

## Universal Time Variations in Space Weather

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### Key Points:

- We introduce polar cap motions into magnetospheric dynamics for the first time
- The results explain the Universal Time variations in hemispheric geomagnetic indices
- The “equinoctial” (“McIntosh”) pattern is well explained by the effects of solar wind dynamic pressure and dipole tilt on the near-Earth current sheet.

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### Abstract (142 words)

We introduce the inductive effects of polar cap motions towards and away from the Sun into magnetospheric electrodynamic and show how this explains observed Universal Time variations in hemispheric geomagnetic indices. The large (and growing) hemispheric asymmetry in the offsets of the geomagnetic (dip or eccentric dipole) poles from Earth’s rotational axis means that the effect is not cancelled out in global indices. By adding this effect to that of the Russell-McPherron effect on solar wind-magnetosphere coupling, that of ionospheric conductivities, and that of the solar wind dynamic pressure and dipole tilt on the near-Earth tail lobe field and cross-tail current sheet, we are able to model the persistent “equinoctial” time-of-day/time-of-year pattern (with additional net Universal time variations) observed in the *am*, *an* and *as* geomagnetic indices since 1959. We discuss the implications for the longitudinal dependence of the effects of extreme space weather events.

### Plain Language Summary

The Universal Time variation in geomagnetic activity was first noted in 1925 but despite many attempts to explain it, its origin has remained a puzzle. We here introduce a previously overlooked factor, namely the effects of polar cap motions towards and away from the Sun caused by the Earth’s rotation. We show the effect is significant and that, when added to other known effects, it can explain the best observations, which are available for the past 60 years. The results have implications for the design and mitigation of space weather effects on ground-based systems, such as power grids and long pipelines, at different longitudes.

## 1 Introduction

Two of the longest-surviving puzzles in solar terrestrial physics and space weather have been the “equinoctial” (or “McIntosh”) time-of-year ( $F$ ) - Universal Time ( $UT$ ) pattern of geomagnetic activity (McIntosh, 1959; Cliver et al. 2000), and its net  $UT$  variation (when averaged over all  $F$ ), initially detected by Bartels (1925). These are closely linked, via the precessions of Earth’s magnetic axis  $\vec{M}$ , to the semi-annual variation, first reported even earlier by Broun (1848), which was explained early in the space age with the highly successful Russell-McPherron (1973) (R-M) paradigm. However, the R-M theory predicts a quite different  $F$ - $UT$  pattern and no net  $UT$  variation. Despite a very large number of postulated additional mechanisms (see review by Lockwood et al., 2020a) none has been able to explain either anomaly satisfactorily. Some of the proposals invoked modulating dayside solar wind-magnetosphere coupling, but a detailed study of data from the global network of magnetometers unambiguously shows that the equinoctial pattern arises on the nightside of the Earth (Finch et al., 2008; Chambodut et al., 2013, Lockwood et al., 2020a). We here use the “expanding-contracting polar cap” (ECPC) model (Cowley and Lockwood, 1992) to show that the missing factor has been the inductive effects of the diurnal sunward and antisunward velocities of the polar caps caused by Earth’s rotation. On a global scale, this introduces a  $UT$  variation because of the hemispheric asymmetry in the geomagnetic field that is now changing faster than at any time since observations began (Thébault et al., 2015).

