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The impact of solar wind ULF $B_z$ fluctuations on geomagnetic activity for viscous timescales during strongly northward and southward IMF

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Abstract We analyze more than 17 years of OMNI data to statistically quantify the impact of IMF $B_z$ fluctuations on $AL$ by using higher-order moments in the $AL$-distribution as a proxy. For strongly southward interplanetary magnetic field (IMF), the $AL$ distribution function is characterized by a decrease of the skewness, a shift of its peak from $-30$ nT to $-200$ nT, and a broadening of the distribution core. During northward IMF, the distribution of $AL$ is characterized by a significant reduction of the standard deviation and weight in the tail. Following this characterization of $AL$ for southward and northward IMF, we show that IMF fluctuations enhance the driving on timescales smaller than those of substorms by shifting the peak of the probability distribution function by more than 150 nT during southward IMF, and by narrowing the distribution function by a factor of 2 during northward IMF. For both southward and northward IMF, we demonstrate that high power fluctuations in $B_z$ systematically result in a greater level of activity on timescales consistent with viscous processes. Our results provide additional quantitative evidence of the role of the solar wind fluctuations in geomagnetic activity. The methodology presented also provides a framework to characterize short timescale magnetospheric dynamics taking place on the order of viscous timescales $\tau \ll 1$ hour.

1. Introduction

Space weather as a discipline aims to understand the energy-momentum entry processes regulating the solar wind-magnetosphere interaction [Akasofu, 1981; Cowley, 1981; Vasyliunas et al., 1982; Baker et al., 1996]. Following the realization that the solar wind must supply energy at a rate of $10^{10}$ W to the magnetosphere, in order to account for energy dissipated in the auroral oval and the formation of ring current, energy conversion processes have loosely been classified in terms of magnetic reconnection [Dungey, 1961] and momentum transfer mechanisms without field-line reconnection [Axford and Hines, 1961] (herein simply termed as viscous processes). More than five decades later, a plethora of observational evidence of magnetic reconnection [Paschmann et al., 1979; Sonnerup et al., 1981; Phan et al., 2000; Öieroset et al., 2001; Vaivads et al., 2004; Phan et al., 2006] and viscous processes [Freeman et al., 1968; Lee et al., 1994; Hasegawa et al., 2004, 2006; Nykyri et al., 2006; Chaston et al., 2007] has confirmed earlier theoretical predictions and clarified the dominant role of reconnection in geomagnetic activity [Pulkkinen, 2007].

Whereas earlier studies focussed primarily on characterizing energy conversion mechanisms for steady state solar wind conditions, recent observations of solar wind-magnetosphere coupling have highlighted the impact of dynamically turbulent solar wind driving on magnetic reconnection [Russell and Elphic, 1978; Paschmann et al., 1982; Owen et al., 2001; Sonnerup et al., 2004; Nakamura et al., 2004; Louarn et al., 2004] and viscous transport [Nykyri et al., 2006; Chaston et al., 2007, 2008; Yao et al., 2011; Dougal et al., 2013]. Characterized by especially high Reynolds numbers (i.e., $R \sim 10^{10} – 10^{11}$, depending on the nature of the viscosity) [Borovsky and Gary, 2009], the solar wind is far from a laminar state and therefore cannot be statistically described in terms of a quasi-stationary steady state [Montgomery, 1987; Rostoker et al., 1987]. It is now established that statistical properties of the solar wind are dominated by large-amplitude fluctuations at small scales and present signatures of intermittency [March and Tu, 1994, 1997; Sorriso-Valvo et al., 1999; Alexandrova et al., 2008; Uritsky et al., 2011; Osman et al., 2012; Alexandrova et al., 2013]. Even though the possible influence of solar wind turbulence on geomagnetic activity has been long recognized...
A primary difficulty in answering the question of how the solar wind fluctuations impact geomagnetic activity resides in characterizing and quantifying energy conversion on viscous timescales ($\tau$) which are typically smaller than 1 h, but sometimes of the order of minutes. These timescales are relevant to processes such as Kelvin-Helmholtz waves [Nykyri and Otto, 2001; Nykyri et al., 2006], kinetic Alfvén waves [Johnson and Cheng, 1997, 2001] and magnetohydrodynamic (MHD) eddy viscosity [Borovsky and Funsten, 2003] which can produce significant plasma transport on the dayside, but also tailward of the terminator where the velocity shear is sufficiently strong for the Kelvin-Helmholtz instability to develop. For instance, it has been determined by Nykyri and Otto [2001] that reconnection via Kelvin-Helmholtz vortices can be triggered during northward IMF on timescales of about 70 Alfvén times $\tau_\alpha \sim L_0/V_\alpha \sim 6$ s, for an Alfvén speed $V_\alpha \sim 100$ km/s and a typical magnetopause thickness $L_0 \sim 600$ km. Therefore, taking into account the onset of the instability, plasma transport tailward of the terminator can be realized on timescales as short as $\tau \sim 70 \times \tau_\alpha \sim 7$ min. Setting aside the notorious difficulties associated with modeling a system composed of spatial scales ranging from electron Larmor radii to tens of Earth’s radii, characterization of small timescales is also beyond the reach of commonly used solar wind-magnetosphere coupling functions [Dungey, 1961; Burton et al., 1975; Kan and Lee, 1979; Akasofu, 1981; Vasyliunas et al., 1982; Newell et al., 2007]. Such functions assume an undisturbed and spatially homogeneous solar wind on scales of $L \sim 200R_E$ averaged over a timescale for $\tau \geq L/V \sim 1$ h for a radial component of the solar wind $V \sim 400$ km/s (see, e.g., Vasyliunas et al. [1982] for a more detailed discussion and Klimas et al., 1992, 1994 for solar wind-magnetosphere coupling models that do not rely on the homogeneous assumption).

