Effects of magnetic clouds on the occurrence of geomagnetic storms: The first 4 years of Wind

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[1] We investigate geomagnetic activity associated with magnetic clouds as well as some aspects of the clouds' magnetic field structure (e.g., magnetic field distributions of the clouds). Thirty-four magnetic cloud events observed by Wind over the years 1995–1998 are investigated in this study. Magnetic clouds are a principal source of strong, long-lasting, interplanetary, negative B_z fields (in solar magnetospheric coordinates) and hence are a major source of geomagnetic activity (*Dst* < −50 nT). The region just upstream of a cloud may be a significant source of southward fields instead of, or as well as, the cloud itself. We call this upstream region a "sheath" if it is bounded by a shock (or a pressure pulse) and the cloud. This study helps to identify the major sources (regions of southward B_z following shock passages or within the magnetic clouds) that are most dominant in the generation of geomagnetic storms. It is found that a geomagnetic storm can be induced by (1) a sheath, (2) the leading (i.e., front part) region of a cloud, (3) the trailing part of a cloud, and (4) both sheath and cloud regions. (Because of this complexity a storm with a multistep main phase can occur.) The related occurrence percentages of storms were 17.6% (six events), 44.1% (15 events), 5.9% (two events), and 20.6% (seven events), and the averaged storm intensities (minimum *Dst*) were −60, −85, −92, and −58 nT, respectively. For the remaining four events (11.8%), there were no storms. The occurrence timing of storm intensity is highly correlated with the occurrence timing of minimum B_z (maximum *VBs* or ϵ) for a magnetic cloud with the field rotating from southward to northward. *INDEX TERMS:* 2788 Magnetospheric Physics: Storms and substorms; 2111 Interplanetary Physics: Ejecta, driver gases, and magnetic clouds; 2134 Interplanetary Physics: Interplanetary magnetic fields; 2139 Interplanetary Physics: Interplanetary shocks; 2164 Interplanetary Physics: Solar wind plasma; *KEYWORDS:* magnetic cloud, geomagnetic storm, two-step storm, interplanetary magnetic field, shock, solar wind

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1. Introduction

[2] Changes in the interplanetary magnetic field (IMF) are well known to be important in regulating geomagnetic activity. In particular, the variation of the north-south component of the IMF (B_z), when rendered in the geocentric solar-magnetospheric (GSM) coordinate system, plays a crucial role in determining the amount of solar wind energy that is transferred to the magnetosphere [*Arnoldy*, 1971; *Tsurutani and Meng*, 1972; *Russell and McPherron*, 1981; *Akasofu*, 1981; *Akasofu et al.*, 1985; *Farrugia et al.*, 1993]. This paper concentrates only on strong geomagnetic activity, geomagnetic storms.

[3] Geomagnetic storms can be categorized, according to *Gonzalez et al.* [1994], in terms of their intensity by *Dst* as follows: (1) great (or intense) storms, minimum *Dst* of −100 nT or less; (2) moderate storms, minimum *Dst* falls between −50 nT and −100 nT; and (3) weak storms, minimum *Dst* falls between −30 nT and −50 nT. As *Tsurutani and Gonzalez* [1997] point out, magnetic storms can be produced by a variety of IMF structures, one type of which is the large (~1 day) flux rope structure and others are sheath-like draped fields in front of the flux rope, especially if it drives a shock wave. Often these large interplanetary flux ropes are magnetic clouds [*Burlaga et al.*, 1981; *Lepping and Berdichevsky*, 2000]. The intensity and onset time of storm activity have been related to the polarity of a magnetic cloud's B_z component [*Wilson*, 1990]. We concentrate here on the relationship between magnetic cloud "complexes" (i.e., the clouds and their upstream sheaths) and related magnetic storms during the early Wind era.

[4] A magnetic cloud is defined as a region of high magnetic field strength, low proton temperature, low proton beta, and smoothly changing (rotating) magnetic field [*Burlaga et al.*, 1981]. We expect a magnetic cloud to be geoeffective (i.e., *Dst* < −30 nT), because of the likelihood of a large long-lasting southward field within or in front of the cloud. Plasma beta is very low in magnetic clouds and, hence, clouds are magnetic field dominated. The average

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size of the cloud's diameter is approximately 0.2 AU at 1 AU, and they are typically 27 hours in duration [*Lepping and Berdichevsky*, 2000]. A cloud is usually expanding as it moves outward from the Sun, as seen at 1 AU in its speed profile, i.e., from high to low speed [*Osherovich et al.*, 1993; *Burlaga et al.*, 1981; *Farrugia et al.*, 1992; *Lepping et al.*, 2001].

[5] Magnetic clouds are often preceded by upstream sheaths in which the plasma is usually hot and dense and the magnetic field is extremely turbulent [*Tsurutani et al.*, 1988; *Tsurutani and Gonzalez*, 1997]. The front "boundary" of the sheath may be a shock, a shock-like structure, a pressure pulse or a sharp rise in density, temperature, or velocity (hereafter we will use the term "sheath" for any one of these types of upstream increases). For example, Figure 1a shows the magnetic-cloud complex for the 10 January 1997 event, which displays the key features of such events: shock, sheath and driver, the magnetic cloud itself, which was reported on in many scientific articles [*Burlaga et al.*, 1998; *Tsurutani et al.*, 1998]. It has been reported that the magnetic clouds observed at 1 AU are not always preceded by a shock [*Klein and Burlaga*, 1982; *Lepping et al.*, 2001]. In this study, approximately 1/4 of observed clouds have no upstream pressure pulse/shock, but all have a density increase. Therefore we use the sharp rise in density as the front boundary of the sheath if there was no upstream shock.

