Dependence of great geomagnetic storm intensity ($\Delta$SYM-H ≤ -200 nT) on associated solar wind parameters

MING-XIAN ZHAO,1 GUI-MING LE,1,2 QI LI,3 GUI-ANG LIU,2 AND TIAN MAO1

1Key Laboratory of Space Weather, National Center for Space Weather, China Meteorological Administration, Beijing, 100081, P. R. China
2School of Physics Science and Technology, Lingnan Normal University, Zhanjiang, 524048, P. R. China
3Institute of Geophysics, China Earthquake Administration, Beijing, 100081, P. R. China

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ABSTRACT

We use $\Delta$SYM-H to capture the variation in the SYM-H index during the main phase of a geomagnetic storm. We define great geomagnetic storms as those with $\Delta$SYM-H ≤ -200 nT. After analyzing the data that were not obscured by solar winds, we determined that 11 such storms occurred during solar cycle 23. We calculated time integrals for the southward interplanetary magnetic field component ($I(B_s)$), the solar wind electric field ($I(E_y)$), and a combination of $E_y$ and the solar wind dynamic pressure ($I(Q)$) during the main phase of a great geomagnetic storm. The strength of the correlation coefficient (CC) between $\Delta$SYM-H and each of the three integrals $I(B_s)$ (CC = 0.74), $I(E_y)$ (CC = 0.85), and $I(Q)$ (CC = 0.94) suggests that the impact of $B_s$ on the great geomagnetic storm intensity is more significant than that of the solar wind speed and the dynamic pressure during the main phase of associated great geomagnetic storm. Because $I(Q)$ has the highest correlation coefficient, we infer that Q, which encompasses both the solar wind electric field and the solar wind dynamic pressure, is the main driving factor that determines the intensity of a great geomagnetic storm. However, the extreme geomagnetic storm intensity can be estimated by solar wind electric field because the contribution made by solar wind electric field is almost equal to that made by Q for extreme geomagnetic storm.

Keywords: Space weather, Solar wind, Geomagnetic fields

1. INTRODUCTION

A geomagnetic storm is the result of the sustained interaction between solar winds with the southward magnetic field and Earth’s magnetic field. Previous works have explored the effect of different solar wind parameters on the intensity of an associated geomagnetic storm by calculating the correlation coefficients (CCs) between the peak value of various solar wind parameters and the minimum Dst index for the associated geomagnetic storm (e.g. Echer et al. 2008a,b; Choi et al. 2009; Kane 2005, 2010; Ji et al. 2010; Richardson & Cane 2011; Wu & Lepping 2002, 2016; Meng et al. 2019; Lawrance et al. 2020). However, these CC values have no physical meaning (Le et al. 2020).

Wang et al. (2003b) proposed that the geomagnetic storm intensity is largely unaffected by the solar wind density or the dynamic pressure, and that it is only a function of the interplanetary dawn-dusk electric field (termed as the solar wind electric field in this study). Echer et al. (2008a) determined that the CC between the time integral of the solar wind electric field during the main phase of the super geomagnetic storm intensity and the minimum of Dst index is equal to 0.62. Balan et al. (2014, 2017) explored the relationship between super geomagnetic storms, the sudden high
enhancement in the solar wind speed, and the southward magnetic field at the leading edge of the associated coronal mass ejection (CME). Based on the work of Burton et al. (1975), Kumar et al. (2015) estimated the magnitude of the interplanetary electric fields responsible for historical geomagnetic storms. Liu et al. (2014a) evaluated an extreme geomagnetic storm intensity only based on solar wind electric field, without considering the effect of the solar wind dynamic pressure on the extrem geomagnetic storm. Xue et al. (2005) identified the interplanetary sources that were responsible for the great geomagnetic storms (Dst ≤ -200 nT) that occurred during the solar maximum (2000 - 2001) and quantified the linear fit between Dst and both the solar wind electric field and the storm duration. These published works provide valuable insight into geomagnetic storms, but largely ignore the possible contributions made by the solar wind density or the solar wind dynamic pressure.

Case studies (Kataoka et al. 2005; Cheng et al. 2020), global MHD simulations (Lopez et al. 2004), and an impulse response function model (Weigel 2010) suggest that the solar wind density is an important parameter that modulating the transfer of solar wind energy to the magnetosphere during the main phase of a storm.

The development of a geomagnetic storm depends on the ring current injection term, Q, and the decay term. Q is either implemented as a linear function of the solar wind electric field (Burton et al. 1975; Fenrich & Luhmann 1998; O’Brien & McPherron 2000), or as a function of both the solar wind electric field and the solar wind dynamic pressure Wang et al. (2003a). A recent study has shown that it is more appropriate to apply the definition of Q that includes the solar wind dynamic pressure for major geomagnetic storms (Dst ≤ -100 nT) (Le et al. 2020).