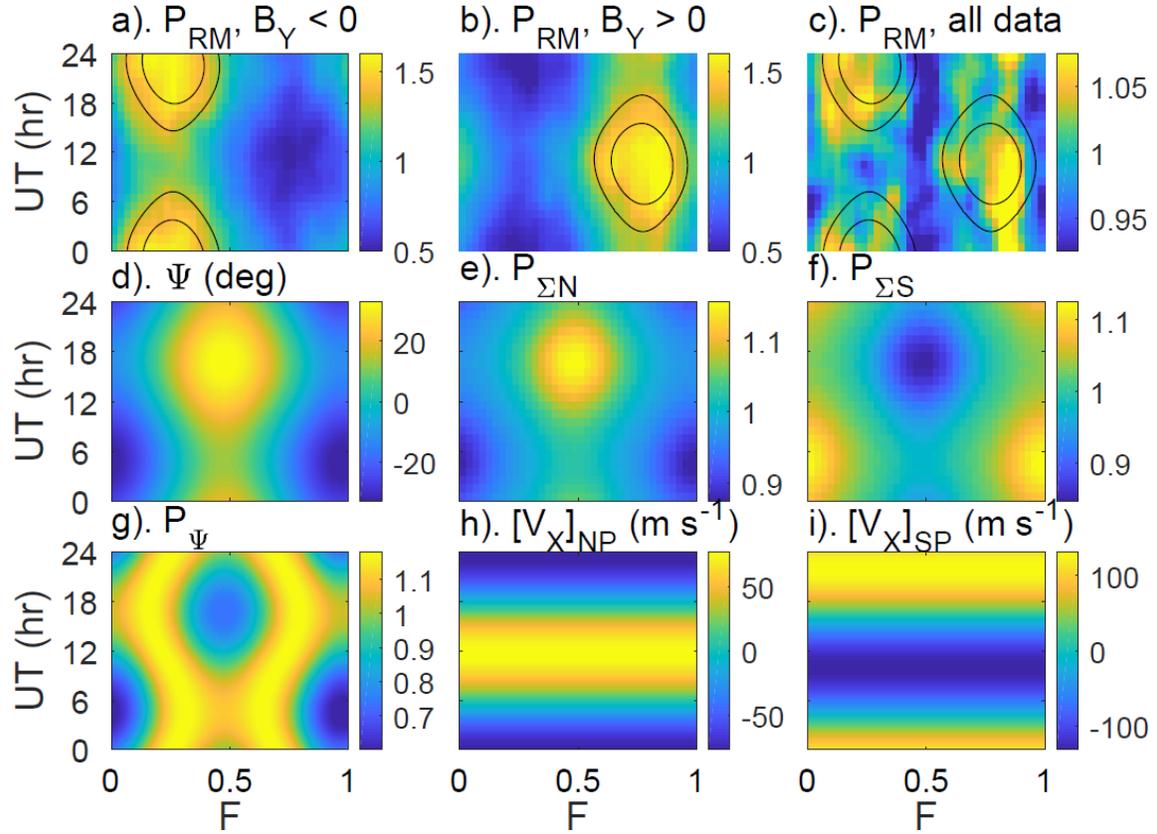
## 2 Methods

### 2.1 Theoretical drivers of $F$ - $UT$ patterns: R-M and equinoctial

The R-M theory is geometric, being based in the facts that the near-Earth interplanetary magnetic field (IMF) is ordered in a solar reference frame (Geocentric Solar Equatorial, GSEQ, where  $X$  points from the center of the Earth to the center of the Sun,  $Y$  is parallel to the solar equatorial plane and is close to duskward and  $Z$  makes up the right hand set and is close to northward) but power input into the magnetosphere,  $P_{\alpha}$ , depends on the IMF orientation in the Geocentric Solar Magnetospheric frame (GSM, which has the same  $X$  axis but is rotated so that the  $Z$  axis lines up with the projection of  $\vec{M}$  onto the  $YZ$  plane) (see review by Lockwood et al., 2020a). This is because the dominant solar wind-magnetosphere coupling mechanism, magnetic reconnection, depends on the magnetic shear across the dayside magnetopause and hence on the IMF  $[B_z]_{GSM}$  component.

The coloured pixels in parts a and b of Figure 1 show the  $F$ - $UT$  patterns of average  $P_{\alpha}$ , computed from 1-minute interplanetary observations available for 1980-2019 (see review by Lockwood, 2019) for IMF  $[B_Y]_{GSEQ} < 0$  and  $[B_Y]_{GSEQ} > 0$ , respectively, and the black contours are the predictions of the R-M effect. The agreement is very close and the effect is considerable (a  $\pm 50\%$  modulation). However, the increase around the March equinox ( $F = 0.218$ ) for  $[B_Y]_{GSEQ} > 0$  in Figure 1a is almost cancelled by the decrease for  $[B_Y]_{GSEQ} < 0$  and the same near-cancellation occurs for the peak around the September equinox ( $F = 0.730$ ) in Figure 1b (Berthelier, 1976; Lockwood et al., 2020b). This cancellation is much smaller for geomagnetic indices than for  $P_{\alpha}$  (Lockwood et al., 2020a; b). Because the distribution of  $[B_Y]_{GSEQ}$  is close to being symmetrical about zero, the net R-M effect in  $P_{\alpha}$  for all data is much weaker (a  $\pm 5\%$  modulation) and much

less clear-cut in all data as shown in Figure 1c. The theoretical pattern of solar wind driving (for all data) is here termed  $P_{RM}(F, UT)$ . The equinoctial pattern of the “tilt angle”  $\psi(F, UT)$ , between  $\vec{M}$  and the sunward ( $X$ ) direction, is shown in Figure 1d with its characteristic “hourglass” form.



