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The semiannual variation of great geomagnetic storms

L. Svalgaard
Easy Took Kit, Inc., Houston, TX, USA

E. W. Cliver
Space Vehicles Directorate, Air Force Research Laboratory, Hanscom AFB, MA, USA

A. G. Ling
Radex Inc., Bedford, MA, USA

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[1] The occurrence frequency of the largest geomagnetic storms from 1868–1998 exhibits a well-defined semiannual modulation with more than twice as many storms occurring during equinoctial months than at the solstices. To examine the cause of this seasonal imbalance, we empirically obtained a new geomagnetic index aa_m that has the same seasonal and Universal Time variation as the *am* index. In effect, this extends the *am* index backward in time to 1868. By normalizing the aa_m time series for Ψ, the angle between the solar wind flow direction and Earth's dipole, we removed 75% of the amplitude of the six-month wave in monthly averages of aa_m and ~75% of the seasonal discrepancy in the numbers of great storms. We obtained similar percentages for the (unmodified) *am* index over the shorter 1959–1998 interval. These results indicate that most, though not all, of the discrepancy in storm counts between the equinoxes and solstices is due to an equinoctial effect. *INDEX TERMS:* 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2788 Magnetospheric Physics: Storms and substorms; 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics

1. Introduction

[2] The tendency for geomagnetic activity to be higher on average at the equinoxes than at the solstices has been known for ~150 years [*Sabine*, 1856]. Only recently, however, has it been appreciated that this seasonal variation is especially prominent when one considers the largest storms, the coronal-mass-ejection-related storms [e.g., *Richardson et al.*, 2001] that produce major "space weather" effects. From 1932–1989, great storms (defined as those with a geomagnetic *Ap** index [*Allen*, 1982] ≥ 100) in the equinoctial months of March/April/September/October outnumbered those during the solstitial months of June/July/December/January by over 3:1 [*Crooker et al.*,1992]. There is currently no accepted explanation for this behavior of great storms [*Newton*, 1948; *Cliver and Crooker*, 1993; *Gonzalez et al.*, 1993; *Crooker and Cliver*, 1993; *Tsurutani and Gonzalez*, 1995].

[3] Over the years three principal mechanisms have been proposed to account for the seasonal variation of geomagnetic activity: the axial hypothesis ([*Cortie*, 1912]; based on the ~7° tilt of the solar equitorial plane to the ecliptic plane); the equinoctial hypothesis ([*Bartels*, 1932; *McIntosh*, 1959; *Svalgaard*, 1977]; based on the ~23° tilt of Earth's equatorial plane to the ecliptic plane and the ~11° offset between Earth's rotation and dipole axes); and the Russell-McPherron mechanism ([*Russell and McPherron*, 1973]; based on the ~26° angle between the Sun's and Earth's equatorial planes and the 11° dipole axis offset).

[4] Recent work [*Cliver et al.*, 2000; *Lyatsky et al.*, 2001; *Temerin and Li*, 2002] affirms earlier studies [e.g. *Berthelier*, 1976; *Svalgaard*, 1977] showing that the equinoctial hypothesis is the principal cause of the semiannual modulation of average values of geomagnetic indices. The case for the dominance of the equinoctial effect is based on a clear imprint of the variation of the Ψ-angle, the angle between the solar wind flow direction and Earth's dipole, on various geomagnetic indices displayed as a function of month of the year and Universal Time. In addition, various studies have indicated that the Russell-McPherron effect, the main competing mechanism, accounts for only ~30% of the six-month wave in geomagnetic activity [*Berthelier*, 1976; *Cliver et al.*, 2000]. Finally, detailed phase studies [*Fraser-Smith*, 1972; *Cliver et al.*, 2002] have obtained maxima and minima (as well as an annual activity profile) that are consistent with the equinoctial hypothesis and inconsistent with either a dominant axial or Russell-McPherron effect.

[5] *Crooker et al.* [1992] suggested that storms are responsible for most of the semiannual variation in monthly averages of geomagnetic indices. *Cliver* [2000] substantiated this suggestion by showing that eliminating minor and larger storms (constituting only about 15% of all values) from the *am* data set removed about three-fourths of the six-month wave in that index. Thus it appears that the seasonal discrepancy in great storm counts is primarily due to the equinoctial effect. In this study we obtain this result more directly by removing the Ψ-angle dependence from geomagnetic indices and showing that in so doing, the bulk of the seasonal imbalance in storm counts also disappears.

