

DIFFERENCES IN THE RESPONSE TO CME AND CIR DRIVERS  
OF GEOMAGNETIC DISTURBANCESРАЗЛИЧИЯ В ОТКЛИКЕ НА ГЕОМАГНИТНЫЕ ВОЗМУЩЕНИЯ,  
ВЫЗВАННЫЕ КВМ И ОКВ**B. Namuun***School of Space and Environment, Beihang University,  
Beijing, China  
Institute of Astronomy and Geophysics, Mongolian Academy  
of Sciences,  
Ulaanbaatar, Mongolia***B. Tsegmed***Institute of Astronomy and Geophysics, Mongolian Academy  
of Sciences,  
Ulaanbaatar, Mongolia, tseg@iag.ac.mn***L.Y. Li***School of Space and Environment, Beihang University,  
Beijing, China  
Key Laboratory of Space Environment monitoring and Infor-  
mation Processing of MIIT,  
Beijing, China***G.M. Leghari***School of Space and Environment, Beihang University,  
Beijing, China  
Pakistan Space and Upper Atmosphere Research Commission,  
Islamabad, Pakistan,***Б. Намуун***Школа космонавтики и окружающей среды, Бейханский  
университет,  
Пекин, Китай  
Институт астрономии и геофизики Монгольской акаде-  
мии наук,  
Улан-Батор, Монголия***Б. Цэгмэд***Институт астрономии и геофизики Монгольской акаде-  
мии наук, tseg@iag.ac.mn  
Улан-Батор, Монголия***Л.Ю. Ли***Школа космонавтики и окружающей среды, Бейханский  
университет,  
Пекин, Китай  
Ключевая лаборатория мониторинга космической среды  
и обработки информации  
Пекин, Китай***Г.М. Легари***Школа космонавтики и окружающей среды, Бейханский  
университет,  
Пекин, Китай  
Пакистанская комиссия по исследованию космоса и верхних  
слоев атмосферы,  
Исламабад, Пакистан*

**Abstract.** Utilizing 1-minute resolution data on the geomagnetic indices  $SYM-H$ ,  $AE$ , solar wind parameters (velocity  $V_{sw}$  and density  $N_p$ ), and  $z$ -component  $B_z$  of the interplanetary magnetic field (IMF) during solar cycles 23 and 24, we have statistically analyzed the correlations between geomagnetic activity (storms and substorms),  $V_{sw}$ ,  $N_p$ ,  $B_z$ , and energy coupling functions of solar wind and Earth's magnetosphere. For the selected 131 CME-driven storms,  $SYM-H$  stronger depends on  $V_{sw}$  and  $B$  than other parameters, whereas the selected 161 CIR-driven storms have nearly the same dependence on the solar wind electric field, the rate of open magnetic flux  $d\phi/dt$ , and the reconnection electric field  $E_{KL}$ . Thus, the solar wind electric field and the dayside magnetic reconnection are likely to have different contributions for storms of the two types. During storms of different types, the substorm intensity  $AE$  relies mainly on the IMF  $B_z$ , rate of open magnetic flux and reconnection electric field.

**Keywords:** solar wind, coronal mass ejections, corotating interaction regions, geomagnetic storms, magnetospheric substorms, correlations.

**Аннотация.** Используя 1-минутные данные геомагнитных индексов  $SYM-H$ ,  $AE$ , параметров солнечного ветра (скорость  $V_{sw}$  и плотность  $N_p$  и  $z$ -компоненту  $B_z$  межпланетного магнитного поля (ММП) во время 23-го и 24-го циклов солнечной активности, мы статистически проанализировали корреляции между геомагнитной активностью (бури и суббури),  $V_{sw}$ ,  $N_p$ ,  $B_z$  и функциями передачи энергии из солнечного ветра в магнитосферу Земли. Для выбранной 131 бури, вызванной КВМ,  $SYM-H$  имеет более сильную зависимость от  $V_{sw}$  и  $B$ , чем другие параметры, тогда как выбранная 161 буря, вызванная CIR, имеет почти такие же зависимости от электрического поля солнечного ветра, скорости открытого магнитного потока  $d\phi/dt$  и электрического поля пересоединения  $E_{KL}$ . Таким образом, электрическое поле солнечного ветра и дневное магнитное пересоединение, возможно, вносят разный вклад бури двух типов. Во время бурь различных типов интенсивность суббури  $AE$  зависит в основном от  $B_z$  ММП, скорости открытого магнитного потока и электрического поля пересоединения.

