterogeneous heat flux
69 conditions imposed by the mantle on the core may have an important in-
70 fluence on core flow, and hence on the observed magnetic field and secular
71 variation (e.g. Bloxham, 2000; Gibbons and Gubbins, 2000; Olson and Chris-
72 tensen, 2002), an effect which might obscure any signature of the boundary
73 conditions at the ICB. Here, we investigate the influence of ICB heterogene-

74 ity on convection in the outer core, and whether this influence is detectable
75 in the geomagnetic field, given the presence of strong CMB heterogeneity.

76 Due to the dynamic nature of core convection, the influence of heteroge-
77 nous boundary conditions at either the ICB or CMB are more likely to be
78 apparent in long timescale averages of the magnetic field, rather than in in-
79 stantaneous snapshots. Therefore, we will consider both the characteristic
80 structure of the ICB-driven signature, as well as the timescale over which it
81 would be observed in the geomagnetic field. Of course, it is possible for a
82 given ICB heterogeneity to have an observable signature that is in contradic-
83 tion with the observed character of the Earth’s magnetic field. Therefore, we
84 also consider how well the models with different ICB heterogeneity strengths
85 match observed characteristics of the modern field and its secular variation.
86 To do this we makes use of existing measures of global field structure (Chris-
87 tensen et al., 2010), and propose new measures of the hemispheric structure
88 of the field and its secular variation.

89 **2. Methods**

90 *2.1. Numerical Simulations*

91 We investigate the influence of CMB and ICB thermal heterogeneity in
92 numerical geodynamo models that solve the magnetohydrodynamic equa-
93 tions for a Boussinesq fluid in a rotating spherical shell (Willis et al., 2007).
94 Key model parameters are summarised in table 1, with the variables defined
95 in table 2. On both the inner and outer boundary we impose no-slip condi-
96 tions on the velocity, electrically insulating conditions for the magnetic field,
97 and fixed heat flux thermal boundary conditions with patterns determined

98 from seismic observations (see below). Compositional effects would introduce
99 an additional source of buoyancy at the ICB resulting in double-diffusive con-
100 vection and likely more vigorous flows. Although chemical buoyancy is likely
101 important in the present Earth, we consider a chemically homogeneous sys-
102 tem heated from below. In this set-up no heat sources exist in the volume
103 making the total radial heat flux at the ICB equal to that at the CMB. Latent
104 heat is released at the ICB and drives convection throughout the shell finally
105 escaping the core at the CMB. This simplification allows us to focus on the
106 effects of the heterogeneity of the forcing without double diffusive effects,
107 allowing us to more easily compare with our previous non-magnetic results
108 (Davies et al., 2013). The chosen values of Ekman, Rayleigh and Prandtl
109 numbers correspond to those used in our previous study of non-magnetic
110 convection with imposed ICB heat flux heterogeneity.

111 At the CMB we apply a heat flux pattern derived from a linear scaling of
112 the S-wave velocity variations of Masters et al. (1996). The seismic velocity
113 variations will arise from a combination of thermal and chemical contribu-
114 tions and the ultimate impact on CMB heat flux depends on a combination
115 of the inferred variations in both temperature and thermal conductivity of
116 the lowermost mantle and thus it is not possible to uniquely determine CMB
117 heat flux from a tomography model. Our scaling from seismic velocity to
118 heat flux variations is chosen following the work of Nakagawa and Tackley
119 (2008) and is sufficiently large that the heterogeneous CMB boundary con-
120 dition is expected to have an important influence on flow at the top of the
121 core (in the absence of any ICB heterogeneity). The amplitude of the het-
122 erogeneous thermal boundary conditions applied at the CMB and ICB is

Table 1: Model Parameters

Parameter	Definition	Value
Ekman Number	$E = \frac{\nu}{2\Omega d^2}$	10^{-5}
Rayleigh Number	$Ra = \frac{\alpha g \beta}{2\Omega \kappa}$	$9 \times Ra_c$
Prandtl Number	$Pr = \frac{\nu}{\kappa}$	1
Roberts Number	$q = \frac{\kappa}{\eta}$	10
Radius Ratio	r_i/r_o	0.35
CMB Heterogeneity	$q_o^* = \frac{q_o^{\max} - q_o^{\min}}{\bar{q}_o}$	2.3
ICB Heterogeneity	$q_i^* = \frac{q_i^{\max} - q_i^{\min}}{\bar{q}_i}$	0.023, 0.23, 4.2

123 measured by the peak-to-peak variations in heat flux relative to the mean,
 124 which we denote q^* .

125 Heterogeneous heat flux imposed at the ICB may also promote large scale
 126 flows, which have the potential to disrupt the influence of an imposed CMB
 127 heterogeneity. Our choice of ICB heterogeneity is motivated by the proposed
 128 inner-core translation, and the strength of the heterogeneity is directly re-
 129 lated to the ratio between the translation speed and the rate of inner core
 130 growth. We impose a spherical harmonic pattern of degree and order 1, ori-
 131 ented such that the inner core is translating from ‘west’ to ‘east’ (i.e. heat flux
 132 is enhanced in the solidifying, quasi-western hemisphere). The orientation
 133 of the pattern is set to match the hemispherical seismic velocity structure
 134 determined by Waszek and Deuss (2011), that is, higher heat flux on the
 135 Western hemisphere with a boundary at 14 degrees East. We consider three
 136 values of q_i^* such that the heat flux heterogeneity at the ICB is weak (Model

Table 2: Definition of Variables

Variable	Symbol
Shell thickness	d
Gravitational acceleration	g
ICB heat flux	q_i
CMB heat flux	q_o
ICB radius	r_i
CMB Radius	r_o
Thermal expansivity	α
Background state radial temperature gradient	β
Magnetic diffusivity	η
Thermal diffusivity	κ
Viscosity	ν
Rotation rate	Ω

137 W), roughly equivalent (Model E), or strong (Model S), in comparison to our
 138 chosen value of q_o^* . Note that our non-dimensionalisation of \bar{q} depends on the
 139 area of the boundary, and thus to apply the same q^{\max} on both boundaries
 140 implies that $q_o^* = (r_o/r_i)^2 q_i^*$. The values of q_i^* were chosen in consideration
 141 of previous non-magnetic convection modelling (Davies et al., 2013), which
 142 suggests that the ICB heterogeneity should be relatively dynamically unim-
 143 portant in Model W, and potentially dominant in Model S.

