

Seasonal and diurnal variation of *Dst* dynamics

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[1] In recent years the debate over the causes of seasonal and diurnal variations in magnetic activity has been revived. Popular explanations rely primarily on the orientation of the terrestrial magnetic dipole relative to heliospheric topology. We investigate the signatures of this geometry in the dynamics of *Dst*, the ring current index. We show that the Russell-McPherron effect is present; however, enhancements in *Dst*, as measured by the *Dst* index, exhibit a seasonal and diurnal pattern that is significantly different from the Russell-McPherron (RM) effect. Specifically, the dynamics of *Dst*, which accommodate the RM effect, demonstrate seasonal and diurnal variations associated with ψ the magnetic colatitude of the subsolar point. Specifically, it is primarily the diurnal signature that distinguishes between various mechanisms for semiannual variations. We suggest that these variations are most consistent with the hypothesis that ψ modulates the depth of penetration of the magnetosheath field into the magnetopause and thereby the amount of magnetic merging and the strength and orientation of magnetopause currents. INDEX

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1. Introduction

[2] The study of seasonal variations in geomagnetic activity has a long history [Broun, 1848; Sabine, 1852; Cortie, 1912; Chapman and Bartels, 1940; McIntosh, 1959]. Such variations have been identified with the projection of the Earth's orbit onto the heliosphere and to the seasonal illumination of the geomagnetic poles. Three angles dominate the persistent debate on these variations: λ , the heliographic latitude of the Earth, ψ the magnetic colatitude of the subsolar point, and θ the angle of the Earth's dipole in the plane perpendicular to the Earth-Sun line. Historically, explanations involving λ have been denoted axial, while explanations involving ψ have been denoted equinoctial. The three angles are depicted in Figure 1. When the Earth is out of the solar equatorial plane, it tends to experience higher solar wind velocities [Hundhausen *et al.*, 1971], giving rise to a possible λ dependence. When the subsolar magnetic colatitude ψ changes, the magnetopause shape and reconnection geometry may change [Crooker and Siscoe, 1986], as well as illumination of the polar ionosphere [Lyatsky *et al.*, 2001] and the orientation of the tail current relative to the geomagnetic equator (hinging) [Kivelson and Hughes, 1990]. As θ decreases, the average Parker spiral tends to

have a larger component parallel or antiparallel to the Earth's dipole; thus θ modulates the probability of dayside reconnection [Russell and McPherron, 1973]. It should be noted that because of the tilt of the magnetic dipole relative to the rotational axis, θ and ψ variations give rise to diurnal, as well as seasonal, variations in geomagnetic activity and that θ and ψ differ primarily in their diurnal signatures.

[3] Until recently, the prevailing explanation of seasonal variation in geomagnetic activity was that of Russell and McPherron [1973]. Figure 2 depicts the seasonal and diurnal pattern of θ . According to the Russell-McPherron (RM) effect, wherever θ is smaller than 90 degrees, there is an increased probability of southward interplanetary magnetic field (IMF) and thus an increased probability of dayside reconnection and energy transfer into the magnetosphere. This increased probability is attributable to the projection of the average Parker spiral magnetic field into the dayside geomagnetic field. However, Cliver *et al.* [2000, 2001, 2002] have recently revived the argument that the RM effect fails to predict the diurnal variation of geomagnetic activity [Mayaud, 1970, 1978; Berthelier, 1976; Svalgaard, 1977]. Specifically, Cliver *et al.* show that geomagnetic activity depends on ψ in a way not accommodated by the RM effect. Cliver *et al.* [2001] conclude that the RM effect is only part of the story, and that the remainder of the variation in *Dst* is attributable to some variation in dayside reconnection or magnetopause geometry.

[4] We will show that the variation of activity with ψ is manifest as a modulation of ring current dynamics; the

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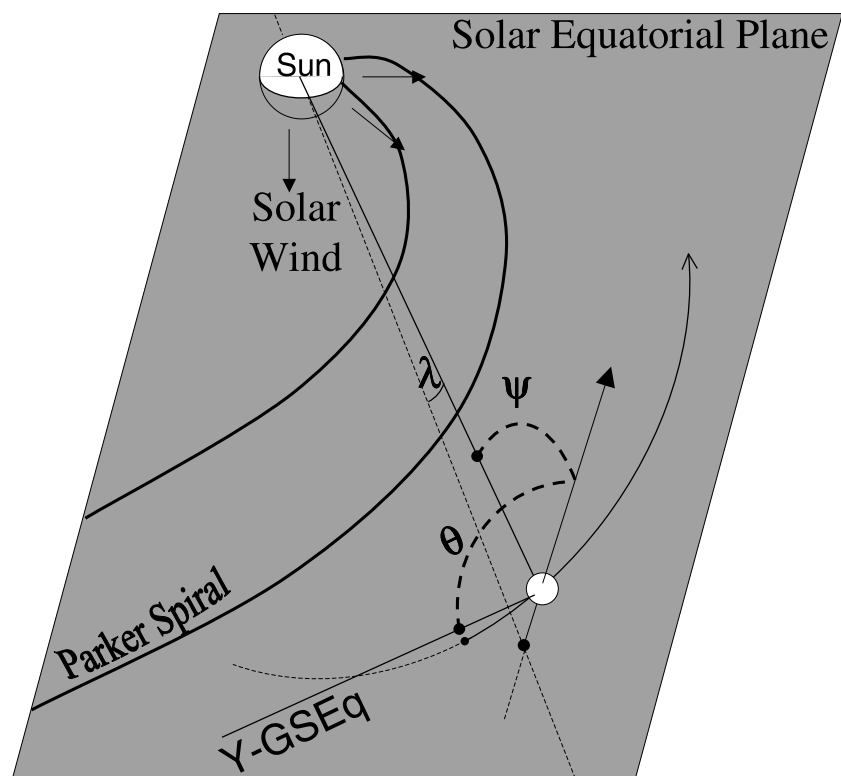


Figure 1. The three angles λ , ψ , and θ that appear to produce seasonal variations in geomagnetic activity. GSEq stands for Geocentric Solar Equatorial coordinates.