**Ключевые слова:** солнечный ветер, корональные выбросы массы, область коротирующего взаимодействия, геомагнитные бури, магнитосферные суббури, функции связи по энергии, корреляционный анализ.

## INTRODUCTION

Coronal mass ejections (CMEs) and corotating interaction regions (CIRs) are two typical drivers of geomagnetic storms and magnetospheric substorms [Tsurutani, Gonzalez, 1997; Gonzalez et al., 1999; Li, Wang, 2018]. According to different drivers, geomagnetic storms are classified as CME-driven and CIR-driven storms [Richardson et al., 2001; Tsurutani et al., 2006; Borovsky, Denton, 2006; Liemohn et al., 2010; Katus et al., 2015]. Intense storms and substorms can cause serious space weather phenomena such as Earth's radiation belts [Li et al., 2006, 2009, 2017, 2020] and plasma sheet [Cao et al., 2013]. Therefore, the solar activity dependence of geomagnetic storms and substorms and their forecast have been hot topics in space weather [Le et al., 2012; Zhao et al., 2022].

The development of geomagnetic storms is associated with the solar wind energy input into Earth's magnetosphere [Du et al., 2008]. Turner et al. have analyzed 118 CME-driven storms and 91 CIR-driven storms during the period from 1995 to 2004 [Turner et al., 2009]. They suggested that the CIR-driven storms provide more energy for the ionosphere and ring current than the CME-driven storms. Verbanac et al. have investigated the magnetospheric activity caused by CIR/HSS (High Speed Streams) structures during the declining phase of solar cycle (2005–2006), and have found that the combination of solar wind parameters ( $BV^2$  and  $BV$ ) plays an important role in the energy transfer from the solar wind to the magnetosphere [Verbanac et al., 2011]. Yermolaev et al. shows that the magnitude of the interplanetary magnetic field (IMF)  $B$  in CIRs and sheaths increases with increasing speed of pistons of both types: HSS and ICME; the piston speed increase results in an increase in geoeffectiveness of both compression regions [Yermolaev et al., 2018]. Alexakis and Mavromichalaki have suggested that the velocity of ICME (Interplanetary CME) structure can be used to predict the generation and intensity of geomagnetic storms [Alexakis, Mavromichalaki, 2019].

During storms of different types, the energy and momentum transfers from the solar wind and IMF to Earth's magnetosphere are still under debate. Moreover, the question of the relationship between geomagnetic storms and magnetospheric substorms has been unanswered so far. To distinguish the contributions of the solar wind density, velocity, and IMF to storms of different types, we have selected 131 CMEs, 161 CIR-driven storms, which occurred during solar cycles 23 and 24, and have analyzed their correlation with geomagnetic indices. In addition, we consider the relationship between geomagnetic activity and solar wind — magnetosphere coupling functions such as the reconnection electric field  $E_{KL}$  [Kan, Lee, 1979], the rate of open magnetic flux at the magnetopause  $d\phi/dt$ , and the energy function  $\epsilon$ .

The goal of this paper is to reveal geomagnetic/auroral activity dependence not only on the solar wind and IMF parameters, but also on energy coupling functions during the solar activity period under study. Moreover, we try to figure out which factor is more effective for the development of geomagnetic storms.