144 In all cases the model resolution is to spherical harmonic degree and order
 145 128. This was found to provide three orders of magnitude convergence in the
 146 magnetic fields and greater convergence in the velocity fields. Each of the
 147 simulations took approximately 0.4-0.5 million CPU hours of computation.
 148 The choice of parameters enabled us to investigate time scales that should
 149 be long enough to investigate the signatures of the heterogeneous forcing in
 150 the time average of the field, with manageable computational costs.

151 Comparison of the numerical simulations with the Earth requires us to re-
 152 dimensionalise time, for which there are two obvious options. Both the mag-
 153 netic diffusion time scale ($\tau^d = d^2/\eta$) and the advection time scale ($\tau^a = d/U$,
 154 where U is a characteristic fluid velocity) have been used successfully in pre-
 155 vious work; the ratio of the two time scales is the magnetic Reynolds number
 156 ($R_m = \tau^d/\tau^a$) which is on the order of 300 in our simulations. In this work we
 157 use the diffusion time scale resulting in time series of approximately 115,000
 158 model years after removal of the initial transients. With this scaling, time
 159 averages over the full model run correspond to durations much longer than
 160 those available from current observational field models. Use of the advective
 161 scaling would result in time series of approximately 40,000 model years and

162 does not significantly alter the discussion below. Further discussion of the
163 merits of the two scalings can be found in, for example, Davies and Con-
164 stable (2014); Olson et al. (2012). After dimensionalisation the simulation
165 time series are divided into consecutive windows lasting 400 model years for
166 comparison to gufm1 (Jackson et al., 2000).

167 *2.2. Observational Field Models*

168 In this work we are interested in comparing our simulations to the ob-
169 served morphology of the geomagnetic field and its secular variation. Global
170 time-dependent representations of the field are only available for the last
171 10,000 years, we do not consider variations on longer timescales. The Earth’s
172 current magnetic field and SV are well described by models derived from sur-
173 face and satellite measurements, for example CHAOS4 (Olsen et al., 2014).
174 The predominant non-dipolar features of the field are four lobes of concen-
175 trated magnetic flux located at high latitudes and both American and Aus-
176 tralasian longitudes. Currently, secular variation is strong in the atlantic
177 hemisphere and weak in the pacific.

178 The gufm1 reconstruction spans the past 400 years and shows that the
179 present field and SV configurations are typical of that timescale (Jackson
180 et al., 2000). Archeomagnetic and paleomagnetic data are used to produce
181 models of the magnetic field that extend over a significant fraction of the
182 Holocene (e.g. CALS3k.4b (Korte and Constable, 2011), PFM9k.1 (Nilsson
183 et al., 2014), CALS10k.1b (Korte et al., 2011)). Although both the tem-
184 poral and spatial resolution of Holocene models are limited compared to
185 the historical or modern record, non-zonal field structure is detected in the
186 time-averaged Holocene field. These patterns may be the result of boundary

187 control on the Earth’s dynamo, or an indication that the available observa-
188 tions do not span a sufficiently long time to remove all transient non-zonal
189 features.

190 Due to its higher spatial and temporal resolution, we will mainly compare
191 our dynamo results with gufm1. However, the continuous evolution of the
192 Earth’s magnetic field implies that the field characteristics determined using
193 the restricted length of gufm1 may not be representative of the field on longer
194 time scales. Since we expect the influence of boundary heterogeneity to be
195 more visible in long time scale averages, we also consider the variation of field
196 structure by evaluating consecutive 400-year windows extracted from the
197 Holocene models. In particular, we consider the evolution of the hemispheric
198 balance of the geomagnetic field over these time scales, as this balance is
199 characteristic of strong hemispheric heterogeneity in the ICB heat flux.

200 **3. Results**

201 *3.1. Field Structure*

202 Figure 1 depicts the time-averaged radial magnetic field at Earth’s sur-
203 face for our three dynamo models. The CMB heat-flux pattern promotes
204 downwelling under the areas of maximum heat flux; since the tomographic
205 pattern is dominated by the Y_2^2 spherical harmonic, it is expected to create
206 two pairs of flux patches, a feature that has been seen in previous studies
207 (Olson and Christensen, 2002; Gubbins et al., 2007). However, our models
208 do not show two clear pairs of patches. In particular, as the magnitude of
209 the ICB heterogeneity is increased a single pair of high-latitude patches is
210 clearly preferred, situated roughly over the Americas. The ICB heterogene-

211 ity promotes a quasi-hemispheric pattern of upwelling and downwelling in
 212 the time averaged flow, which tends to concentrate the downwelling near the
 213 CMB into a single longitudinal band.

214 We compare the structure of the magnetic fields produced by our models
 215 to that of the Earth using the criteria devised by Christensen et al. (2010).
 216 The first criterion (AD/NAD) is a measure of the field's relative axial dipole
 217 power,

$$\text{AD/NAD} = \frac{P_{1,0}}{P_{1,1} + \sum_{n=2}^8 \left(\frac{a}{c}\right)^{(2n-2)} \sum_{m=0}^n P_{n,m}}, \quad (1)$$

218 where a is the radius of the Earth, c the radius of the CMB, and the power at
 219 a given degree depends on the Gauss coefficients $g_{n,m}$ and $h_{n,m}$ and is defined
 220 by

$$P_{n,m} = (n+1) (g_{n,m}^2 + h_{n,m}^2). \quad (2)$$

221 The second criterion (O/E) is a measure of the field's equatorial symmetry,
 222 defined as the ratio of power at the CMB between spherical harmonics in
 223 which $(n+m)$ is odd (i.e., equatorially antisymmetric structure) to those that
 224 are even (i.e., equatorially symmetric structure). The third criterion (Z/NZ)
 225 is a measure of the zonality of the field, defined as the ratio of power at the
 226 CMB in all zonal components to the power in all non-zonal components. The
 227 final criterion (FCF) is a measure of flux concentration defined by

$$\text{FCF} = \frac{\langle B_r^4 \rangle - \langle B_r^2 \rangle^2}{\langle B_r^2 \rangle^2}, \quad (3)$$

228 where $\langle \dots \rangle$ indicates the mean value over the area of integration, in this
 229 case the whole of the CMB.