2. Analysis

2.1. The Geomagnetic *am* and *aa* Indices

[6] The geomagnetic *am* and *aa* indices [*Mayaud*, 1980] are mid-latitude range indices based on maximum excursions of the horizontal (H) or declination (D) components of the field over a 3-hr interval after removing the regular variation (S_R). While the *am* index is based on a set of mid-latitude (subauroral) stations optimally positioned (insofar

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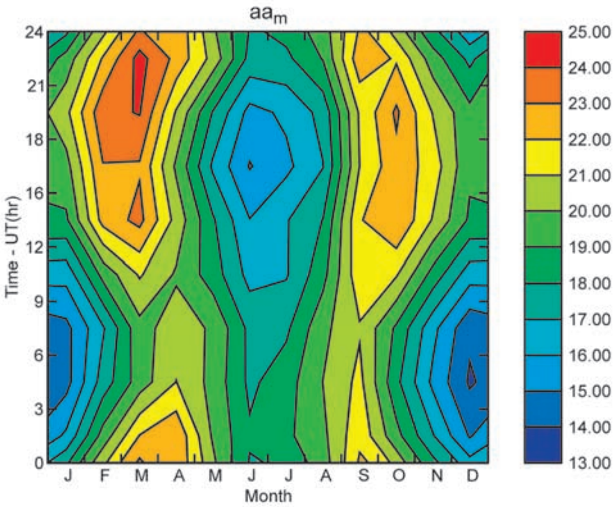

Figure 1. Seasonal/Universal Time variation of the geomagnetic *aa*$_m$ index.

as possible) in both latitude and longitude to yield an index free of local time effects, the *aa* index is based on only two, albeit nearly antipodal, stations (in England and Australia) and exhibits strong local time dependence. The *am* index covers the period from 1959–present and *aa* is available since 1868. Both indices respond to a variety of ionospheric and magnetospheric currents (e.g., auroral electrojets, field-aligned currents, ring current) spanning all latitude ranges and are distinguished from the *AE* and *Dst* indices that focus on high- and low-latitude regions, respectively.

2.2. The Geomagnetic *aa*$_m$ Index

[7] In this section, we empirically obtain a new long-term (1868–1998) geomagnetic index *aa*$_m$ that has the same seasonal and UT variation as the *am* index. To obtain correction factors to convert aa to *aa*$_m$, we compared *aa* with the *am* index for the period since 1959, the year for which *am* was first derived. The *aa* correction factors consisted of the ratio of *am* to *aa* for each of the 96 combinations of month (M) of the year and 3-hour period of the UT-day (UT). Thus for any given 3-hr *aa* value, *aa*$_m$ is computed as follows:

$$aa_m = kaa\left[\sum am(1959-1998)/\sum aa(1959-1998)\right]_{M,UT} \tag{1}$$

The constant k (=0.967) is introduced because $\langle am\rangle/\langle aa\rangle = 1.034$ for the 1959–1998 period. The derived *aa*$_m$ index exhibits the same UT dependence throughout the year as the *am* index (Figure 1). The localized peaks and valleys in *aa*$_m$ (and *am*) indicate that any attempt to understand the semiannual variation must consider the strong UT-dependence. While the correction factors are calculated using *am*-values since 1959 only, the seasonal/UT-dependence of the corrected *aa*-index, showing the characteristic imprint of the equinoctial hypothesis (the correlation coefficient between Ψ and *aa*$_m$ is 0.88; see *Svalgaard* [1977] and *Cliver et al.* [2002]), is equally strong for all data going back to 1868, attesting to the homogeneity of the series. It is important to note that the UT correction to *aa* does not significantly change the semiannual variation. A comparison of the variations of *aa* and *aa*$_m$ throughout the year is given in Figure 2. The amplitude of the six-month wave in *aa*$_m$ is ~13% (2.5/19.3) vs. ~12% (2.3/19.3) for *aa*.

