Spring-fall asymmetry of substorm strength, geomagnetic activity and solar wind: Implications for semiannual variation and solar hemispheric asymmetry

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[1] We study the seasonal variation of substorms, geomagnetic activity and their solar wind drivers in 1993–2008. The number of substorms and substorm mean duration depict an annual variation with maxima in Winter and Summer, respectively, reflecting the annual change of the local ionosphere. In contradiction, substorm mean amplitude, substorm total efficiency and global geomagnetic activity show a dominant annual variation, with equinoctial maxima alternating between Spring in solar cycle 22 and Fall in cycle 23. The largest annual variations were found in 1994 and 2003, in the declining phase of the two cycles when high-speed streams dominate the solar wind. A similar, large annual variation is found in the solar wind driver of substorms and geomagnetic activity, which implies that the annual variation of substorm strength, substorm efficiency and geomagnetic activity is not due to ionospheric conditions but to a hemispherically asymmetric distribution of solar wind which varies from one cycle to another. Our results imply that the overall semiannual variation in global geomagnetic activity has been seriously overestimated, and is largely an artifact of the dominant annual variation with maxima alternating between Spring and Fall. The results also suggest an intimate connection between the asymmetry of solar magnetic fields and some of the largest geomagnetic disturbances, offering interesting new pathways for forecasting disturbances with a longer lead time to the future. **Citation:** Mursula, K., E. Tanskanen, and J. J. Love (2011), Spring-fall asymmetry of substorm strength, geomagnetic activity and solar wind: Implications for semiannual variation and solar hemispheric asymmetry, *Geophys. Res. Lett.*, *38*, L06104, doi:10.1029/2011GL046751.

1. Introduction

[2] Magnetospheric substorms are among the most common ways by which the Earth's magnetosphere reacts to the changes in the solar wind and interplanetary magnetic field. During a substorm, high-latitude magnetic stations in the night sector observe a reduction in horizontal field of a few hundred nanotesla. On an average, two to four substorms occur daily [*Kamide*, 1982; *Borovsky et al.*, 1993], with substorm duration varying typically from 1 to 5 hours [*Kullen and Karlsson*, 2004]. Substorms also form a large fraction of disturbances included in various indices of global geomagnetic activity, the most reliable of which are the Kp/Ap indices [*Bartels et al.*, 1939; *Menvielle and Berthelier*, 1991]. We use here Ap which is the linearized version of the quasi-logarithmic Kp index.

[3] Recently, methods have been developed to identify substorms using magnetic field observations by the IMAGE network in the Fenno-Scandian region (56°–76° GMlat, 96°–112° GMlong). Using the IL index, a local analogue of the auroral AE index based on IMAGE data [*Viljanen and Häkkinen*, 1997], a search engine was constructed to identify substorm onsets as rapid decreases of the IL index of at least 80 nT in 15 min [*Tanskanen*, 2009]. The IMAGE network detects substorms occurring roughly in the 16–03 UT time interval, thus allowing nearly half of all substorms to be detected. One of the virtues of using a latitudinally dense network is to obtain a reliable estimate of substorm intensity.

[4] These methods have allowed to collect and analyze a long-term set of substorms for the years 1993–2008 (8717 substorms), covering more than one solar cycle [*Tanskanen*, 2009; *Tanskanen et al.*, 2011]. The number of substorms and, e.g., substorm peak amplitude (strength) were found to depict a clear solar cycle variation with a maximum in the declining phase of the solar cycle, when high-speed streams dominate the solar wind. High-speed streams enable a long-lasting feed of extraneous magnetic flux, intervened by frequent intervals of negative IMF B_z, thus providing ideal conditions for generating substorms and producing enhanced geomagnetic activity [*Holzer and Slavin*, 1981; *Tanskanen et al.*, 2005; *Tsurutani et al.*, 2006].

[5] Figure 1 depicts the monthly total substorm numbers (N_s), monthly mean substorm peak amplitudes (a_s), monthly mean substorm durations (t_s), monthly total efficiencies (E_s) (product of duration and peak amplitude divided by two) and monthly averaged Ap indices in 1993–2008. About 45 substorms were detected in a month (i.e., 1.5 substorms per day), whose average peak amplitude is −394 nT and mean duration 178 minutes. These numbers are in good agreement with the above mentioned estimates. The average monthly efficiency is about $1.91 * 10^6$ nT*min.