From a statistical standpoint, one difficulty for characterizing possible geomagnetic responses to solar wind variability on short timescales (here understood as 1 min $< \tau < 1$ h), resides in the non-Gaussian probability distribution function (PDF) of geomagnetic indices [Consolini and De Michelis, 1998; Borovsky and Funsten, 2003; Hnat et al., 2005] and therefore in the nonstationarity of the geomagnetic activity [Vassiliadis et al., 1996]. Whereas the computation of the mean and variance for the representation of geomagnetic activity can be justified for long timescales, magnetospheric indices are not well predicted for shorter timescales [Vassiliadis et al., 1996; Li et al., 2007] and demonstrate a strong departure from a Gaussian distribution both for quiet and disturbed periods. This departure from Gaussianity often translates into an asymmetric probability distribution and/or fat tails [Consolini and De Michelis, 1998; Hnat et al., 2005; Consolini et al., 2013]. In a statistical study, Pulkkinen et al. [2006b] constructed a Langevin model to produce an analytical solution for the PDF of $AE$. While they managed to capture similar power spectrum and waiting distributions, their model did not provide a good fit on intermediate values of $AE$ and was limited to fluctuations between 3 and 0.07 mHz. Hence, it is unclear which properties of the PDFs, if any alone, are appropriate measures of geomagnetic activity. This is especially true of smaller timescales between 1 and 10 min, which can be associated, though not exclusively, with viscous processes. We note that pseudobreakups or flow bursts can also take place on similar timescales [Koskinen et al., 1993; Nakamura et al., 1994; Pulkkinen et al., 1998; Yang et al., 2010].

This paper addresses the problem of statistically quantifying the impact of solar wind fluctuations on timescales where a multitude of nonreconnection mechanisms can occur. One simple approach to depart from an analysis relying solely on the first two moments of the distribution function for non-Gaussian statistics, and still be able to quantify the impact of short timescale processes in the solar wind on the geomagnetic indices, simply consists of the inclusion of higher-order moments of the PDF of geomagnetic indices. By using higher-order moments of the PDF, without making any initial assumptions on the validity of the first- or second-order moments, we can provide a more complex and richer framework in quantifying the possible impact of the dynamical solar wind on the geomagnetic processes. This approach is similar in aim, and complementary, to that of Voros et al. [2002], Hnat et al. [2005], and Jankovićová et al. [2008], in that it focuses on statistical features of geomagnetic activity for various driving and solar wind conditions, but is different in the sense that it does not assume that statistical features in the magnetosphere arise from those in the solar wind. That is, non-Gaussian fluctuations in the solar wind are not necessarily the
source of non-Gaussian fluctuations in geomagnetic indices because nonlinearity precludes Gaussianity [Krommes, 2002]. Since plasma transport equations are inherently nonlinear (i.e., $\partial \Psi / \partial t \sim \Psi^2$ for a scalar field $\Psi$ that could represent the particle distribution $f(x,v,t)$ or a magnetic field component $B_i(x,t)$), even a Gaussian driving by the solar wind may result in a non-Gaussian response of geomagnetic activity.

In order to characterize the possible short timescale impact of solar wind fluctuations on geomagnetic activity, we require an index that can have a strong and direct response to short timescale variations in the solar wind. Unlike the $Dst$ index responding to magnetospheric currents arising from strong long-lasting solar wind driving, $AL$ and $AE$ indices fit this necessary requirement [Li et al., 2007] and can be considered as proxies of magnetospheric processes related to the occurrence of storms and substorms and allows us to monitor some of the relevant current systems, which are activated during magnetic storms and substorms. Both indices are commonly used as measures of magnetospheric activity. We hereafter choose $AL$ since it can be very responsive on small timescales. Timescales for decay of the $AL$ index are less than 1 h and decrease with the amplitude of $AL$. The index can easily have a large response to short timescale variations in the solar wind that barely affect other indices such as $Dst$. It has also been demonstrated that $AL$ is notoriously difficult to predict on small timescales [Li et al., 2007; Newell et al., 2007]. In Li et al. [2007], two models are presented to predict $AL$. Predictions are reasonable for scales above 1 h but poor on scales smaller than 1 h with linear correlation of 0.135. In Newell et al. [2007], $AL$ is shown to poorly correlate with every single solar wind driving function. In fact, the correlation for $AL$ and various correlation functions are the smallest of all geomagnetic indices. Whereas the results by Newell et al. [2007] are interpreted as evidence that magnetospheric dynamics is more central than solar wind driving for the determination of $AL$, it could also indicate that small timescale fluctuations in $AL$ do not correlate with driving functions defined for large scales.

In this report, our aim is to statistically quantify the impact of $B_z$ interplanetary magnetic field fluctuations on $AL$ during northward and southward IMF by using higher-order moments in the distribution of $AL$ as a proxy. We first proceed by separating our data set in terms of strongly northward and southward IMF since the statistical response of $AL$ is significantly different due to the dominance of magnetic reconnection for $B_z < 0$ [Pulkkinen, 2007; Tanskanen et al., 2002]. To ensure strongly northward and southward (remove other IMF orientations), we impose a criterion which only accepts intervals when the IMF $B_z$ is at least 75% of the IMF modulus. We should also point out that even though this separation of our database is limited in physical meaning (solar wind conditions under which the $z$ component of the IMF is 75% of the IMF modulus are rare, covering about 2 years of data out of 17), it allows us to rigorously differentiate between two statistically distinguishable regimes in $AL$. Once we clearly distinguish the statistical features of the distribution of $AL$ independently of the level of fluctuations in $B_z$, we repeat the analysis for various ranges of average $B_z$ spectral power in the ULF range. For both southward and northward IMF, we demonstrate that high-power fluctuations in $B_z$ systematically result in greater level of activity on timescales consistent with viscous processes. Even in the case of strongly northward IMF, we show that the tail of the distribution persists with increasing fluctuation levels.