[6] Many coupling functions for solar wind-magnetosphere interaction studies have been widely used (e.g., B_z, vB_z, vB_T, $vB_T \sin^2(\psi/2)$, $\epsilon = vL_o B^2 \sin^4(\psi/2)$, $(\rho v^2)^{1/2} vB_z$, etc.) to ascertain the mechanism for magnetospheric energization for magnetic storms [e.g., *Gonzalez et al.*, 1989, and references therein, 1994]. *Burton et al.* [1975] presented a formula for predicting the *Dst* index from knowledge of the velocity and density of the solar wind and the north-south component of the interplanetary magnetic field in GSM coordinates. This formula was recently improved by *Fenrich and Luhmann* [1998], who studied three magnetic cloud-associated geomagnetic storms. They also studied 29 magnetic clouds and found that a density enhancement is common (44% or 13 out of 29 events) in a cloud's trailing region, and 64% of those 13 clouds showed an increase in magnetic field strength at the same time. This enhancement, as they interpret, is caused by a cloud's rear compression due to the impact of a fast stream, which tends also to strengthen the field's magnitude in the latter region. Hence an N-S polarity magnetic cloud (in which the magnetic field within the cloud rotates from northward to southward) followed by a strong, high-speed stream may be considered a condition with high potential for "geoeffectiveness." Studies of magnetic clouds covering the active and quiet parts of the solar cycle show that the field is compressed significantly more in the cloud's leading region than in its trailing region, apparently due to the cloud's slightly greater speed than the upstream plasma's speed [*Lepping and Berdichevsky*, 2000]. *Lepping et al.* [2001] discuss this point with respect to clouds as drivers of upstream shocks for the quiet period using Wind data only. *Lepping and Berdichevsky* [2000] also showed the likelihood of increased density in the trailing part of about 1/2 of Wind magnetic clouds, covering the years 1995–1998 (quiet part of solar cycle), and they interpret it as mainly due to solar birthplace conditions. It is probably also due to some rear compression, as *Fenrich and Luhmann* [1998] claim, but this was shown to be a minor contribution. Some Wind clouds have very significant density enhancement in their latter regions without suffering any rear impact by a solar wind stream, disallowing compression as the explanation for the density enhancement or for any IMF magnitude increase. *Fenrich and Luhmann* [1998] did not specify what spacecraft observed their 29 examined clouds nor from which solar epoch (i.e., active or quiet) the events occurred.

[7] *Farrugia et al.* [1998] studied three good S-N polarity Wind magnetic clouds (where the magnetic field rotates from southward to northward) during 1995–1997, and showed profound differences in magnetospheric responses elicited by the clouds. These were interpreted as due to the amplitude, duration, and rapidity of change of the cloud-associated interplanetary parameters. It has been shown that the most negative *Dst* value usually occurs within 12 hours of cloud onset (meaning the passage of its front boundary) at Earth for S-N clouds, whereas it is delayed until after 12 hours from cloud onset for N-S clouds [*Wilson*, 1990], consistent with the typical magnetic cloud duration of 27 hours and with the fact that most cloud structures are not severely inclined with respect to the ecliptic plane [*Lepping and Berdichevsky*, 2000]. These studies explored the importance of magnetic clouds associated with geomagnetic storms.

[8] Recently, relationships between storm intensity (minimum *Dst* during a storm) and southward interplanetary magnetic field (B_z) strength, in ejecta or sheath regions, for events associated with front-side halo CMEs were studied by [*Cane et al.*, 2000]. They found that (1) the maximum southward magnetic field (B_z) in either the ejecta or the adjacent disturbed solar wind correlates well with *Dst* (correlation coefficient (CC) = −0.74) and (2) the geomagnetic storm intensity is poorly correlated with the transit time, i.e., with average transit speeds. Since most magnetic clouds contain a long-lasting, strong southward magnetic field structure, magnetic clouds often provide enough energy to power up geomagnetic storms. In the present paper, we investigate 34 published magnetic cloud events which were observed by Wind over the years of 1995–1998 [*Lepping et al.*, 2001]; the start and end times of these events are given in the Wind/MFI Website (http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_pub1.html). The Wind magnetic field and plasma investigations are described by *Lepping et al.* [1995] and *Ogilvie et al.* [1995], respectively.

[9] In the present paper, in order to understand solar wind–magnetosphere coupling mechanisms and to model the intensity of the cloud-associated geomagnetic storms (measured by the minimum value of *Dst*), several solar wind parameters (e.g., B_z, VB_s, and $\epsilon = vL_o{}^2B^2 \sin^4(\psi/2)$) are investigated. The correlations between storm intensity and the different solar wind parameters, including various timing delays, will also be presented.