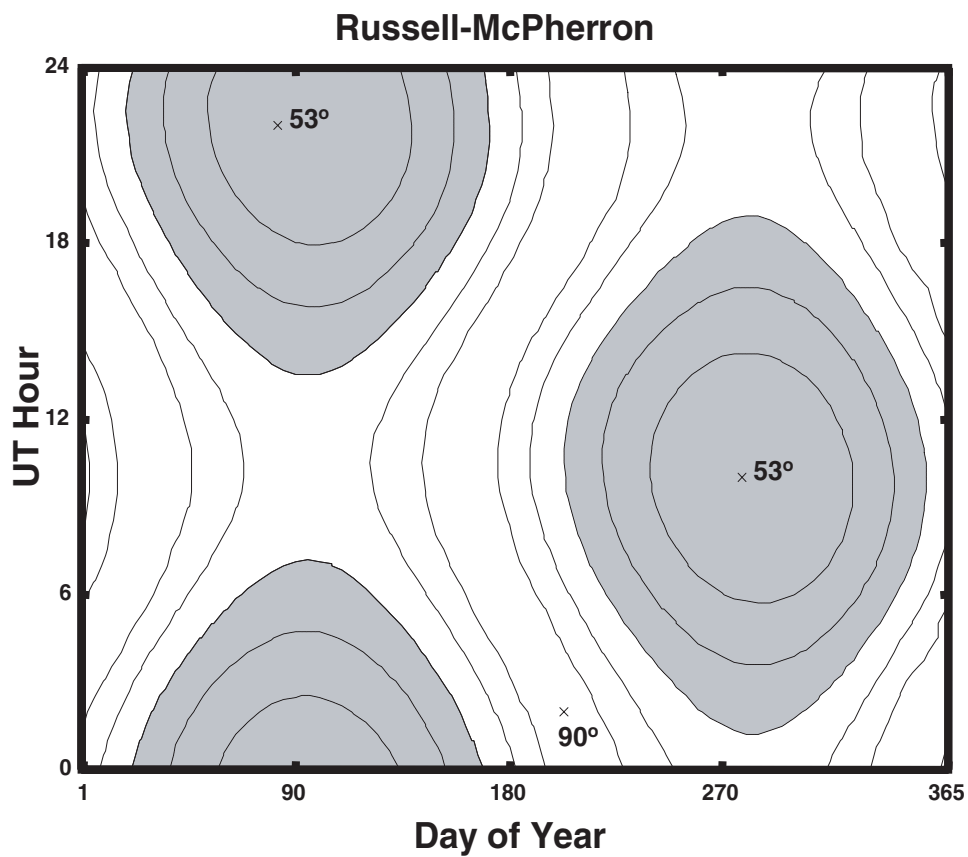


Figure 2. The seasonal and diurnal variation of θ , the angle of the Earth's dipole in the plane perpendicular to the Earth-Sun line. See Figure 1.

strength of dayside coupling and magnetopause current contamination of Dst depend on ψ . We will frame our inquiry into internal dynamics as variations in the parameters of the Burton equation [Burton *et al.*, 1975], as modified by O'Brien and McPherron [2000]:

$$\frac{d}{dt} Dst^* = Q(vBs) - \frac{Dst^*}{\tau(vBs)}, \quad (1)$$

$$Dst^* = Dst - b(\sqrt{p_{dyn}} - \langle \sqrt{p_{dyn}} \rangle), \quad (2)$$

$$Q(vBs) = \begin{cases} \alpha(vBs - E_c) & vBs > E_c \\ 0 & vBs \leq E_c \end{cases}, \quad (3)$$

$$\tau(vBs) = \tau_\infty e^{\frac{V_0}{V_q + vBs}}. \quad (4)$$

We define the solar wind driver vBs as $v B_z$ in Geocentric Solar Magnetospheric (GSM) coordinates, and we have rectified $v B_z$ such that $vBs > 0$ for southward B_z and $vBs = 0$ for northward B_z . The solar wind dynamic pressure p_{dyn} is used here in nPa. O'Brien and McPherron give $b = 7.3 \text{ nT nPa}^{-1/2}$, $\langle \sqrt{p_{dyn}} \rangle = 1.5 \text{ nPa}^{1/2}$, $\alpha = -4.4 \text{ nT m (mV h)}^{-1}$, $E_c = 0.5 \text{ mV m}^{-1}$, $\tau_\infty = 2.4 \text{ h}$, $V_0 = 9.7 \text{ mV m}^{-1}$, and $V_q = 4.7 \text{ mV m}^{-1}$. In their derivation, Q represents ring current injection, τ represents loss through charge exchange or drift through the dayside, b controls magnetopause contamination of Dst , α controls coupling between the solar wind electric field and the storm-time convection electric field, V_0 scales the total convection electric field (quiet + storm-time), and V_q represents the strength of the quiet convection electric field. The distinction between storm-time and quiet-time electric field arises because Dst measures the storm component of the magnetic perturbation at the surface of the Earth; therefore injection measures only the enhanced field, whereas decay, which is a function of the entire plasma population, depends on the combined electric field. If we can determine how the parameters of equations (1)–(4) vary with season and universal time (UT), we can constrain the physical processes that could be contributing to the ψ variation observed by Cliver *et al.* [2000, 2001, 2002].