**Figure 1.** Fraction of year ( $F$ ) - Universal Time ( $UT$ ) patterns. Color contoured in (a)-(c) are the power input into the magnetosphere  $P_\alpha$  estimated from 1-minute interplanetary observations (available for 1980 onwards) for (a) IMF  $[B_Y]_{GSEQ} < 0$ ; (b) IMF  $[B_Y]_{GSEQ} > 0$ ; and (c) all data. The black lines in (a), (b) and (c) are the best fit theoretical R-M patterns. Other panels are  $F$ - $UT$  patterns of: (d) the dipole tilt angle,  $\psi$  for the eccentric dipole fit to geomagnetic data in 1989; (e) the northern hemisphere index ( $an$ ) conductivity factor,  $P_{\Sigma N}$ ; (f) the southern hemisphere index ( $as$ ) conductivity factor,  $P_{\Sigma S}$ ; (g) the tail squeezing factor  $P_\psi$ ; (h) the sunward velocity of the north axial magnetic pole,  $[V_X]_{NP}$ ; (i) the sunward velocity of the south axial magnetic pole,  $[V_X]_{SP}$ .

## 2.2 Modelling $F$ - $UT$ patterns in geomagnetic indices

We predict the  $F$ - $UT$  patterns of the hemispheric indices  $an$  and  $as$  (here generically referred to as  $ans$ ) from the product of 4 terms:

$$ans_m(F, UT) = P_{RM}(F, UT) \cdot P_{\Sigma NS}(F, UT) \cdot P_\psi(F, UT) \cdot [P_{PM}(F, UT)]_{NS} \quad (1)$$

where the terms  $P_{\Sigma NS}(F, UT)$ ,  $P_{PM}(F, UT)$  and  $P_{\psi}(F, UT)$  and account for the effects of, respectively, ionospheric conductivities, pole motions and dynamic pressure and dipole tilt on the tail lobe, as described in the following subsections. In each case, equations for, and further information on, all terms are given in the supporting information file. We then combine the two modelled hemispheric indices in the same way as for observations:

$$am_m(F, UT) = \{an_m(F, UT) + as_m(F, UT)\}/2 \quad (2)$$

### 2.3 The ionospheric conductivity terms $P_{\Sigma N}(F, UT)$ and $P_{\Sigma S}(F, UT)$

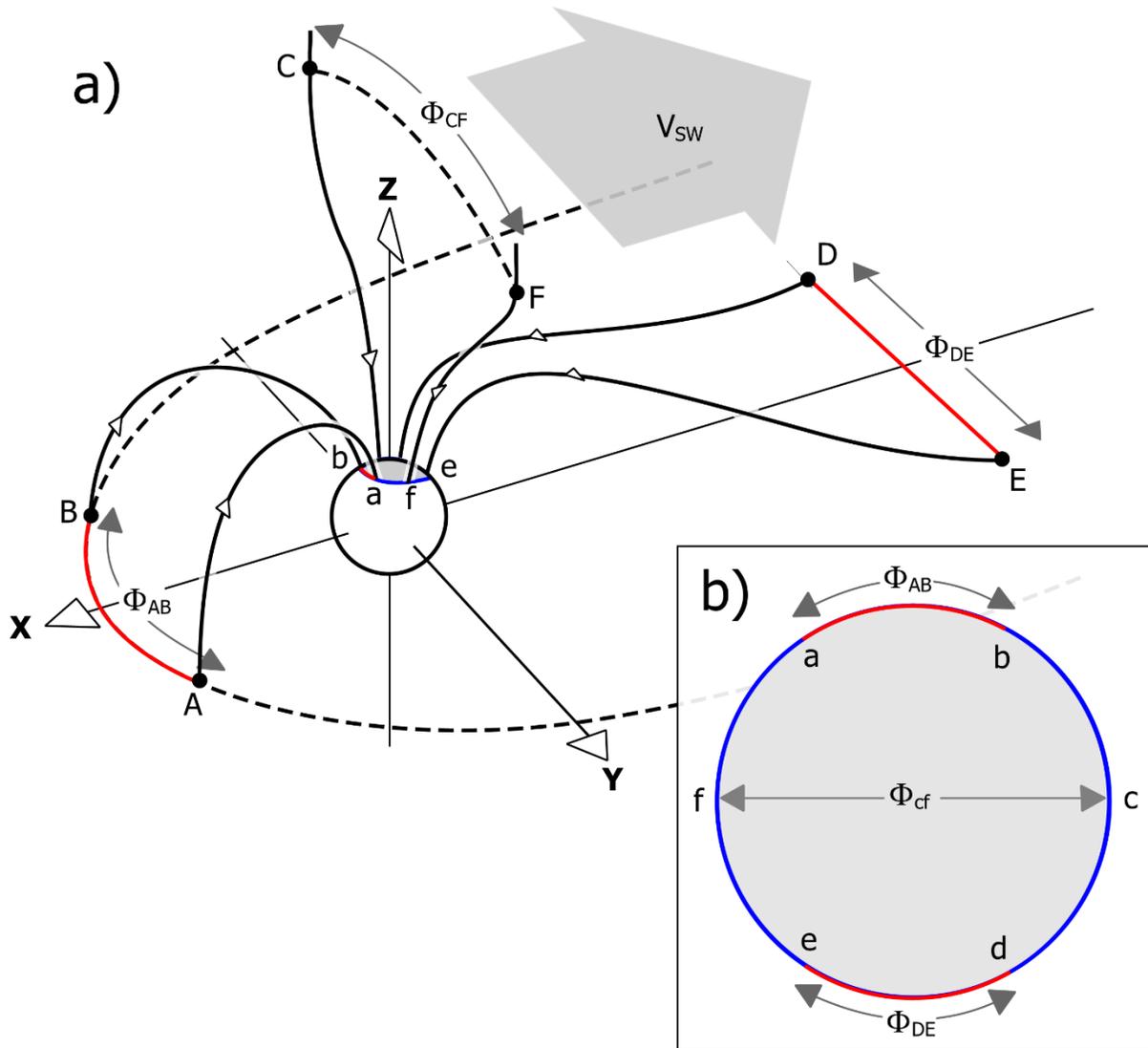
These terms allow for the effects of ionospheric Hall and Pedersen conductivities generated by photoionization. These both depend on the solar zenith angle (e.g., Ieda et al., 2014) and so, at any fixed geomagnetic location, on the tilt angle  $\psi$ . Comparing the observed variations of  $an$  and  $as$  with time-of-year  $F$  yields the functions  $P_{\Sigma N}(\psi)$  and  $P_{\Sigma S}(\psi)$  hence, from the  $\psi(F, UT)$  pattern shown in Figure 1c,  $P_{\Sigma N}(F, UT)$  (Figure 1e) and  $P_{\Sigma S}(F, UT)$  (Figure 1f).

### 2.4 The tail squeezing factor $P_{\psi}(F, UT)$

Lockwood et al. (2020b) show that, after the effect of  $P_{\alpha}$  is accounted for, the amplitude of the equinoctial pattern in  $am$  depends linearly on the solar wind dynamic pressure,  $p_{SW}$ , which is known to also increase the magnetic field in the near-Earth tail lobes (and hence the stored magnetic energy and cross-tail current) (Caan et al., 1973), consistent with its squeezing effect on the near-Earth tail (Lockwood, 2013) and its effect on geomagnetic activity (Finch et al., 2008; Lockwood et al., 2020a;b). The factor  $P_{\psi}(F, UT)$  shown in Figure 1g is derived from the  $\psi(F, UT)$  pattern using the variation  $P_{\psi B}(\psi)$ , obtained by considering the tail lobe field at a given  $\psi$ . This is derived by assuming that the near-Earth geomagnetic tail is in pressure equilibrium and using an empirical model of the locations of the magnetopause. We use a model that includes north-south asymmetries in the magnetopause which therefore includes the effects of hemispheric asymmetry in the geomagnetic field (Lin et al., 2010). To scale this factor we match the amplitude of  $P_{\psi B}(F, UT)$  to the equinoctial pattern in  $am$  for the mode value of the observed  $p_{SW}$  (Lockwood et al., 2020b).

### 2.5 The effect of pole motions $P_{PM}(F, UT)$

The new factor introduced in this paper arises from the velocity (rather than the location) of the geomagnetic poles in the two hemispheres and has been overlooked until now and is explained by Figure 2. A key part of the highly successful ECPC model of ionospheric convection (Cowley and Lockwood, 1992) is that the interplanetary electric field caused by the flow of solar wind and its embedded magnetic field, the IMF, does not map down the “open” geomagnetic field lines that have been interconnected with the IMF field lines by magnetic reconnection in the dayside magnetopause: only in the case of steady state, which is relatively rare on averaging timescales shorter than the substorm cycle (typically 1-2 hours), does such mapping apply. This is because the normal response of the magnetosphere to the generation of open field lines by magnetopause reconnection (and the consequent power input into the magnetosphere,  $P_{\alpha}$ ) is the substorm cycle of energy storage and release in the geomagnetic tail.