2.3. Ψ-angle Dependence of *am* and *aa*$_m$

[8] From an analysis of solar wind data from 1965–1973, [*Svalgaard*, p. 413, 1977] obtained the following expression for the *am* index in terms of solar wind parameters and Ψ, the angle between the solar wind flow direction and Earth's dipole axis:

$$am = am_0k_0/\left(1+3\cos^2\Psi\right)^{2/3} \tag{2}$$

The normalization factor k_0 = 1.157 is the yearly mean value of the denominator and am_0 is a function of solar wind density, speed, and magnetic field strength. The separation of the solar wind and Ψ dependencies is critical to our analysis because it allows us to "normalize" for Ψ and isolate the non-equinoctial component of the semiannual variation. The factor $(1 + 3\cos^2\Psi)$ is not unique, but was chosen because it appears in the mathematical description of the magnetic field of a dipole. The value of the exponent was determined empirically.

[9] We are in the process of updating *Svalgaard*'s [1977] analysis using the complete solar wind and *am* data sets through the present time; the work will be presented elsewhere in a more extensive report. Here we show that the Ψ-angle dependence for the complete data set generally conforms to that given in equation (2). Figure 3 contains a plot of average *am* values ("O" data points) from 1959–1998 versus cos Ψ for the full range of Ψ ($55° \le \Psi \le 125°$) values. The data points represent the average value of *am* for both negative and positive cos Ψ values. This "folding over" of the data compensates for less than ideal station location in both latitude and longitude. Figure 3 also contains plots of the function

$$am = 26\left(1+3\cos^2\Psi\right)^{-n} \tag{3}$$

for values of n from n = 0.2 to n = 1.0. It can be seen that this equation provides a good fit to the data for n = 0.6,

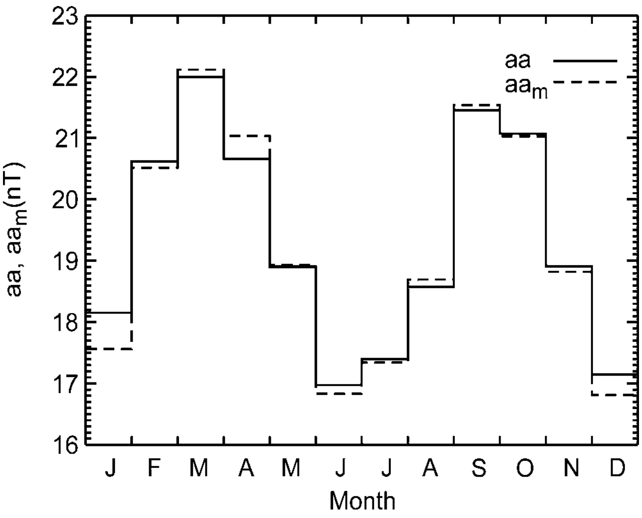

Figure 2. Seasonal variation of the geomagnetic *aa* and *aa*$_m$ indices.

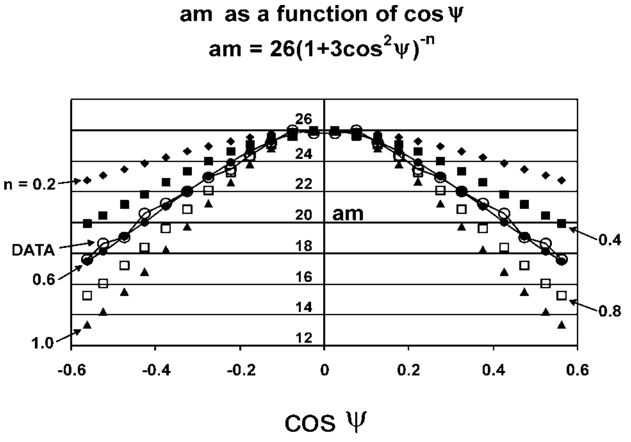

Figure 3. The dependence of the geomagnetic *am* index on the function $(1 + 3\cos^2\Psi)^{-n}$.

close to the 0.67 value used in equation (2). Note that in equation (3), any seasonal dependence other than that due to the variation of Ψ (e.g., entering through an axial effect on solar wind parameters) will be incorporated in the exponent. Because we do not expect n to diverge greatly from 0.67 when the complete 1965–present data set is considered in detail, we will use $n = 0.67$ in the analysis below.