[5] Before we begin, we must make a decision as to what we mean by seasonal and diurnal variation. Some have chosen to define seasonal variation in terms of averages of Dst or other geomagnetic indices. Using such a definition, Cliver *et al.* [2001] found that roughly half of the seasonal variation in Dst occurred on quiet days. We, however, choose a definition of the variation that is more consistent with the work of Russell and McPherron [1973]; namely, we will determine how the probability of a large injection into the ring current varies with UT and season. We feel that the latter definition is more appropriate because it accommodates the fact that the derived seasonal and diurnal variations in quiet-time behavior can be heavily influenced by the details of calculating the Dst index and by contaminating currents, such as the magnetopause and tail currents. That is, we want to understand the UT and seasonal variation of the particular dynamics of magnetic storms. It should be noted that less than 7% of hourly Dst values fall below -50 nT , so that the bulk of the Dst time series measures non-storm behaviors. Additionally, most of the

time, even most of the time when $Dst < -50 \text{ nT}$, ring current injection is small, and vBs exceeds 1 mV m^{-1} less than 20% of the time.

2. Russell-McPherron Effect and Upstream Conditions

[6] We begin our data analysis by demonstrating that the Russell-McPherron (RM) effect is indeed present when the upstream IMF is rotated into GSM coordinates. Specifically, the RM effect predicts higher probability of southward IMF at certain times of year. In order to relate this to ring current injection, we use vBs rather than B_s alone. We measure the probability of hourly $vBs > 1 \text{ mV m}^{-1}$, from the OMNI database, in a 24×24 lattice of UT and day of year (season). Figure 3 provides the UT and seasonal pattern of $P[vBs > 1 \text{ mV m}^{-1}]$, which agrees well with the pattern predicted by the RM effect in Figure 2. Figure 4 shows that there is a rank order correlation coefficient (ROCC) of -0.55 ± 0.03 between θ and $P[vBs > 1 \text{ mV m}^{-1}]$. Therefore the RM effect explains $\sim 30 \pm 3\%$ of the variation in $P[vBs > 1 \text{ mV m}^{-1}]$.

[7] If the RM effect were the only source of UT and seasonal variations in magnetic activity, we would expect large ring current injections to reflect a pattern similar to Figure 3. We identify large ring current injections as those times when $Q < -10 \text{ nT h}^{-1}$, where $Q = \frac{d}{dt} Dst^* + Dst^*/\tau$ is the rate of injection into the ring current calculated from the hourly change in Dst corrected for decay. Figure 5 provides the UT and seasonal variations in $P[Q < -10 \text{ nT h}^{-1}]$. As identified by previous authors [Berthelier, 1976; Cliver *et al.*, 2001], the UT variations in the ring current behavior do not correspond to what is predicted by the RM effect. Quantitatively, θ explains $19 \pm 4\%$ of the variation in $P[Q < -10 \text{ nT h}^{-1}]$ (ROCC = -0.44 ± 0.04) (not shown). On the other hand, ψ explains $26 \pm 4\%$ of the variation (ROCC = 0.51 ± 0.04) (not shown). Given the uncertainties, there is a 13% chance that these correlations are the same, which means that their difference is not significant at the usual upper limit of 5%. We will see later that an empirical model that combines the ψ and θ effects explains $36 \pm 4\%$ of the variation (ROCC = 0.60 ± 0.03), which has only a 3% chance of being the same as the correlation for either angle alone. Because they are correlated, two angles combined do not explain as much variance as would be expected by simply summing the variance described by each individually.

3. Seasonal and Diurnal Variation in Dst Dynamics

[8] We begin our study of the seasonal and diurnal variation in Dst dynamics by allowing the parameters of equations (1)–(4) to vary with day of year (DOY) and UT. Specifically, we use a neural network to model the hourly evolution of Dst in terms of vBs and p_{dyn} , with an arbitrary periodic variation with DOY and UT.

$$Dst(t) = NN[Dst(t-1), vBs(t), p_{dyn}(t), p_{dyn}(t-1),$$

$$\sin(\Omega_D DOY), \cos(\Omega_D DOY), \sin(\Omega_H UT), \cos(\Omega_H UT)]. \quad (5)$$

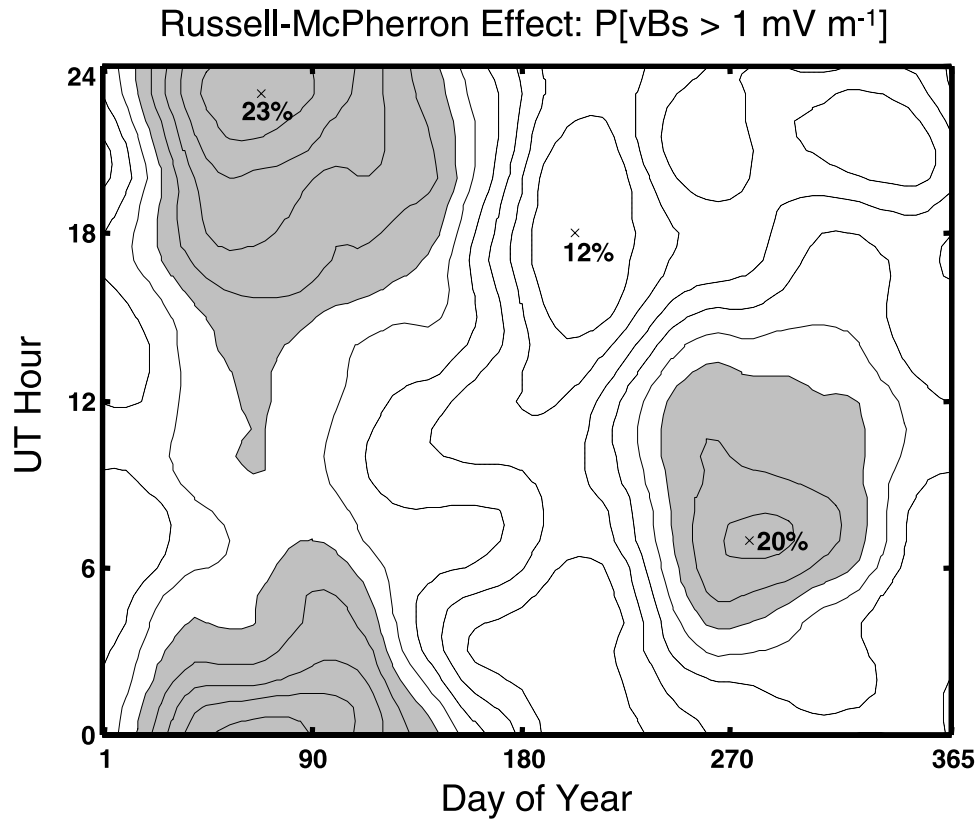


Figure 3. The signature of the Russell-McPherron effect in the probability of $vBs > 1 \text{ mV m}^{-1}$ in the OMNI database (1963–1996). Probabilities were calculated on a 24×24 lattice and then smoothed for visualization using a 3×3 average.

