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Mountains versus valleys: Semiannual variation of geomagnetic activity

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Abstract. The semiannual variation in geomagnetic activity is generally attributed to the Russell-McPherron effect. In that picture, enhancements of southward field B_s near the equinoxes account for the observed higher geomagnetic activity in March and September. In a contrary point of view, we argue that the bulk of the semiannual variation results from an equinoctial effect (based on the ψ angle between the solar wind flow direction and Earth's dipole axis) that makes B_s coupling less effective (by ~25% on average) at the solstices. Thus the semiannual variation is not simply due to "mountain building" (creation of B_s) at the equinoxes but results primarily from "valley digging" (loss of coupling efficiency) at the solstices. We estimate that this latter effect, which clearly reveals itself in the diurnal variation of the *am* index, is responsible for ~65% of the semiannual modulation. The characteristic imprint of the equinoctial hypothesis is also apparent in hourly/monthly averages of the time-differentiated *Dst* index and the *AE* index.

1. Introduction

The Blue Mountains west of Sydney, Australia, are unusual in that they were not formed by upthrust and folding of the Earth's mantle (mountain building) but rather resulted from the erosion of a plateau (valley digging). When early explorers of these "mountains" attempted to pass through them in the conventional way by following valleys, they were thwarted by steep walls at the ends of valleys where the erosion began. It was not until 1813 (25 years after the first European settlement of Sydney) when G. Blaxland, W. Lawson, and W. Wentworth successfully traversed the mountains by sticking to high ground that a pass was found and the true nature of the Blue Mountains was indicated. We suggest that a similar "mountain versus valley" misconception in solar-terrestrial physics has hindered space scientists in their attempts to identify the cause of the semiannual variation in geomagnetic activity.

The fact that geomagnetic storms are more intense and numerous at the equinoxes than at the solstices has been known for over 150 years [*Broun*, 1848; *Sabine*, 1856]. The three principal hypotheses to account for the semiannual variation are (1) the axial hypothesis [*Cortie*, 1912], based on the varying heliographic latitude of Earth throughout the year; (2) the equinoctial hypothesis [*Bartels*, 1925, 1932; *McIntosh*, 1959], based on the varying angle between the Earth-Sun line and Earth's dipole axis; and (3) the Russell-McPherron effect [*Russell and McPherron*, 1973], based on the variation of the angle between the z axis in the geocentric solar magnetospheric (GSM) coordinate system and the solar equatorial plane (see *Russell* [1971] for a discussion of coordinate systems). These three mechanisms work in two fundamentally different ways. Geomagnetic activity depends on the following factors: (1) the properties of the solar wind and (2) the response of the magnetosphere to the driving wind. The axial and Russell-McPherron (RM) mechanisms create a semiannual variation by modifying factor 1; they provide a stronger solar wind input at the equinoxes. The axial hypothesis does this by bringing Earth to higher heliographic latitudes near the equinoxes where it is more in line with the sunspot zones [*Cortie*, 1912] or, in the modern view of this hypothesis [*Bohlin*, 1977], with midlatitude coronal holes. The RM effect does this via coordinate transformation. Solar wind magnetic fields lying completely in the solar equatorial plane can have a southward component (in GSM coordinates) near the equinoxes. Strong solar wind magnetic fields (plausibly linked to the sunspot zones), high-speed streams from coronal holes, and southward fields are highly correlated with increased geomagnetic activity. The equinoctial hypothesis works in an as yet unknown way [*Svaalgard*, 1977] by modifying factor 2; it reduces the coupling efficiency of the magnetosphere near the solstices. Thus while the axial and

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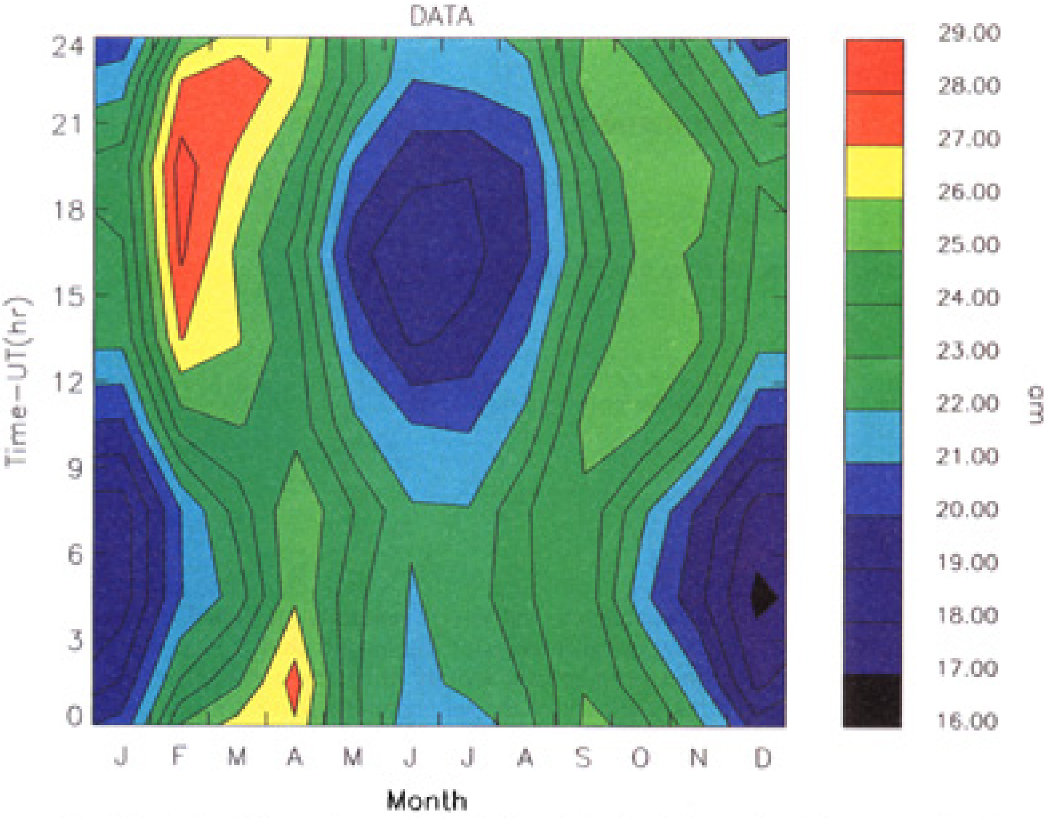

Plate 1. Seasonal and diurnal variation of the *am* index, 1959-1997. The color coding of the contours is given at the right.