The paper is structured as follows: in section 2 we describe the processed data set for the solar wind input and $AL$ index. In section 3, we first describe the different statistical response of $AL$ to strongly northward and southward IMF; we then quantify the impact of solar wind fluctuations on the distribution of $AL$ separately for strongly northward and southward IMF. In section 4, we discuss our results in the light of recent observational and numerical studies tackling similar questions. In section 5 we conclude by suggesting further extensions to the current approach to determine the role of a wide range of solar wind drivers on geomagnetic activity.

2. Methodology

The most efficient plasma transport at the magnetopause boundary occurs via magnetic reconnection which takes place predominantly during southward IMF ($B_z < 0$) when the shear angle (i.e., the angle between the magnetic field and the boundary normal) is large. As a result of this, geomagnetic activity during southward IMF and northward IMF are strikingly different in both magnitude and behavior. Plotted in Figure 1 are the quantities of $B_z$ (top), $AL$ (middle), and $|V|$ (bottom) taken from the OMNI database over an 18 h period starting from 16 April 2013 03:35 UT. This time interval demonstrates a case of prolonged northward IMF before quickly switching to a period of prolonged southward IMF. In addition, this interval represents typical solar wind conditions (i.e., $B_z \sim 2.5$ nT, $|V| \sim 400$ km/s) rather than an extreme event such as a magnetic cloud. The IMF is northward for the first 11 h of the interval, after which the IMF switches to southward for the remaining 7 h.
Figure 1. An example of an interval of prolonged northward IMF quickly followed by an interval of prolonged southward IMF. (top, middle, and bottom) $B_z$, $AL$, and $|V|$. The $AL$ index responds rapidly, on timescales of the order of viscous timescales [Bargatze et al., 1985]. It takes approximately 10–15 min before any notable change is observed in the $AL$, after which it changes from around $-25 \text{nT}$ to $-250 \text{nT}$ over a total time period of approximately 1 h. During northward IMF, the values are much lower at around $-25 \text{nT}$ and the variations are relatively smooth. During the southward IMF period, the values are an order of magnitude larger and exhibit significant oscillations on timescales ranging from 10 min to over 60 min. What becomes apparent here is that the $AL$ response consists of the superposition of the low-frequency components, but also pulsations on shorter timescales. As a result, to correctly characterize the $AL$ response, shorter timescales should also be included. Having said that, it is often difficult to distinguish processes on these viscous timescales (especially during southward IMF) since the response is dominated by magnetic reconnection. To quantify the response of the $AL$ indices during northward and southward IMF, we isolate periods of very strongly northward and southward IMF and also filter the data with respect to $B_z$ pulsations in the ULF frequency range. Since geomagnetic fluctuations occur in a frequency range between 1 Hz and 1 mHz (ULF) and the magnetosphere has been shown to act as a low-pass filter [Ilie et al., 2010a], we limit our study to corresponding timescales in the solar wind; i.e., we compute the average spectral power over this range. Later in the manuscript we filter values of ULF power, but this filtering is performed with respect to amplitude of the ULF waves and not frequency.

2.1. Data Sets
We exclusively apply data from the high resolution 1 min OMNI database. The OMNI database consists of measurements made by multiple spacecraft (IMP 8, Geotail, Wind, and ACE) upstream of the Earth which are then propagated/shifted to the location of the bow shock nose based on the nose location provided by the Farris and Russell [1994] bow shock model. For a more thorough description of the OMNI data production, we refer readers to the publication by King and Papitashvili [2005] and also the OMNI webpage at http://omniweb.gsfc.nasa.gov. It is also worth noting that all vector quantities expressed throughout this manuscript are in the Geocentric Solar Ecliptic (GSE) coordinate system. To measure the geomagnetic response from the solar wind input, we use the $AL$ index which provides an estimate of the maximum westward electrojet intensity using 12 magnetometer stations around the northern auroral region [Berthelier and Menvielle, 1993]. Outside of substorm intervals, $AL$ can be thought of as a measure of convection, while during isolated substorms, the largest deviations in the $H$ component of the ground magnetic field typically
originate from the substorm current wedge. Additionally, during storm time there is also a large contribution coming from tail and partial ring current. By nature, $AL$ is therefore highly asymmetric and peaks at low values corresponding to quiet time convection effects, whereas heavy tails are associated with substorm occurrences [Tanskanen et al., 2002; Newell et al., 2007].

2.2. Preliminary Processing of the OMNI Data Set

The present study focuses exclusively on the behavior of the $AL$ indices during northward and southward IMF intervals as a function of ULF $B_z$ spectral power. Therefore, first, we need to extract periods of northward and southward IMF from the complete OMNI data set. In practice, this is achieved by applying selection criteria to the solar wind data set to isolate northward and southward IMF intervals. We begin by performing sliding windowed averages of the OMNI data and then apply specific criteria to each window in order to extract subsets corresponding to different solar wind conditions. For estimates of $E_y = -(\vec{V} \times \vec{B})_y$ and $B_z$, we perform a 21 min center-weighted sliding average. The 21 min window length was chosen based on the following: (1) the propagation time from the magnetopause to the ionosphere is between 3 and 15 min, and (2) the time necessary to completely reconfigure the ionospheric convection in response to solar wind driving is between 10 and 25 min. These estimates have been theoretically derived [Coroniti and Kennel, 1973] and observationally tested [see, e.g., Goldstein et al., 2003 and references therein]. The 21 min averaging allows us to eliminate errors caused by transients, and assess the IMF orientation for an interval consistent with time delays for geomagnetic indices such as $AL$. Similarly to the solar wind parameters, we perform a 21 min windowed average of the $AL$ index but offset by 10 min so that the start of each $AL$ window corresponds to the end of each solar wind interval. Therefore, the initial response time for the $AL$ index for a given solar wind driver possesses a 10 min offset with respect to the solar wind measurement.