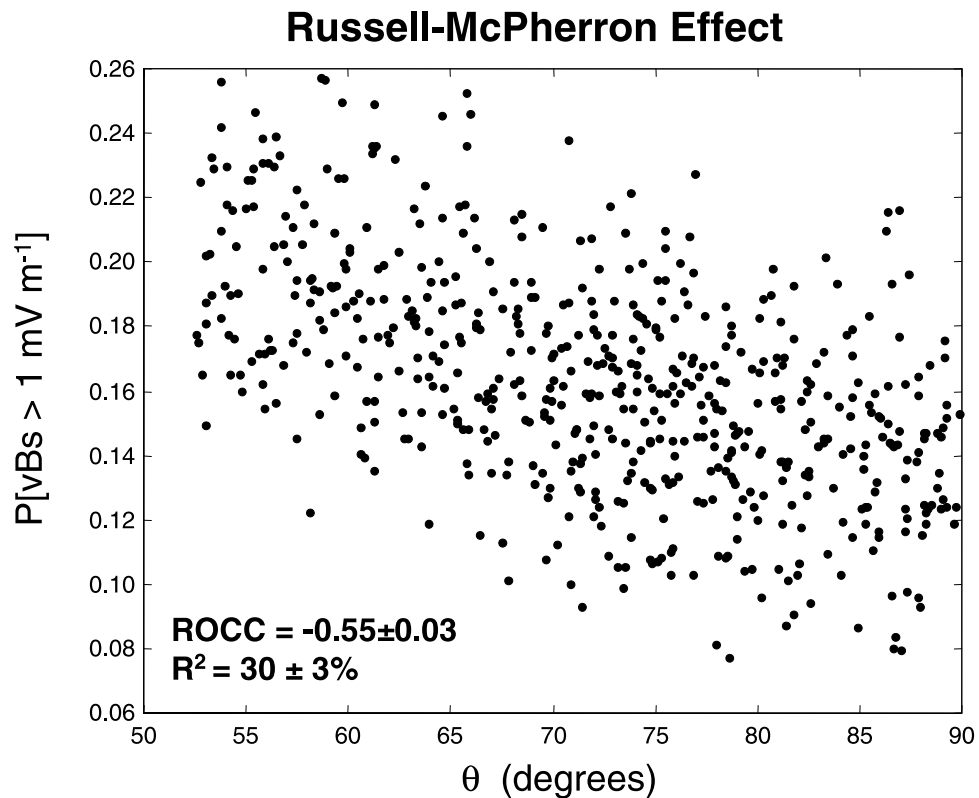


Figure 4. As predicted by the Russell-McPherron effect, the probability of large vBs is related to the angle θ between the Earth's dipole and the GSEq-Y direction.

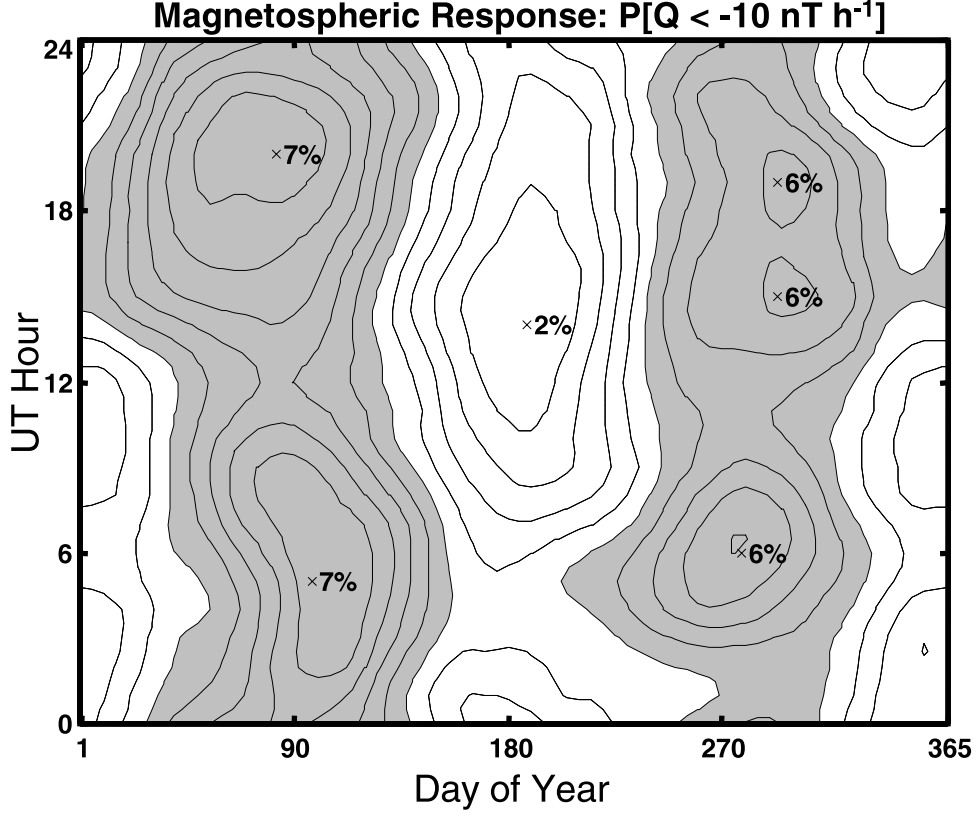


Figure 5. The probability of large injections to the ring current (1963–1996), smoothed as in Figure 3.