230 Agreement between model and observed field is measured by comparing
 231 the values of the individual measures from model windows (Π_i) to the average

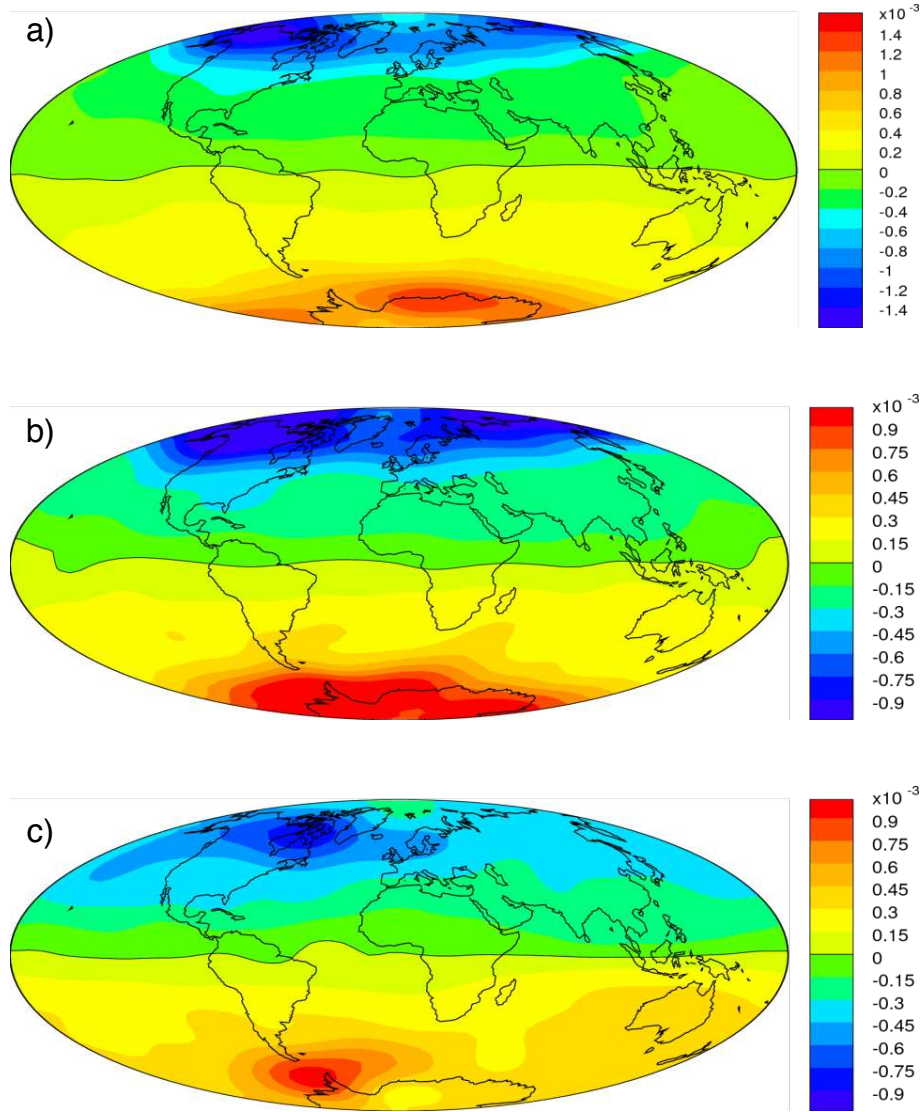


Figure 1: Time-averaged radial magnetic fields at the CMB from the dynamo models with q_i^* equal to a) 0.023, b) 0.23, and c) 4.2, all other parameters as in Table 1. Colour bars indicate dimensionless field strength. Fields are truncated at spherical harmonic degree 12.

Table 3: Field Criteria for gufm1

	AD/NAD	O/E	Z/NZ	FCF
Π^E	1.4	1.0	0.15	1.5
σ	2.0	2.0	2.5	1.75

All values from Christensen et al. (2010)

232 values of those measures over gufm1 (Π_i^E). The misfit of the simulations to
 233 the observed field values is measured relative to an assigned deviation for
 234 each characteristic (σ_i), and defined by a chi-squared misfit for each measure

$$\chi_i^2 = \left(\frac{\ln(\Pi_i) - \ln(\Pi_i^E)}{\ln(\sigma_i)} \right)^2. \quad (4)$$

235 The model agreement with the gufm1 characteristics are deemed to be excel-
 236 lent, good, and marginal if the sum of the individual misfits is less than 2, 4,
 237 and 8, respectively. The values of the measures and the assigned deviations
 238 found by Christensen et al. (2010) are summarised in table 3.

239 The evolution of the misfit between the dynamo models and the char-
 240 acteristics derived from gufm1 is shown in figure 2. Model S has the best
 241 average agreement with the field structure ($\bar{\chi}^2 = 2.7$), with excellent agree-
 242 ment in nearly half of all windows, and at least a good agreement in 79%
 243 of the individual time windows. In comparison, model W matches the field
 244 poorly ($\bar{\chi}^2 = 9.1$), with no individual windows achieving excellent agreement
 245 with gufm1 and good agreement in only 3% of the windows. Model E fares
 246 worst ($\bar{\chi}^2 = 11.7$), with no windows that achieve even good agreement. If
 247 we adopt the advection time scale to renormalise our simulations, the num-
 248 ber of gufm1-length windows in each run is different; however, we again find

249 that model S much more frequently matches the observed character of the
250 historical field.

251 The contribution of each criterion to the total misfit is designated by the
252 different coloured areas in the time series plotted in figure 2. The total misfit
253 of models W and E are often dominated by contributions from FCF (note the
254 predominance of the red bands in panels a and b). Conversely, for model S no
255 individual criterion tends to dominate the total misfit. For all three models,
256 the time-average field from windows with particularly large FCF misfits often
257 show high-latitude flux patches that are of the expected geographic extent,
258 but that are exceptionally strong; rather than a preponderance of small yet
259 intense flux patches.

260 Although model S best matches the global characteristics of gufm1 field
261 structure, this model also has a very clear preference for concentration of
262 high-latitude flux into a single pair of patches at American longitudes, as
263 opposed to the two pairs of patches seen in gufm1. The FCF measure of
264 Christensen et al. (2010) was specifically designed to ignore the longitudinal
265 location of flux concentration as it was intended to be applied to simula-
266 tions with homogeneous boundary conditions. In such cases the resultant
267 longitudinal positions have no inherent meaning. However, with heteroge-
268 neous boundary conditions designed to match seismic constraints, as in this
269 study, the resultant model longitudes are directly relatable to the Earth.
270 Therefore, in order to investigate the tendency of ICB forcing in our simula-
271 tions to concentrate flux in two patches at American longitudes we consider
272 two new criteria that measure the flux balance between eastern and western
273 hemisphere.