2. Data Analysis and Statistical Results

[10] A magnetic cloud is a region in the solar wind having enhanced magnetic field strength, a smooth change in field direction as observed by a spacecraft passing through the

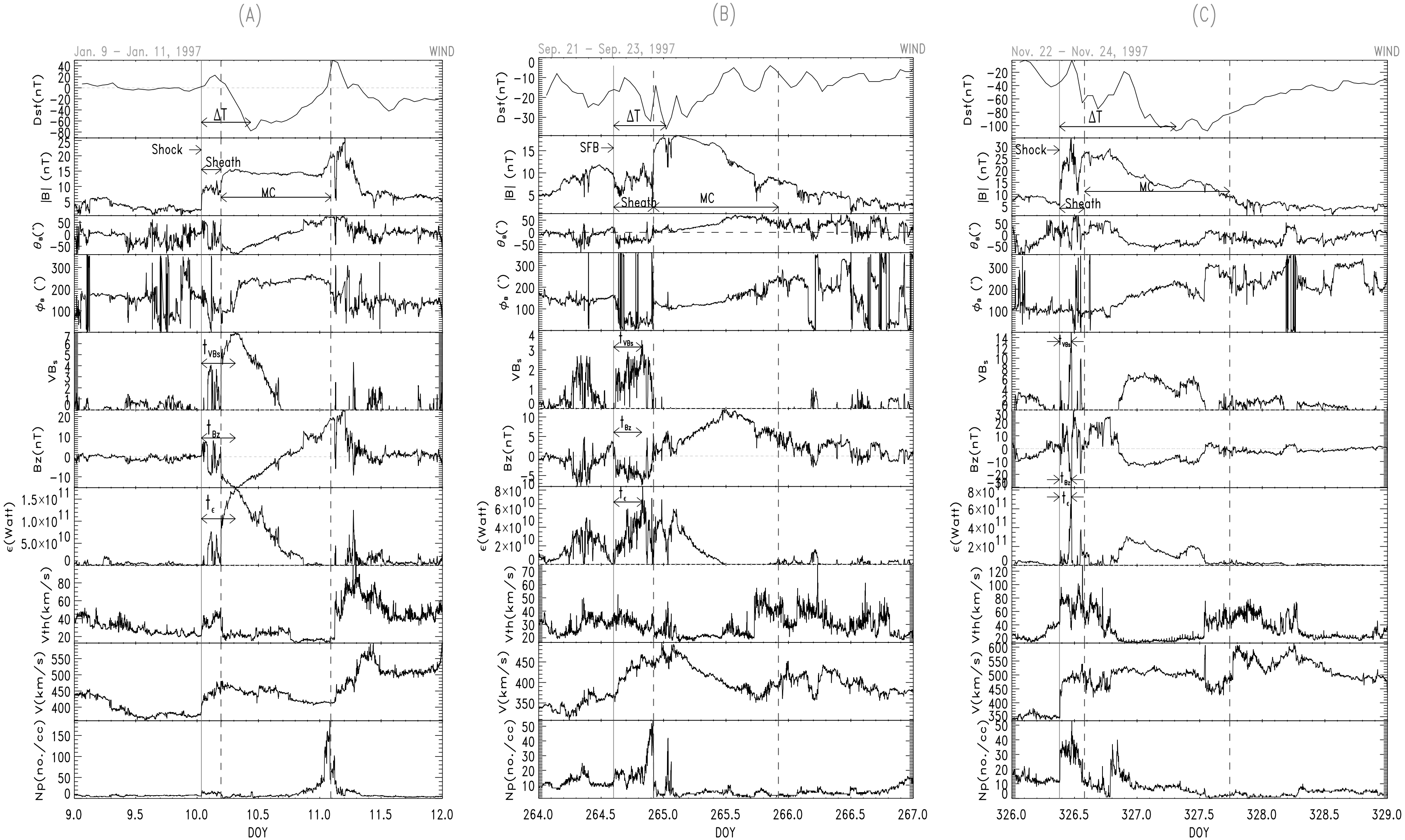

Figure 1. Solar wind parameters and *Dst* for the three magnetic cloud events: (a) January 1997, (b) September 1997, and (c) November 1997. The parameters are (from top to bottom): geomagnetic index (*Dst*), interplanetary magnetic field magnitude ($|B|$), latitude (θ_B), and longitude (ϕ_B), induced electric field (VB_s), north-south component of the IMF (B_z), *Akasofu* [1981] ϵ, proton thermal speed (V_{th}), plasma bulk speed (V), proton density (N_P). The time delays ΔT, t_{VBs}, t_{Bz} and t_ϵ are discussed in the text. "SFB" means sheath front boundary in Figure 1b.

cloud, and low proton temperature compared to the ambient proton temperature [*Burlaga et al.*, 1981]. Using the above three cloud features and an empirical cloud fitting model [*Lepping et al.*, 1990] for guidance in choosing boundaries of a cloud event, 34 clouds were identified in Wind data [*Lepping et al.*, 2001]. The time delays due to solar wind travel from Wind to Earth for these clouds is in a range between 0.25 and 1.17 hours. For these events the front "boundary" of the sheath can be a shock, a shock-like structure, pressure pulse, or a sharp rise in density, temperature or velocity (e.g., see Figures 1a–1c). We simplify the analysis by considering two aspects of the *Dst* geomagnetic index: its relative minima (storm intensity) and time delays. Use of *Dst* is well known to help identify and quantify magnetic storms [*Gonzalez et al.*, 1994]. Minimum values of *Dst* are unique indicators of storm strength. Hence we employ only the strength and timing of these relative *Dst* minima during storms connected to magnetic cloud complexes for our analysis. Moreover, in order to understand the specific sources within the complex which create geomagnetic storms, related solar wind parameters are collected and calculated. Some variables used here are defined in the notation section.