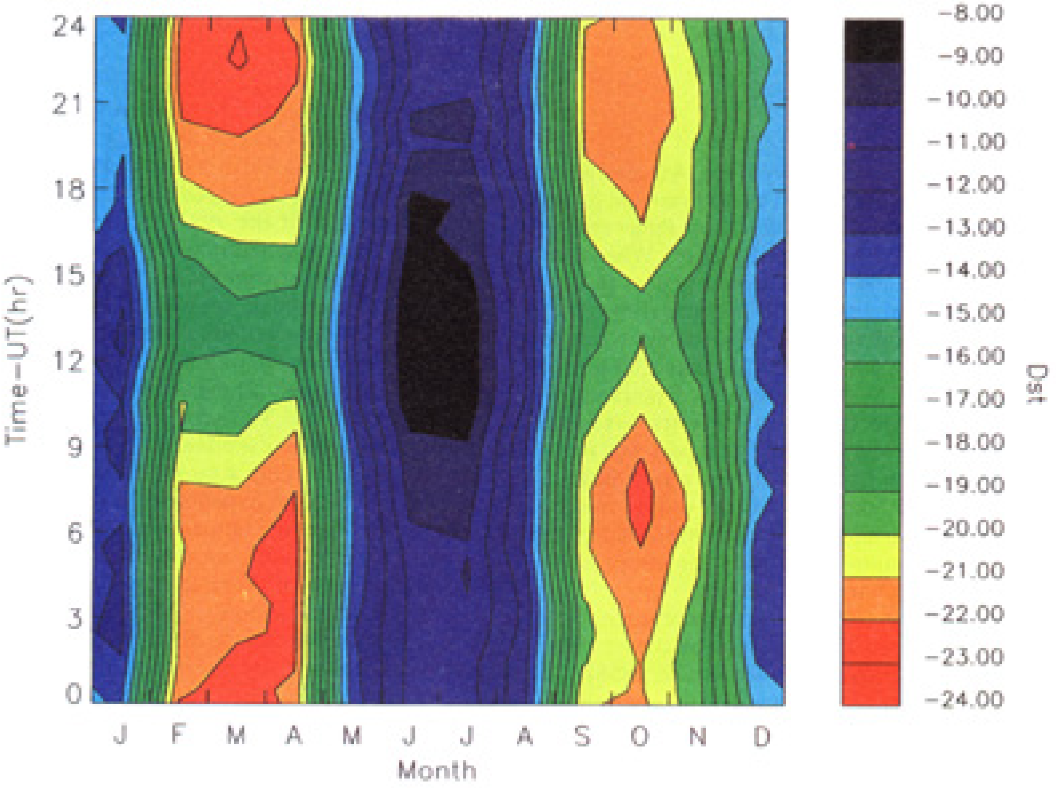

Plate 2. Seasonal and diurnal variation of the *Dst* index, 1957-1997. The color coding of the contours is given at the right.

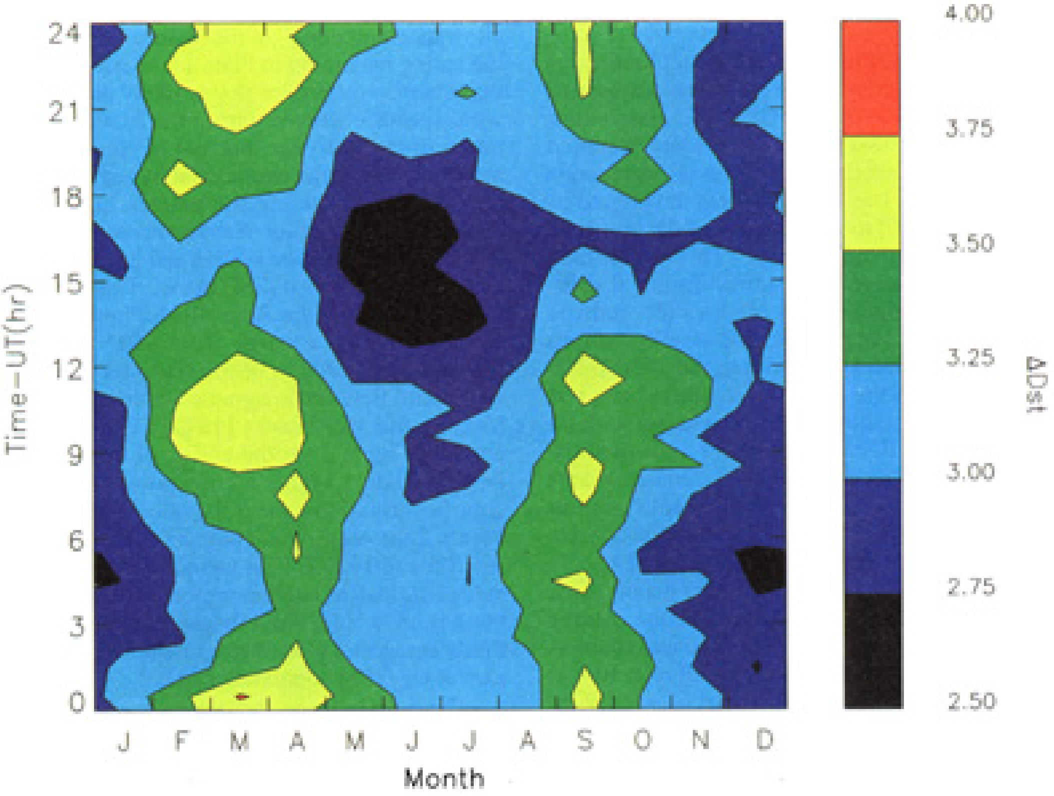

Plate 3. Seasonal and diurnal variation of the hourly time derivative of the *Dst* index, 1957-1997. The color coding of the contours is given at the right.

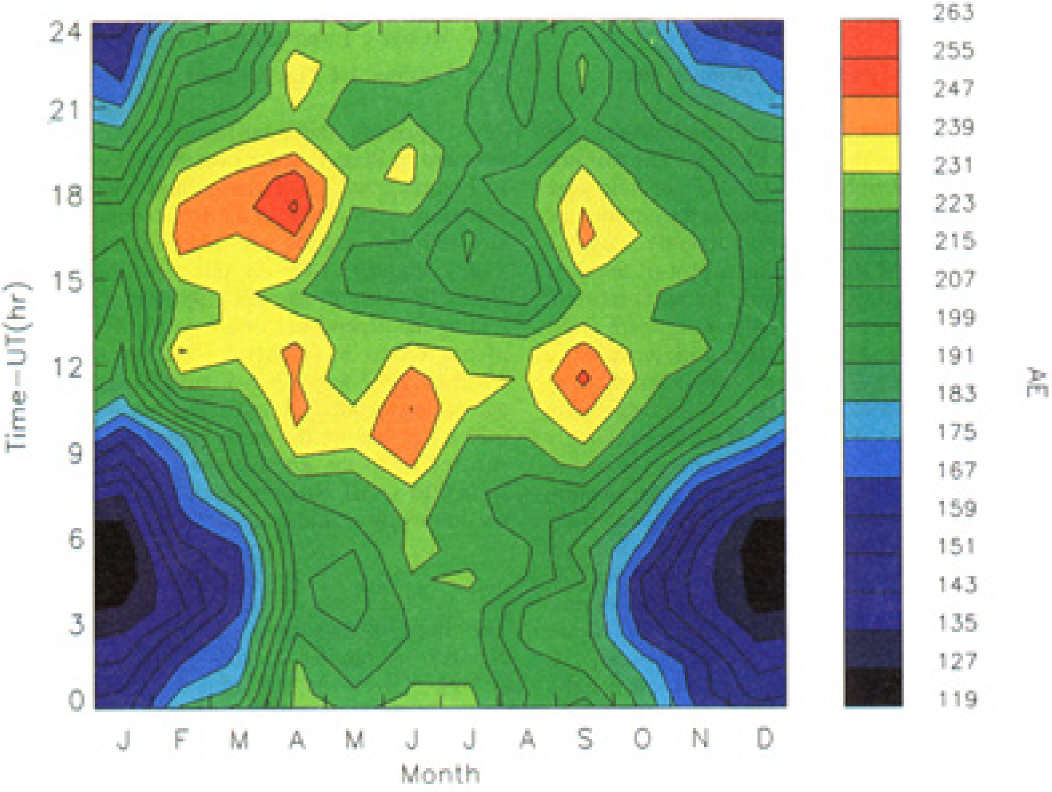

Plate 4. Seasonal and diurnal variation of the *AE* index, 1957-1988. Data were not available for 1976-1977. The color coding of the contours is given at the right.