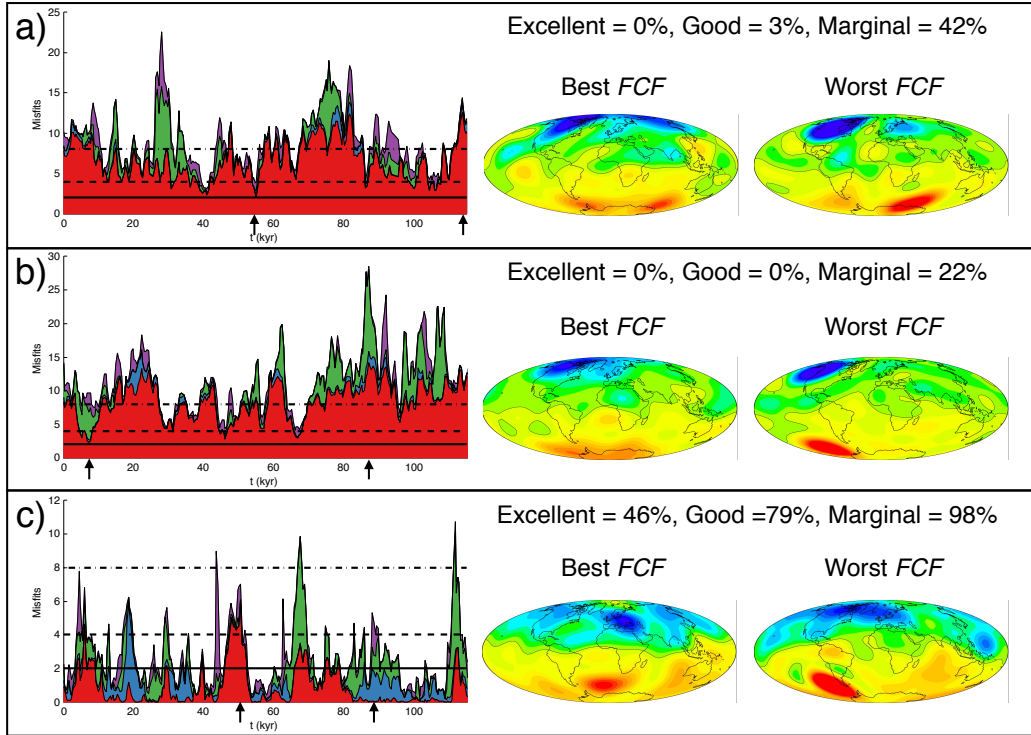


Figure 2: Agreement with observations for the the dynamo models with q_i^* equal to a) 0.023 (model W), b) 0.23 (model E), and c) 4.2 (model S), all other parameters as in Table 1. The coloured regions show the contributions from individual Christensen criteria: red = FCF, blue = AD/NAD, green = O/E, purple = Z/NZ. Horizontal lines indicate the misfit required for excellent (solid), good (dashed) and marginal (dash-dotted) agreement. Arrows below the time axis indicate the the times of the presented examples of the field for each model, times are correspond to the windows that provide the best and worst match to gufm1 according to only the FCF criterion.

274 We divide the CMB into ‘high-latitude quadrants’ bounded by the 0° and
 275 180° lines of longitude, the north/south pole and the 30° lines of latitude.
 276 Within each quadrant we evaluate the Christensen flux concentration factor
 277 (FCF) and the total integrated flux

$$F = \iint B_r dS. \quad (5)$$

278 For both FCF and F the field is truncated at spherical harmonic degree eight,
 279 and we evaluate the surface integrals numerically using Lebedev quadrature
 280 (Lebedev, 1976). The measures for each quadrant are then divided by the
 281 value obtained by considering only the axial dipole component of the field
 282 to produce normalised measures denoted FCF* and F*. This normalisation
 283 accounts for the contribution of the dipole component of the field to high
 284 latitude flux and hence the variations in the measures that could arise from
 285 changes in dipole intensity rather than redistribution of smaller scale features
 286 in the field.

287 The two measures provide complementary information on the structure
 288 of the field. The flux concentration factor FCF* depends on even powers of
 289 B_r , and thus measures the ‘patchiness’ of the field but does not distinguish
 290 between patches of normal or reversed flux. Integrating B_r results in can-
 291 cellation of normal and reversed flux patches within a quadrant, although a
 292 large value of F* does not guarantee flux is concentrated into patches. Using
 293 both measures means that not only can the strength of flux concentration
 294 be measured, but we can distinguish between the influence of normal and
 295 reversed flux patches. The construction of the quadrants is also motivated to
 296 enable comparison with the high-latitude flux patches at American and Aus-
 297 tralasian longitudes that are clearly present in gufm1, as well as the general

298 hemispheric balance of the field.

299 The normalised values (FCF^* , F^*) in the four quadrants (northwest,
300 southwest, northeast, southeast) are combined to produce a measure of the
301 hemispheric difference in high-latitude flux concentration,

$$H_{\text{FCF}^*}, H_{F^*} = \frac{(Q_{\text{NW}}^* + Q_{\text{SW}}^*) - (Q_{\text{NE}}^* + Q_{\text{SE}}^*)}{(Q_{\text{NW}}^* + Q_{\text{SW}}^*) + (Q_{\text{NE}}^* + Q_{\text{SE}}^*)}, \quad (6)$$

302 where Q^* stands for the relevant quadrant value. These measures of hemi-
303 spheric bias are analogous to that used by Dietrich and Wicht (2013) for de-
304 scribing the hemispheric field structure of Mars. The measures are bounded
305 by ± 1 and equal to zero if east and west are equal.