2.2.1. Northward and Southward IMF Selection Criteria

Although northward/southward IMF intervals can be identified based on the $B_z$ component alone, some of these intervals may inadvertently contain an array of other IMF orientations. To ensure our data set contains clear northward and southward IMF intervals, we weigh the $B_z$ component against the strength of the IMF vector. In practice, this is achieved by applying the following criterion to each 21 min window:

$$C_1 = \begin{cases} \text{northward}, & \text{if } B_z > 0.75 |B|, \\ \text{southward}, & \text{if } B_z < -0.75 |B|. \end{cases}$$  \hfill (1)

The criterion described by equation (1) removes all instances when the magnitude of $B_z$ is below 75% of the IMF modulus. In effect, this removes cases when the IMF is Parker spiral, ortho Parker spiral, and radial. The northward/southward orientation is then assigned according to the polarity of $B_z$. Ideally, the threshold would be 100%, meaning the IMF is completely comprised of the $B_z$ component and is truly northward or southward; in reality, the IMF $B_x$ and $B_y$ are always nonzero and a value of 100% is not feasible. The current value of 75% was chosen experimentally to provide a good trade-off between accuracy and data availability but does not affect our statistical results. To identify intervals of clear positive and negative $E_y$, we apply an additional criterion for the electric field orientation:

$$C_2 = \begin{cases} \text{unclear (northward)}, & \text{if } \bar{E}_y + \sigma > 0, \\ \text{unclear (southward)}, & \text{if } \bar{E}_y - \sigma < 0. \end{cases}$$  \hfill (2)

where $\sigma$ represents the standard deviation of $E_y$ computed over the 21 min interval. The inclusion of this extra criterion ensures that if $E_y$ varies between positive and negative values, the window is excluded. The reason for eliminating these cases is that it is meaningless to assign a northward or southward polarity to such intervals. Therefore, removing these data ensures that the driving conditions remain clearly defined.

2.2.2. Computation of the IMF $B_z$ Spectral Power

To investigate the dependancy of $AL$ on ULF $B_z$ pulsations, we compute the mean spectral power ($P_z$) of $B_z$ over the ULF range (2–12 min). We apply the discretized continuous wavelet transform [see Graps, 1995 and references therein] to estimate $P_z$ for scales between the ULF limits, i.e.,

$$P_z(t, a, b) = \left( \frac{1}{\sqrt{a}} \sum_{n=1}^{N} B_z(t) \psi \left( \frac{t - b}{a} \right) dt \right)^2$$  \hfill (3)

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where \(a\), \(b\), and \(N\) correspond to the wavelet scale parameter, translation (time shift) value, and data set length, respectively. The function \(\psi\) represents the Morlet mother wavelet where larger scales correspond to lower frequencies. The wavelet function is shifted and scaled over the \(B_z\) data set to obtain a data set of \(P_z\) for scales between 2 and 12 min. Wavelet scales can be related to frequencies by computing the Fourier transform of a particular Morlet function for any given scale \(a\) value. The final value of \(P_z\) adopted is the average over the ULF scales. Similar results could be obtained via the short-term Fourier transform, however this would require a fixed window length for the scales between 2 and 12 min. The wavelet transform is therefore better suited to this particular case since the Morlet wavelet function can be appropriately dilated for each scale, therefore providing a more optimal time-frequency resolution trade-off within the ULF limits. To account for the presence of occasional and irregular data gaps, we initially perform a linear interpolation over missing data to ensure a continuous data set. During these intervals, the wavelet transform returns zero power and does not introduce artificial values into our statistical dataset. To account for errors in the solar wind propagation, \(AL\) estimation, and to limit the effect from transient solar wind features, we introduce a 5 min sliding average to the \(P_z\) time series data. Only windows which satisfy 100% data coverage are accepted to the final statistical data set. The window length of 5 min was chosen as twice the lowest ULF timescale which was increased to 5 min to allow a symmetric window.

2.2.3. Filtering of Data Set With Respect To ULF \(B_z\) Amplitude

We also sort our data set according to the magnitude of \(P_z\) to determine its impact on \(AL\). A high-pass filter with a varying threshold is applied to the \(P_z\) data set to systematically remove lower values of \(P_z\), i.e.,

\[
P_z = P_z > L
\]

The variable \(L\) indicates the threshold of the high-pass filter such that all values of \(P_z\) below \(L\) are removed. We would like to reiterate here that the high-pass filter removes amplitudes and not frequency. The frequency of each \(P_z\) range remains fixed as the average computed over the ULF range. For each value of \(L\), we analyze the PDF of \(-AL\) corresponding to that specific range of \(P_z\). Since 98% of the data set is distributed between 0 and 3 nT²/Hz, we bound our investigation such that the maximum value of \(L\) does not exceed 3 nT²/Hz. We adopt a high-pass filter approach as opposed to a sliding window such that the effect from higher \(P_z\) values remain. The rationale behind this approach is to simultaneously determine the effect from a given range of \(P_z\) and to reveal the relative dominant ranges of \(P_z\). For example, what is the behavior of \(AL\) as lower \(P_z\) amplitudes are removed.