**Figure 2.** Schematic illustrating inductive decoupling of solar wind and ionospheric electric field and flows that is a key part of the Expanding-Contracting Polar Cap (ECPC) model of non-steady convection. Active reconnection neutral lines and their ionospheric footprints are shown in red. In (a) the X, Y, and Z axes of the Geocentric Solar Magnetospheric frame are shown. The points a, b, c, d, e and f are the ionospheric footprints of the points on the magnetopause or cross tail current sheet A, B, C, D, E and F, respectively. AB is the dayside magnetopause reconnection X-line (across which the voltage  $\Phi_{AB}$  is applied by the magnetic reconnection that opens field lines) and DE is the reconnection X-line in the cross tail current sheet (where the voltage  $\Phi_{DE}$  is caused by reconnection that recloses open field lines). CF is the “Stern Gap” (open field lines in interplanetary space that are “frozen”-into the solar wind flow,  $V_{SW}$ ) that maps to the diameter, cf, of the open polar cap (shown in grey). ABba, DEed and CFfc are all considered here as fixed loops in the GESQ reference frame to which Faraday’s law (in integral form) is applied. (b) shows the northern polar cap viewed in the  $-Z$  direction. (after Lockwood and Cowley, 1990 and Lockwood and Morley 2004).

Consider the loop CFfc in Figure 2: we know from the minimum energies of primary precipitating ions and electrons that the field-parallel voltages along Cc and Ff ( $\Phi_{Cc}$  and  $\Phi_{Ff}$ ) are very small compared to the voltage  $\Phi_{CF}$  placed by the solar wind flow across the ‘‘Stern gap’’ (the region of open field lines in interplanetary space between C and F), and the transpolar voltage placed across the ionospheric polar cap diameter (cf),  $\Phi_{cf}$ . Applying Faraday’s law to this loop (in integral form) yields (Lockwood and Cowley, 1990; Lockwood and Morley, 2004)

$$\oint_{CFfc} \vec{E} \cdot d\vec{l} = \Phi_{CF} + \Phi_{Ff} + \Phi_{fc} + \Phi_{Cc} \approx \Phi_{CF} - \Phi_{cf} = -\frac{\partial}{\partial t} \int_{CFfc} \vec{B} \cdot d\vec{A} \quad (3)$$

hence the growth or decay of field threading the loop decouples the voltages  $\Phi_{CF}$  and  $\Phi_{cf}$  which is an essential part of the substorm cycle of magnetic energy storage and release in the near-Earth geomagnetic tail. The factor that has previously been overlooked is that the offsets of the magnetic and rotational poles causes the polar caps to undergo a diurnal cycle of sunward and antisunward motion in the GSEQ frame in which the solar wind flow, and hence interplanetary electric field and the voltage  $\Phi_{CF}$ , are measured. Observations related to the open-closed field line boundary (OCB) show that, at most, 10% of the dipole tilt is reflected in the polar cap location in a geomagnetic frame (Newell and Meng, 1989). This is confirmed by global numerical modelling of the magnetosphere (Kabin et al., 2004) and means that at least 90% of the motions of poles in the GSEQ frame must be reflected in the OCB motions. The effects of these diurnal pole motions have also been seen in the auroral ovals, both in empirical models (Tsyganenko, 2019) and simultaneous whole-oval auroral images of both hemispheres (Stubbs et al., 2005). Fitting an eccentric dipole model to the observed intrinsic geomagnetic field (where the magnetic axis is not forced to pass through the Earth’s center) reveals that the offset from the rotational pole of the southern ‘‘axial’’ magnetic pole is currently roughly twice as large as that for the northern (Koochak and Fraser-Smith, 2017) and hence the amplitude of the sinusoidal sunward velocity in the north,  $[V_X]_{NP}$ , is roughly half that in the south,  $[V_X]_{SP}$ . Furthermore, the longitude difference of these poles is not exactly  $180^\circ$  and so these velocities are not quite in antiphase. Transforming pole locations in the geographic frame into the GSEQ frame (we use axial pole positions for the year 1989, at the center of the *am* data period) shows that  $[V_X]_{NP}$  and  $[V_X]_{SP}$  are almost independent of *F* and their *F-UT* patterns are shown in Figures 1h and 1i, respectively. When a polar cap is moving antisunward/sunward it effectively increases/reduces the voltage applied by the antisunward solar wind flow to the polar cap that hemisphere but also increases/reduces the energy stored in that tail lobe. Because the motions are close to being in antiphase, the energy in one tail lobe grows while the other declines but because of the hemispheric asymmetry in the geomagnetic field, these *UT* variations do not cancel. The effect is significant. The ionospheric magnetic field normal to the *X* direction  $B_{YZ}$  averages about  $4.5 \times 10^{-5}$  T over the polar cap, so 90% of the peak  $V_{SP}$  of about  $120 \text{ ms}^{-1}$  is an ionospheric electric field in the GSEQ frame of  $0.9V_{SP}B_{YZ} \approx 5 \text{ mVm}^{-1}$ ; integrating this up over a polar cap of angular radius of  $15^\circ$  (a diameter of about 3500 km, roughly consistent with a value of  $\Phi_{cf} = 39$  kV used below) gives a peak voltage modulation of  $\Delta\Phi_{cf} = \pm 17$  kV and  $\pm 8.8$  kV for the southern and northern polar caps which are not negligible fractions of typical transpolar voltages  $\Phi_{cf}$  (which vary between about 20kV and 180 kV). Note that the pole velocities are zero at minimum and peak displacement towards the Sun and so *UT* variations due to pole velocities and conductivity are in quadrature.