RM mechanisms work by "building mountains" at the equinoxes, the equinoctial hypothesis "digs valleys" at the solstices.

Today the Russell-McPherron (RM) mechanism is generally regarded as the principal cause of the semiannual variation [e.g., *Orlando et al.*, 1993, 1995; *Siscoe and Crooker*, 1996]. We take issue with this widely accepted viewpoint. Our point of departure is the diurnal variation of the planetary *am* index. The *am* index was developed by *Mayaud* [1968, 1974, 1980] to permit study of the universal time variation of geomagnetic activity. This midlatitude range index is based on data from a more uniformly distributed network of stations than is the case for older indices such as *Kp*. The *am* record of geomagnetic activity exhibits deep holes centered at 0430 UT in winter and 1630 UT in summer. These holes in the solstitial "valleys" are not predicted by the RM effect, but they are consistent with the equinoctial hypothesis. Because the holes significantly reduce monthly *am* averages in June and December, we are compelled to ask what fraction of the semiannual variation might be accounted for by valley digging versus the conventional explanation in terms of RM mountain building.

Because the RM effect is dependent on both the tilt of the Sun's rotation axis and Earth's dipole axis to the ecliptic plane, it may be thought of as a combined axial and equinoctial hypothesis. In this paper, however, we will refer to it as being separate from the equinoctial hypothesis because of the different ways in which the RM and equinoctial hypotheses work to produce a semiannual variation. As noted by *Russell and McPherron* [1973], in the RM model the geomagnetic maxima are true peaks while in the equinoctial hypothesis the maxima represent ridges formed by the depression of the surrounding terrain.

2. Analysis

2.1. Holes in the Valleys: Diurnal Variation of *am*

The diurnal variation of the *am* index throughout the year for the period 1959-1997 is shown in Plate 1. The minima centered at 0430 UT in December and 1630 UT in June were predicted by *McIntosh* [1959] on the basis of the equinoctial hypothesis and were identified in the *am* data by *Mayaud* [1970]. *Svalgaard* [1977] showed that a plot of *am* data similar to Plate 1 for the 1959-1974 period could be fitted empirically with an expression for the magnetic field surrounding a dipole that was parameterized in terms of ψ, the angle between the Sun-Earth line (solar wind flow direction) and Earth's dipole axis. Angle ψ is the controlling parameter in the equinoctial hypothesis. It varies seasonally because of the 23½° tilt of Earth's rotation axis to the ecliptic plane and diurnally because of the 11½° inclination of the dipole axis to the rotation axis. Its full range is from 55° to 125°; the range of the acute angle between the Earth-Sun line and the dipole axis (ψ_A) is 55° to 90°. A contour plot of ψ_A as a function of season and universal time (Figure 1) closely resembles Svalgaard's function. The *am* data in Plate 1 are highly correlated ($r = 0.91$) with ψ_A. A comparable coefficient ($r = -0.89$) is obtained for the correlation between *am* and $\cos^2\psi$. Maximum *am* activity occurs at the equinoxes when ψ (or ψ_A) = 90°; for all other times and seasons, *am* is reduced. At the equinoxes, ψ_A varies between 78.5° and 90°, and the resulting diurnal variation is relatively weak compared to that at the solstices when ψ_A varies between 55° and 78.5°.

The control of the average *am* index by the ψ angle is remarkable, especially when one considers that it makes no allowance for "noise" in the input solar signal. For example, the spring maximum in Plate 1 is clearly larger than the fall maximum, a difference that is likely due to the higher solar wind speeds observed during the first half of the year over much of this 40-year interval [*Orlando et al.*, 1993]. It seems clear that the equinoctial hypothesis plays an important role in producing the pattern in Plate 1. Figure 2 contains a contour plot of the acute angle between the z axis of the GSM coordinate system and the solar equatorial plane, measured in the y-z (GSM) plane. This angle is the governing parameter in the Russell-McPherron hypothesis. Its variation (over a range from ~52° to 90°) mimics the theoretical prediction of the seasonal/diurnal variation of southward field (geomagnetic activity) given in Figure 5 of *Russell and McPherron* [1973]. Comparison of the RM angle in Figure 2 (or the cosine of this angle) with the *am* data in Plate 1 yields a correlation coefficient of 0.47, significantly below the 0.91 value we obtained for ψ_A. In Figure 2 the ellipsoidal contours centered near 2230 UT on April 5 and 1030 UT on October 8 corresponding to ~52° values of the RM angle represent geomagnetic maxima. At these times a solar wind magnetic field lying entirely in the Sun's equatorial plane has its maximum projection on the z axis of the GSM coordinate system.

The deep holes in the diurnal variation of the *am* index (Plate 1) are outstanding features, not some second order effect. They play an important role in producing the semiannual variation. This can be seen in Figure 3 which gives monthly averages of *am* for the years 1959-1997. A substantial part of the reduction of solstitial *am* values below the mean value of 22.7 nT over this interval can be accounted for by the deep holes in the solstitial valleys.

2.2. Relative Importance of RM and Equinoctial Mechanisms

To quantify the contribution of the equinoctial effect apparent in Plate 1 to the overall semiannual variation shown in Figure 3, we will estimate how much of the semiannual variation in *am* is due to the RM mountain-building hypotheses and then ascribe (at least for now) the remainder to valley digging. To do this, we follow the analysis of *Berthelier* [1976], *Russell* [1989], and others by first determining the dependence of *am* on B_z. Figure 4 contains a plot of *am* versus B_z (GSM) for all 3-hour *am* intervals from 1963 to 1997 for which hourly averages of B_z data were available (for all 3 hours). The *am* values plotted for each 0.25 nT B_z bin are the mean values for that interval. A least squares fit to the *am* averages for negative B_z (B_s) values from 0 to −4 nT (representing 85% of the ($-B_z$) data) yields the following relationship:

$$\langle \mathrm{am} \rangle = 5.5\, B_s + 17.1 \qquad (1)$$

The slope of this line, i.e., the sensitivity of *am* to B_s changes, is similar to that (5.9) determined by *Russell* [1989]. Given the semiannual variation of B_s from solar wind observations, we can use (1) to compute the amplitude of the semiannual *am* variation due to RM creation of southward fields at the equinoxes. The seasonal variation of B_s during 1963-1997 is given in Figure 5a. The amplitude of the second harmonic in a fast Fourier transform (FFT) analysis of these data is only 0.08 nT. Thus the semiannual