## DATA AND METHOD

The 1-min averaged data on solar wind parameters  $V_{sw}$ ,  $N_p$ ,  $B_z$ , and the geomagnetic indices  $SYM-H$  and  $AE$  have been taken from the OMNI database in CDAWeb [https://omniweb.gsfc.nasa.gov/form/omni\_min.html].  $AE$  denotes the substorm intensity, whereas the 1-min resolution  $SYM-H$  is often used to replace the 1-hr resolution  $Dst$  index to indicate the intensity of storms [Wanliss, Showalter, 2006]. For reference, we have also used the sunspot numbers [https://www.sidc.be/silso/datafiles].

The sunspot numbers during solar cycle 23 (1996–2007) are larger than those during solar cycle 24 (2007–2018). Therefore, the CME-driven storms are more intense during solar cycle 23 than during solar cycle 24 [Alexakis, Mavromichalaki, 2019]. In front of CMEs, IMF,  $V_{sw}$ ,  $N_p$  and temperature  $T$  increase suddenly and form a strong interplanetary (IP) shock [Kataoka et al., 2005]. However, IMF,  $V_{sw}$ ,  $T$ , and  $N_p$  increase gradually around the stream interface of CIRs [Zhang et al., 2008]. Consequently, the CIR-driven and CME-driven storms have different rate of development.

Figure 1 gives two examples of the CIR-driven storm that occurred on January 11, 2000 and the CME-driven storm that occurred on August 3, 1997. The development phases of the storms are indicated by  $SYM-H$ . Since the increases in IMF  $B$ ,  $V_{sw}$  from  $\sim 360$  to  $\sim 500$  km/s and  $N_p$  are gradual, there is no storm sudden commencement (SSC) before the main phase of the CIR-driven storm, and the CIR-driven storm develops slowly into the main phase. Moreover, the CIR-driven storm recovery phase is also long because of IMF quasi-periodic southward turn ( $B_z < 0$ ).

In contrast, the CME-driven storm has a prominent SSC because of the impact of the IP shock with the sudden increase in IMF  $B$ ,  $V_{sw}$ ,  $N_p$ , and its main and recovery phases are short because of fast southward and northward turn of IMF.

According to different features of storms of two types, we have selected 131 CME- and 161 CIR-driven storms with a minimum  $Dst \leq -30$  nT from 1996 to 2017. These storm events were selected from the list compiled by Turner et al. [2009], which covered the period from 1996 to 2004. For the period from 2005 to 2017, we have used the information on SSC taken from [https://www.ngdc.noaa.gov/stp/geomag/geoib.html] and [https://isgi.unistra.fr/events\_sc.php],  $V_{sw}$ , ring current and  $Dst$  from [https://omniweb.gsfc.nasa.gov/ow.html]. To identify magnetic storms, we took into account several patterns including the occurrence of SSC preceding the storm, the development of  $V_{sw}$ , and the behavior of the  $Dst$  index.

We have calculated Pearson's linear correlation coefficient  $CC$  between the  $SYM-H$ ,  $AE$ , and a single solar wind parameters  $N_p$ ,  $V_{sw}$ , and IMF  $B_z$  for all selected storms. Furthermore, we estimated  $CC$  between the geomagnetic indices and combined solar wind parameters.

The combined solar wind parameters represent the energy coupling relationship between the solar wind and Earth's magnetosphere. The energy coupling functions of the solar wind and magnetosphere are calculated through the following empirical formulas. The Akasofu