Le et al. (2020) found that the time integrals for the southward interplanetary magnetic field component (I(B_s)), the solar wind electric field (I(E_y)), and a combination of E_y and the solar wind dynamic pressure (I(Q)) during the main phase of the major geomagnetic storm make small, moderate, and crucial contributions to the intensity of the major geomagnetic storm, respectively. Great geomagnetic storms (∆SYM-H ≤ -200 nT) are much stronger than major geomagnetic storms (Dst_{min} ≤ -100 nT). To determine whether a similar statistical trend exists for great geomagnetic storms, we calculated the CCs between ∆SYM-H and these three time integrals for great geomagnetic storms. We will discuss whether an extreme geomagnetic storm intensity can only be estimated by solar wind electric field. The data analysis, discussion, and summary for this study are presented in Section 2, Section 3, and Section 4, respectively.

2. DATA ANALYSIS

2.1. Solar Wind Data and Geomagnetic Storm Data

The SYM-H index was obtained from the World Data Center for Geomagnetism in Kyoto (http://wdc.kugi.kyoto-u.ac.jp/aeasy/index.html). In this study, our data set consists of solar wind data recorded by the Advanced Composition Explorer (ACE) (ftp://mussel.srl.caltech.edu/pub/ace/level2/magswe) from 1998 to 2006 with a time resolution of 64 seconds.

2.2. The criteria for a great geomagnetic storm

Seventeen geomagnetic storms with a minimum of Dst ≤ -200 nT occurred during solar cycle 23. However, the main phases of five of those great geomagnetic storms coincided with a data gap caused by the solar wind. The SYM-H index can be treated as a high time resolution Dst index (Wanliss & Showalter 2006), we used ∆SYM-H to represent the variation in SYM-H during the main phase of a geomagnetic storm. In this study, we define storms with ∆SYM-H ≤ -200 nT as great geomagnetic storms. The geomagnetic storm that occurred on November 9th and 10th in 2004, with ∆SYM-H = -165 nT during the main phase of the geomagnetic storm, does not meet the criteria for a great geomagnetic storm; as such, we do not include it in our data set. Because the variation in SYM-H during the main phase of the geomagnetic storm on September 25th in 1998 is equal to -177 nT, this storm is also not included in our data set. The minimum Dst value for a major geomagnetic storm that occurred on October 21st 2001 is -184 nT. However, because ∆SYM-H = -217 nT during the main phase of the storm, we treat this storm as a great geomagnetic storm. Our final data set consists of the solar wind parameters for 11 great geomagnetic storms that occurred during solar cycle 23.

2.3. The calculation of the solar wind parameters

I(B_s), I(E_y), and I(Q) represent the time integrals of the southward component of interplanetary magnetic field (IMF), the solar wind electric field, and the ring current injection term (Wang et al. 2003a) during the main phase of the associated great geomagnetic storm, respectively. These integrals are defined as

\[ I(B_s) = \int_{t_{start}}^{t_{end}} B_z dt \] (1)
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\[ I(E_y) = \int_{t_{\text{start}}}^{t_{\text{end}}} V_{sw} B_z \, dt \]  \hspace{1cm} (2)

\[ I(Q) = \int_{t_{\text{start}}}^{t_{\text{end}}} Q \, dt \]  \hspace{1cm} (3)

where \( t_{\text{start}} \) and \( t_{\text{end}} \) are the start and the end times of the main phase of a great geomagnetic storm, respectively, and \( V_{sw} \) is the solar wind speed. \( B_z \) is set to zero if \( B_z > 0 \) in Equations (1) and (2). The \( Q \) variable in Equation (3) is defined as

\[ Q = \begin{cases} 
0 & V_{sw}B_s \leq 0.49mV/m \\
-4.4(V_{sw}B_s - 0.49)(P_k/3)^{1/3} & V_{sw}B_s > 0.49mV/m
\end{cases} \]  \hspace{1cm} (4)

where \( P_k \) is the solar wind dynamic pressure.