[6] Most parameters in Figure 1 attain the highest values in 1994 and in 2003, in the declining phase of solar cycles (SC) 22 and 23, when frequent, long-lasting high-speed streams took place. Although the relative size of these two maxima varies from one parameter to another, they are particularly clear and simultaneous in a_s, E_s and Ap, which also have the largest mutual correlations. For example, correlation coefficients of the monthly Ap index with the four substorm

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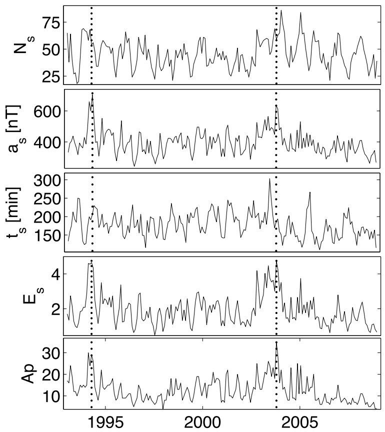

Figure 1. Monthly substorm numbers (N_s), monthly mean substorm peak (absolute) amplitudes (a_s ; unit nT), monthly mean substorm durations (t_s ; unit minute), monthly total efficiencies (E_s; in unit of 10^6 nT*minute) and monthly mean Ap indices from 1983 until 2008. Vertical dotted lines denote the months, April 1994 and October 2003 when a_s attains maximum values.

parameters are 0.50 for N_s, 0.86 for a_s, 0.34 for t_s, and 0.89 for E_s. Thus, Ap correlates very well with substorm efficiency and amplitude but considerably less with the other two substorm parameters.

[7] Note also the high level of short-term variability in all parameters in Figure 1, which is mainly due to seasonal (annual and semiannual) variation. In the three parameters (a_s, E_s and Ap) correlating best with each other this short-term variability is mostly in phase, but in the two other parameters (N_s and t_s) it is different. In this letter we study this short-term variability in more detail.

2. Seasonal Distribution of Substorm Parameters and Geomagnetic Activity

[8] Figure 2 shows the averaged seasonal distributions in 1993–2008 for N_s, a_s, t_s, E_s and Ap. As found earlier [*Tanskanen et al.*, 2011], the seasonal variations of N_s, a_s and t_s are quite different. Figure 2 shows that substorms occur roughly twice more often in local Winter (on an average almost 60 substorms in January) than in Summer, thus depicting a pronounced annual variation (with small side maxima around equinoxes). The annual variation also dominates substorm mean duration t_s, but its phase is opposite to N_s, with Summer substorms being roughly one hour longer than in Winter.

[9] Contrary to the dominantly annual variation of N_s and t_s, the seasonal distributions of a_s and E_s are dominated by semiannual variation with equinoctial maxima, greatly resembling the semiannual variation of the Ap index (Figure 2, bottom). Correlations between the seasonal variation of the Ap index and the seasonal variations of a_s and E_s are excellent (0.92 and 0.90) but poor (0.36) with N_s and nil (0.00) with t_s.

[10] The semiannual variation of geomagnetic activity with equinoctial maxima is one the first facts learned of the near-Earth space [*Sabine*, 1852; *Cortie*, 1912]. Three mechanisms have been proposed to explain this phenomenon: axial hypothesis [*Cortie*, 1912; *Bohlin*, 1977], equinoctial hypothesis [*Bartels*, 1932; *McIntosh*, 1959; *Boller and Stolov*, 1970], and Russell-McPherron (RMP) effect [*Russell and McPherron*, 1973]. The axial hypothesis relates seasonal changes to the heliographic latitude of the Earth and the latitudinally varying distribution of solar wind in corona. The RMP effect pleads to the variable amount of southward field induced from the equatorial component of the solar magnetic field to the geocentric coordinate system. After a groundbreaking work by *Cliver et al.* [2000], a new interpretation of the equinoctial model was proposed in terms of seasonally varying illumination (ionization) of high-latitude ionospheres [*Lyatsky et al.*, 2001; *Newell et al.*, 2002]. However, we will argue that the size of semiannual variation is largely overestimated and that it is yet premature to conclude which is the dominant mechanism for semiannual variation.

3. Spring-Fall Asymmetry in Substorm Strength and Geomagnetic Activity

[11] Figure 3 depicts the absolute values of the monthly a_s for the whole time interval 1993–2008 in a two-dimensional color (or b&w intensity) plot. Time in years is given in x-axis, and the seasonal variation in each year is depicted as a column from January (top) to December (bottom), with color (or b&w intensity) indicating the monthly a_s value. Figure 3 shows that by far the largest monthly amplitudes were found in the three Spring months in 1994 (a_s maximum in April), and the two Fall months in 2003. These two periods also stand out in Figure 1 as the two highest peaks in a_s, as well as in E_s and Ap, although their relative heights slightly vary.