306 The evolution of FCF^* and F^* in the four quadrants over the duration
307 of *gufm1* is shown in figure 3. The most noticeable feature is the monotonic
308 increase in the value of FCF^* in the southwest quadrant (red line, panel a),
309 accompanied by a monotonic decrease in F^* within that quadrant (red line,
310 panel b). These changes reflect the growth of the reverse flux patch at the
311 CMB that produces the South Atlantic Anomaly (SAA), the field within the
312 southwest quadrant becomes patchier through time but the total integrated
313 flux decreases. Within *gufm1* the northern high-latitude flux patches are less
314 prominent at the earliest times, which may well reflect limitations in the data
315 coverage rather than a change in field structure. Within the *gufm1* recon-
316 struction the intensity of the northwestern patch increases approximately a
317 century before that of the northeastern patch and this timing difference is
318 clearly visible in the evolution of FCF^* in the relevant quadrants.

319 We are particularly interested in the hemispheric balance of the field,
320 and the evolution of the relevant measures ($H_{\text{FCF}^*}, H_{F^*}$) are plotted as a
321 phase diagram (panel c of figure 3). Each blue dot in this figure represent an

322 individual snapshot from gufm1, with the most recent times residing within
323 the upper-left region of this phase diagram. The present-day magnetic field
324 in the high latitudes of the western hemisphere is patchier than in the eastern
325 hemisphere ($H_{\text{FCF}^*} > 0$) but with less total flux ($H_{\text{F}^*} < 0$), again reflecting
326 the influence of the SAA reverse flux patch. The magnetic field evolves
327 over the course of gufm1, but on average the concentration of flux is nearly
328 balanced between eastern and western hemispheres (red square, panel c).

329 We also consider the evolution of the hemispheric distribution of flux
330 patches throughout CALS10k.1b in figure 3, panel d. In this case we truncate
331 the model at spherical harmonic degree 4 as the field is less well constrained
332 over the Holocene than in the historical model of gufm1. The hemispheric
333 pattern of individual snapshots from CALS10k.1b is generally biased slightly
334 towards more flux in the west, but with more patchiness in the east; the
335 present field configuration of more flux in the east, but patchier in the west,
336 appears unusual within the Holocene. The present field configuration may
337 not be unusual as it is possible that the geographic distributions of the data
338 used may result in CALS10k.1b not adequately capturing the hemispheric
339 balance of the Earth’s field throughout the model. It is also possible that the
340 length of CALS10k.1b is insufficient to establish the long-term hemispheric
341 balance of the Earth’s field. The hemispheric balance in our dynamo models
342 varies considerably through time (figure 4), and we find that if we consider
343 the progressive running average of the hemispheric measures it takes approx-
344 imately 25,000 model years to accurately determine the final time-averaged
345 field morphology. This is similar to the timescale found by Davies and Con-
346 stable (2014) for the non-zonal components of the field to converge on their

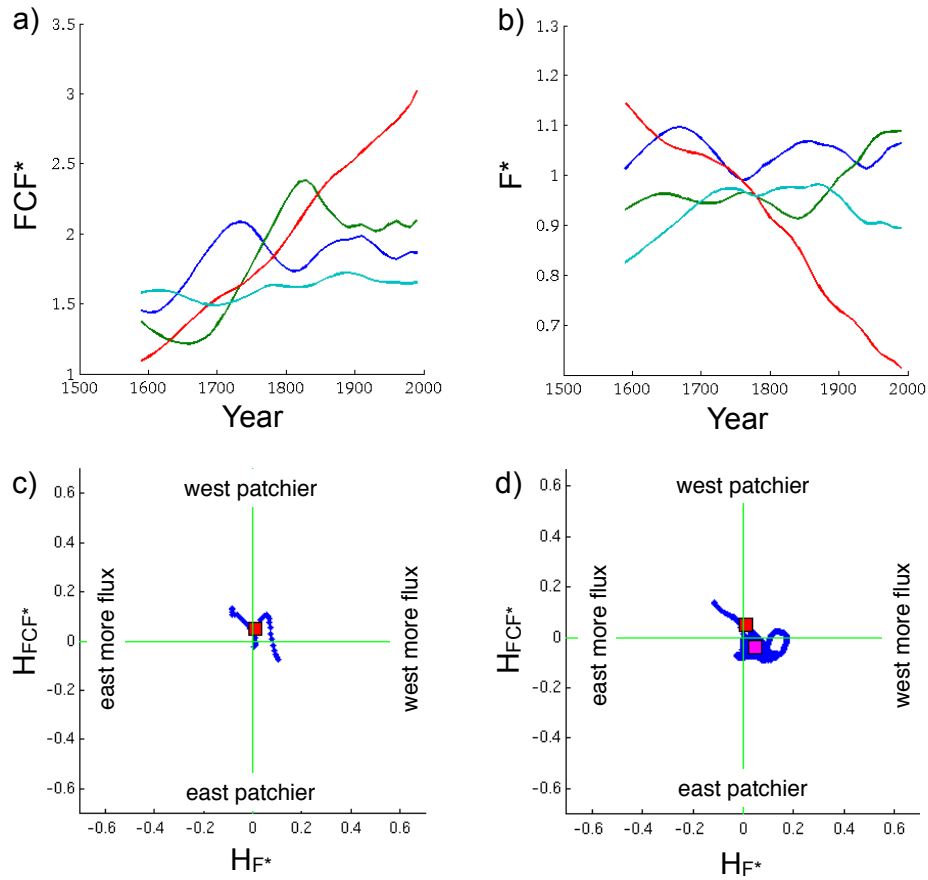


Figure 3: Flux concentration in observational models. Evolution of the a) FCF^* measure and b) F^* measure through time in gufm1 in the northwest (blue), northeast (green), southwest (red) and southeast (cyan) quadrants. Hemispheric measures through time: c) blue dots are values for individual snapshots from gufm1, the red square is the average of all snapshots; d) blue dots are values for individual snapshots from CALS10k.1b, the magenta square is the average of all snapshots, the red square is the gufm1 average for comparison.

347 long-term averages.

348 Phase diagrams showing the hemispheric balance of flux in our three dy-
349 namo models are shown in figure 4; note that in this case each individual dot
350 represents the average over a window spanning 400 model years. The models
351 show a great deal of variability in their east-west flux balance and can reach
352 rather large values of hemispheric disparity; for example, model E contains
353 windows in which H_{F^*} exceeds 0.6, implying that the sum of F^* in the west-
354 ern quadrants is more than four times greater than in the eastern quadrants.
355 For our simulations, model W has the average hemispheric balance that is
356 most similar to that of `gufm1`; as q_i^* is increased in the models there is an
357 increasing tendency for flux to be concentrated in the west and model S is
358 dominated by fields in which both H_{FCF^*} and H_{F^*} are positive. The magnetic
359 fields of all three models are highly variable through time, showing a much
360 greater range of values in their 400-year window averages, than either `gufm1`
361 or `CALS10k.1b` showed in their individual snapshots. Although a definitive
362 long-term time-average requires approximately 25,000 model years to obtain,
363 the preference for the patches of strong flux to form at American longitudes
364 in model S is clear not only in the long-term time average but also in the ma-
365 jority of individual 400-year windows; only $\sim 1\%$ of windows have $H_{F^*} < 0$
366 in this model.