\( \Delta \text{SYM-H} \), which represents the difference in the storm magnitude between the beginning and the end of the main phase of a great geomagnetic storm, is defined as

\[ \Delta \text{SYM-H} = \text{SYM-H}\big|_{t_{\text{end}}} - \text{SYM-H}\big|_{t_{\text{start}}} \]  \hspace{1cm} (5)

If \( \text{SYM-H}\big|_{t_{\text{start}}} \) is equal to zero, and \( \text{SYM-H}\big|_{t_{\text{end}}} = \text{SYM-H}_{\text{min}} \), then

\[ \Delta \text{SYM-H} = \text{SYM-H}\big|_{t_{\text{end}}} - \text{SYM-H}\big|_{t_{\text{start}}} = \text{SYM-H}_{\text{min}} \]  \hspace{1cm} (6)

If \( \text{SYM-H}\big|_{t_{\text{start}}} \) is not equal to zero, and \( \text{SYM-H}\big|_{t_{\text{end}}} \) is not equal to \( \text{SYM-H}_{\text{min}} \). In this scenario, \( \Delta \text{SYM-H} \) is defined according to Equation (12) in Le et al. (2020):

\[ \Delta \text{SYM-H} \simeq \int_{t_{\text{start}}}^{t_{\text{end}}} Q(t) \, dt = I(Q) \]  \hspace{1cm} (7)

After determining the start and the end times of the main phase of the great geomagnetic storm, we calculate \( \Delta \text{SYM-H} \), identify the interplanetary source responsible for that \( \Delta \text{SYM-H} \), and calculate the corresponding solar wind parameters \( I(B_s) \), \( I(E_y) \), and \( I(Q) \).

For example, let us examine the great geomagnetic storm that occurred on May 15\textsuperscript{th} in 2005 (Fig. 1). The ACE spacecraft recorded an interplanetary shock at 02:05 UT on May 15\textsuperscript{th} in 2005 (the first vertical dashed line in Fig. 1). The shock reached the magnetosphere at 02:38 UT and caused a sudden storm (the first vertical solid red line in Fig. 1). The main phase of the storm, which is the period between the second and third vertical solid red lines in Figure 1, has a \( \Delta \text{SYM-H} \) value of -350 nT. Solar wind between the second and third vertical dashed lines in Figure 1 is the interplanetary source responsible for the main phase of the storm. The \( I(B_s) \), \( I(E_y) \), and \( I(Q) \) values for the main phase of the storm are -3723.95 nT/min, -3292.92 mV·m⁻¹·min, and -35045.2 mV·m⁻¹·nPa·min, respectively.

The calculations for a second storm, which occurred on October 21\textsuperscript{st} to 22\textsuperscript{nd} in 1999, are shown in Figure 2. The main phase of the storm is the period between the first and second vertical red lines, and it was caused by the solar wind between the first and second vertical dashed lines in Figure 2. During the main phase of the storm, \( \Delta \text{SYM-H} = -269 \) nT, and the \( I(B_s) \), \( I(E_y) \), and \( I(Q) \) values are -9183.60 nT/min, -4647.12 mV·m⁻¹·min, and -24798.4 mV·m⁻¹·nPa·min, respectively.

2.4. The results

After determining the \( I(B_s) \), \( I(E_y) \), \( I(Q) \), and \( \Delta \text{SYM-H} \) values for each great geomagnetic storm, we calculated the CC values between \( \Delta \text{SYM-H} \) and each of the three time integrals: \( \text{CC}(I(B_s), \Delta \text{SYM-H}) = 0.74 \), \( \text{CC}(I(E_y), \Delta \text{SYM-H}) = 0.85 \), and \( \text{CC}(I(Q), \Delta \text{SYM-H}) = 0.94 \).

3. DISCUSSION

A previous estimation of \( \text{CC}(I(E_y), \text{Dst}_{\text{min}}) = 0.62 \) (Echer et al. 2008a) is much lower than our \( \text{CC}(I(E_y), \Delta \text{SYM-H}) \) value of 0.85. The difference in these values arises due to the difficulty in determining the start and end time of a geomagnetic storm precisely using the Dst index. The time resolution of the Dst index is one hour; the SYM-H index has a much finer time resolution, which allows for more exact determination of the start and end time of the main phase of a geomagnetic storm, and then the interplanetary source responsible for the geomagnetic storm main phase.
can be determined exactly. Equation (7) tells us that $I(E_y)$ is related to $\Delta$SYM-H rather than SYM-H$_{min}$ or Dst$_{min}$. These should be reason why $\text{CC}(I(E_y), \Delta$SYM-H) in the present study is much larger than $\text{CC}(I(E_y), Dst_{min})$ in the article by Echer et al. (2008a).