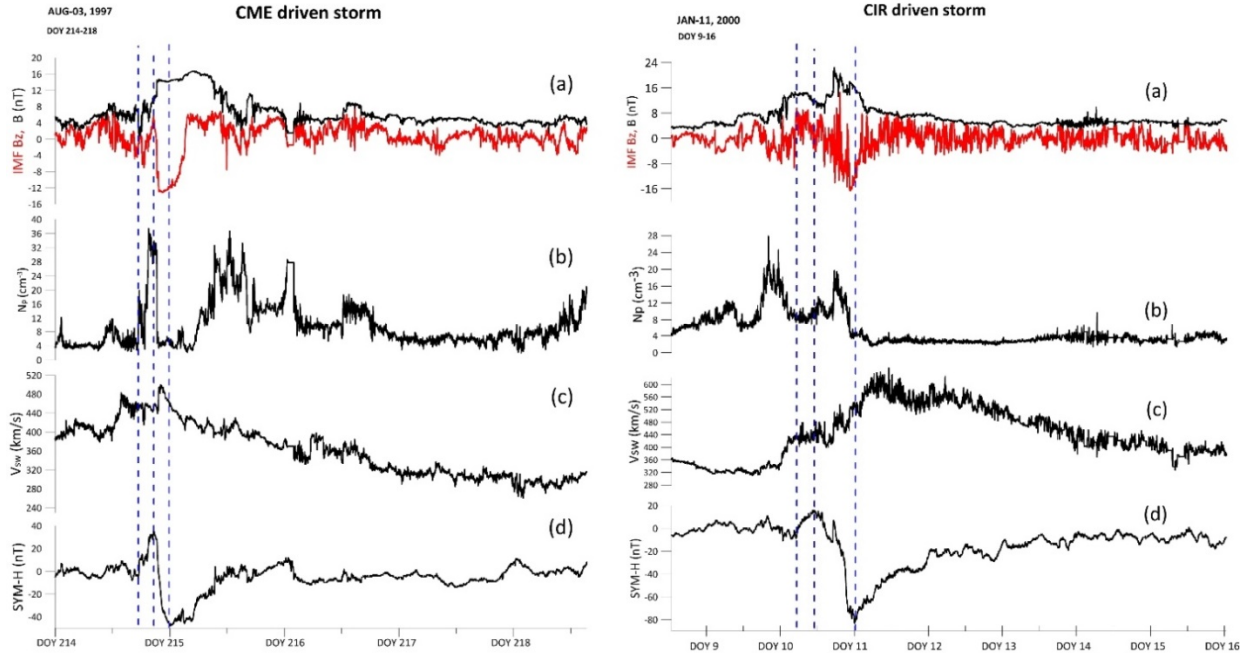


Figure 1. Interplanetary magnetic field and solar wind parameters during CIR-driven and CME-driven storms: IMF  $B$  and  $B_z$  variations (a),  $N_p$  (b),  $V_{sw}$  (c), and  $SYM-H$  (d) during CIR/CME-driven storms. Dashed vertical lines indicate the beginning of the initial, main, and recovery phases

function correlates not only with magnetic storms but also with individual substorm [Akasofu, 1981]. It is expressed as [Perrault, Akasofu, 1978]:

$$\varepsilon = V_{sw} B^2 \sin^4(\theta/2) l_0^2, \quad (1)$$

where  $l_0$  is a constant length ( $\sim 7R_E$ ,  $R_E = 6371$  km is Earth radius). The scaling factor  $l_0$  was obtained by considering the magnetospheric disturbance phenomena as a manifestation of the dissipation process of energy produced by the solar wind — magnetosphere interaction;  $\theta$  is the projection of the polar angle of IMF onto YZ plane in solar magnetospheric coordinates, and

$$\theta = \tan^{-1}(|B_y|/|B_z|), \quad B_z > 0, \quad (2)$$

$$\theta = 180^\circ - \tan^{-1}(|B_y|/|B_z|), \quad B_z < 0. \quad (3)$$

The Akasofu function depends not only on IMF clock angle on YZ plane, but also on  $V_{sw} B^2$ .  $V_{sw} B$  represents the solar wind electric field that plays an essential role in the magnetospheric convection [Burton et al., 1975].