367 *3.2. Secular Variation*

368 We also compare our dynamo models to the pronounced quiet Pacific
369 secular variation observed in the modern field. To define our measure of
370 Pacific SV quietness we first define the secular variation density within a

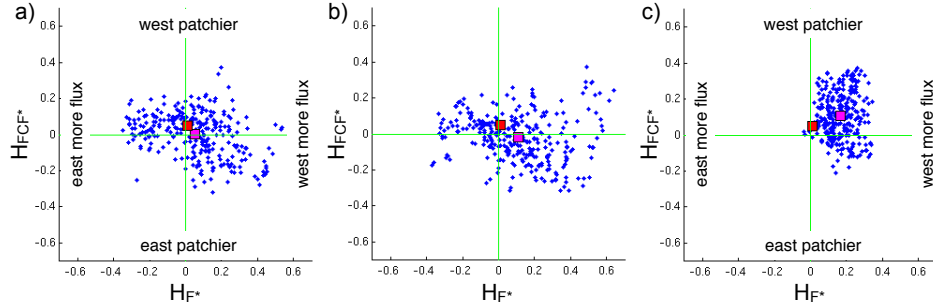


Figure 4: Dynamo model flux concentrations. Hemispheric measures of FCF^* and F^* through time for the models with q_1^* equal to a) 0.023 (model W), b) 0.23 (model E), and c) 4.2 (model S); blue dots are values for individual 400-year windows, the pink square is the average of all windows, the red square is the average of gufm1.

371 given region as

$$\rho_{SV} = \langle |\dot{B}_r| \rangle, \quad (7)$$

372 where the time derivative of the radial field is evaluated on the CMB. For
 373 convenience we define ‘the Pacific’ as either the hemisphere between $90^\circ E$
 374 and $90^\circ W$, or by the more restricted region bounded by $50^\circ S$, $50^\circ N$, $135^\circ E$
 375 and $90^\circ W$. Similar to our measures of hemispheric flux concentration, we
 376 construct a measure of Pacific SV quietness by comparing the secular vari-
 377 ation density within the Pacific (ρ_{SV}^p) to that in the rest of the world (ρ_{SV}^{np})
 378 as defined by

$$H_\rho = \frac{\rho_{SV}^p - \rho_{SV}^{np}}{\rho_{SV}^p + \rho_{SV}^{np}}. \quad (8)$$

379 This measure is zero when ρ_{SV} is equal within and outside the Pacific, is
 380 bounded by ± 1 , and is positive/negative when the Pacific is noisy/quiet.

381 We evaluate the average and standard deviation of H_ρ over the duration
 382 of both our numerical simulations and selected observational models of the
 383 geomagnetic field (figure 5). The reduced temporal and spatial resolution at

384 early times in gufm1 and the Holocene models means that in these cases the
385 resultant estimates of secular variation are not directly comparable to the
386 effectively instantaneous SV determinations that are possible for the present
387 field and our geodynamo models. However, changes in the spatial structure
388 of the magnetic field through time in these models must ultimately reflect
389 the accumulated action of an underlying pattern of secular variation and
390 thus provide some insight into the persistence of the quiet Pacific. When
391 evaluating H_ρ for our simulations and the modern field models we truncate
392 at spherical harmonic degree 8, for the Holocene models we truncate at degree
393 4.

394 The modern magnetic field, as described by the CHAOS4 model, clearly
395 has quiet Pacific secular variation, particularly if we consider our more re-
396 stricted region rather than the hemispheric balance. The Pacific is quiet
397 throughout gufm1, with the value of H_ρ based on the more restricted region
398 being more variable than the hemispheric H_ρ , but the two measures result in
399 very similar averages ($\bar{H}_\rho = -0.24 \pm 0.07$ or $\bar{H}_\rho = -0.26 \pm 0.13$). H_ρ varies
400 considerably in the Holocene models, with an average value of approximately
401 zero. There are times when large changes in the magnetic field are seen over
402 the Pacific, as well as times during which the Pacific field is relatively steady.
403 Although not as well constrained as gufm1, the Holocene models suggest that
404 the quiet Pacific may not be representative of the Earth's field over long time
405 scales.

406 Similar to the Holocene models, H_ρ varies considerably in our geodynamo
407 models, with all three models showing times of both quiet and noisy Pacific
408 SV. We consider our simulations to have an excellent, good or marginal

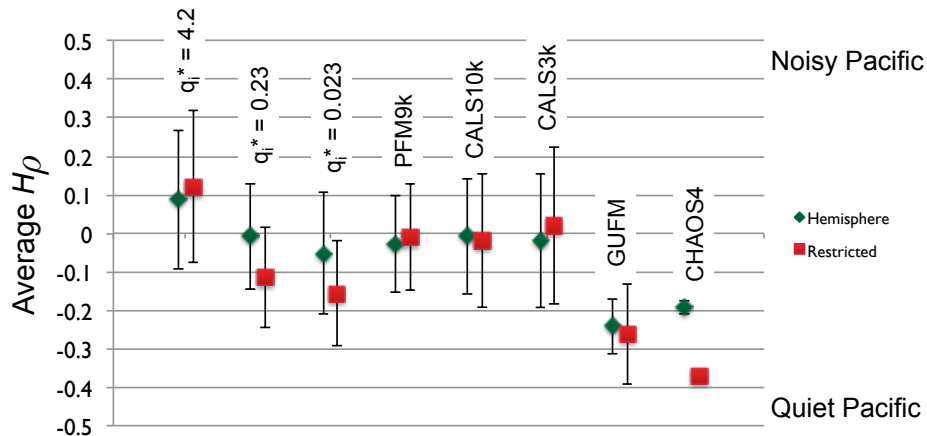


Figure 5: Quietness of Pacific secular variation for different field models computed using hemispheres (green) and our more restricted Pacific region (red). Error bars represent one standard deviation in the values of H_ρ based on the sampling interval of the given model.

