Effect of solar wind velocity on magnetic cloud-associated magnetic storm intensity

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[1] We investigate geomagnetic storm activity during periods of 135 magnetic clouds identified with hourly averages of OMNI data from 1965 to 1998. It is found that the storm *Dst* index correlates well with both the B_z component (correlation coefficient, c.c. = −0.86) and the "rectified" electric field VB_S (c.c. = −0.88) but does not correlate well with solar wind speed (c.c. = −0.58), indicating that the role of magnetic cloud speed in predicting storm intensity is a minor one. Solar wind speed does become important in predicting *Dst* for the studied cloud events when high solar wind speeds are considered. The correlation coefficient (c.c.) for *Dst* versus B_z increases dramatically when the solar wind speed exceeds 600 km/s. For example, the c.c. for *Dst* versus B_z is 0.99 for speeds between 600 and 750 km/s (15 events). This implies that solar wind velocity is also important indirectly for predicting the storm intensity when using B_z as a direct predictor. Specially, over the next 2 or 3 years, cloud speed is expected to increase, on average, as has already been observed. This provides us a good opportunity to estimate the intensity of cloud-associated geomagnetic storms by using the observed upstream B_z. *INDEX TERMS:* 2788 Magnetospheric Physics: Storms and substorms; 2111 Interplanetary Physics: Ejecta, driver gases, and magnetic clouds; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2134 Interplanetary Physics: Interplanetary magnetic fields; *KEYWORDS:* magnetic cloud, magnetic storm, solar wind speed, storm intensity prediction, storm intensity

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1. Introduction

[2] A magnetic cloud [*Burlaga et al.*, 1981] is defined by a region of high magnetic field strength, low temperature, low proton beta, and a significant rotation in the magnetic field vector. Magnetic clouds are a major source of geomagnetic activity (*Dst* < −50 nT), because they are usually a source of long-lasting, strong, southward interplanetary magnetic field (IMF) in solar magnetospheric coordinates. Many studies have suggested that B_z and *VBs* (rectified electric field) are the most important solar wind parameters in controlling storm activity [e.g., *Gonzalez et al.*, 1994, and references therein]. The intensity ($Dst_{\min}$) and onset of storm activity are related to the polarity of the cloud's B_z component [*Wilson*, 1990]. Although magnetic clouds are a major source of southward IMF B_z, resulting in magnetic storms [*Burlaga*, 1988], large magnetic clouds are not always associated with intense field strengths [*Farrugia et al.*, 1997].

[3] A geomagnetic storm may be driven by a magnetic cloud itself or by the sheath fields of a magnetic cloud [*Tsurutani and Gonzalez*, 1997] when an upstream shock or pressure pulse exists. Recently, *Wu and Lepping* [2002] studied the relationships between *Dst* and solar wind parameters for 34 magnetic clouds observed by the Wind spacecraft. They found that B_z, VB_s, and *Akasofu* [1981] ϵ within cloud regions are well correlated with *Dst*. They also found that, although a geomagnetic storm can occur during the passage of different parts of a cloud, the majority of events (∼50%) corresponded to the cloud's leading (front) region.

[4] *Wu and Lepping* [2002] studied clouds only for solar minimum (1995–1998). In order to understand the long–term relationship between solar wind parameters and *Dst*, and to provide a statistical base for the relationship between the magnetic clouds and magnetic storms, we analyze magnetic clouds based on 33 years (1965–1998) of OMNI hourly data. The results are described in this brief report.

2. Data Analysis and Statistical Results

[5] Magnetic cloud events used in the present study have been extracted from three previously published reports [*Klein and Burlaga*, 1982; *Bothmer and Rust*, 1997; *Lepping and Berdichevsky*, 2000]. A total of 135 events that cover the period from 1965 to 1998 are obtained for further analysis. Hourly averages of solar plasma and magnetic field data from OMNI, and *Dst* during these cloud events are compiled into a database.

[6] For space weather forecasting purpose, predicting the magnitude of a magnetic storm (minimum *Dst*) is the main