The only remaining requirement is to scale the hemispheric factors  $P_{PM}(F, UT)$  that quantify the effect of the pole motions on the  $an$  and  $as$  indices. As noted above, the fractional effect depends on the transpolar voltage  $\Phi_{cf}$ . Taking the mean  $am$  over the entire interval 1950-2019 of 21 nT and the regression given by Lockwood et al. (2020b) we get an average  $\Phi_{cf}$  of 39 kV, for which the peak effect in the southern polar cap is  $\Delta\Phi_{cf}/\Phi_{cf} \sim 17/39 = 0.44$ : i.e., a  $\pm 44\%$  modulation. That in the northern hemisphere is a  $\pm 22.5\%$  modulation. In theory, this effect could modulate energy stored in the tail on a diurnal timescale without altering the field-aligned currents and the geomagnetic indices or it could be fully reflected in the indices. This gives rise to the one free fit parameter in our model  $c_{PM}$  that is the ratio of the induced fractional variation in the hemispheric index to the ratio  $\Delta\Phi_{cf}/\Phi_{cf}$  and which is between 0 and 1.

### 3 Data Used

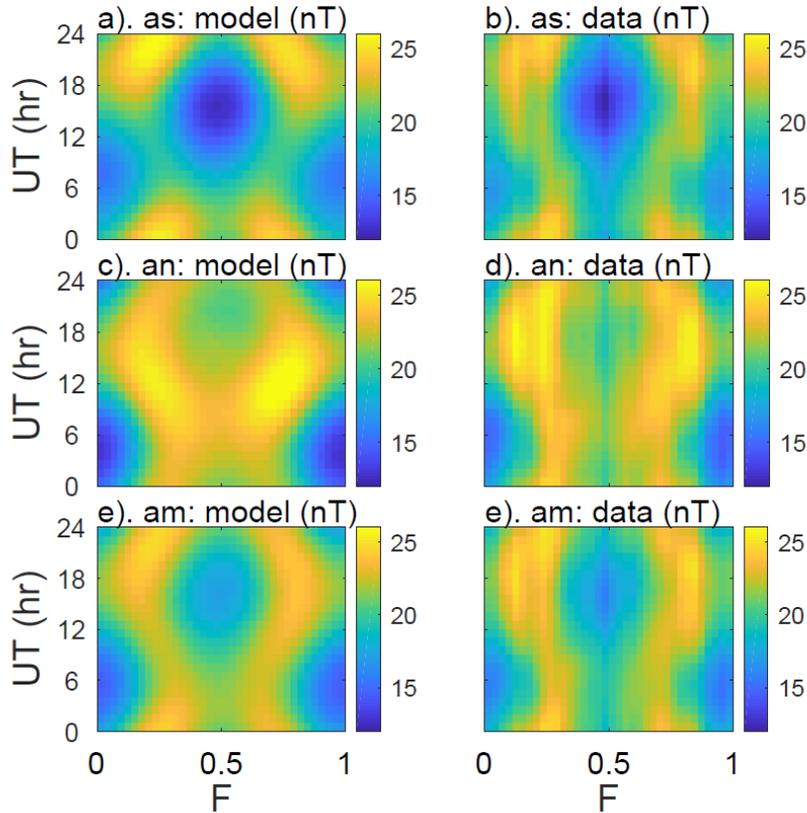
In Figures 1a-1c we use 1-minute data on the solar wind and interplanetary magnetic field made available from 1980 onwards in the Omni2 dataset to estimate the power input into the magnetosphere  $P_\alpha$  (see supporting information). Data gaps are handled using the criteria for the required number of samples for each parameter that ensures that the error in hourly  $P_\alpha$  values is below 5%. These criteria were established by Lockwood et al (2019a) by introducing synthetic data gaps into almost continuous data.