2.2.4. Final Solar Wind Statistical Data Set

Figure 2 shows the distribution of the main parameters used for this study after the aforementioned criteria were applied. Figures 2a–2e correspond to \(B_y\), \(E_y\), \(-AL\), \(P_z\), \(|V|\) and yearly data frequency, respectively. The central columns of data missing from \(B_y\) and \(E_y\) reflect the criteria described by equations (1) and (2) in which other IMF periods have been removed. Although data still remains when \(B_y\) is weak (\(|B_y| < 2\) nT), the magnitude of \(B_y\) and \(B_z\) would be comparatively much smaller. The asymmetric distribution of \(-AL\) possesses a low distinctive peak corresponding to convection during the absence of magnetic reconnection. As expected, the distribution possess a strong tail which is driven primarily by substorm-induced subsolar magnetic reconnection [Tanskanen et al., 2002]. The distribution of \(P_z\) is mostly estimated around 0.1 nT²/Hz with a tail extending past 3 nT²/Hz (see Figure 2d). In fact, we calculate that almost 98% of the data lies in the range of 0 to 3 nT²/Hz, and thus, we do not apply data outside of this range. The distribution of solar wind velocity has a mean around 400 km/s reflecting typical solar wind conditions and a strong tail exceeding 800 km/s due to faster solar wind streams and interplanetary coronal mass ejections.

2.3. Delayed Response of \(AL\) Index

In order to further analyze the delayed response of the \(AL\) index for a given solar wind driver, we introduce a time shift to identify the time delay that produces the maximum \(AL\) response to a given solar wind driving. We do this by introducing a delay increment \(\Delta t\):

\[
AL(\tau) = AL(t_0 + \Delta t)
\]

where \(t_0 = 10\) min is the time of the initial measurement. We perform this delay analysis for both positive (causal) and negative (advanced delay) values of \(\tau\) to investigate (1) optimal delay time and (2) the memory of the system. For each \(\tau\), we calculate the statistical properties of the \(AL\) index.
A significant property of the $AL$ index is that its PDF for a given set of conditions is far from being Gaussian. The PDF has a high peak located around $-15$ nT and a long tail extending to values exceeding $-3000$ nT. Since the mean value is misleading for non-Gaussian distributions, another quantity should be used to indicate where the bulk of the distribution lies. Therefore, instead of using the mean, we record the peak value of the distribution for each value of $\tau$. The peak value is less sensitive to the variation of the distribution tails and therefore indicates a shift of the core of the distribution. The moment of the distribution are computed according to

$$m_j = \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^j,$$  \hspace{1cm} (6)

where for instance the standard deviation is computed as $\sigma = \sqrt{m_2}$. To obtain a measure of the asymmetry of the probability distribution, we compute the skewness defined as

$$S = \frac{m_3}{\sigma^3},$$ \hspace{1cm} (7)

In order to complete the characterization of the non-Gaussian PDF in $AL$, we also compute the kurtosis defined as

$$K = \frac{m_4}{\sigma^4}.$$ \hspace{1cm} (8)

During southward IMF, the standard deviation varies only slightly from the typical value (150 nT), which makes the kurtosis $K$ an appropriate parameter to characterize the weight in the tails. However, during these intervals, the low convection $AL$ values ($<150$ nT) are overcome by reconnection based driving which shifts the core of the distribution to larger $-AL$ values. As the distribution core is translated to larger values, this is reflected by an increase in the distribution peak value. Therefore, we track the location of the probability distribution

Figure 2. Distributions of the solar wind parameters for our data sets of northward and southward IMF. The removal of the central peak of $B_z$ (see equation (1)) and $E_y$ (see equation (2)) is a direct result of the strict criteria we applied to ensure strongly northward and southward IMF orientations. (f) The distribution of data points over the 18 year interval of data we selected.
Figure 3. The AL response for southward IMF as a function of time delay $\tau$. Figures 3a–3c denote, respectively, the peak of the probability distribution function, the kurtosis normalized by the average kurtosis $<K> \sim 16$, and the skewness of the PDF, as a function of time delay $\tau$. Figures 3d–3h show the evolution of the PDF for $\tau = (0, 20, 40, 60, 80)$ min. The red line indicates the position of the peak for various values of $\tau$. Hence, it is clear that the driving for southward IMF affect higher-order moments of the PDF in AL on timescales $\tau \leq 60$ min.

We can summarize the data processing steps as follows:

1. Linear interpolation of the IMF $B_z$ time series.
2. Computation of ULF $B_z$ spectral power $P_z$ (equation (3)).
3. Sliding window averages performed: 21 min ($B_z$, $E_y$, and AL) and 5 min ($P_z$).
4. Application of data selection criteria (equations (1) and (2)).
5. Estimation of the AL time delay for each solar wind subset using the $-AL$ PDF statistical properties and the higher-order moments (see equations (7), (6), and (8)) of the AL PDF.
6. The response of \( AL \) due to northward and southward IMF is investigated based on the PDF computed for each IMF subset (using each delay value).

7. The dependency of \( AL \) on the magnitude of \( P_z \) is determined based on computing the properties of the \(-AL\) PDF for the high-pass filtered subset (see section 2.2.3 and equation (4)).