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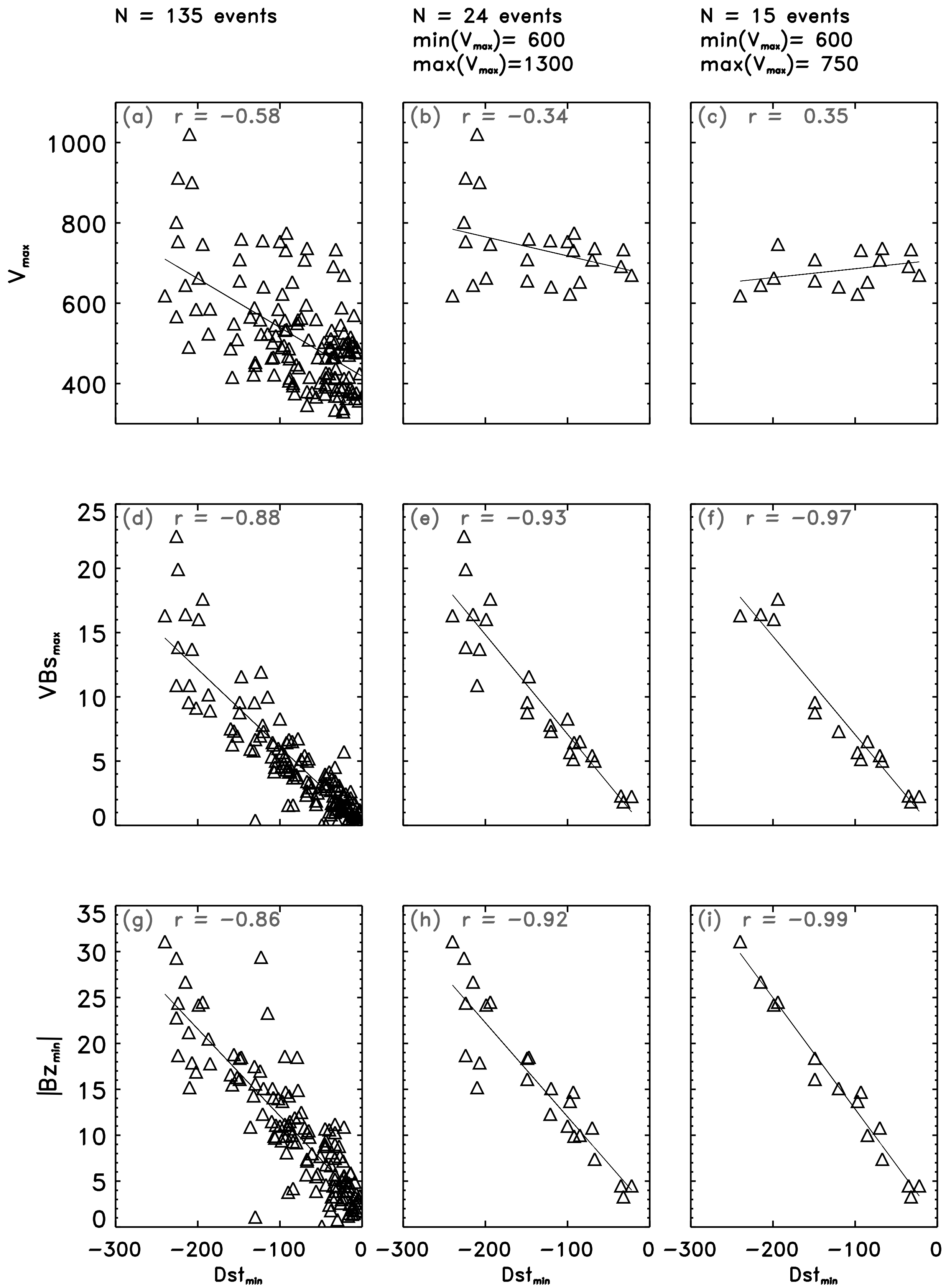

Figure 1. Relationships and linear correlation coefficients (c.c.) for Dst_{min} (a measure of storm intensity) versus various solar wind parameters for various V_{max} ranges. Figures 1a–1c show Dst_{min} versus V_{max}; Figures 1d–1f show Dst_{min} versus VBs_{max}; and Figures 1g–1i show Dst_{min} versus $|Bz_{min}|$.

Table 1. Correlation Coefficients Between Minimum *Dst* and Different Solar Wind Parameters for Various V_{max} Ranges

	V_{max}	$\|Bz_{min}\|$	VBs_{max}
300 km/s < V_{max} < 400 km/s (27 events)	−0.09	−0.59	−0.62
400 km/s < V_{max} < 500 km/s (49 events)	−0.09	−0.79	−0.81
500 km/s < V_{max} < 600 km/s (35 events)	−0.32	−0.78	−0.84
600 km/s < V_{max} < 750 km/s (15 events)	0.35	−0.99	−0.97
V_{max} > 600 km/s (24 events)	−0.34	−0.92	−0.93
All events (135 events)	−0.58	−0.86	−0.88

goal of the present study. On the basis of many previous studies, the magnitude of a storm is very likely determined by certain extreme values of solar wind parameters. For simplicity, we examine the minimum value of *Bz* (Bz_{min}), the maximum value of *VBs* (VBs_{max}), and the maximum value of solar wind speed (V_{max}) during or in front of a cloud event to find which parameters are most important in determining storm magnitude. This can generally be done with a simple correlation study. Both *Bs* (southward magnetic field) and B_z are measured in the GSM coordinate system. The value of *VBs* was assigned to zero if the magnetic field has no southward component.