[12] Figure 3 shows that the dominant pattern in the seasonal variation of substorm amplitude in most years by far is not the semiannual variation but rather an annual variation. Most importantly, the phase of the annual variation is seen to vary between Spring maximum in SC 22 and Fall maximum in SC 23. The dominant, large semiannual variation presented in Figure 2 is an artifact which results when years with a dominant annual variation with opposite equinoctial maxima are averaged.

[13] This interpretation is further supported by Figure 4 which shows the similar distribution for monthly Ap. The Ap index also attains its highest values in Spring 1994 and Fall 2003, the seasonal variation being dominated, as for a_s,

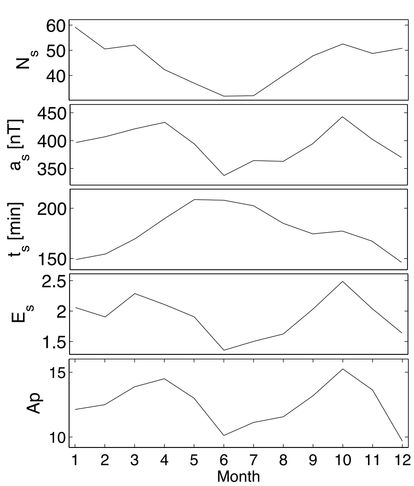

Figure 2. Seasonal superposed distributions of the same parameters as in Figure 1.

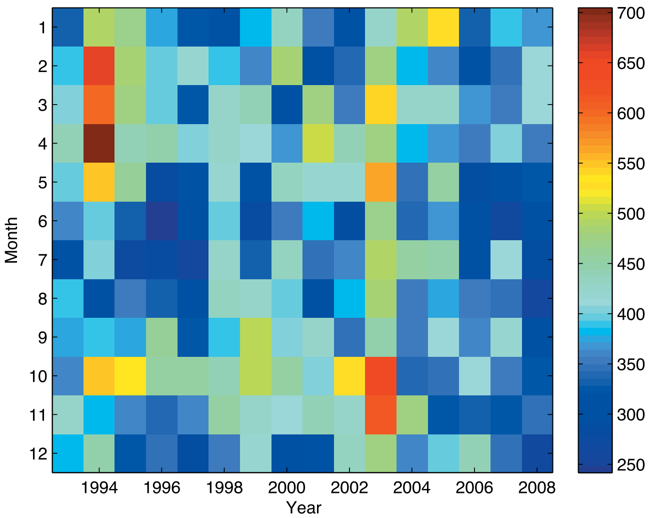

Figure 3. Two-dimensional plot of the absolute values of monthly mean substorm peak amplitudes in 1993–2008. Time in years runs in x-axis, while the seasonal variation in each year is depicted as a column. Color (b&w intensity) indicates the mean amplitude during the respective month (values of color bar in nT).

by annual (rather than semiannual) variation with maxima alternating between Spring in SC 22 and Fall in SC 23. (Actually there is only one year in Figure 4, 2001, where the semiannual variation with equinoctial maxima is dominant and of notable amplitude). Thus, the large overall semiannual variation depicted in Figure 2 for a_s, E_s and Ap does not result from an accumulation of individual years with a dominant semiannual variation, but from a long-term average of years with a dominant annual variation whose phase is systematically alternating between Spring and Fall.

[14] Note that most earlier studies of semiannual variation use the seasonal average of Figure 2 as input and, therefore, largely overestimate it. It is clear that the present results call for a reanalysis in order to better quantify the semiannual variation in the various geomagnetic and interplanetary parameters.

[15] We note that a highly similar distribution with maxima in Spring 1994 and Fall 2003 is also obtained for E_s (not shown). However, these two periods do not form the highest peaks for N_s or t_s. Rather, the two highest peaks of N_s (see Figure 1) are in January 2004 and 2005, i.e., in Winters following large geomagnetic activity in Oct 2003. One can also find fairly large values of N_s in Winter months prior to Spring 1994. Similarly, the highest peak of t_s is seen in July 2003, just prior to Fall 2003. These results agree with the overall Winter (Summer) maximum in N_s (t_s, resp.) depicted in Figure 2. In fact, these solstice maxima are very persistent, which supports the suggestion [*Wang and Lühr*, 2007; *Tanskanen et al.*, 2011] that the seasonal variations in N_s and t_s are mainly affected by the ionization conditions of the local ionosphere. The different phasing of the annual variation of N_s and t_s also leads to their small correlation with the parameters with equinoctial maxima (a_s, E_s and Ap), as earlier noted.