Here, we have used the notation $t - 1$ to indicate a 1-hour time lag for certain quantities. The frequencies Ω_D and Ω_H are $2\pi/365 \text{ rad day}^{-1}$ and $2\pi/24 \text{ rad h}^{-1}$ respectively; higher harmonics are available implicitly owing to the nonlinearity of the neural network model. The neural network is given by

$$NN(\vec{x}) = v_0 + \sum_{i=1}^M v_i \tanh\left(w_{i,0} + \sum_{j=1}^N w_{i,j} x_j\right), \quad (6)$$

where the coefficients \vec{v} and \vec{w} are determined by nonlinear least-squares optimization [Hagan et al., 1996]. The free parameter M determines the complexity of the neural network by specifying the number of “hidden units” in the first summation. We tried several values of M and found that $M = 8$ gave the best out-of-sample performance. After the coefficients are determined, we can use them to reconstruct the parameters of equations (1)–(4). For example,

$$\begin{aligned} \alpha(DOY, UT) &= \frac{d}{d(vBs)} \frac{d}{dt} Dst \Big|_{DOY, UT}, \\ &\approx \frac{d}{d(vBs)} \left(\frac{NN - Dst(t-1)}{\Delta t} \right)_{DOY, UT}, \end{aligned} \quad (7)$$

where the outer derivative is calculated by varying vBs over a range of values with constraints $vBs > E_c$, $Dst(t-1) = 0$, $p_{dyn}(t) = p_{dyn}(t-1) = \langle \sqrt{p_{dyn}} \rangle^2$, and $\Delta t = 1 \text{ h}$ (we estimate the derivative with $NN - Dst(t-1)$ because it is a direct measure of the variation produced by the neural network). Similarly, we can obtain $b(DOY, UT)$, $\tau_\infty(DOY, UT)$,

$V_q(DOY, UT)$, $V_0(DOY, UT)$, and $E_c(DOY, UT)$. It turns out that only b , V_0 , and α exhibit systematic variations with DOY and UT. For example, in Figure 6 we see how V_0 varies with DOY and UT. This figure bears striking resemblance to the seasonal and diurnal pattern of ψ , given in Figure 7. Both b and α (not shown) exhibit similar patterns that resemble Figure 7. We remind the reader that b modulates the contamination of Dst by the magnetopause, α controls the coupling of the solar wind electric field to the magnetospheric convection electric field, and V_0 scales how the strength of the total convection electric field controls ring current loss. The neural network, which was not given ψ explicitly as a control parameter has reconstructed a ψ dependence in the dynamics of Dst . A similar but noisier result can be obtained by fitting the parameters of equations (1)–(4) in bins of DOY and UT.

[9] As we did for $P[vBs > 1 \text{ mV m}^{-1}]$ with θ , we can see more clearly how α , V_0 and b vary with ψ in scatter plots. Figure 8a shows that there is a strong correlation between α and ψ ; ψ explains $50 \pm 10\%$ of the variation in α (ROCC = -0.7 ± 0.1). We have estimated the uncertainties by treating the neural network as an 8×8 lattice of nonoverlapping bins. We have also performed several fits to the empirical function $S(\psi)$ developed by Svalgaard [1977],

$$S(\psi) = \frac{1.15}{(1 + 3 \cos^2 \psi)^{2/3}}. \quad (8)$$

We have determined the most appropriate fit to be

$$\alpha(\psi) = (-3.7 \pm 0.1) S(\psi) \text{ nT m (mV h)}^{-1}. \quad (9)$$

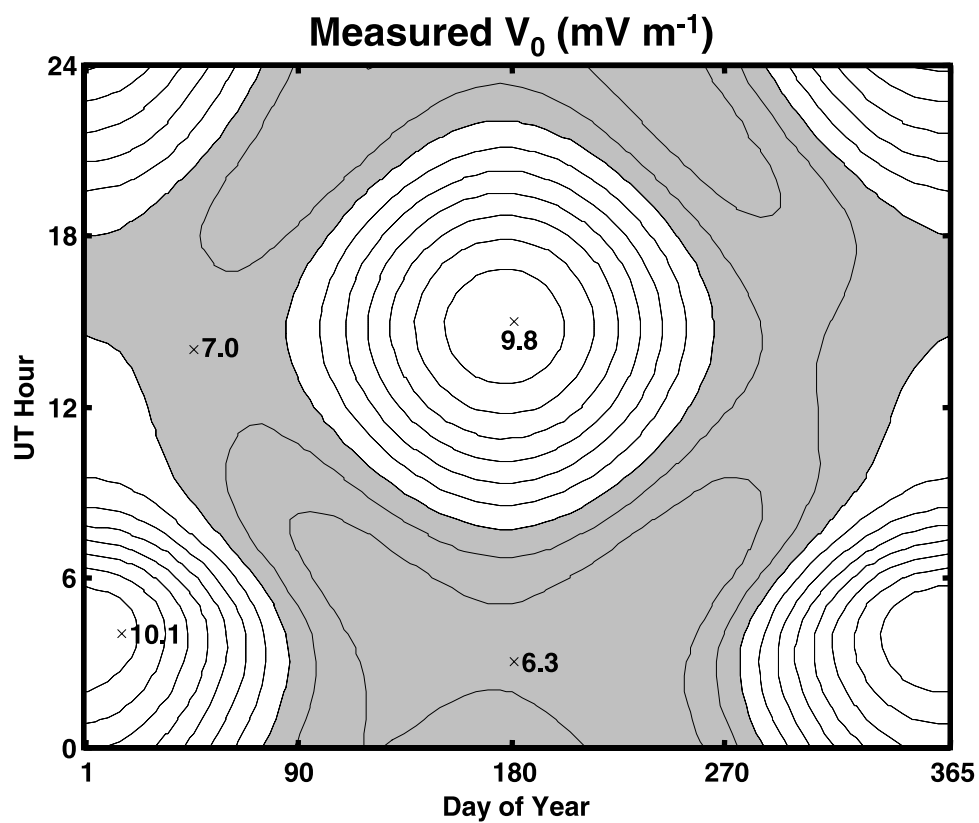


Figure 6. The variation of V_0 with season and universal time.