**3. Results**

**3.1. Impact of \( B_z \) on Distribution of \( AL \)**

Presented in Figure 3 are the peak location (a), kurtosis (b), and skewness (c) of the probability distribution function of \( AL \) as a function of the time delay \( (\tau) \) under southward IMF conditions as defined above. The red curve denotes \( \tau < 0 \), and the black corresponds to \( \tau > 0 \). Figure 3 presents the statistical response of \( AL \) for southward IMF. The figure showing the kurtosis of the PDF is normalized by the average kurtosis \( < K > \sim 16 \). We also notice from Figure 3a that the typical peak location lies at \(< 30 \) nT. However, at approximately \( \tau = 42 \) min, the peak undergoes a dramatic shift to a value of \( AL \sim 194 \) nT, indicating substantial driving. Associated with the shift of the peak, the skewness reduces to a value of \( S = 0.94 \) at \( \tau = 14 \) min. The kurtosis is also reduced, dipping at a value of \( K / < K > = 0.25 \), that is, the kurtosis \( K \sim 4 \), at \( \tau = 10 \). The response in \( AL \) for southward IMF is thus characterized by a shift in the peak of the PDF to \( \sim 200 \) nT and a reduction of the asymmetry and weight of the tails. These effects can be noticed by observing the distribution function for different time delays as well. Figure 3a–3h show the evolution of the PDF for \( \tau = (0, 20, 40, 60, 80) \) minutes. The red vertical line indicates the position of the peak for various values of \( \tau \). Hence, it is clear that the driving for southward IMF affects higher-order moments of the PDF in \( AL \) on timescales \( \tau \leq 60 \) min. We note that the choice to use the peak value of the distribution, instead of the mean of the distribution, provides a much more coherent and clearer response as a function of time delay \( \tau \) for southward IMF. This simple exercise highlights that by averaging the value of \( AL \) over 60 min, significant enhancements of \( AL \) values in the tail are potentially removed.

Figure 4 presents the statistical measures of the \( AL \) index for time delay \( \tau \) during northward IMF. Figure 4 therefore presents the statistical response of \( AL \) for northward IMF. Figure 4a shows the peak of the probability distribution function in \( AL \), Figure 4b the skewness, and Figure 4c the standard deviation. Unlike the southward IMF case, the standard deviation fluctuates to 2 orders of magnitude under northward IMF conditions. Consequently, the kurtosis for different \( \tau \) values do not give an adequate description of the broadening of the distribution tails, and we avoid relying on it for northward IMF conditions. During northward IMF, the peak remains relatively unchanged, indicating no significant shift in the bulk of the \( AL \) values. The skewness, unlike for southward IMF driving, significantly decreases to \( S \sim -6.6 \) at \( \tau = 76 \) min, and the weight around the peak of the distribution is substantially reduced. In Figures 4d and 4e, the distributions are shown for delays of 20 and 120 min, respectively. We notice that even though the median, denoted by the red line and the peak are barely affected, the standard deviations are reduced by more than \( 100 \) nT.

In order to compare the difference between northward and southward driving on \( AL \), it is useful to plot the PDF in \(-AL\) for the optimal time delay. In Figure 5, the PDF of \(-AL\) for northward (a) and southward IMF (b) are represented for their specific optimal time delay. The red curves in both figures show the typical PDF of \(-AL\) for data collected during all solar wind conditions. For northward IMF the PDF of the peak remains unchanged but the PDF becomes narrower, resulting in a smaller standard deviation. For southward IMF, the PDF broadens and the peak is shifted toward \( AL \sim -200 \) nT. We also notice that for southward IMF the kurtosis \( K \) and skewness \( S \) have reduced weight in the tails and asymmetry \((K \rightarrow 3, S \rightarrow -1)\). Hence, the driving of \( AL \) for southward IMF results in a PDF whose characteristics are in sharp contrast to the mean PDF, and the PDF resulting from prolonged northward IMF, where the core shrinks and the skewness increases in magnitude.

**3.2. Effect of IMF Fluctuations on \( AL \)**

The distinct characterization of \( AL \) for northward and southward IMF and the above methodology can also be used to infer the impact of solar wind fluctuations on geomagnetic activity under these solar wind conditions. As previously pointed out by Borovsky and Funsten [2003], if there is enhanced driving as a result of increasing fluctuation power, there should be a correlation between the solar wind turbulence amplitude and the geomagnetic indices. Using the above argument, modifications in the PDF of \( AL \) that would indicate greater driving would translate for southward IMF as a larger peak and for northward IMF as a narrowing of the PDF and enhancement in the tail. In order to test these hypotheses, we characterize the effect of solar wind fluctuations in terms of high-pass filtered power of the IMF \( B_z \). For southward IMF, the response can be...
Figure 4. Evolution of $AL$ distribution for northward IMF as a function of time delay $\tau$. Figure 4a denotes the peak of the probability distribution function in $AL$, Figure 4b the skewness, and Figure 4c the standard deviation. For northward IMF, the peak in the PDF does not change, the asymmetry significantly increases ($S \rightarrow -7$), and the weight in the tail and the core of the distribution are significantly reduced.

measured by the maximum peak in $AL$ (see Figure 3a), and for northward IMF, the response is taken to be the minimum value of the $AL$ standard deviation (see Figure 4c). The results are summarized in Figure 6 for southward IMF and Figure 7 for northward IMF.

In Figure 6e, we plotted the percentage of the distribution less than 100 nT (black curve) and more than 500 nT (orange curve) as a function of high-pass filtered power denoted as $P_z$. This figure demonstrates that as the power in $B_z$ increases, density for low values of $AL < 100$ nT decreases by $\sim 10\%$, whereas density for high $AL$ values ($>500$ nT) increases by $15\%$. This effect can also be distinguished in the distributions shown in Figures 6a–6d where the distribution for high-pass filtered powers are plotted in black and the average distribution in red. We note that even though little difference is observed between the distributions for a high-pass filter of $P_z > 0.1$, for $P_z > 2.0$, the tail is comparatively enhanced and the peak is shifted to around $-AL$ values of 500 nT. We also observe that the peak increases monotonically from 190 nT for all conditions up to 340 nT in excess of 2 nT$^2$/min. We therefore note that for southward IMF, solar wind fluctuations in $B_z$ are observed to affect both the peak values of the distributions and the tail.