[11] If the magnetic fields are southward in both the sheath and solar ejecta, a two-step main phase storm can result [e.g., *Tsurutani and Gonzalez*, 1997; *Gonzalez et al.*, 2001]. A two-step storm is defined as a storm in which a *Dst* decrease (induced by the southward fields in the sheath) does not fully recover to the prestorm level before a second *Dst* decrease (induced by the southward fields in the solar ejecta) follows [e.g., *Kamide et al.*, 1998]. The southward field in the solar ejecta will (negatively) enhance the already low *Dst* and create a so-called two-step storm. There are a number of mechanisms that may lead to southward component fields in the sheath [e.g., *Tsurutani and Gonzalez*, 1997; *Gonzalez et al.*, 2001].

[12] Figure 1 shows examples of three different kinds of events: those of 9 January, 21 September, and 22 November 1997 (the event of 9 January 1997 generated a storm by the cloud's leading region (LR); the 21 September event generated a storm by the sheath region; and the 22 November event generated a two-step main phase storm (henceforth we will call this simply a two-step storm)), one by the sheath and one by the cloud itself.

[13] Figure 1a shows *Dst* variation and solar wind parameters for the January 1997 cloud event. A geomagnetic storm was generated by the long duration southward B_z in the magnetic cloud. This event has been studied extensively in many articles [e.g., *Burlaga et al.*, 1998; *Tsurutani et al.*, 1998; *Lu et al.*, 1998; *Arballo et al.*, 1998; *Wu et al.*, 1999]. The vertical line represents the location of the upstream shock, which was driven by the magnetic cloud. The dashed lines represent the boundaries of the magnetic cloud. The region bounded by the shock (the solid line) and the front of the cloud (the dashed line behind the shock) is the "sheath" region. Panels from bottom to top are the solar wind proton density, bulk velocity, thermal speed, the Akasofu ϵ (= $VB^2 l_o^2 \sin^4(\psi/2)$), solar wind magnetic field in the z direction (B_z), the product of solar wind speed and southward component of IMF (VB_s, $B_s = |B_z|$ for $B_z < 0$ and $B_s = 0$ for $B_z \geq 0$), the longitude angle (ϕ_B) and latitude angle (θ_B) of the solar wind magnetic field, the magnitude of solar wind magnetic field ($|B|$), and *Dst*. For the ϵ (= $VB^2 l_o^2 \sin^4(\psi/2)$) parameter, V is the speed of the solar wind, B is the strength (or magnitude) of the IMF, l_o^2 is an empirically determined value of the effective interaction area at the front of the magnetosphere ($l_o = 7\ R_E$), and ψ is the clock angle of the IMF which is defined as the polar angle between the IMF as projected into the $y - z$ plane and the z axis in GSM coordinates.

[14] Figures 1b and 1c show solar wind parameters and *Dst* for the September 1997 and November 1997 events, respectively. The September 1997 event resulted in a weak storm, whereas the November 1997 event resulted in a two-step storm. For the September 1997 event the magnetic field in the cloud is mainly northward, while in the sheath it is southward with $Bz_{\min} \simeq -7$ nT. There was only a weak storm (minimum $Dst = -36$ nT) generated. This small southward B_z may have caused the weak storm in the magnetosphere. For the November 1997 event, there are two dips in *Dst* as shown in Figure 1c. The first dip ($Dst \sim -75$ nT) was associated with a southward B_z ($Bz_{\min} \simeq -30$ nT) in the sheath and the second dip ($Dst \simeq -108$ nT) was associated with the cloud's southward B_z (peak $B_z \simeq -20$ nT). This type of *Dst* profile is a two-step main phase storm. Previous studies have shown that two-step main phase storms can result when the magnetic field is southward in both the sheath and the following solar ejecta [e.g., *Tsurutani and Gonzalez*, 1997; *Gonzalez et al.*, 2001].

[15] On the basis of the 34 cloud events investigated in this study, we found that the resulting geomagnetic storms were induced by the southward magnetic field sources from four different cloud complex regions: (1) the sheath, (2) the cloud's leading region (LR), (3) the trailing region of cloud (TR), and (4) both sheath and cloud regions. The last type of event (type 4) can induce a two-step main phase storm: one part generated by the southward fields in the sheath region and the other generated by the cloud itself. In addition, the $Dst_{\min}$ generally is associated with the cloud's field. About 17.6% of the events (six events) belong to type 1, 44.1% of the events (15 events) belong to type 2, 5.9% of the events (two events) belong to type 3, and 20.6% of the events (seven events) belong to type 4. However, 11.8% of the events (four events) have no storm association. It is clear that $Dst_{\min}$ is generally induced by the clouds themselves.

[16] Figure 2 shows the relationships and correlation coefficient between storm intensity ($Dst_{\min}$) and $Bz_{\min}$, $\epsilon_{\max}$, $VBs_{\max}$, $\Sigma\epsilon\Delta t$, and $\Sigma B_z\Delta t$ for the 34 events. The left column shows the results for all 34 events; the middle column shows the results for the 12 events for which the magnetic field of the cloud was northward first then southward (N-S); and the right column shows the result for the 22 events for which the magnetic field of the cloud was southward first then northward (S-N). For all events it is shown that $Dst_{\min}$ is best correlated with $VBs_{\max}$ (CC = 0.79). In general, $Dst_{\min}$ is well correlated with $VBs_{\max}$ (CC = 0.79), $Bz_{\min}$ (CC = 0.77), $\epsilon_{\max}$ (c.c. = 0.72), and $\Sigma\epsilon\Delta t$ (CC = 0.7), except $\Sigma B_z\Delta t$ (CC = 0.49). It is clear that $Bz_{\min}$ and $VBs_{\max}$ are good indicators for measuring the intensity of these geomagnetic storms. For the 12 N-S events the correlation coefficient between $Dst_{\min}$ and $VBs_{\max}$, $Bz_{\min}$, $\epsilon_{\max}$, $\Sigma\epsilon\Delta t$ and $\Sigma B_z\Delta t$ are 0.80, 0.79, 0.79, 0.82 and 0.81, respectively. For the 22 S-N events