Moreover,  $E_{KL}$  and  $d\phi/dt$  also depend on the solar wind electric field and IMF clock angle.  $E_{KL}$  is expressed as [Kan, Lee, 1979]

$$E_{KL} = V_{sw} B \sin^2(\theta/2), \quad (4)$$

$d\phi/dt$  is expressed as [Newell et al., 2007],

$$\frac{d\phi}{dt} = V_{sw}^{4/3} B^{2/3} \sin^{8/3}(\theta/2), \quad (5)$$

$d\phi/dt$  is proportional to the rate at which the magnetic flux is opened at the magnetopause, whereas the open magnetic flux depends on  $E_{KL}$ . Thus,  $E_{KL}$  and  $d\phi/dt$  correlate with the dayside magnetic reconnection that transports solar wind mass, energy, and IMF into the magnetosphere.

## STATISTICAL RESULTS

### Correlation for CME-driven storms

Figures 2 and 3 display the correlation coefficients  $CC$  between geomagnetic indices  $SYM-H$ ,  $AE$ , single solar wind parameter  $V_{sw}$ ,  $N_p$ , IMF  $B_z$ , and energy coupling functions during 131 CME-driven storms. Three correlation levels are defined: almost no or weak correlation ( $|CC| \leq 0.4$ ), moderate correlation ( $0.4 < |CC| < 0.6$ ), and strong correlation ( $|CC| \geq 0.6$ ).

The CME-driven storms have a moderate correlation with the solar wind velocity ( $CC = -0.51$  between  $SYM-H$  and  $V_{sw}$ ) and a strong correlation with the solar wind electric field ( $CC = -0.6$  between  $SYM-H$  and  $V_{sw} B$ ). Meanwhile, the CME-driven storms have also a moderate correlation with the open magnetic flux ( $CC = -0.5$  between  $SYM-H$  and  $d\phi/dt$ ) or the reconnection electric field ( $CC = -0.49$  between  $SYM-H$  and  $E_{KL}$ ). These results suggest that the CME-driven storms are mainly caused by the convection electric field driven by the high-speed solar wind. Yet, the dependence of the CME-driven storms on  $N_p$  and IMF  $B_z$  alone is very weak ( $CC < 0.4$ ).

During 131 CME-driven storms, the substorm intensity  $AE$  has a moderate correlation with IMF  $B_z$  ( $CC = -0.54$ ) and strong correlations with the rate of open magnetic flux ( $CC = 0.71$  between  $SYM-H$  and  $d\phi/dt$ ) and the reconnection electric field ( $CC = 0.66$  between  $SYM-H$  and  $E_{KL}$ ), indicating that the substorm activity mainly correlate with the dayside magnetic reconnection.

However, substorm activities have only a weak correlation with the solar wind velocity ( $CC = 0.37$  between  $AE$  and  $V_{sw}$ ) and moderate correlations with the Akasofu function ( $CC = 0.49$  between  $AE$  and  $\varepsilon$ ) and the convection electric field ( $CC = 0.5$  between  $AE$  and  $V_{sw} B$ ). Thus, the contribution of the solar wind velocity or the convection electric field is relatively small for the substorm activity.