For northward IMF, Figures 7a–7f quantify the effect of solar wind fluctuations on the distribution of $-AL$. The distributions in Figures 7a–7d show that unlike for southward IMF, the peak of the distribution in $-AL$ is not affected by the change in $P_z$. Instead, we observe that the tail is enhanced for high $P_z$, similarly to what is observed for southward IMF. The abscissa coordinate in Figures 7e and 7f are the threshold value $L$ for $P_z$. Figure 7e shows that the weight in the distribution increases for large $-AL$ values ($>100$ nT). Figure 7f shows
Figure 5. Distribution function (PDF) of $-AL$ for (a) northward and (b) southward IMF for their optimal $\tau$. The red curves in both figures show the PDF of $-AL$ for all solar wind conditions. For northward IMF, the PDF of the peak remains unchanged but the PDF becomes narrower, resulting in a smaller standard deviation. For southward IMF, the PDF broadens, and the peak is shifted toward $AL \sim 200$ nT.

that the standard deviation also grows for increasing power in fluctuations. In both Figures 7e and 7f, we plotted the weight for the optimal time delay $\tau = 20$ min and a very large time delay $\tau = 10,000$. The black lines denote the optimal delay. The orange curves in Figures 7e and 7f are for a very large time delay of $\tau = 10,000$ min where the fluctuations should not have an impact on the distributions. In both figures, we observe that the curve for the optimal time delay increases as a function of increasing fluctuation powers (i.e., the tail in $AL$ is enhanced by about 15%), whereas the curves for very large time delay remain relatively flat.

Figures 6 and 7 therefore demonstrate that a higher level of solar wind magnetic fluctuations lead to stronger driving for southward IMF and reduce the narrowing of the $AL$ distribution for northward IMF. Even if the effect of fluctuations on $AL$ for northward and southward IMF is different, the changes in the statistical properties

Figure 6. (a–e) The effect of solar wind fluctuations on the distribution of $AL$, in terms of high-pass filtered power and for southward IMF. The distributions in Figures 6a–6d show that the peak of the distribution in $AL$ increases as the high-pass filter value is increased. The abscissa coordinate on Figure 6e is the threshold value for the high-pass filtered fluctuations. Figure 6e shows that the weight in the distribution reduces for $-AL < 100$ nT, whereas it increases for $-AL > 500$ nT as $P_z$ increases. This figure indicates that solar wind magnetic fluctuations result in enhanced geomagnetic activity for southward IMF.
Figure 7. (a–f) The effect of solar wind fluctuations on the distribution of $AL$, in terms of high-pass filtered power and for northward IMF. The distributions in Figures 7a–7d show that the peak of the distribution of $AL$ is not affected by the change in $P_z$. Instead, we observe that the tail is enhanced for $P_z$. The abscissa coordinate in Figures 7e and 7f is the threshold value for $P_z$. Figure 7e shows that the weight in the distribution increases for large $-AL > 100$ nT. Figure 7f shows that the standard deviation also grows for increasing power in fluctuations. These figures indicate that solar wind magnetic fluctuations result in enhanced geomagnetic activity for northward IMF.

of $AL$ are indicative of energy and momentum deposition into the magnetospheric current system. Stronger solar wind fluctuations translate into enhanced geomagnetic activity.

4. Discussion

We have characterized geomagnetic activity by using the probability distribution/rate of occurrence of $AL$ and associated higher-order moments. Our approach provides a framework for situations where the mean and median are either poorly defined (e.g., due to dual or multiple peaks) or are inappropriate indicators of the activity (e.g., due to strong departure from Gaussian distribution resulting in nonzero skewness and kurtosis $\neq 3$) [Sivia, 2006]. In the case of the $AL$ index, the PDF is not Gaussian, and the dynamics for northward and southward IMF have different statistical properties. We would like to stress that the bimodal response of $AL$ for strongly northward and southward IMF is not a new result and can be understood by the fact that outside of substorm intervals, $AL$ can be thought of as a measure of convection, with the consequence of a reduction of the weight in the tail. However, our analysis clearly demonstrates the importance of departing from analyses relying solely on the first two moments of the PDF. Our characterization of the response in $AL$ through the higher-order moments proves particularly useful for timescales of the order of 40 min or less, when the mean and the median fail to quantify the change in the PDF.

By characterizing the distribution of $AL$ for strongly southward and northward IMF, we have demonstrated that larger amplitude of fluctuations in the solar wind lead to nontrivial modifications of the PDF. Our results compare favorably with previous observational [Borovsky and Funsten, 2003; D’Amicis et al., 2007; Jankovičová et al., 2008] and numerical [McGregor et al., 2014] studies, indicating that IMF fluctuations can enhance the magnetospheric activity.

By computing the correlation between the amplitude of MHD turbulence in the solar wind and the value of the geomagnetic activity indices, Borovsky and Funsten [2003] argued that solar wind/magnetosphere coupling is enhanced as a result of MHD fluctuations. By analyzing the effect for both northward and southward IMF (while making sure that the fluctuations do not reverse the IMF), Borovsky and Funsten [2003] conclude
that viscous interactions, are responsible for the enhancement of geomagnetic activity. Whereas Borovsky and Funsten [2003] conduct their analysis for hourly averages, our study demonstrates that viscous interactions might also be present on much shorter timescales.

Using $AE$ as a measure of geomagnetic activity, D'Amicis et al. [2007] argued that Alfvénic fluctuations are geoeffective at solar minimum, whereas at solar maximum, magnetic structures play a role. In order to reach this conclusion, D'Amicis et al. [2007] use a different methodology to ours. Most notably, they took the mean value of $AE$ over 4 min intervals and do not differentiate between southward and northward IMF. However, the study by D'Amicis et al. [2007] has the advantage of differentiating between solar minimum and maximum, as well as differentiating between Alfvén fluctuations and magnetic structures. In our study, as well as that of Borovsky and Funsten [2003], we solely consider the amplitude of solar wind magnetic fluctuations as hypothetical indicator of geo-effectivity. Future work could therefore reproduce our methodology and include a criterion to differentiate between magnetic structures and Alfvén waves.