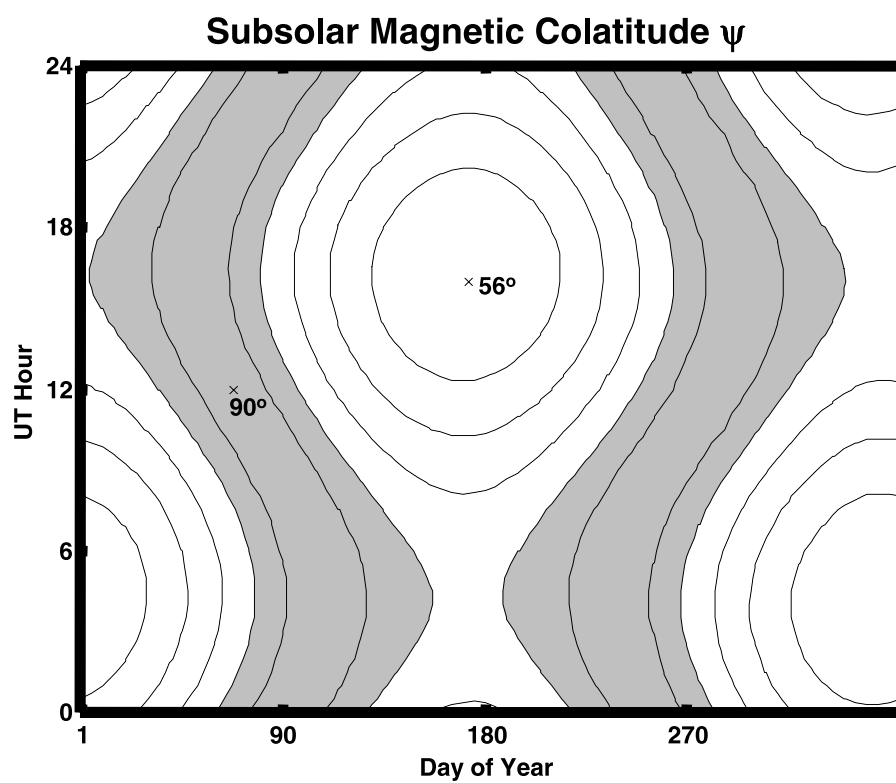


Figure 7. The variation of the dipole tilt angle ψ with season and universal time. See Figure 1.