The  $am$  geomagnetic index (Mayaud, 1980), and its north and south hemisphere components,  $an$  and  $as$ , is by far the best to use in this context because it employs the most uniform network of stations in both hemispheres and is compiled using an algorithm that has been shown to give an almost constant response to solar wind forcing in both  $F$  and  $UT$ . Lockwood et al. (2019b) show that for low  $am$  ( $< 20$  nT) the  $F$ - $UT$  patterns of response of the  $an$  and  $as$  indices to solar wind

forcing are constant to within 2% and the deviations largely cancel, such that the  $am$  response is constant to within 0.5%. For high  $am$  ( $>60$ nT) these errors are reduced to just 0.2% and 0.05%.

## 4 Results

### 4.1 Comparison of modelled and observed $F$ - $UT$ patterns



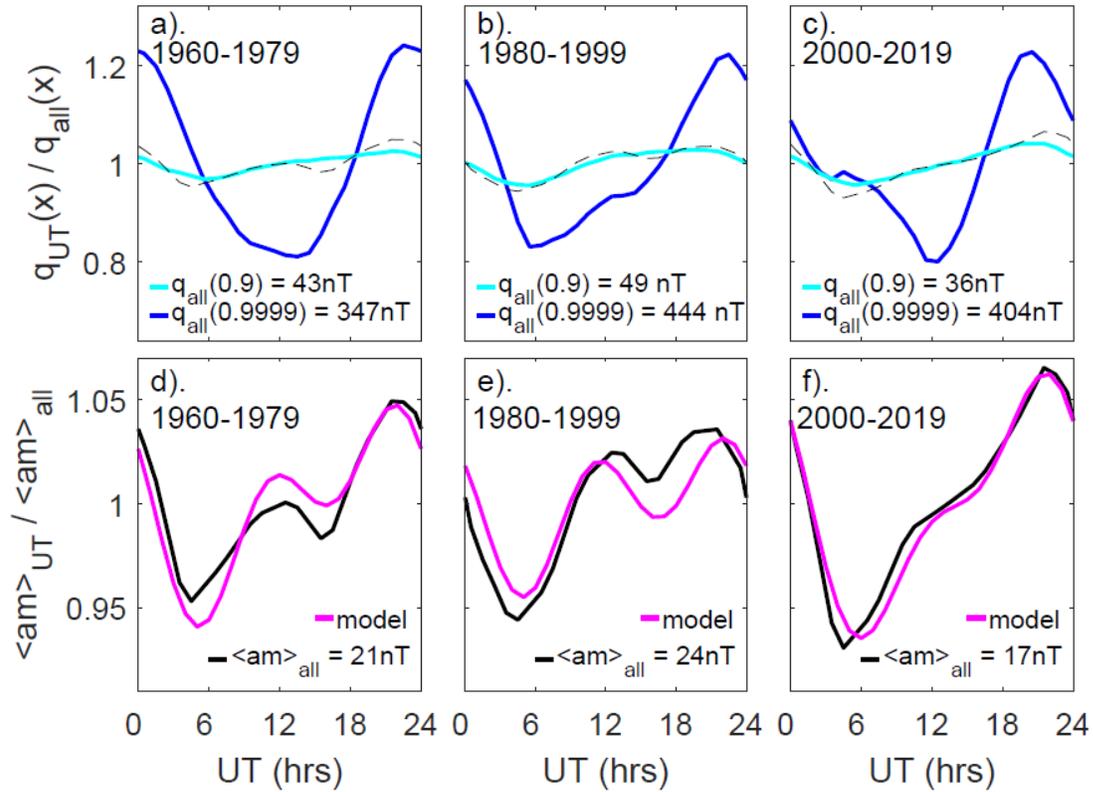
**Figure 3.**  $F$ - $UT$  plots of: (top row) the southern hemisphere  $as$  index; (middle row) the northern hemisphere  $an$  index; and (bottom row) the global index  $am = (an + as)/2$ . The left hand column shows the model predictions, the right hand column shows observations from 1959-2019, inclusive.