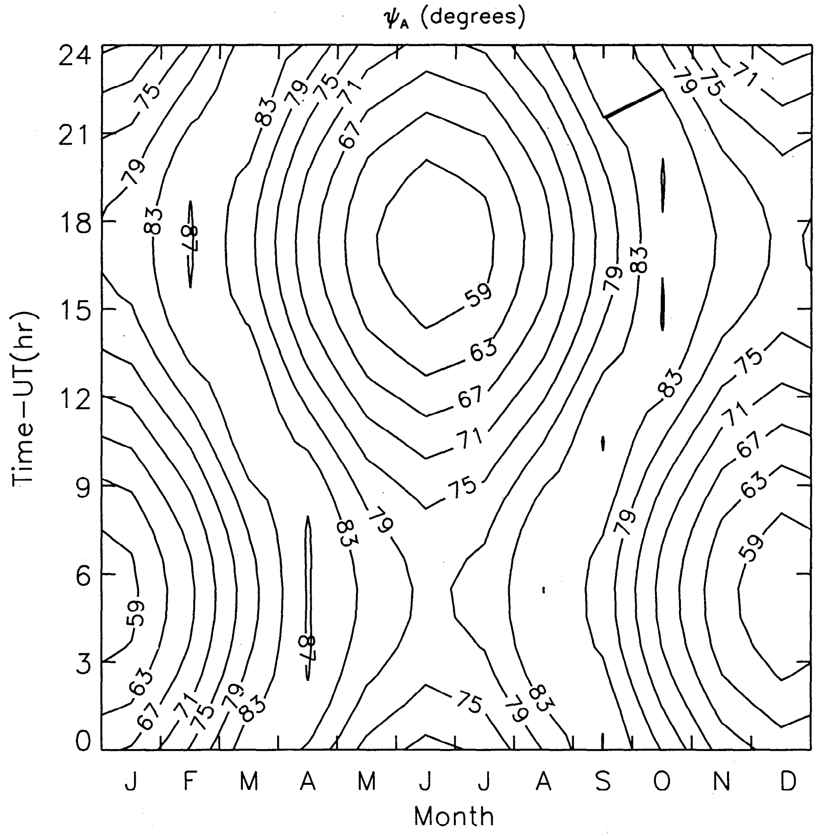

Figure 1. Contour plot of ψ_A, the acute angle between the Earth-Sun line (solar wind flow direction) and Earth's dipole axis, as a function of month and UT hour.

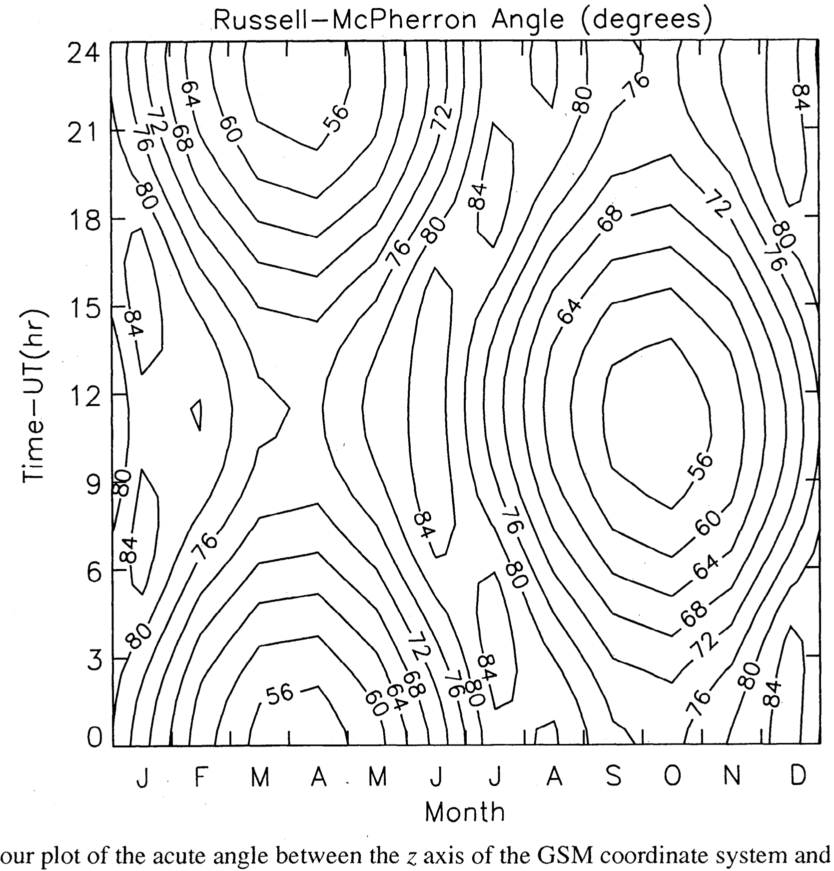

Figure 2. Contour plot of the acute angle between the z axis of the GSM coordinate system and the solar equatorial plane, measured in the y-z (GSM) plane, as a function of month and UT hour.

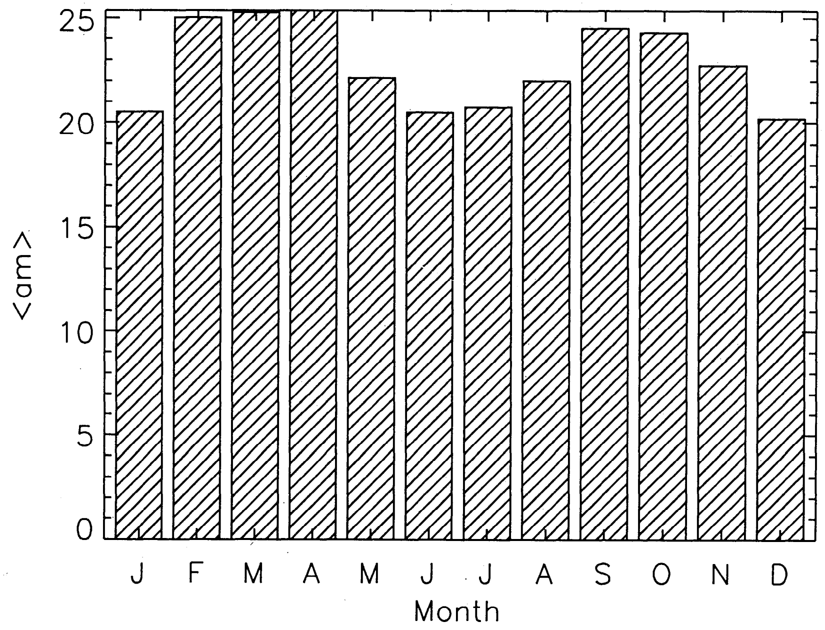

Figure 3. Monthly averages of the *am* index, 1959-1997.

variation of B_s due to the RM effect accounts for only 17% (0.44 nT / 2.58 nT) of the annual *am* variation (0.44 nT = 0.08 nT x 5.5, and 2.58 nT is the FFT-determined amplitude of the semiannual variation of *am*). On the basis of the good agreement between Plate 1 and Figure 1, it appears that the dominant cause of the semiannual modulation is an equinoctial, valley-digging, effect.