In the observational study of Jankovičová et al. [2008], the authors argue that non-Gaussian fluctuations in the solar wind could influence geomagnetic activity. Using $SYM-H$ as a measure of geomagnetic activity, they argued that the kurtosis of solar wind magnetic fluctuations appeared to be a geoeffective parameter and concluded that intermittency in the solar wind can influence the efficiency of the solar wind. While direct comparison of our results with that of Jankovičová et al. [2008] is difficult, it is nonetheless possible to infer that high kurtosis translates into large fluctuation amplitudes, our results and those of Jankovičová et al. [2008] are consistent. However, we would like to stress that contrary to the work of Jankovičová et al. [2008], we do not assume that non-Gaussian solar wind properties are the cause for non-Gaussian properties in the geomagnetic activity. That is, non-Gaussian fluctuations in the solar wind are not necessarily the source of non-Gaussian fluctuations in geomagnetic indices because nonlinearity precludes Gaussianity [Krommes, 2002]. Since plasma transport equations are inherently nonlinear (i.e., $\partial \Psi / \partial t \sim \Psi^2$ for a scalar field $\Psi$ that could represent the particle distribution $f(x, v, t)$ or the magnetic field $B(x, t)$), even a Gaussian driving by the solar wind should result in a non-Gaussian response of geomagnetic activity. Our results are also independent of any assumption of intermittency in the solar wind and simply rely on the presence of large-amplitude fluctuations in $B_z$ as a means to enhancing geomagnetic activity.

Numerical evidence of the impact of fluctuations on viscous interactions was also evidenced by recent numerical study of McGregor et al. [2014] using the Lyon-Fedder-Mobarry code to simulate the Earth’s magnetosphere driven by southward IMF conditions with and without synthetic Alfvénic fluctuations. For runs where Alfvénic fluctuations are present, they report on a strong enhancement of the dayside magnetospheric ULF wave power along the flanks. These fluctuations may penetrate deep into the magnetosphere to reach the radiation belt zone, where they play an important role in electron energization and transport. While the simulation results do not provide a direct comparison during northward IMF conditions, they confirm the link between enhanced fluctuations and increased viscous interaction at the magnetopause.

Our results also provide a new explanation as to why prediction models using solar wind mean values fail to reproduce the dynamics of $AL$ on timescales shorter than 1 h [Li et al., 2007, and references therein]. The evolution of the PDF of $AL$ on small timescales is not captured by the mean or by the integrated values, especially during northward IMF when the skewness increases by a factor of 2. Additionally, it takes longer than 1 h for the third and fourth moment of the PDF of $AL$ to recover from their initial state. This last point is apparent in Figures 3 and 4, where the skewness and kurtosis for southward IMF and the fourth moment for northward IMF are found to reach their mean values on timescales greater than 3 h. Consequently, prediction studies aimed at reproducing variations on timescales less than 1 h may have to consider the PDF of the geomagnetic indices.

Our results, combined with those of Borovsky and Funsten [2003]; Jankovičová et al. [2008]; D'Amicis et al. [2007] and McGregor et al. [2014], form a compelling set of evidence that enhanced upstream fluctuations result in greater energy and momentum transport from the solar wind into the magnetosphere-ionosphere system.

**5. Conclusion**

Using more than 17 years of OMNI data and robust criteria to differentiate between IMF orientations, we have used the probability distribution function of the $AL$ index to characterize the impact of northward and southward IMF driving on geomagnetic activity for timescales ranging from several minutes to several hours.
For northward IMF, the PDF of AL is characterized by a decrease of the standard deviation and vanishing tails, i.e., the distribution is narrowed down. For southward IMF, the PDF of AL is characterized by a decrease of the skewness, a shift of its peak from $-30$ nT to $-200$ nT, and a broadening of the core. Whereas it is well known that the different energy-momentum entry processes lead to different magnetospheric states during prolonged southward and northward driving conditions [Akasofu, 1981; Baker et al., 1996], our study provides a framework to characterize short timescale dynamics, taking place on the order of minutes and resulting from either viscous processes, enhanced magnetospheric convection, and/or pseudobreakups [Koskinen et al., 1993; Nakamura et al., 1994; Pulkkinen et al., 1998; Yang et al., 2010].

In order to demonstrate the benefits of using the full PDF to quantify driving of AL, we have quantified the impact of solar wind magnetic fluctuations for northward and southward IMF. We show that IMF fluctuations enhance the driving by shifting the peak of the PDF by $150$ nT during southward IMF and during northward IMF reduce the narrowing of the PDF by a factor of 2. Our results, combined with the observational results of Borovsky and Funsten [2003], D’Amico et al. [2007]; Jankovičová et al. [2008] and with the numerical study of McGregor et al. [2014], provide quantitative evidence of the role solar wind fluctuations have in enhancing viscous interaction and/or magnetospheric convection on timescales $\tau \ll 1$ h.

While the present study focuses on the impact during strongly northward and southward IMF, similar methodology can easily be extended to a variety of IMF orientations (e.g., Parker spiral or radial) and different solar wind driver functions (e.g., $E_x$ or $E_y$) and geomagnetic indices. Future studies will (1) expand the analysis by characterizing the short timescale statistical properties of other well-known geomagnetic indices and (2) incorporate statistical mapping tools of the magnetosheath [Dimmock and Nykyri, 2013; Dimmock et al., 2014] to determine the contribution of viscous processes [Axford and Hines, 1961] such as Kelvin-Helmholtz instabilities [Nykyri and Otto, 2001; Nykyri et al., 2006] and kinetic Alfvén waves [Johnson and Cheng, 1997, 2001] in the plasma transport at the magnetopause.

References