4. Spring-Fall Asymmetry in Solar Wind Drivers

[16] Although the seasonal (annual) variation of N_s and t_s is dominated by local ionospheric conditions, this is not the case for a_s, E_s and Ap. Most interestingly, the annual variation with alternating equinoctial maxima is also seen in the solar wind drivers of geomagnetic activity. This is depicted in Figure 5, which shows the seasonal variation in each year for $V_{SW}^2 B_{HMF}$, where V_{SW} is the solar wind speed and B_{HMF} is the intensity of the heliospheric magnetic field. This parameter and $V_{SW}B_{HMF}$ have been shown to be the main drivers of long-term geomagnetic activity at high and middle latitudes, respectively [*Finch et al.*, 2008; D. Martini et al., Comparing indices of geomagnetic activity at a high-latitude station, submitted to *Journal of Geophysical Research*, 2010].

[17] Most importantly, Figure 5 shows that the two highest monthly values for $V_{SW}^2 B_{HMF}$ occur in Spring 1994 and Fall 2003, as for a_s, E_s and Ap. (A similar distribution is also found for $V_{SW}B_{HMF}$; not shown). Accordingly, the seasonal distributions of solar wind and HMF are very asymmetric in

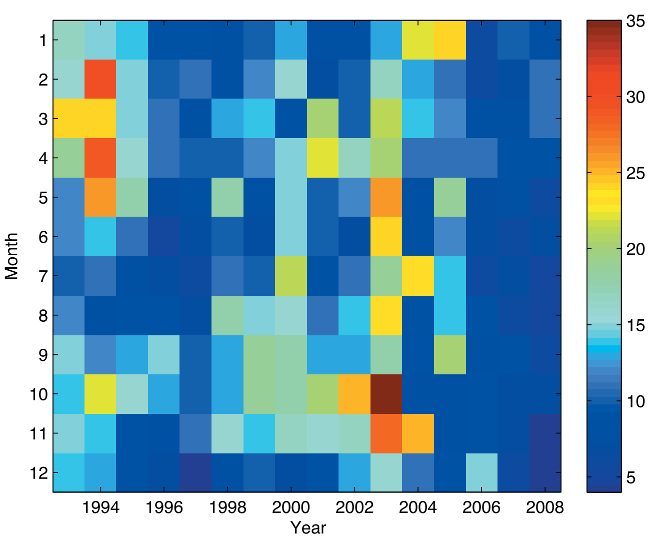

Figure 4. Similar plot as Figure 3 for monthly means of the Ap index. Color indicates the mean Ap index during the respective month.

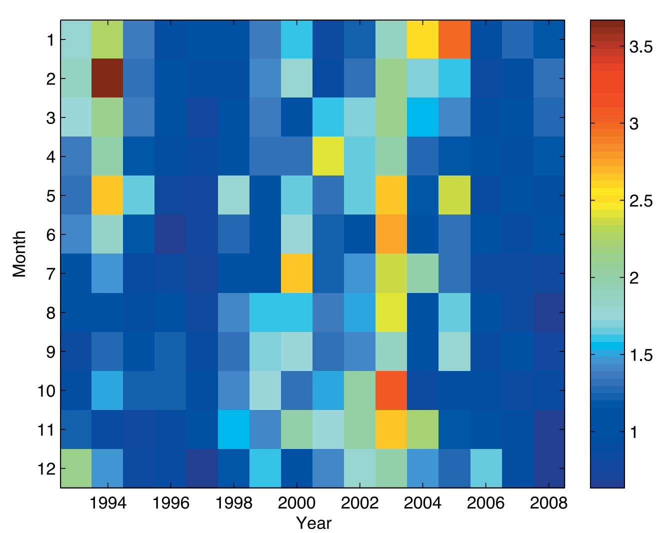

Figure 5. Similar plot as Figure 3 for monthly means of $V_{SW}^2 B_{HMF}$. Values are given in units of 10^6(km/s^2 nT).

these years, and produce the corresponding annual variations with alternating phase in a_s, E_s and Ap. The correlation coefficient between the monthly values of $V_{SW}^2 B_{HMF}$ ($V_{SW} B_{HMF}$) with a_s, E_s and Ap are 0.76, 0.80 and 0.88 (0.72, 0.74, and 0.85 respectively). As a comparison, correlations with N_s and t_s are only 0.48 and 0.30 (0.43 and 0.33).