[7] Figure 1 shows the relationships between storm intensity (Dst_{min}) versus various solar wind parameters for various V_{max} ranges (correlation coefficients are also calculated and given in each panel). Figures 1a–1c show the correlation coefficient (c.c.) of Dst_{min} versus V_{max} for various V_{max} ranges. There are 24 events with V_{max} greater than 600 km/s, and 15 events with 600 km/s < V_{max} < 750 km/s. Those events with fast solar wind speed were broadly distributed over the years 1968–1998. The c.c.'s are −0.58 (for all events), −0.34 (V_{max} > 600 km/s), and 0.35 (600 > V_{max} > 750 km/s). It is clear that the storm intensity is not related to V_{max} in any simple way.

[8] Figures 1d–1f show Dst_{min} versus VBs_{max} for various V_{max} ranges. The c.c.'s are −0.88 (for all events), −0.93 (V_{max} > 600 km/s), and −0.97 (600 km/s > V_{max} > 750 km/s). Figures 1g–1i show Dst_{min} versus $|Bz_{min}|$ for various V_{max} ranges. The c.c. are −0.86 (for all events), −0.92 (V_{max} > 600 km/s), and −0.99 (600 km/s > V_{max} > 750 km/s), respectively. The results clearly show that storm intensity is proportional to Bz_{min} for the high-speed cloud events (V_{max} > 600 km/s). In addition, we also computed c.c. for V_{max} versus VBs_{max} (−0.66), V_{max} versus Bz_{min} (−0.48) and Bz_{min} versus VBs_{max} (−0.92) for all 135 cases. It is clear that VBs_{max} is most strongly related to Bz_{min} for almost all V_{max} ranges.

[9] Table 1 shows the c.c.'s between Dst_{min} and different solar wind parameters for various V_{max} ranges. The c.c. for Dst_{min} versus Bz_{min} is −0.59 for the velocity range between 300 and 400 km/s; −0.79 for the velocity range between 400 and 500 km/s; −0.78 for velocity range between 500 and 600 km/s; 0.92 for velocity range greater than 600 km/s. It is clear that the c.c. for Dst_{min} versus VBs_{max} (or Bz_{min}) increased when the speed of the solar wind increased.

[10] According to the value of *Dst*, there are three kinds of storms: (1) great (or intense) storms: minimum *Dst* of −100 nT or less, (2) moderate storms: minimum *Dst* falls between −50 and −100 nT, and (3) weak storms: minimum *Dst* falls between −30 and −50 nT [*Tsurutani and Gonzalez*, 1997]. We investigated the probability occurrence of storm intensity according to *Dst*. We found 37 events with $Dst \geq -30$ nT, 25 events with -30 nT $\geq Dst > -50$ nT, 35 events with -50 nT $\geq Dst > -100$ nT, and 38 events with -100 nT $\geq Dst$. This implies that 37 events (≈27%) had no storms, 25 events (≈19%) were weak storms, 35 events (≈26%) were moderate storms, and 38 events (≈28%) were great storms. The occurrences of Dst_{min} for the studied clouds are almost evenly distributed among every kind of storm when categorized according to *Tsurutani and Gonzalez* [1997].

3. Discussion and Conclusion

[11] For geomagnetic storm events with *Dst* < −50 nT, the relationship between storm intensity (*Dst*) and southward interplanetary magnetic field strength in ejecta or sheath regions for events associated with front-side halo CMEs during 1996–1999 was studied recently [*Cane et al.*, 2000]. They found that *Dst* versus the maximum southward magnetic field (*Bs*) in either the ejecta or the adjacent disturbed solar wind has a correlation coefficient of −0.74. Using Wind observation between 1995 and 1998, *Wu and Lepping* [2002] studied 34 cloud events associated geomagnetic storms. They found that the intensity of storms is strongly correlated with VBs_{max} and $|Bz_{min}|$ with c.c. = −0.79 and −0.77, respectively. Both of the previous studies [*Cane et al.*, 2000; *Wu and Lepping*, 2002] show that the intensity of a storm is strongly correlated with the magnitude of B_z. However, both studies cover less than 1/4 of solar activity cycle (where 22 years is a full solar cycle). The correlation coefficient of $|Bz_{min}|$ and Dst_{min} is similar for both studies (−0.74 for Cane et al. and −0.77 for Wu and Lepping). The period of coverage of this present study is one and a half full solar cycles (33 years). The study shows that the intensity of a geomagnetic storm is primarily related to the solar wind parameters B_z and *VBs*. Our results confirmed the two previous studies [*Cane et al.*, 2000; *Wu and Lepping*, 2002]. The c.c. of $|Bz_{min}|$ versus Dst_{min} is −0.86 for this extended study which means that the long-