409 match to the Earth's SV when \bar{H}_ρ over the 400-year window is within one,
 410 two or four standard deviations of the gufm1 value, respectively. As q_i^* is
 411 increased in our models there is a trend towards noisier Pacific SV, resulting
 412 in an increase in the time-averaged value of H_ρ (figure 5). All three models
 413 sometimes produce 400-year windows with average H_ρ values that match
 414 gufm1; however, such windows are more common in model W. The preference
 415 for patches of strong flux to be located at American longitudes in model S
 416 means that changes in those patches also results in localisation of regions of
 417 high SV at American longitudes, and hence the western hemisphere, for that
 418 model.

419 In figure 6 we consider the overall match of our simulations to the observed
 420 properties of gufm1 based on six characteristics. Misfit to the morphology
 421 of the field, excluding flux concentration, is measured by the Christensen

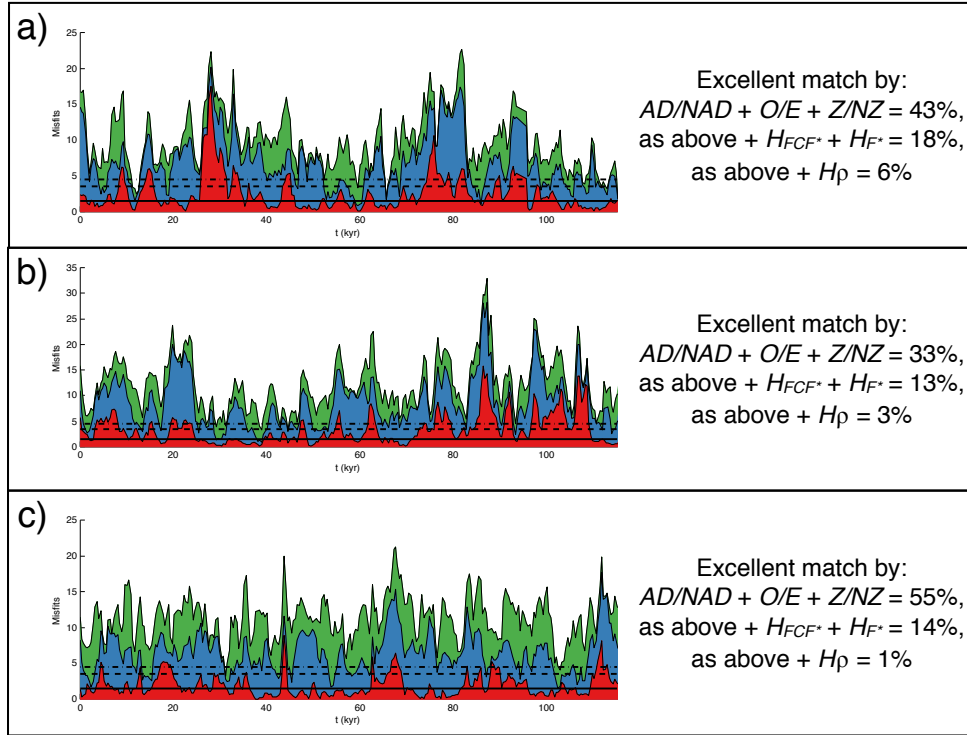


Figure 6: Misfit between 400-year windows from the dynamo models and gufm1 as determined by a combination of the Christensen criteria and our new measures, for models with q_i^* equal to a) 0.023 (model W), b) 0.23 (model E), and c) 4.2 (model S). The red area show the misfit contribution from $AD/NAD + O/E + Z/NZ$, the blue area shows the misfit contribution from $H_{FCF^*} + H_{F^*}$, and the green area the misfit contribution from H_{ρ} . Horizontal lines show the misfit levels required for excellent agreement based on the ‘red’ criteria (solid), the ‘red’ plus ‘blue’ criteria (dashed), the ‘red’ plus ‘blue’ plus ‘green’ criteria (dash-dotted).

422 criteria AD/NAD, O/E and Z/NZ, and indicated by the red bands. Misfit
423 to the flux concentration is measured by H_{FCF^*} and H_{F^*} , and indicated by
424 the blue bands. Misfit to the quiet Pacific secular variation is measured by
425 H_{ρ} , and indicated by the green bands. All models occasionally, although
426 rarely, have excellent matches to the total misfit based on both field and SV
427 structure. Model S most frequently matches the field morphology of gufm1,
428 as measured by the three Christensen criteria; however, it least frequently
429 manages an excellent match to all six criteria simultaneously. The propensity
430 for our strong ICB heterogeneity to concentrate flux and SV at American
431 longitudes means that it only rarely matches the hemispheric balance of the
432 field in gufm1.

433 **4. Discussion**

434 Hemispheric heat flux boundary conditions applied at the ICB can have
435 a detectable influence on the structure and secular variation of the magnetic
436 field, even in the presence of strong heterogeneity in CMB heat flux. Strong
437 ICB heterogeneity promotes the existence of a single pair of high latitude
438 patches of anomalously intense flux when the field is averaged over a suffi-
439 ciently long time. This flux concentration is located at American longitudes
440 in our models; however, previous simulations of non-magnetic convection
441 (Davies et al., 2013) found that the location of upwelling and downwelling
442 flows below the CMB varied with both Ra and q_i^* . Therefore, we expect
443 the location of the downwelling flow in dynamo models, and the longitude of
444 any resultant flux and SV concentrations, will also depend on the particular
445 combination of model parameters chosen. Regardless of the exact longitu-

446 dinal placement of the flux patches, a persistent hemispheric bias in core
447 flow and hence the geomagnetic field and its secular variation represents an
448 observational signature of inner core translation.

449 Increasing q_i^* in our simulations results in a model field that matches the
450 structure of the gufm1 magnetic field more frequently, compared to models
451 with weaker ICB heterogeneity, as measured by the global morphological
452 criteria of Christensen et al. (2010). When ICB heterogeneity is weak the
453 model produces a preference for quiet SV within the Pacific, conversely there
454 is a preference for Pacific SV to be noisy when ICB heterogeneity is increased.
455 This trend in \bar{H}_ρ is caused by the tendency for strong SV to be associated
456 with the high-latitude flux patches that preferentially develop at American
457 longitudes in the time average of our model with strong ICB heterogeneity. In
458 contrast, the time-averaged flow in our model with weak ICB heterogeneity
459 is strongly influenced by the imposed CMB heat flux variations which tends
460 to promote quiet Pacific SV.