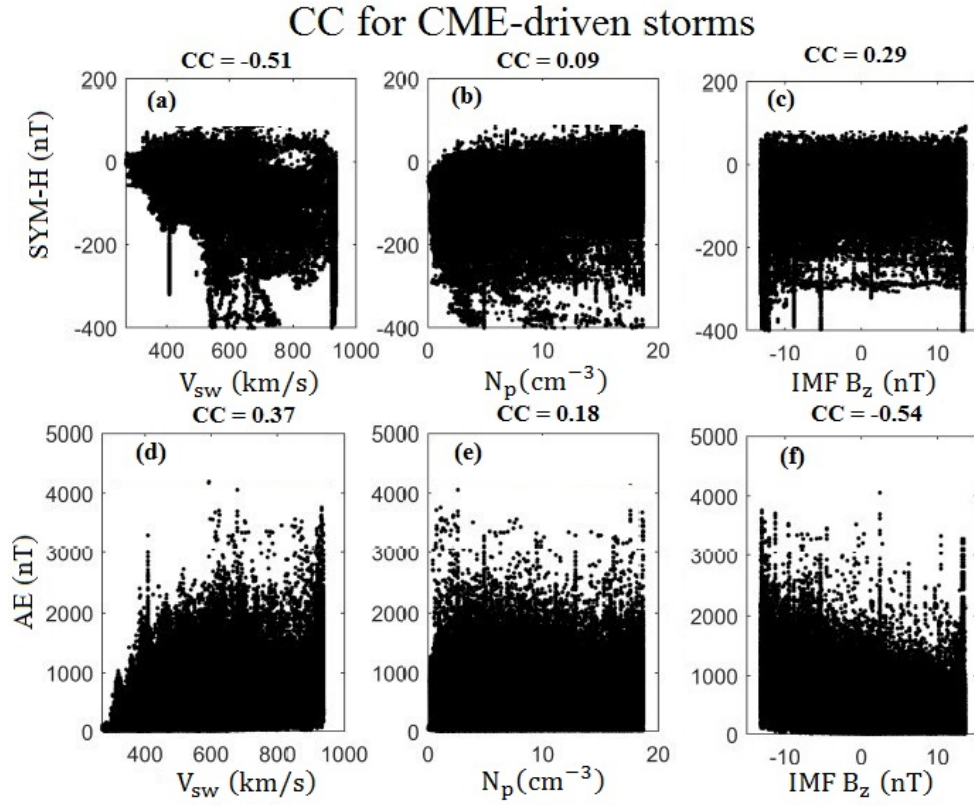


Figure 2. Correlation coefficients  $CC$  between geomagnetic indices  $SYM-H$ ,  $AE$ , and single solar wind parameters  $V_{sw}$ ,  $N_p$ ,  $IMF B_z$  during CME-driven storms

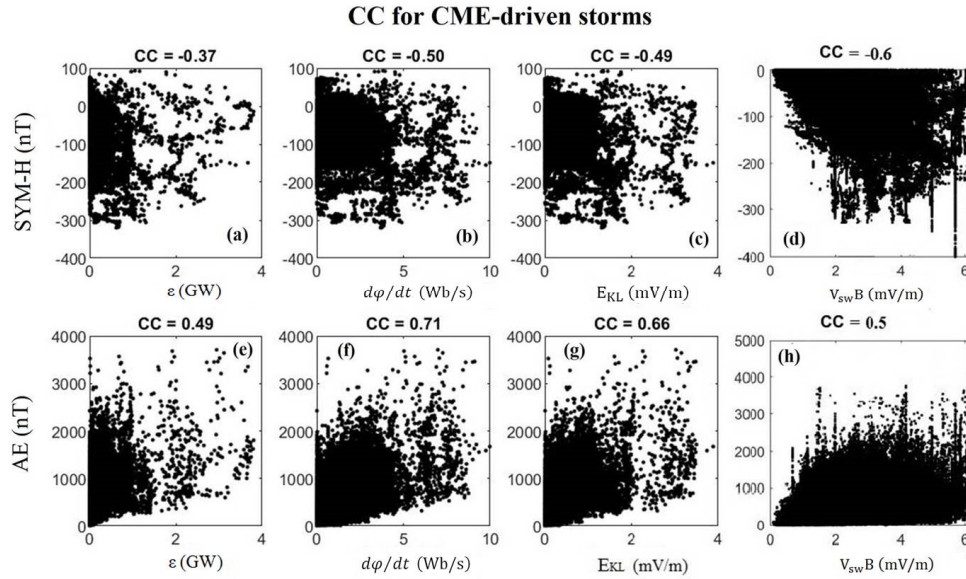


Figure 3. Correlation coefficients  $CC$  between geomagnetic indices and energy coupling functions during 131 CME-driven storms;  $\varepsilon$  is the Akasofu function;  $d\phi/dt$  is the rate at which a magnetic flux is opened at the dayside magnetopause;  $E_{KL}$  is the reconnection electric field;  $V_{sw}B$  is solar wind electric field