the correlation coefficients between $Dst_{\min}$ and $VBs_{\max}$, $Bz_{\min}$, $\epsilon_{\max}$, $\Sigma\epsilon\Delta t$ and $\Sigma Bz\Delta t$ are 0.87, 0.81, 0.83, 0.72, and 0.33. The statistical results for Figure 2 are listed in Table 1.

[17] Figure 3 shows the relationships and correlation coefficient between ΔT and t_{VBs}, t_{B_z}, and t_ϵ. The left column shows the results for all 34 events; the middle column shows the results for the 12 N-S events; and the right column shows the results for the 22 S-N events. The correlation coefficients between ΔT and each of t_{VB_s}, t_{B_z} and t_ϵ for all 34 events are 0.65, 0.67, and 0.61, respectively; for the 12 N-S type of events, they are 0.60, 0.62, and 0.57; for the 22 events of the S-N type they are 0.81, 0.80, and 0.81, respectively. The correlation coefficients for Figure 3 are listed in Table 2. For all events the correlation coefficients between ΔT and t_{VB_s}, t_{B_z} and t_ϵ increase slightly to 0.70, 0.72, and 0.67, respectively, if we count a two-step storm as two individual storms for the seven two-step storms studied in this paper.

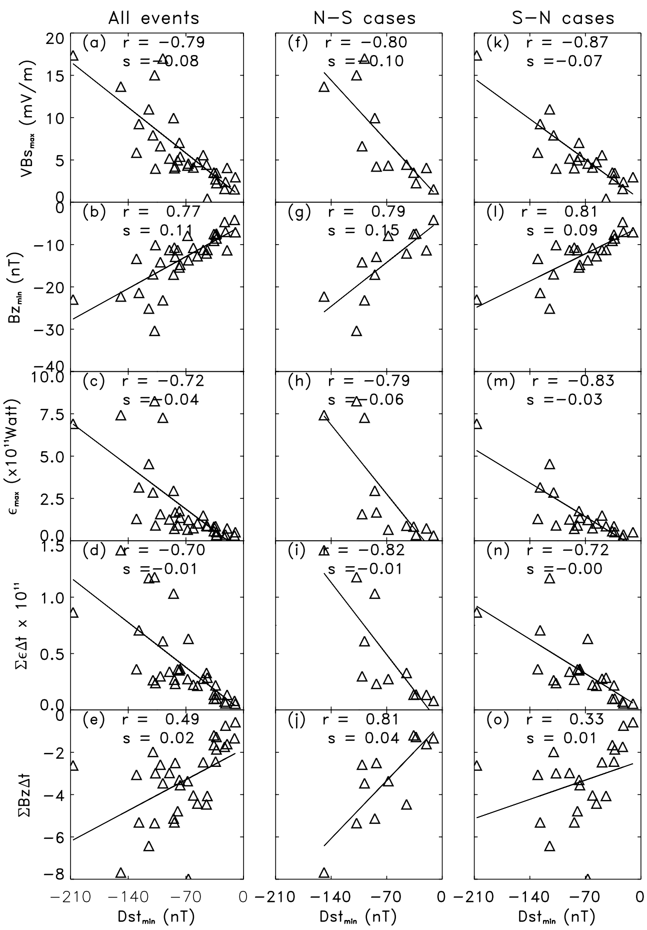

Figure 2. Relationships and correlation coefficients for storm intensity (*Dst*) versus various solar wind parameters. The left column represents the results for all events; the middle column represents the results for the 12 events for which the magnetic field of the cloud was northward first, then southward (N-S cases); the right column represents the results for the 22 events for which the magnetic field of the cloud was southward first then northward (S-N cases).

Table 1. Correlation Coefficients Between $Dst_{\min}$ and Different Solar Wind Parameters

	$VBs_{\max}$	$Bz_{\min}$	$\epsilon_{\max}$	$\Sigma\epsilon\Delta t$	$\Sigma Bz\Delta t$
All events (34)	0.79	0.77	0.72	0.7	0.49
N-S events (12)	0.80	0.79	0.79	0.82	0.81
S-N events (22)	0.87	0.81	0.83	0.72	0.33

[18] Figure 4 shows the histograms of time delays, t_ϵ, t_{B_z}, ΔT, and t_{VBs}. They show that (1) t_ϵ occurred in a wide range between 0.24 and 39.84 hours with 5 hours being the mostly likely occurrence, (2) t_{B_z} occurred in a wide range between 0.24 and 42.72 hours with 5 hours being the mostly likely occurrence, (3) ΔT occurred in a wide range between 1.92 and 44.88 hours with 10 hours being the mostly likely occurrence, and (4) t_{VBs} occurred in a wide range between 0.24 and 42.72 hours with 10 hours being the mostly likely occurrence.