Given the overwhelming evidence that energy is transferred from the solar wind to the magnetosphere predominantly through the reconnection of southward pointing fields [e.g., *Cowley*, 1984; *Scurry and Russell*, 1990; *Kamide*, 1992; *Gonzalez et al.*, 1994], our result implies that the efficiency of this coupling process is somehow modulated by ψ, the angle between the solar wind flow direction and Earth's dipole axis. If this inference, and our conclusion that the Russell-McPherron effect is not the whole story for

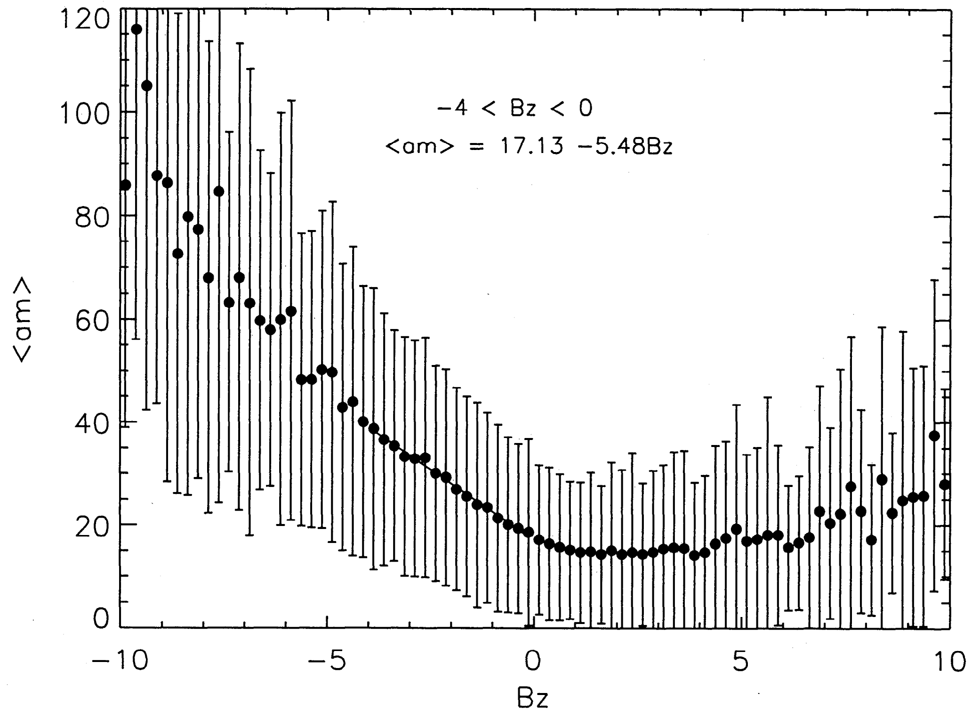

Figure 4. The geomagnetic index *am* versus B_z (GSM), 1963-1997. The plotted *am* values represent the average value for each B_z bin. The solid line is the least squares fit to weighted *am* values for negative B_z over the range 0 to −4 nT. The error bars are $\pm 1\sigma$.

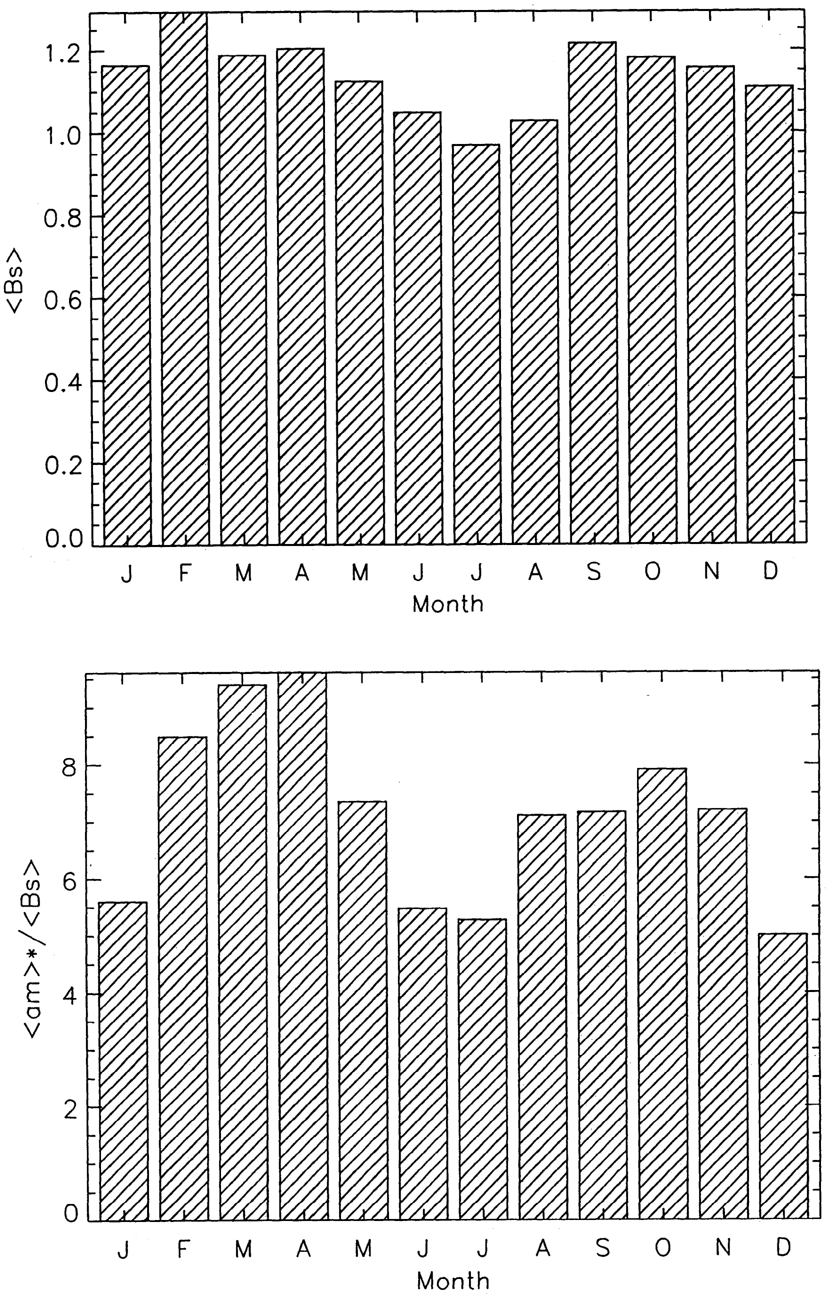

Figure 5. (a) Monthly variation of B_s, 1963-1997. (b) Monthly variation of <*am*>*/<B_s>, where <B_s> is the monthly average of B_s and <*am*>* is the monthly average of *am* minus 14 nT (see text). Only days with ≥13 hours of B_s data were used in computing <*am*> and <B_s>.