Figure 3 shows that the modelled  $F$ - $UT$  patterns match the observed ones very closely. The value of the one free fit parameter  $c_{MP}$  used in Figure 2 is 0.27, derived using the Nelder-Mead search method to find the minimum r.m.s. deviation between modelled ( $am_m$ ) and mean observed  $am$  for the 864  $F$ - $UT$  bins used. The largest disagreement is for  $an$  for which the predicted peak in the  $UT$  variation at both equinoxes is near 13 hrs whereas in  $an$  data it is near 16 hrs. This almost certainly arises from the closeness of the northern geomagnetic dip pole from the rotation pole in recent decades (Thébault, et al., 2015) which makes it likely that the eccentric dipole fit to the field is underestimating how far the longitude separation of the two poles has fallen from  $180^\circ$ .

#### 4.1 $UT$ variations of average values and large event occurrence

This model predicts that the  $F$ - $UT$  pattern will vary slowly over time as the geomagnetic axial poles migrate, but also will vary with the average level of the transpolar voltage and hence of the  $am$  index. To investigate this we here break the  $am$  data into three 20-year intervals, 1960-1979, 1980-1999 and 2000-2019 for which average  $am$  values are 21, 25 and 17 nT

(corresponding to  $\Phi_{cf} \sim 39, 43$  and  $34$  kV) and compute  $[V_X]_{NP}$  and  $[V_X]_{SP}$  for the pole locations at the middle of each interval.



**Figure 4.** Universal time variations averaged over all  $F$  for: (a) and (d) 1960-1979; (b) and (e) 1980-1999; and (c) and (f) 2000-2019. The top panels show the  $UT$  variation in the 90% quantile of the distribution of  $am$  values ( $q(0.9)$ , cyan lines) and the 99.99% quantile ( $q(0.9999)$ , blue lines). The dashed lines show the variation for the mean  $am$ . Bottom panels show the variations for mean observed  $am$  (black lines) and modelled  $am$ ,  $am_m$  (mauve lines).

The observed (black) and modelled (mauve)  $UT$  variations (averaged over all  $F$ ) are shown in parts d-f of Figure 4. The higher activity levels for 1980-1999 mean that the pole motions are less important and the  $UT$  variation is dominated by the other two factors. For 2000-2019 the lower activity level means that the pole motions have a much greater effect. For 1960-1979 the effect is a more-even mix of the two. Parts a-c of Figure 3 compare the  $UT$  variations in average fields (reproduced as dashed black lines) with the occurrence of large geomagnetic storms giving the 90% quantile of the distribution of 3-hourly  $am$  ( $q(0.9)$ , cyan lines) and the 99.99% quantile ( $q(0.9999)$ , blue lines): it can be seen that, despite their rarity, even the latter are showing  $UT$  variation consistent with the effect of pole motions that have been introduced here for the first time.

## 5 Discussion and Conclusions

We have shown how pole motions in the sunward/antisunward direction introduce a *UT* variation into hemispheric geomagnetic activity that explains observed variations when combined with the R-M forcing effect and the effect of solar wind dynamic pressure in squeezing the near-Earth tail, an effect that varies with dipole tilt angle. This *UT* effect is significant for the forecasting and mitigation of space weather effects because the largest geomagnetic disturbances occur around midnight magnetic local time ( $MLT = 0$  hrs) and hence the *UT* effect means there will be a longitudinal dependence. For example, Moscow and Helsinki are at  $MLT = 0$  at around 21:46 and 22:29 *UT*, respectively, when the *UT* variation in storm occurrence peaks. The equivalent *UT*s for London and Cape Town are 00:04 and 23:38 when occurrence is only a little lower, but for New York and Buenos Aires it is 04:43 and 04:41 when it is considerably lower. When geomagnetic activity is high, the main feature is the minimum at 06 *UT* caused by the tail squeezing effect (Figures 3b and 3e) which Figure 1e shows to mainly occur around the December solstice. Hence, for example, disruption to power distribution networks (e.g., Hübert et al., 2020) in winter should be less likely in central in the mid-west of North America than, for example in Eurasia. Note that the effect identified in this paper depends of the axial magnetic pole locations that are now moving faster than at any time since observations began and empirical climatologies of space weather phenomena may need to allow for this.

## Acknowledgments, Samples, and Data

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