[10] The variable am_0 in equation (2) includes the effects of modulation due to both the Russell-McPherron (seasonal variation of southward pointing solar wind magnetic field (B_S)) and axial (seasonal variation of solar wind velocity (v) and total magnetic field strength (B)) effects. The maximum value of the Ψ-dependent factor is 1.575 and the minimum value is 1.0, so the modulation can reach ~35% below the peaks. Because our new index aa_m is essentially an extension of *am* back to 1868, we can write equation (2) as

$$aa_m = aa_{m0}k_0/\left(1+\cos^2\Psi\right)^{2/3} \qquad (4)$$

2.4. Monthly Averages of *aa* and *aa_m*

[11] A plot of monthly averages of the aa_{m0} index (obtained from equation (4)) is given in Figure 4 where it can be seen that removing the Ψ dependence from aa_m greatly reduces the seasonal variation; the FFT-determined amplitude of the six-month wave in aa_{m0} is only 0.6 nT (0.8 nT for $n = 0.6$). We conclude that the equinoctial effect accounts for ~75% ((2.5 − 0.6)/2.5) of the semiannual variation of monthly averages of the aa_m (or *aa*) index, with the remainder due to some combination of the Russell-McPherron and axial effects. Our 25% estimate for the contribution of the combined Russell-McPherron and axial effects is comparable to the ~35% figure obtained by *Cliver et al.* [2000], (see also *Crooker and Siscoe* [1986]).

2.5. Seasonal Counts of Great Storms

[12] For space weather forecasting purposes, geomagnetic storms are currently defined in terms of the daily geomagnetic *Ap* index as follows: minor storm ($Ap \geq 30$), major storm ($Ap \geq 50$), and severe storm ($Ap \geq 100$) [*Joselyn*, 1995]. (Note that *aa*, *am*, and *ap* refer to 3-hr values of these indices while *Aa*, *Am*, and *Ap* indicate daily values.) We used a linear relationship ($Aa = 0.91\ Ap + 15.5$) between daily averages of *Ap* and *Aa* over the range $Ap = 20 - 110$ to obtain corresponding levels for Aa_m (~40, ~60, and ~105). Because storms are not normally aligned with calendar days, we identified periods when 24-hr running averages of 3-hr aa_m values met or exceeded these thresholds. (This is the Aa_m (*Aa*) equivalent of Allen's *Ap** index [*Allen*, 1982]). Our counts of Aa_m storms at these three thresholds, subdivided for equinoctial (March, April, September, October), solstitial (June, July, December, January), and intermediate months are shown in Table 1.

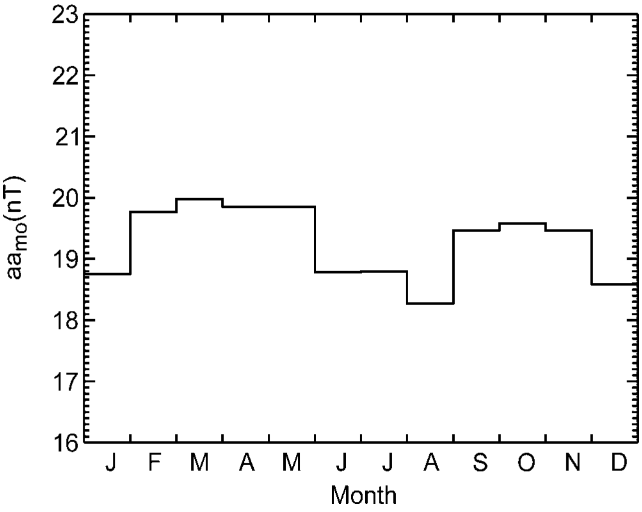

Figure 4. Seasonal variation of the Ψ-normalized geomagnetic aa_{m0} index.

[13] Table 1 shows the increasing concentration of storms towards the equinoxes for progressively larger thresholds [*Green*, 1984]. For a threshold of $Aa_m^* \geq 40$ ($Ap^* \geq 30$), ~1.5 times as many storms occur at the equinoxes than at the solstices. For $Aa_m^* \geq 60$ ($Ap^* \geq 50$), this factor increases to ~2.0 and for $Aa_m^* \geq 105$ ($Ap^* \geq 100$), it becomes ~2.6 (with poorer statistics for each increase in threshold). Table 2 gives the storm counts at the various thresholds for the Ψ-normalized index Aa_{m0}^*. For Aa_{m0}^*, the equinoctial concentration of geomagnetic storms at these various thresholds is reduced significantly, to factors of ~1.1, ~1.2, and ~1.4, respectively. Thus at these successively higher thresholds, removing the Ψ dependence from aa_m to obtain aa_{m0} eliminates all but 20%, 20%, and 25% of the seasonal variation in storm counts. (Corresponding figures for $n = 0.6$ are 23%, 30%, and 34%.)