semiannual variation, is correct, then we would expect that a given B_s input will be more geoeffective at the equinoxes than at the solstices. We can check this expectation by dividing monthly averages of *am* (<*am*>) (Figure 3) by monthly averages of B_s (<B_s>) (Figure 5a) for periods of overlapping data. First, however, we remove that part of the monthly *am* average which is not responsive to B_s variation. The residual *am* value for $B_s = 0$ in (1) is 17.1 nT. Note in Figure 4, however, that the minimum *am* value, corresponding to positive B_z values of ~1-4 nT, is ~14 nT. Thus we define

$$<am>^* = <am> - 14 \qquad (2)$$

The resulting variation of <*am*>* /<B_s> given in Figure 5b reveals a clearly defined semiannual variation, indicating that something besides creation of additional B_s at the equinoxes is at work. If the six-month modulation of *am* was entirely due to RM mountain building, then we would expect <*am*>*/<B_s> to be constant with season. We can compare the percentage modulation of <*am*>* and <*am*>*/<B_s> to determine the relative importance of the RM and non-RM effects. The percentage modulation of <*am*>* is given by 2.58 nT / 8.21 nT = 31.4% (where 8.21 nT is the average value of <*am*>* over all months). The corresponding percentage modulation for <*am*>*/<B_s> is 25.8% (1.84 nT / 7.13 nT). Thus we deduce that the non-RM component of

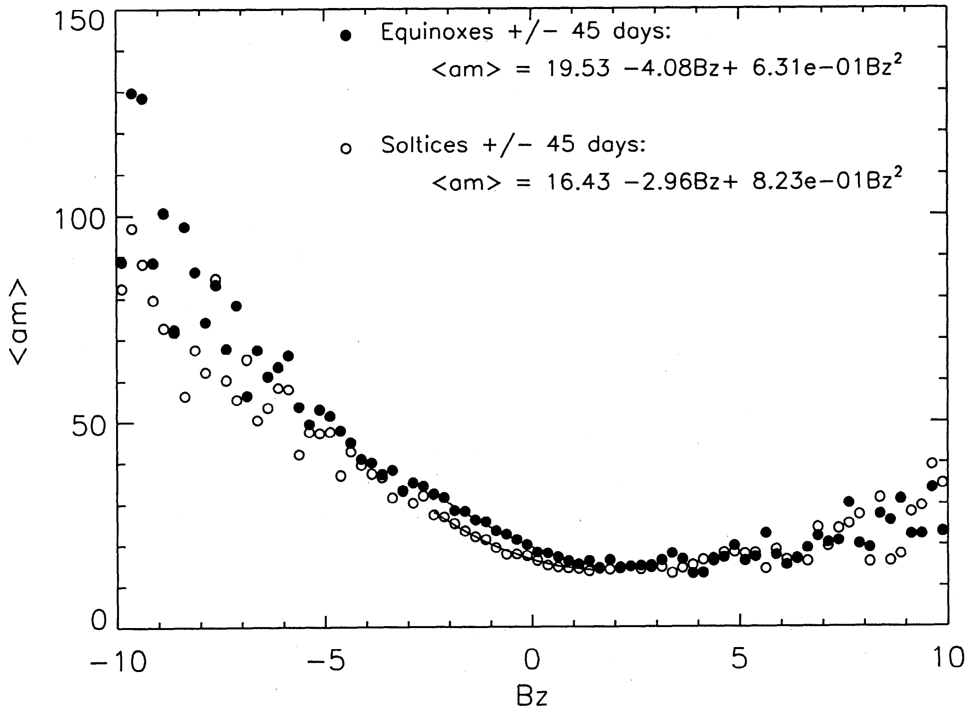

Figure 6. The geomagnetic index $<am>$ versus B_z (GSM), 1963-1997 for equinoctial (±45 days from the equinoxes; filled circles) and solstitial (±45 days from the solstices; open circles) epochs. The plotted $<am>$ values represent the average values for each B_z bin. The curves drawn represent quadratic fits to the data over the range from +1.5 to −2.5 nT.

the semiannual variation can account for 82% (25.8 / 31.4) of the total modulation, consistent with the 83% figure (100 − 17) determined above.

If the solar wind flow speed v observed at Earth varies with season in accordance with the axial hypothesis of *Bohlin* [1977], then this axial mountain-building effect can also contribute to the semiannual variation of geomagnetic activity. Any such effect would reduce the 80-85% of the seasonal modulation of *am* that we ascribe to the equinoctial effect. *Feynman* [1980] and others have shown that the midlatitude range indices, such as *am*, are highly correlated with the product v^2B_s. Thus we repeated the above analysis by determining the percentage modulation of the normalized index $<am>^*/<v^2B_s>$. In this case, we found that the combined RM and axial effects could account for 31% (1.0 − (21.8 / 31.4)) of the observed modulation. As a check on this result, we multiplied the amplitude of the semiannual variation in v^2B_s, 2.4 x 10^4, by the slope of the relationship between $<am>$ and v^2B_z for negative B_z values (4 x 10^{-5}). The resulting v^2B_s contribution to the semiannual variation is 0.96 nT/2.58 nT, i.e., 37% of the total variation. Thus it appears that ~60-70% of the seasonal variation of *am* is due to an equinoctial valley-digging mechanism. The 15-20% axial contribution that we infer results from a 6 km s^{-1} semiannual variation in v on a background average of ~440 km s^{-1}.

2.3. Variable Coupling Efficiency of the Magnetosphere

The average $<am>^*/<B_s>$ values for the six solstitial and six equinoctial months in Figure 5b are 5.99 nT and 8.28 nT, respectively. The ratio of these values (5.99 / 8.28 = 0.72) indicates that the magnetosphere is 28% less responsive, on average, to a given southward field near the solstices than at the equinoxes. This reduced responsiveness at the solstices can be seen in Figure 6, where we have repeated the analysis of Figure 4 separately for equinoctial (filled circles) and solstitial (open circles) intervals. The fact that the two curves begin to rise at a B_z value of +1.5 nT, rather than at zero, reflects the mixing of southward and northward fields in the 3-hour averages. We fitted the curves with a quadratic over the range from +1.5 to −2.5 nT. For values less than -2.5 nT the scatter increases, but it is clear that a difference between the seasons persists to -10 nT, corresponding to the larger geomagnetic storms. If the RM mechanism were the sole source of the semiannual variation, the two curves in Figure 6 would coincide. A similar result for v^2B_z, which takes into account any seasonal variation in flow speed, is given in Figure 7. In this case the separation between the equinoctial and solstitial curves corresponds to the amount of the semiannual variation that cannot be accounted for by the combined RM and axial mechanisms. The difference between equinoctial and solstitial mean values of $<am>^*/<v^2B_s>$ indicates that on average, the magnetosphere is 24% less responsive to a given v^2B_s input in summer and winter than in spring and fall.