[19] By comparing *Dst* with various solar wind parameters (especially, the southward B_z) for each event, we may determine the probable occurrence-location of cloud events that may have induced the storms. Figure 5 shows the $Dst_{\min}$ occurrence-location for the 34 magnetic clouds. The $Dst_{\min}$ occurred in the sheath region in six cases, in the cloud's leading region in 15 cases, in both the cloud and sheath region in seven cases, and in the cloud's trailing region in two cases. However, there were four magnetic clouds for which no storms were reported (the averaged $Dst_{\min}$ was -16 nT and the median value of $Dst_{\min}$ was -11 nT). For the same ordering (sheath, leading, both, trailing) the averaged

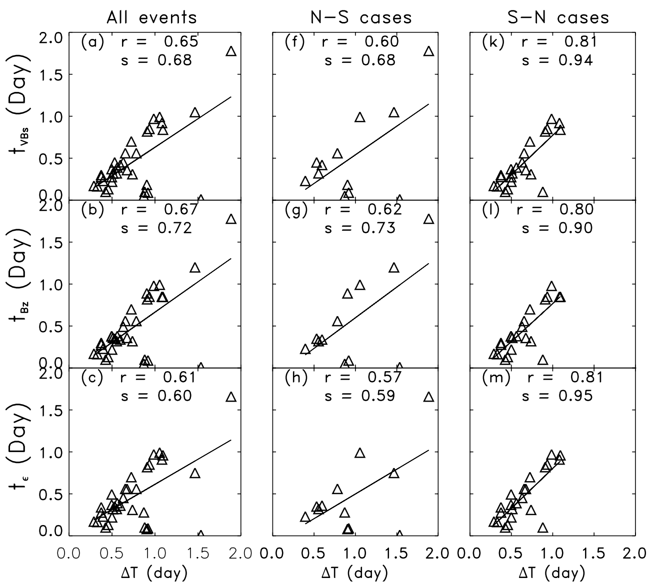

Figure 3. Relationships and correlation coefficients for ΔT and t_{Bz}, t_ϵ and t_{VBs}. The left column represents the results for all 34 events; the middle column represents the results for the 12 events for which the magnetic field of the cloud was northward first then southward (i.e., N-S cases); the right column represents the results for the 22 events for which the magnetic field of the cloud was southward first then northward (S-N cases). At the top of each panel, r represents the value of the correlation coefficient and s represents the slope of the fit.

Table 2. Correlation Coefficients Between ΔT and t_{VB_s}, t_{B_z} and t_ϵ

	t_{VB_s}, day	t_{B_z}, day	t_ϵ, day
All events (34)	0.65	0.67	0.61
N-S events (12)	0.60	0.62	0.57
S-N events (22)	0.81	0.80	0.81

storm intensities ($Dst_{\min}$) were −60, −85, −92, and −58 nT, and median storm intensities were −36, −84, −80, and −33 nT. The square symbol in Figure 5 represents the no-storm category.

[20] Typically, the leading region of a magnetic cloud during this epoch of study was the mostly likely occurrence-location of $Dst_{\min}$. Most storms were induced by the field structure in the cloud's leading region, consistent with the observations of *Bothmer and Rust* [1997].

3. Discussion

[21] We find that interplanetary magnetic clouds usually generate magnetic storms, but they do not always do so (e.g., the September 1997 event generated only weak geomagnetic activity). It is possible for a cloud complex to create a two-step storm (e.g., the November 1997 event). About 21% of our cloud complexes generated two-step storms.

[22] In order to understand in more detail the phenomenon of a two-step storm, we investigated 261 storms (i.e., *Dst* magnitudes of < −80 nT), during the continuous 37-year interval of 1964–2000. We found that some of them were related to magnetic clouds, but some were not. The following conditions are required for a two-step storm: (1) The two dips in *Dst* must be separated by more than 3 hours, and the value of the earlier *Dst* dip must be less than −30 nT; (2) the later dip of *Dst* must be greater than the earlier one; (3) there must be no storm sudden commencement (SSC) or sudden impulse (SI) between the two dips of *Dst*.

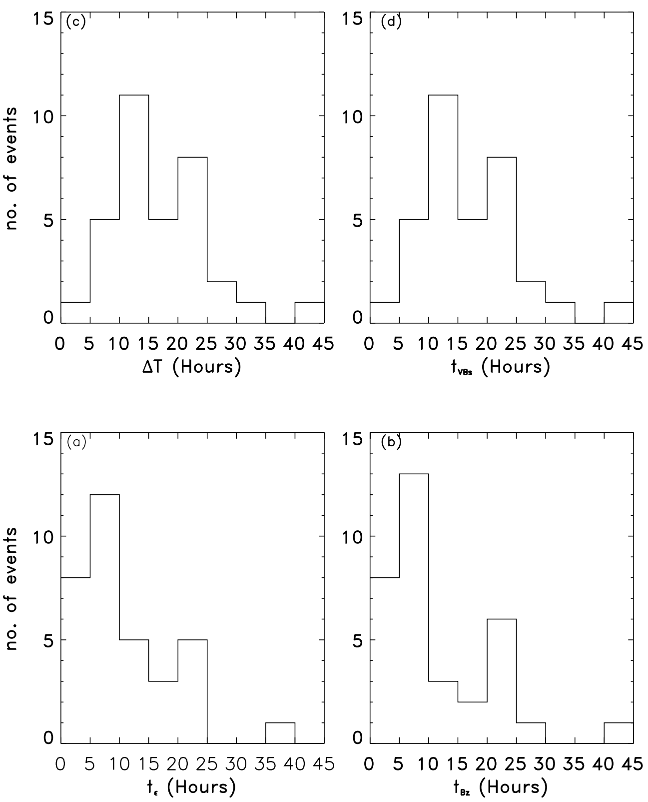

Figure 4. Histograms of time delays, t_{B_z}, t_ϵ, ΔT and t_{VBs}.