2.6. Monthly Averages and Seasonal Counts of Storms for the *am* Index

[14] The above results were obtained by imposing an empirical UT variation on *aa* to obtain the aa_m index

Table 1. Number of Storms Where the 24-hr *aa*-Index Corrected for Station Distribution (Aa_m^*) was ≥ Various Thresholds as a Function of Time of Year

$Aa_m^* \geq$	Equinox Months 3,4,9,10	Intermediate Months 2,5,8,11	Solstice Months 6,7,12,1
40($Ap^* \geq 30$)	1481	1192	979
60($Ap^* \geq 50$)	645	501	325
105($Ap^* \geq 100$)	128	89	50

Table 2. Number of Storms Where the 24-hr *aa*-Index Corrected for Station Distribution and Reduced for Ψ-Dependence (Aa^*_{m0}) was ≥ Various Thresholds as a Function of Time of Year

$Aa^*_{m0} \geq$	Equinox Months 3,4,9,10	Intermediate Months 2,5,8,11	Solstice Months 6,7,12,1
40($Ap^* \geq 30$)	1292	1204	1171
60($Ap^* \geq 50$)	496	486	414
105($Ap^* \geq 100$)	97	93	69

(1868–1998) from which we then removed the Ψ-angle dependence. We obtained essentially the same results for the unmodified *am* index, covering the shorter 1959–1998 interval. Normalizing *am* for Ψ removes ~80% of the amplitude of the six-month wave in *am* averages and all but 8% ($Am^* \geq 40$), 28% ($Am^* \geq 60$), and 29% ($Am^* \geq 105$) of the seasonal imbalance in storm counts.

3. Discussion

[15] We have shown that removing the Ψ-dependence from aa_m, the *aa* index we empirically modified to have the same UT-variation as the *am* index, reduced the amplitude of the semiannual variation in monthly averages of aa_m (1868–1998) by ~75%. In contrast, *Cliver et al.* [2000] found that normalizing monthly averages of *am* for the seasonal variation of B_S (the key solar wind variable in the Russell-McPherron mechanism) reduced the amplitude of the six-month wave in that index by only ~20%.

[16] We find that normalizing aa_m for Ψ throughout the year removes much (~75%) of the discrepancy in great storm counts between equinoctial and solstitial months. Our result is consistent with other lines of evidence (UT variation of the *am* index, annual phases and profiles of geomagnetic activity, relative weakness of the Russell-McPherron effect) for a dominant equinoctial mechanism pointed out by various researchers over the years [*Bartels*, 1932; *McIntosh*, 1959; *Mayaud*, 1974; *Berthelier*, 1976; *Svalgaard*, 1977].

[17] Our analysis was based on *Svalgaard*'s [1977] derivation of equation (2) from the 1965–1973 solar wind data set. While our findings are in accord with previous results, they should be regarded as preliminary pending the rederivation of (2) using the full 1965–present data set.

[18] The equinoctial hypothesis has been described as a "valley digging" mechanism [*Cliver et al.*, 2000] that, by reducing the solar wind/magnetosphere (B_S) coupling efficiency outside of the equinoxes, causes the lower geomagnetic activity observed at the solstices. Our procedure to remove the effect of the varying value of Ψ throughout the year can then be seen as a "valley filling" exercise. (The decrease in equinoctial aa_{m0} values in Figure 4 relative to corresponding aa_m values in Figure 2 (and of equinoctial storm counts in Table 2 versus those in Table 1) is due to the 1.157 normalization factor.)

[19] The non-equinoctial component of the semiannual modulation, while secondary, is not negligible; in Table 2, ~40% more great storms ($Aa^*_{m0} \geq 105$) occur at the equinoxes than at the solstices. Presumably, this remaining difference is due to some combination of the Russell-McPherron (or postshock Russell-McPherron [*Crooker et al.*,1992]) and axial [*Tsurutani and Gonzalez*, 1995] mechanisms.

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L. Svalgaard, Easy Tool Kit, Inc., 6927 Lawler Ridge, Houston, TX, 77055, USA. (leif@leif.org)

E. W. Cliver, AFRL/VSBXS, 29 Randolph Rd., Hanscom AFB, MA, 01731-3010, USA.

A. G. Ling, Radex Inc., 3 Preston Ct., Bedford, MA, 01730, USA.