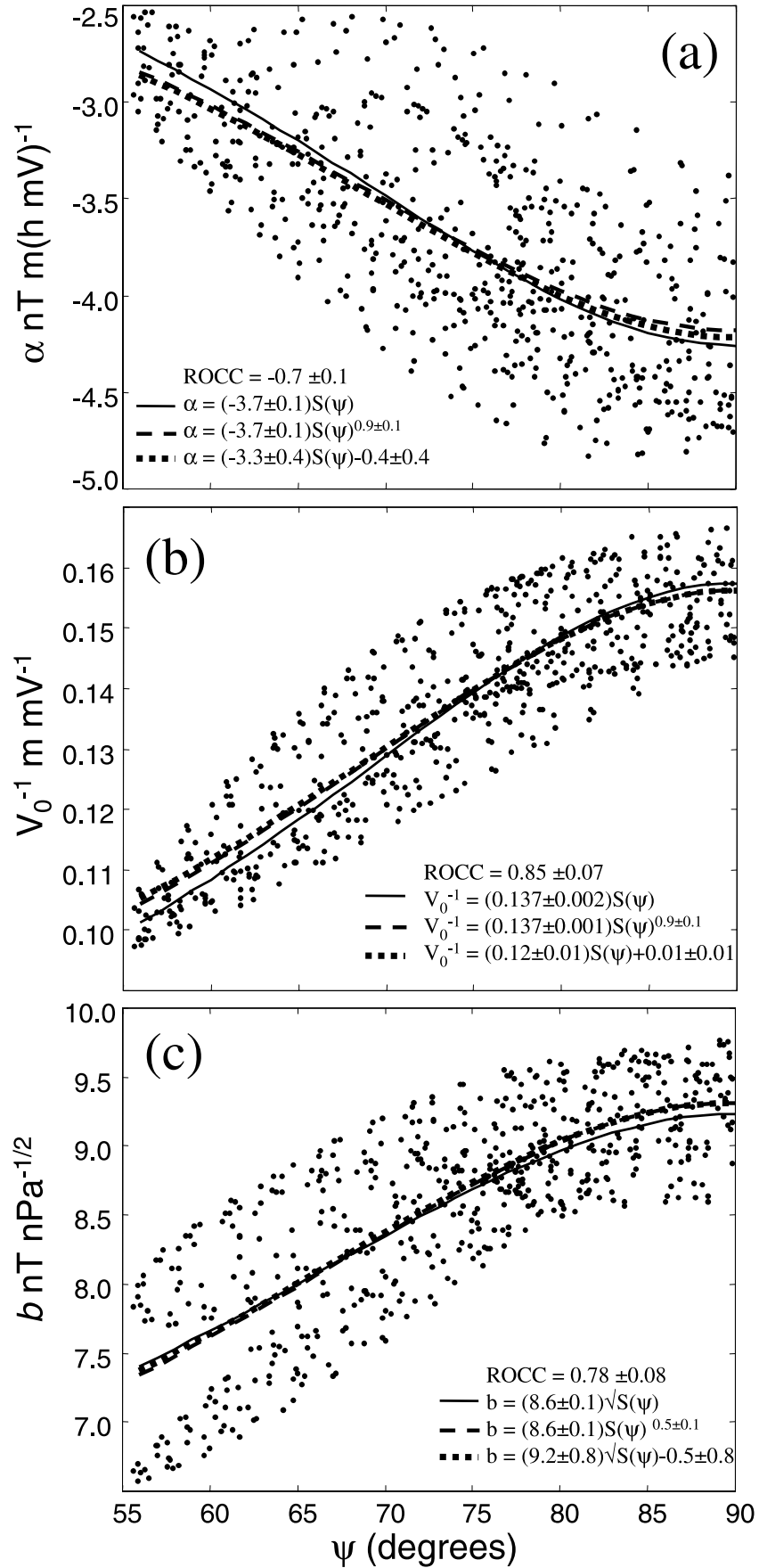


Figure 8. The variation of α , V_0 , and b with ψ . The curves represent three simple analytical models of the variations with ψ .

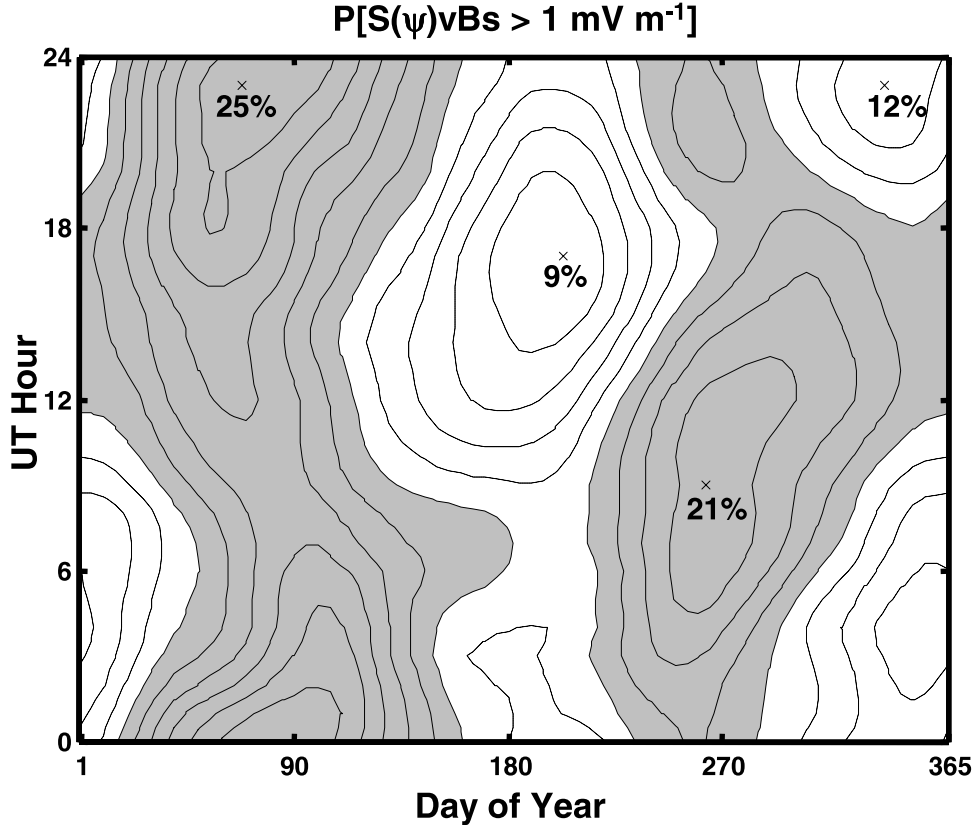


Figure 9. Probability of ring current injection, accounting for the ψ dependence, smoothed as in Figure 3.

[10] Figure 8b shows the dependence of V_0^{-1} on ψ , which explains $70 \pm 10\%$ of the variation (ROCC = 0.85 ± 0.07). The most appropriate fit is

$$V_0^{-1}(\psi) = (0.137 \pm 0.002)S(\psi) \text{ m mV}^{-1}. \quad (10)$$

It is important to note that α and V_0^{-1} both serve to scale vBs in equations (1)–(4). The variation of these scale parameters indicates that ψ modulates the coupling between the solar wind electric field and the convection electric field. *Cliver et al.* [2001] noted that the relationship between $\langle Dst \rangle$ and $\langle vBz \rangle$ was different at the equinoxes than at the solstices, which can be explained by the ψ dependence we observe.

[11] Finally, we examine the magnetopause contamination parameter b . Figure 8c shows that b also varies with ψ . The subsolar latitude ψ explains $60 \pm 10\%$ of the variation in b (ROCC = 0.78 ± 0.08). We have determined the most appropriate fit to be

$$b(\psi) = (8.6 \pm 0.1)\sqrt{S(\psi)} \text{ nT(nPa)}^{-1/2}. \quad (11)$$

It is likely that b represents contaminations from both the magnetopause and tail current systems. Changes in one or both of these current systems is the probable cause of the variation in b .

4. New Dynamic Equation for Dst

[12] Equations (9)–(11) describe a modification to the original equations for Dst evolution. Including the ψ varia-

tions and slightly redefining α , V_0 , and b , we can rewrite equations (1)–(4),

$$\frac{d}{dt}Dst^* = Q(vBs) - \frac{Dst^*}{\tau(vBs)}, \quad (12)$$

$$Dst^* = Dst - b\sqrt{S(\psi)}(\sqrt{P_{dyn}} - \langle \sqrt{P_{dyn}} \rangle), \quad (13)$$

$$Q(vBs) = \begin{cases} \alpha S(\psi)(vBs - E_c) & vBs > E_c \\ 0 & vBs \leq E_c, \end{cases} \quad (14)$$

$$\tau(vBs) = \tau_\infty e^{\frac{V_0}{S(\psi)(V_0 + vBs)}}, \quad (15)$$

$$S(\psi) = \frac{1.15}{(1 + 3 \cos^2 \psi)^{2/3}}. \quad (16)$$

Under these definitions of the parameters, $b = 8.6 \pm 0.1 \text{ nT nPa}^{-1/2}$, $\alpha = -3.7 \pm 0.1 \text{ nT m (mV h)}^{-1}$, $V_0 = 7.3 \pm 0.1 \text{ mV m}^{-1}$, and the other parameters remain unchanged.