The $\text{CC}(I(B_s), \Delta$SYM-H) for great geomagnetic storms is much larger than that of major geomagnetic storms (Le et al. 2020). We attribute this differences to the fact that the $B_s$ value for a great geomagnetic storm is much larger than that of a major geomagnetic storm. Because $E_y = B_s \cdot V_{sw}$, $\text{CC}(I(B_s), \Delta$SYM-H) and $\text{CC}(I(E_y), \Delta$SYM-H) are 0.74 and 0.85 respectively, indicates that the contribution to the great geomagnetic intensity made by the solar wind speed is much lower than southward component of IMF. The comparison between $\text{CC}(I(B_s), \Delta$SYM-H) and $\text{CC}(I(Q), \Delta$SYM-H) implies that the contributions to the great geomagnetic intensity made by the solar wind speed and dynamic pressure are much lower than southward component of IMF. Based on our CC values, we infer that $B_s$ contribution to the great geomagnetic storm intensity is more significant than those of the solar wind speed and the dynamic pressure. Because our value of $\text{CC}(I(B_s), \Delta$SYM-H) is obtained under the condition that $P_k$ is larger than 3 nPa during the main phase of a great geomagnetic storm, $\text{CC}(I(Q), \Delta$SYM-H) is still much larger than $\text{CC}(I(B_s), \Delta$SYM-H), indicating that the solar wind speed and the dynamic pressure are also important factors in the great geomagnetic storm intensity besides $B_s$.

$\text{CC}(I(Q), \Delta$SYM-H) is larger than $\text{CC}(I(E_y), \Delta$SYM-H), suggesting that the ring current injection term $Q$ that includes both the solar wind electric field and the solar wind dynamic pressure is more accurate than the Q definition that only depends on the solar wind electric field for great geomagnetic storms.

For Q defined in Equation (4), $V_{sw}B_s = E_y$ should be much larger than 0.49 mV/m during the main phase of a great geomagnetic storm. As such, Q can be written as

$$Q \approx -4.4E_y(P_k/3)^{1/3}$$

As seen in Equation (8), numerically, the impact of $E_y$ on Q is larger than that of $P_k$, and that influence increases with the magnitude of the geomagnetic storm intensity. Therefore, $\Delta$SYM-H depends more on $E_y$ than on $P_k$ for a
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Figure 2. ACE spacecraft observations on October 21st and 22nd in 1999. The panels and lines are identical to those shown in Figure 1.

A stronger geomagnetic storm. Based on this explanation, we would expect the value of CC(I(E_y), ∆SYM-H) to be much larger for a great geomagnetic storm than it is for a major geomagnetic storm. Similarly, the difference between the values of CC(I(Q), ∆SYM-H) and CC(I(E_y), ∆SYM-H) will decrease as the geomagnetic storm intensity increases. In this context, the extreme storm intensity can be estimated using the solar wind electric field (Liu et al. 2014a,b, 2020) because the difference between the contributions made by the solar wind electric field and by Q will be very small for extreme geomagnetic storms.

4. SUMMARY

Our CC values that capture the statistical relationship between ∆SYM-H and the time integrals for the southward interplanetary magnetic field component (I(B_s)), the solar wind electric field (I(E_y)), and a combination of E_y and the solar wind dynamic pressure during the main phase of these great geomagnetic storms (∆SYM-H ≤ -200 nT) are equal to 0.74, 0.85, and 0.94, respectively. These results suggest that B_s, rather than the solar wind speed and dynamic pressure, makes a significant contribution to the great geomagnetic storm intensity. With the strength of the correlation between ∆SYM-H and I(Q), we infer that Q is the most important solar wind parameter in the determination of the intensity of a great geomagnetic storm. Furthermore, our results imply that it is better to use the ring current injection term definition proposed by Wang et al. (2003a) than it is to define Q as the solar wind electric field alone when it comes to assessing the intensity of a great geomagnetic storm. However, the extreme geomagnetic storm intensity can be estimated using the solar wind electric field because the contribution made by the solar wind electric field is almost equal to that made by Q during the main phase of an extreme geomagnetic storm.
Figure 3. Statistical analyses of the relationships between $\Delta$SYM-H and a) $I(B_s)$, b) $I(E_y)$, and c) $I(Q)$.

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REFERENCES

Balan, N., Skoug, R., Tulasi Ram, S., et al. 2014, Journal of Geophysical Research: Space Physics, 119, 10,041, doi: 10.1002/2014JA020151
Balan, N., Ebihara, Y., Skoug, R., et al. 2017, Journal of Geophysical Research: Space Physics, 122, 2824, doi: 10.1002/2016JA023853

Burton, R. K., McPherron, R. L., & Russell, C. T. 1975, Journal of Geophysical Research (1896-1977), 80, 4204, doi: 10.1029/JA080i031p04204
Cheng, L.-B., Le, G.-M., & Zhao, M.-X. 2020, Research in Astronomy and Astrophysics, 20, 036, doi: 10.1088/1674-4527/20/3/36