[18] The alternation of the annual phase in the two solar cycles included in this study is not random. It was found earlier [*Zieger and Mursula*, 1998; *Mursula and Zieger*, 2001; *Mursula et al.*, 2002] that the phase of the annual variation of solar wind speed and geomagnetic activity changed systematically from one solar cycle to another. Annual variation was largest in the declining phase of solar cycles and annual maxima were located in Spring during positive polarity periods and in Fall during negative polarity periods. The present results are in an excellent agreement with these results, verifying the validity of this rule for substorm properties during cycles 22 and 23 and extending the rule for geomagnetic activity for cycle 23.

[19] Annual variation in the solar wind drivers of geomagnetic activity imply a systematically occurring and alternating hemispheric asymmetry in the Sun. Since solar wind in Spring (Fall) preferably comes from the southern (northern) hemisphere, the annual variation with Spring maximum suggests that the product $V_{SW}^2 B_{HMF}$ is larger in the southern hemisphere in the declining phase of SC 22 (more generally: during positive polarity times). Similarly during the declining phase of SC 23 (negative polarity times) the more efficient solar wind comes from the northern hemisphere. Accordingly, the overall semiannual variation depicted in Figure 2 is mainly an artifact related to the latitudinal-hemispheric variation of solar wind properties causing an annual variation with maximum varying from Spring in one solar cycle to Fall in another.

[20] A more detailed analysis of V_{SW} and B_{HMF} separately shows that V_{SW} has its overall monthly maximum in Spring 1994 while HMF intensity maximum is in Fall 2003. Although both parameters have enhanced values in both periods, their relative contribution seems to vary. In particular, it is likely that the large perturbations due to the coronal mass ejections in October–November 2003 have enhanced the HMF intensity to its maximum. It is interesting to note how the above described general pattern regulates the timing of the largest solar bursts. This allows a possibility for improved forecasting of such perturbations in the future.

5. Conclusions

[21] We have studied the seasonal variation of substorms and geomagnetic activity using substorms registered in Fenno-Scandia, and the global geomagnetic Ap index. As noted earlier [*Tanskanen et al.*, 2011], the number of substorms and substorm mean duration depict a dominant annual variation with maxima in Winter and Summer, respectively. The number of substorms is about twice as large in Winter as in Summer, but the Summer substorms are about an hour longer than their Winter counterparts. These annual variations are due to the change of ionization in the local in ionosphere [*Wang and Lühr*, 2007; *Tanskanen et al.*, 2011].

[22] In contradiction, substorm mean amplitude, substorm total efficiency, and global geomagnetic activity show a dominant annual variation with equinoctial maxima alternating between Spring during solar cycle 22 and Fall in solar cycle 23. The largest annual variations were found in Spring 1994 and Fall 2003, i.e., in the declining phase of solar cycles 22 and 23 when high-speed streams dominate the solar wind.

[23] We found out that a similar annual variation with alternating phase is found in the main solar wind drivers of geomagnetic activity. This implies that the annual variation of substorm amplitude, substorm efficiency or geomagnetic activity is not mainly due to the ionospheric conditions but rather due to the hemispherically asymmetric distribution of the solar wind driver. Moreover, the alternation of the dominant hemisphere seems to be systematic, as earlier found for centennial evolution of geomagnetic activity [*Mursula and Zieger*, 2001; *Mursula et al.*, 2002].

[24] Our results imply that the semiannual variation, first reported nearly 160 years ago [*Sabine*, 1852; *Cortie*, 1912], is largely an artifact of the dominant annual variation with annual maxima alternating between Spring and Fall. In fact, one can hardly find years with a dominant semiannual variation. Accordingly, the level of semiannual variation in, e.g., geomagnetic activity has been seriously overestimated, and needs to be revised. Therefore, it is still premature to conclude which of the theories of semiannual variation (axial theory, equinoctial theory or Russell-McPherron mechanism) is the main mechanism.

[25] Finally, we note that the annual variation in global geomagnetic activity (and substorm strength and efficiency) shows an intimate connection between the systematically asymmetric long-term evolution of solar magnetic fields and the largest activations and disturbances of the Sun. This fact offers interesting new pathways for forecasting the largest activations with a longer lead time to the future.

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