[13] We have seen that $S(\psi)$ modulates the efficacy of vBs on the magnetosphere. Therefore we would like to know whether the inconsistency between Figure 3 (the RM effect) and Figure 5 (actual injection into the ring current) can be resolved by replacing vBs with $S(\psi)vBs$. Figure 9 depicts $P[S(\psi)vBs > 1 \text{ mV m}^{-1}]$ as a function of season and UT. It clearly resembles Figure 5 more closely than does Figure 3, suggesting that the ψ dependence of ring current dynamics resolves the inconsistency. Quantitatively, $P[S(\psi)vBs > 1 \text{ mV m}^{-1}]$ explains $36 \pm 4\%$ of the variation in $P[Q < -10$

nT h^{-1}] ($\text{ROCC} = 0.60 \pm 0.03$), which is significantly more than either ψ or θ explains alone (see section 2).

5. Discussion

[14] We determined how the empirical parameters of *Dst* dynamics change with season and UT. By approaching the problem this way, we remove the variations attributable to θ and λ , which are manifest only in the upstream conditions, not in the dynamics themselves. Numerous physical processes have been suggested to account for the ψ variations we have observed. We begin with the Malin-Isikara effect [Malin and Isikara, 1976], which states that the ring current is actually displaced in magnetic latitude by the off-equator impact of the solar wind, and consequently the Northern Hemisphere bias in magnetic observatories used in calculating *Dst* gives rise to a seasonal variation. Berthelier [1976] found that Southern Hemisphere *As* and Northern Hemisphere *An* subauroral indices showed the same seasonal and diurnal variations as did $Am = (As + An)/2$, contradicting the Malin-Isikara effect. A similar study is in progress at the Finnish Meteorological Institute (FMI) using low-latitude stations analogous to those used in *Dst*.

[15] Svalgaard [1977] suggested that the tilted dipole presents a stronger magnetic field to the solar wind, thereby increasing the magnetopause standoff distance and enlarging the magnetospheric cavity. This enlarged cavity would dilute the electric and magnetic gradients and thereby diminish magnetic activity. Olson [1969] used a more sophisticated pressure balance calculation than Svalgaard's to obtain the shape of the magnetopause for various tilt angles. Olson found that the magnetopause standoff distance varied by less than 3% over the full range of tilt angles and that the cross-tail dimension changed by less than 1%. Therefore we find it unlikely that Svalgaard's hypothesis describes the dominant physical process.

[16] Alexeev *et al.* [1996] suggested that *Dst* consists of a large contribution from the tail current. Since the tail current is reconfigured for a tilting dipole, the ψ angle would control the contribution of the tail current to *Dst*. On the basis of solar wind pressure control of the tail current intensity and location, we feel that this ψ dependence would appear in the *b* parameter, which nominally accommodates the magnetopause contamination. The tail current contributes to *Dst* in the negative direction (opposite to the magnetopause contamination). According to a displaced planar sheet current model, a negative tail current contamination would have its largest magnitude for $\psi = 90^\circ$ and would diminish by $\sim 1\%$ for $\psi = 55^\circ$, giving $\partial b/\partial \psi < 0$. Figure 8c shows that $\partial b/\partial \psi$ is positive. Therefore we feel that the variation in *b* is primarily attributable to changing magnetopause currents and is not an artifact of tail current contamination.

[17] Lyatsky *et al.* [2001] suggested that auroral conductivity variations associated with solar illumination of the polar ionosphere would control the rate of dayside reconnection and other coupling processes. In a very preliminary MHD modeling study with J. Raeder (for a description of the MHD model see Raeder *et al.* [1998]) we determined that varying the angle of attack of the solar wind was more influential on magnetospheric dynamics than was varying the angle of illumination. If a more detailed MHD study

confirms this result, it will eliminate the polar illumination as a primary source of the ψ variation.

[18] Finally, we suggest that the ideas of Crooker and Siscoe [1986] hold the most promise for explaining the ψ variation. They modeled the magnetopause as a linear transition from magnetosheath to geomagnetic field. At a critical depth there were two magnetic nodes which allowed for the kind of reconnection that transfers energy into the magnetosphere. This depth and hence the amount of sheath field available to reconnect varies strongly with ψ , causing as much as a factor of 2 peak-to-peak variation in reconnection efficiency. This model provides its strongest reconnection for $\psi = 90^\circ$, consistent with the variations we observe in α and V_0 . The model also implies that magnetopause currents would be dramatically affected by the tilt angle ψ , although the details of that dependence have yet to be calculated. Therefore we conclude that the Crooker-Siscoe effect is the best available candidate explanation for why ring current dynamics depend on the dipole tilt angle ψ .

[19] We have several suggestions for future investigations that may help resolve between the various explanations of seasonal and diurnal variations in magnetic activity. First, we suggest that a ψ variation in the PC index, which measures the polar-cap potential, would favor the Crooker-Siscoe explanation, whereas no variation would favor the Malin-Isikara and Svalgaard explanations. A detailed MHD simulation that varied the solar wind attack angle independently of the solar illumination angle would help resolve whether the conductivity of the polar ionosphere is the vehicle for ψ variations. A study of magnetopause crossings as a function of season and UT would test the Malin-Isikara and Svalgaard explanations. Finally, a study such as the one underway at FMI, using northern and southern hemisphere analogues to *Dst*, would test the Malin-Isikara explanation directly.

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