2.4. Imprint of ψ on the *Dst* and *AE* Data Sets

The *am* index is based on observations at midlatitudes. To see if the ψ angle is important for modulating geomagnetic activity at lower and higher latitudes as well, we examined the seasonal/diurnal variation of the *Dst* and *AE* indices [*Mayaud*, 1980]. *Dst* is responsive to variations of Earth's ring current (although it is becoming increasingly appreciated that *Dst* monitors fields from a variety of current systems) while *AE* is a measure of global auroral electrojet activity.

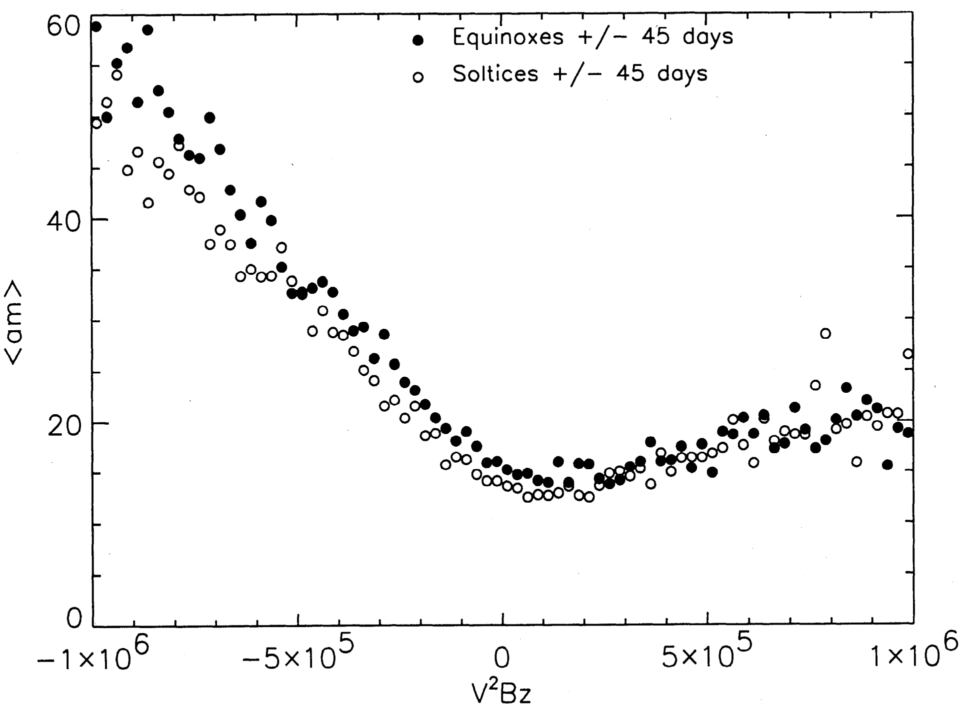

Figure 7. The geomagnetic index <*am*> versus v^2B_z (GSM), 1963-1997 for equinoctial (±45 days from the equinoxes; filled circles) and solstitial (±45 days from the solstices; open circles) epochs. The plotted <*am*> values represent the average values for each v^2B_z bin.

A plot showing the seasonal/diurnal variation of the *Dst* index for 1957-1997 is given in Plate 2. The semiannual variation with spring and fall activity maxima is apparent. However, the diurnal variation of the *Dst* index is markedly different from that expected if the dominant cause of the semiannual variation was either the classic equinoctial effect (Figure 1) or the Russell-McPherron mechanism (Figure 2). While the RM mechanism correctly predicts the spring activity maximum at ~2230 UT (although in April rather than in March as observed), the fall maximum is centered at ~0730 UT rather than at ~1030 UT. The equinoctial hypothesis predicts deep activity minima at the solstices (~0430 UT in winter and ~1630 UT in summer) that do not appear in Plate 2. To remove the effect of any slow underlying variation in *Dst* and to focus on the rapid changes associated with geomagnetic storms, we examined the time derivative of this index. The result of this exercise is shown in Plate 3, where we have plotted the contours of averages of the absolute values of hour-to-hour differences in *Dst* over the course of a year for the full 1957-1997 data set. The classic equinoctial pattern is evident in the differentiated data set. Comparison of the differentiated *Dst* data with the ψ_A angle in Figure 1 yields a correlation coefficient of $r = 0.75$ (versus 0.45 for the RM angle). The equinoctial pattern can also be discerned in Plate 4 for the (undifferentiated) *AE* index for 1957-1988.

3. Discussion

3.1. Early Critiques of the RM Hypothesis

When the RM mechanism was first proposed, its inability to reproduce the diurnal variation was pointed out by *Mayaud* [1974], *Berthelier* [1976], and *Svalgaard* [1977]. Mayaud stressed the difference in view between a modulation (valley-digging; equinoctial) and excitation (mountain-building; RM or axial) mechanism. In addition, several authors, including *Murayama* [1974], *Berthelier* [1976], and *Schreiber* [1981] (using more limited data sets than were available to us in a variety of approaches), argued that the RM effect was not sufficient to account for the full amplitude of the semiannual variation. In general, these researchers found that the RM effect could only account for about a quarter of the observed modulation [see *Crooker and Siscoe*, 1986a]. Our results are in accord with those of the earlier studies. We find that the RM effect can account for only 15-20% of the semiannual variation in *am* while an axial variation in solar wind flow speed can account for an additional 15-20%. We attribute the remaining 65% to an equinoctial effect that is apparent in the seasonal/diurnal variation of geomagnetic indices for all latitude ranges. Several studies [e.g., *Roosen*, 1966; *Green*, 1984] have shown that the phasing and distribution of geomagnetic activity throughout the year are consistent with a dominant equinoctial mechanism for the semiannual variation.

3.2. Previous Rejection of the Equinoctial Hypothesis

Why was the RM hypothesis generally adopted in the face of the criticisms of *Mayaud* [1974], *Svaalgard* [1977], *Berthelier* [1990], and others? There are various possible reasons. First, following *Murayama* [1974], the "missing component" needed to supplement the RM effect was often taken to be a semiannual variation in solar wind speed [see *Russell and Scurry*, 1990]. Such an axial variation, presumed to result from the 7° tilt of the solar rotation axis to the ecliptic plane, would work by building mountains at the equinoxes, similar to the RM mechanism. We find that the seasonal wind speed variation (measured to be 6 km s^{-1} peak to valley on an average background speed of ~440 km s^{-1})

can account for only 15-20% of the observed semiannual modulation of *am*. The emphasis on wind speed variation as a contributing mechanism may have deflected attention from the more convincing evidence (Plate 1; cf. *Svalgaard* [1977]) for a substantial equinoctial (valley-digging) effect.