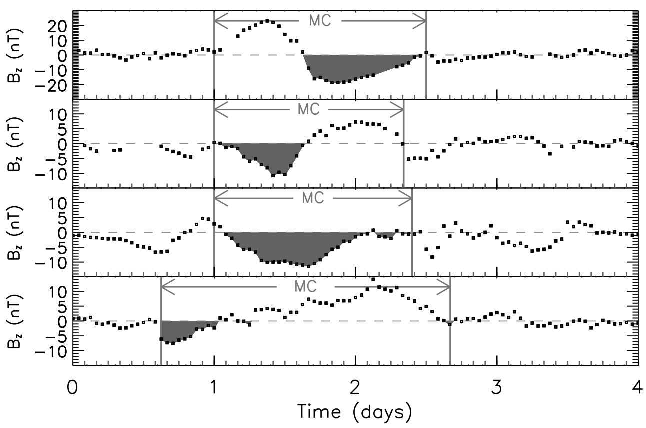

Figure 2. The *z* component of the IMF, B_z, for magnetic clouds observed by IMP spacecraft. The top panel shows the cloud event of 13–16 January 1988; the second panel shows the cloud event of 25–28 September 1973; the third panel shows the cloud event of 29 October to 1 November 1978; and the bottom panel shows the cloud event of 25–28 May 1996.

term study apparently gives a better correspondence than the short-term studies between a storm and $|Bz_{\min}|$.

[12] Inside a cloud, the magnetic field is usually either southward early, then northward (SN type) or northward early then southward (NS type). Figure 2 shows some examples of B_z profiles for interplanetary magnetic clouds, which were observed by various IMPs near 1 AU. The two vertical lines in each row of Figure 2 show the chosen boundaries of the magnetic clouds, consistent with their definition [*Klein and Burlaga*, 1982; *Burlaga*, 1988; *Lepping et al.*, 1990]. The four panels of Figure 2 show different kinds of clouds: (1) top panel shows an NS magnetic cloud; (2) the second panel from the top shows an SN cloud; (3) the third panel from the top shows a cloud with southward fields for most of its extent; and (4) the bottom panel show a cloud with northward fields for most of its extent, but with some southward fields in the early part.

[13] The study by *Wilson* [1990] shows that the minimum *Dst* value of a geomagnetic storm usually occurs within 12 hours of cloud onset at Earth for SN clouds, whereas it is delayed 12 or more hours from cloud onset for N-S clouds. The results of both short-term [*Wu and Lepping*, 2002] and long-term (this study) effects show that the storm intensity is strongly correlated with the magnitude of the interplanetary magnetic field in the *z* direction for the clouds. This implies that intensity of a storm might be predictable, if we know the field structure of a cloud observed by a spacecraft well upstream of the Earth even to the L1 point, because clouds are so large (duration $\sim$27 hours [*Lepping and Berdichevsky*, 2000]). During the next part of the solar cycle (years of 2002–2012) the Sun's field polarity and that of magnetic clouds will be such that negative B_z (southward) is expected to occur generally late in the cloud, i.e., the tailing part (for the most common, low or moderately low inclination, clouds). Therefore this period provides that best opportunity, via cloud modeling (under development by Lepping et al.), to predict when B_z will reach minimum (and the value of the minimum itself) many hours later, based on real-time observations of the early (positive B_z) part of the cloud. So it may be possible to predict the intensity of a geomagnetic storm when a spacecraft observes a cloud event well upstream of Earth.

[14] In this study we cataloged the speeds of the solar wind into various ranges. It is interesting to note that the c.c. of $Dst_{\min}$ versus $|Bz_{\min}|$ (1) increased (ignoring sign) to -0.92 (24 events) when the solar wind speeds was greater than 600 km/s, and (2) increased to -0.99 (15 events) when solar wind speeds were in the range between 600 and 750 km/s. The c.c. of $|Bz_{\min}|$ versus $Dst_{\min}$ markedly increased when the solar wind speeds increased. The c.c. of $VBs_{\max}$ versus $Dst_{\min}$ also increased when the solar wind speeds increased. This implies that the estimation of geomagnetic storm intensity based on $|Bz_{\min}|$ (or $VBs_{\max}$) becomes more reliable when the solar wind speeds are faster than 600 km/s for magnetic cloud intervals. However, the results of this present study show that the c.c between $V_{\max}$ and $Dst_{\min}$ is -0.58. This indicates that solar wind speed is not reliable (by itself) for estimating storm intensity but is important for measuring storm intensity when using $|Bz_{\min}|$ or $VBs_{\max}$. Over the next 2 or 3 years, cloud speed is expected to increase, on average, as has already been initiated. This provides a good opportunity for us to predict the intensity of a geomagnetic storm when the $Bz_{\min}$ (or $VBs_{\max}$) inside a magnetic cloud is observed.

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