461 The field and SV characteristics of all three dynamo models vary con-
462 siderably through time. All models occasionally produce 400-year windows
463 that simultaneously meet our criteria for excellent agreement with both the
464 gufm1 field and SV. Measurement with the Christensen FCF criteria indicate
465 that the model with strong ICB heterogeneity best matches the Earth's flux
466 concentration, despite a pronounced preference for flux patches at American
467 longitudes that is not apparent in gufm1. We therefore consider new criteria
468 that measure the hemispheric bias of the field. These measures show that
469 all three simulations sometimes produced fields with very strong hemispheric
470 biases, with an overall bias towards the west becoming more pronounced as

471 ICB heterogeneity strength increases.

472 The previous work of Aubert et al. (2013) preferred a more moderate
473 value of q_i^* , similar to our model E, which we do not find to be associated
474 with a strong hemispheric bias. This difference may result from our adop-
475 tion of no-slip conditions at both the inner and outer boundary, whereas
476 their work had a free-slip condition at the outer boundary. As in the study
477 of Aubert et al. (2013) we assume that the orientation of the ICB heterogene-
478 ity remains fixed through time as differential rotation of the inner core with
479 respect to the mantle would preclude a longitudinal structure in the long-
480 term time average. However, in contrast with the preferred model of Aubert
481 et al. (2013), which had enhanced ICB heat flux in the eastern hemisphere,
482 our models have enhanced heat flux in the western hemisphere of the ICB.
483 The seismic observations establish a pattern of inner core heterogeneity, but
484 interpretation of these results in terms of proposed mechanisms of inner core
485 growth can suggest either melting in the west or melting in the east (Mon-
486 nerieau et al., 2010; Cormier et al., 2011), and Aubert et al. (2013) argue that
487 the geomagnetic observations require enhanced heat flux (i.e., solidification)
488 in the east. Changing the orientation of the ICB heterogeneity in our models
489 would alter the orientation of the observed geomagnetic hemispheric signal;
490 however, our previous non-magnetic modelling (Davies et al., 2013) indicate
491 that the orientation of hemispheric patterns of core flow are not simply re-
492 lated to the choice of control parameters. Given the sensitivity to control
493 parameters and the inherent time variability of the models, caution must
494 be exercised in considering any relation between the orientation of the ICB
495 heterogeneity and the orientation of a geomagnetic hemispheric imbalance

496 over a relatively short time window.

497 The time variability of the generated field in all of our simulations means
498 that they often depart from both the field and SV characteristics of gufm1.
499 We find that heterogeneous ICB forcing is not required for our simulations to
500 produce windows spanning 400 model years that have a field and SV structure
501 that matches gufm1. Although there is a weak ICB heterogeneity in model
502 W, the CMB heterogeneity is more important in that model, and that model
503 does sometimes produce magnetic fields similar to gufm1. However, it should
504 be noted that gufm1 may not be typical of the longer-term average structure
505 of the Earth’s field, particularly for our measure of SV. The magnetic fields
506 of our geodynamo models, and perhaps the Earth, only show the influence
507 of boundary control in the time average. Individual snapshots of the field
508 or SV can depart significantly from the average structure, which takes on
509 the order of tens of thousands of years to be resolved in our models, when
510 rescaled using τ^d . Use of τ^a to rescale time would bring this averaging time
511 to just within the reach of current Holocene models. If a strong hemispheric
512 imbalance of both field and SV is a persistent feature of the Earth’s field,
513 then an explanation involving hemispheric heterogeneity at the ICB does
514 seem to be required.

515 The influence of the boundaries on dynamo action would change over
516 geologically long timescales as the processes responsible for the boundary
517 heterogeneity evolve. At the CMB, mantle convection will redistribute hot
518 and cold material, altering both the pattern and amplitude of the heat flux
519 heterogeneity. Any influence of ICB heterogeneity on outer core flow obvi-
520 ously would not exist prior to the formation of the inner core or the onset

521 of inner core translation. Structures with a longitudinal preference that per-
522 sist in the magnetic field over millions of years almost certainly require some
523 form of boundary influence (e.g. Gubbins and Kelly, 1993; Olson and Deguen,
524 2012) as these timescales are much longer than any timescale expected for
525 the internal dynamics of core convection (e.g. Hollerbach, 2003).

526 In gufm1 there are two pairs of strong flux patches in the time average,
527 one at American and one at Australasian longitudes. In the time average
528 of CALS10k.1b, only the American patch is evident in the northern hemi-
529 sphere. In the southern hemisphere both patches are evident in the full time
530 average of CALS10k.1b; however, if the average is restricted to times post-
531 5000 BC the patch near South America is somewhat stronger than the patch
532 near Australia (Korte et al., 2011). The time-averaged field of PFM9k.1
533 (Nilsson et al., 2014) also shows a preference for a relatively stronger patch
534 at American longitudes in the souther hemisphere, but more of an east-west
535 balance in the northern hemisphere patches. The density of observations at
536 high-latitudes, particularly in the southern hemisphere, means that the flux
537 patches are difficult to resolve (Nilsson et al., 2014); however, the Holocene
538 models may suggest an east-west imbalance in flux concentration. Based on
539 our results, such a hemispheric imbalance is not expected from the pattern
540 of CMB heterogeneity, but does arise naturally from the imposed pattern of
541 ICB heterogeneity. It is important to establish the robustness, and strength,
542 of any hemispheric bias in the geomagnetic field from observations over multi-
543 millennial timescales in order to better constrain the relative importances of
544 ICB and CMB heat flux heterogeneity on the dynamics of the outer core.

545 **5. Acknowledgments**

546 C.D. received support for this work from a Natural Environment Re-
547 search Council personal fellowship, NE/H01571X/1. J.M. and L.S. received
548 funding from the Natural Environment Research Council through Grant
549 NE/G002223/1. This work made use of the facilities of HECToR, the UK's
550 national high-performance computing service, which was provided by UoE
551 HPCx Ltd at the University of Edinburgh, Cray Inc and NAG Ltd, and
552 funded by the Office of Science and Technology through EPSRC's High End
553 Computing Programme. We thank Julien Aubert and an anonymous re-
554 viewer for their useful comments.

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