Without doubt, the general acceptance of the RM mechanism also owes much to its spirited defense by C.T. Russell and colleagues in the face of objections over the years [*Russell and McPherron*, 1974; *Russell and Scurry*, 1990]. A key aspect of this defense has been the unequivocal result that a separation of the solar wind magnetic field into toward and away polarities produces two annual variations, one peaking in spring for toward polarity and the other in fall for away polarity. Addressing this idealized situation, however, is not the same as solving the problem that nature presents. As reviewed by *Crooker and Siscoe* [1986a, p. 209], "...although the polarity effect itself is an outstanding feature in data sets separated according to polarity, the net effect of mixed polarities makes only a small contribution to the semiannual variation." By our determination and those of others listed above, the contribution from the RM mechanism amounts to only 15-20% of the total seasonal variation of the *am* index. The dominance of the equinoctial (ψ angle) effect over RM-induced B_s and/or axial-induced v effects for the full (i.e., mixed polarity) *am* data set is borne out by the regression analysis of *Orlando et al.* [1995]. Moreover, analyses based on polarity separation fail to address the discrepancy between the observed and RM-predicted diurnal variation of this index evident in a comparison of Plate 1 and Figure 2. From their analysis of geomagnetic activity associated with northward solar wind fields, *Scurry and Russell* [1990] concluded that while the diurnal variation must be associated with reconnection, a mechanism somewhat different than that proposed by *Russell and McPherron* [1973] was required.

In our opinion, the primary reason for the rejection thus far of a substantial valley-digging contribution to the semiannual variation lies in the explanation of the RM mechanism in terms of B_s coupling. Following J. Dungey's theoretical work in the early 1960s and the experimental verification that followed, it was clear that B_s fields made geomagnetic storms. The RM mechanism, which made B_s fields at the equinoxes where geomagnetic activity had maxima, appeared to be the natural answer to a long-standing problem. In contrast to the RM hypothesis the equinoctial effect suffered because its theoretical explanation in terms of viscous interaction and the Kelvin-Helmholtz instability [*Boller and Stolov*, 1970] was independent of B_s and therefore outside the reconnection picture. Thus accepting the equinoctial hypothesis for the semiannual variation entailed jettisoning the newly won and strongly supported B_s coupling paradigm. It is not surprising that the equinoctial hypothesis failed to gain support. Rejecting the implications of Plate 1 did less violence to one's beliefs.

3.3. Seasonal Variation of B_s Coupling Efficiency

The first suggestion that an equinoctial effect might modulate the B_s reconnection process [*Crooker and Siscoe*, 1986b] did not come until the RM picture was fairly well entrenched. As *Crooker and Siscoe* [1986b] noted, the cusp-masking mechanism they proposed solved the diurnal variation discrepancy while retaining the most attractive feature of the RM mechanism, its explanation in terms of B_s coupling. Subsequently, other mechanisms dependent on the angle between solar wind flow and Earth's dipole that could modulate the magnetosphere's coupling efficiency (or the release of previously stored energy) have been proposed (*la Belle-Hamer et al.* [1988] and *Kivelson and Hughes* [1990]; see discussion by *Scurry and Russell* [1990]). It is beyond the scope of this paper to address which, if any, of these mechanisms may apply.

On the basis of our analysis we conclude that the level of mountain building that takes place via the RM and axial effects is too small to account for the amplitude of the semiannual variation. We have demonstrated this by showing (1) that the RM-induced semiannual variation of B_s (~0.1 nT; based on 35 years of solar wind observations) can account for only 15-20% of the amplitude of the semiannual modulation and (2) that a substantial semiannual variation (~65% of the total) remains in a "normalized" planetary index ($\langle am\rangle^*/\langle v^2 B_s\rangle$) obtained by removing both the RM-induced seasonal variation of B_s and an axial variation of v. In addition, we have shown that the response of the magnetosphere to a given B_s or $v^2 B_s$ input is seasonally dependent, being higher at the equinoxes (Figures 6 and 7). Given the clear imprint of the equinoctial hypothesis on the seasonal/diurnal variation in Plate 1 (and Plates 3 and 4) and the overwhelming evidence for B_s reconnection as the solar wind - magnetosphere coupling mechanism, an equinoctial effect that modulates the B_s coupling efficiency (in effect, digging valleys at the solstices) is the leading candidate to account for the ~65% of the semiannual modulation of *am* that cannot be explained in terms of the annual variation of B_s and v. As the early Australian explorers found, there is more than one way to make a mountain, or a modulation.

3.4. Semiannual Variation of Great Storms

A magnetosphere that is less responsive to solar wind at the solstices might help to clear up one other puzzle. Recently, *Crooker et al.* [1992] have drawn attention to the marked semiannual variation in the occurrence rate of great storms. For example, from 1932 to 1989, no geomagnetic storms with $Ap^* \geq 100$ were observed during December and only 5 occurred in June, versus 21 such storms in March and 25 in September. *Crooker et al.* [1992] suggested that an "enhanced" RM effect based on compression and draping of in-ecliptic fields in front of a coronal mass ejection could account for the creation of great storms (large B_s values) at the equinoxes. While this suggestion found some support from a statistical study by *Phillips et al.* [1993], it was criticized in an analysis of individual large storms by *Gonzalez et al.* [1993; cf. *Kamide et al.*, 1998]. Great storms are observed for which the RM coordinate transformation makes no appreciable contribution to B_s. There is no compelling reason why such storms, unaided by the RM mechanism, should occur almost exclusively at the equinoxes. The near absence of large storms near the solstices is most easily understood in terms of a reduced coupling efficiency at those times. The finding by *Cliver and Crooker* [1993] that more energetic solar eruptions are required to produce great storms near the solstices than at the equinoxes is consistent with this point of view.

3.5. Semiannual Variation of the Undifferentiated *Dst* Index

While it seems clear from Plate 3 that the equinoctial hypothesis is an important factor in the seasonal variation of rapid changes of the *Dst* index (i.e, the storm component), the cause of the slow underlying seasonal variation that dominates the undifferentiated *Dst* index remains an open question. Some effect other than the Russell-McPherron mechanism or the classic equinoctial hypothesis is responsible for the pattern in Plate 2. A possible explanation for the behavior of the "raw" *Dst* index, involving a seasonal deformation of magnetosphere, has been advanced by *Mayaud* [1978, 1980] based on the work of *Malin and Isikara* [1976]. From an investigation of the annual variation of geomagnetic activity at 69 observatories covering the full range of latitude, *Malin and Isikara* [1976] concluded that the ring current moved bodily in latitude throughout the year. They suggested that because of the tilt of Earth's rotation axis to the ecliptic plane, solar wind compression of the magnetosphere would push the ring current toward the south in Northern Hemisphere summer and toward the north six months later. *Malin and Isikara* [1976] referred only to the ring current, but it is clear that the tail current will be similarly affected, likely more so. Detailed modeling, complicated by the multiplicity of current systems reflected in the *Dst* index, will be required to substantiate this picture.

3.6. Sources and Sinks of Geomagnetic Activity

Historically, the search for the sources of geomagnetic activity [e.g., *Cliver*, 1995; *Kamide et al.*, 1998] has been just that, a search for sources. Interpreting the valleys in the semiannual variation in terms of sinks of incipient activity has implications for space weather forecasting (e.g., Figures 6 and 7). In addition, a reduced coupling efficiency of the magnetosphere at the solstices (when ψ is furthest from 90°) should provide insight into the reconnection process.

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