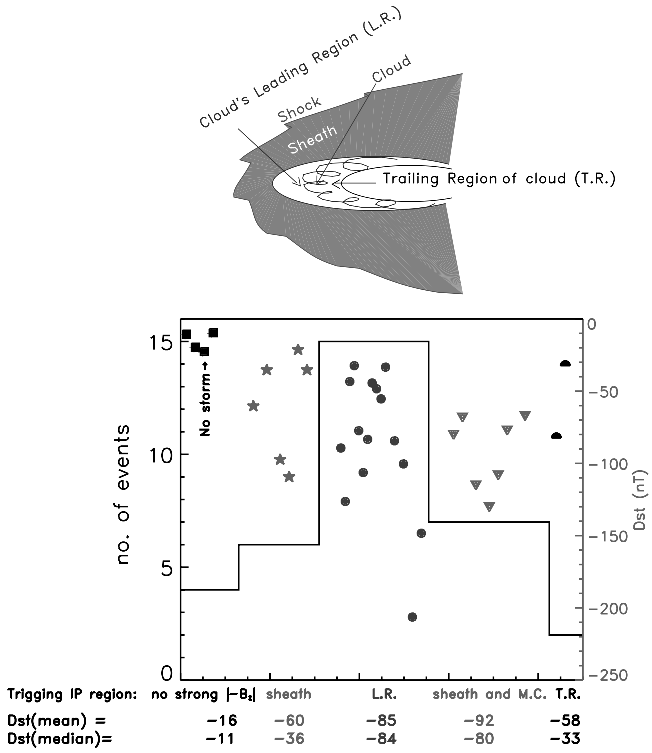

Figure 5. Histogram of the locations within magnetic cloud complexes of interplanetary triggers of magnetic storms.

[23] By examining both solar wind data (from OMNI and Wind data sets) and storm sudden commencement (SSC), we found that 25% (64 in 261) of the magnetic storms had two-step profile. We also observed that 22.2% (58 out of 261) of the storms were cloud associated, and 32.8% (19 out of 58) of two-step storms were clouds associated. These 58 clouds are reported from previous articles [*Klein and Burlaga*, 1982; *Bothmer and Rust*, 1997; *Lepping and Berdichevsky*, 2000]. This is in reasonably good agreement with our more limited Wind study result of 21% (seven out of 34 events) for two-step events. A slightly smaller occurrence rate may be due to the fact that the 34 magnetic clouds of this study occurred during solar minimum.

[24] Minimum *Dst* of a storm can occur in association with various regions within a magnetic cloud complex, including the sheath (17.6%), cloud's leading regions (40.1%), trailing regions (5.9%), and both sheath and cloud regions (20.6%). The storm is an extended process not fully considered here. Our results are based on the time of minimum *Dst*. According to the results of this study it is interesting that average two-step storm intensities generated by both the clouds' sheath and leading regions were stronger than the average storm intensity generated by other portions of the cloud complex (e.g., sheath or trailing region of cloud complex).

[25] Using Wind observations of 33 magnetic clouds covering the same period studied here for an examination of the southward magnetic fields in and surrounding magnetic clouds (which we call a cloud complex), *Simmerer et al.* [2000] showed results in contrast with some earlier findings, which suggested that sheaths of ejecta, on average, are as geoeffective as the ejecta themselves [*Tsurutani et al.*, 1988; *Cane et al.*, 2000]. Their study shows no evidence that a given southward field is more geoeffective in the sheath, or even as geoeffective, than in the cloud (considered here to be the ejecta) owing to higher density in the sheath. Our study confirms the findings of *Simmerer et al.* [2000].

[26] There is a good correlation between $Dst_{\min}$ and the solar wind parameters, $VBs_{\max}$ and $Bz_{\min}$. This indicates that the variation of B_z (or VB_s) specifically plays an important role in determining the intensity of a geomagnetic storm. The correlation of $Dst_{\min}$ with $VBs_{\max}$ (CC = 0.87) is slightly larger than with $Bz_{\min}$ (CC = 0.81), making *VBs* the most important indicator of the intensity of a geomagnetic storm, for the S-N type of cloud. This result is not unexpected because *Dst* is a measure of the ring current which is enhanced by the southward component of IMF. *Cane et al.* [2000] found that storm intensity (*Dst*) and the southward interplanetary magnetic field (B_s) strength in ejecta or in upstream sheath regions for events associated with front-side halo CMEs during 1996–1999 are strongly correlated. There is an anticorrelation between B_s and *Dst* (CC = −0.74) [*Cane et al.*, 2000]. Our results (CC = 0.77) are consistent with the results of *Cane et al.* [2000], except our events were not restricted by any characteristics of solar origin.

[27] The *Akasofu* [1981] ϵ has been used for measuring energy input of the solar wind to the magnetosphere for many years [e.g., *Gonzalez et al.*, 1994]. This study shows that ϵ is also a good solar wind indicator for studying geomagnetic storms caused by magnetic clouds, especially for cases when there was an early southward turning (see Figure 2m). Our results consist with the previous studies [e.g., *Akasofu*, 1981]. Using many different coupling functions for the energy input to the magnetosphere, *Gonzalez et al.* [1989] have followed the time evolution of *Dst* during the main phase of intense and moderate storms. They found that several coupling functions, especially ϵ and VB_S, represent the energy input fairly well. In this study, we test only the peak values of solar wind parameters and minimum *Dst* and found that the three variables, $Bz_{\min}$, $\epsilon_{\max}$, and $VBs_{\max}$ are well correlated with $Dst_{\min}$, and the differences among the correlations are very small. Also, $\Sigma\epsilon\Delta t$ and $\Sigma B_z\Delta t$ are good solar wind indicators for studying geomagnetic storms, especially for N-S cases (see Figures 2i and 2j). The correlation coefficients between ΔT and t_{VB_s}, t_{B_z} and t_ϵ (Figure 3) are relatively high ($\geq$0.8) for S-N cases. This suggests that the occurrence time of $Dst_{\min}$ can be more accurately predictable for the S-N cases than other cases.

[28] From the study of 34 Wind magnetic clouds during 1995–1998 we find that the intensity of magnetic storms is strongly related to these quantities: $Bz_{\min}$, $VBs_{\max}$ or $\epsilon_{\max}$. For all 34 clouds the quantities, $Bz_{\min}$, $VBs_{\max}$ or $\epsilon_{\max}$ were always observed to occur before $Dst_{\min}$. This suggests that the intensity of a storm might be predictable if any of these quantities within a cloud complex is known sufficiently long before it encounters the Earth.

4. Conclusions and Remarks

[29] When a magnetic cloud interacts with Earth's magnetosphere any one of the following may be generated: no storm, a weak storm, a moderate or great storm, or a two-step main phase storm, as was seen by Wind during years 1995–1998. The 15 storms generated by the cloud's leading region during this time were all S-N clouds. We have determined that 44% of the storms were caused by southward B_z within the cloud's leading region. Therefore the cloud's leading region was a major driving force for storms during this epoch.

[30] The results show that there is a good correlation between $Bz_{\min}$ ($\epsilon_{\max}$ or $VBs_{\max}$) and the geomagnetic activity index $Dst_{\min}$ for these cloud events, as expected. Since both ϵ and VB_s contain B_z, the southward IMF was the major determinant of the generation and intensity of geomagnetic storms for these events. The results also suggest that the intensity of a geomagnetic storm (measured by $Dst_{\min}$) may be predictable, if the storm is induced by an interplanetary magnetic cloud and the parameters of the magnetic cloud are known in advance. The occurrence time of the geomagnetic storm's minimum *Dst* has a better chance of being accurately predicted, if it is induced by an S-N type of magnetic cloud, rather than an N-S type.

[31] For all storms (N-S, S-N, or combined), $Bz_{\min}$, $VBs_{\max}$, and $\epsilon_{\max}$ all provide nearly equally good measures of storm intensity. In addition, for N-S storms, $\Sigma Bz\Delta t$ or $\Sigma\epsilon\Delta t$ also do a good job for measuring storm intensity.

[32] The present study consisted of 22 S-N cases and 12 N-S cases. The field structure of a magnetic cloud is related to the solar cycle variations. For example, following the sunspot maximum of 1981, most magnetic clouds were of the N-S type, but following the sunspot maximum of 1991, the S-N type was most common [*Bothmer and Rust*, 1997]. In our study, S-N cases were almost twice as common as N-S cases, consistent with the finding of *Bothmer and Rust* [1997].

[33] In this investigation we studied only storms caused by magnetic cloud complexes. An intriguing phenomenon is the two-phase storm, which is apparently caused by southward B_z in two portions of a cloud complex, the upstream sheath and part of the cloud. In future studies of this kind more events need to be investigated, especially if obtained from other epochs (e.g., active solar periods).

Notation

- $Dst_{\min}$ minimum *Dst* value observed during a cloud "event." (The word "event" here and below usually means the entire "sheath"/cloud complex.)
- $Bz_{\min}$ minimum B_z value observed during or in front of a cloud event (i.e., in sheath).
- $VBs_{\max}$ maximum value of *VBs* observed during a cloud event where B_s is the southward component of the IMF ($B_s = |B_z|$ for $B_z < 0$ and $B_s = 0$ for $B_z \geq 0$).
- $\epsilon_{\max}$ maximum value of *Akasofu* [1981] ϵ observed during a cloud event.
- $\Sigma_\epsilon\Delta t$ time-integrated ϵ for the period between the start of

a sheath and the occurrence of $Dst_{\min}$ (ϵ is *Akasofu* [1981] ϵ and Δt is the "sample time" between ϵ).

$\Sigma B_z \Delta t$ time-integrated B_z for the period between the start of a sheath and the occurrence of $Dst_{\min}$ (B_z is IMF B_z and Δt is the "sample time" between B_z).

ΔT time interval between the start of a sheath and the occurrence of $Dst_{\min}$ corrected for the traveling time from Wind to Earth.

t_{B_z} time interval between the start of a sheath and the occurrence of $Bz_{\min}$.

t_ϵ time interval between the start of a sheath and the occurrence of $\epsilon_{\max}$.

t_{VB_s} time interval between the start of a sheath and the occurrence of $VBs_{\max}$.

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