### Correlation for CIR-driven storms

Table lists correlation coefficients  $CC$  between geomagnetic indices  $SYM-H$ ,  $AE$ , single solar wind parameters  $V_{sw}$ ,  $N_p$ ,  $IMF B_z$ , and energy coupling functions for 161 CIR-driven storms and 131 CME-driven storms. The dependence of CIR-driven storms on the solar wind velocity ( $CC = -0.27$ ) and the convection electric field ( $CC = -0.48$ ) decreases in comparison with that of the CME-driven storms ( $CC = -0.51$  and  $-0.6$ ),

but their dependence on  $IMF B_z$  are nearly the same ( $CC = 0.29$  and  $0.28$ ). The dependence of the CIR-driven storms on the convection electric field ( $CC = -0.48$  between  $SYM-H$  and  $V_{sw}B$ ) is comparable to that on the rate of open magnetic flux ( $CC = -0.42$  between  $SYM-H$  and  $d\phi/dt$ ) and the reconnection electric field ( $CC = -0.44$  between  $SYM-H$  and  $E_{KL}$ ), indicating that the CIR-driven storms depend simultaneously on the convection electric field and the dayside magnetic reconnection.



During CIR-driven storms,  $AE$  has a moderate correlation with IMF  $B_z$  ( $CC=-0.56$ ) and strong correlations with the rate of open magnetic flux ( $CC=0.64$  between  $AE$  and  $d\phi/dt$ ) and the reconnection electric field ( $CC=0.64$  between  $AE$  and  $E_{KL}$ ), indicating that substorm activity is also closely associated with the dayside magnetic reconnection. However, the dependence of the substorm activity on the solar wind velocity and the convection electric field decreases remarkably during CIR-driven storms.

Correlation coefficients for CME and CIR-driven storms

CME-driven storms							
	$V_{sw}$	$N_p$	$B_z$	$\epsilon$	$d\phi/dt$	$E_{KL}$	$V_{sw}B$
<i>SYM-H</i>	-0.51	0.09	0.29	-0.37	-0.50	-0.49	-0.6
<i>AE</i>	0.37	0.18	-0.54	0.49	0.71	0.66	0.5
CIR-driven storms							
	$V_{sw}$	$N_p$	$B_z$	$\epsilon$	$d\phi/dt$	$E_{KL}$	$V_{sw}B$
<i>SYM-H</i>	-0.27	0.15	0.28	-0.39	-0.42	-0.44	-0.48
<i>AE</i>	0.08	0.14	-0.56	0.51	0.64	0.64	0.39

## DISCUSSION

The space parameter data and geomagnetic field indices provided on the Internet have different time resolutions such as 1 min, 5-min, and 1 hr. Badruddin et al. [2022] have studied the correlation coefficients of the solar wind parameters and IMF with geomagnetic field indices of 10 selected individual storms, using three time resolutions. The results show that the correlation coefficient between  $Dst$  (1-hour or smoothed data) and the solar wind parameters turns out to be higher than 0.5 only during the main phase of 50 % of storms. The results also suggest that the hourly development of geomagnetic storms during the main phase could not be unambiguously associated with a simultaneous change in solar wind parameters. High-resolution data may be helpful not only in understanding the physical processes during the development of a geomagnetic storm but also in predicting space weather.

Although there is no obvious correlation between the CME-driven storms and IMF  $B_z$  alone ( $CC=0.29$ ), the CME-driven storms have also moderate correlations ( $CC>0.4$ ) with the rate of open magnetic flux and the reconnection electric field (combined solar wind parameters). The dependence of the CME-driven storms ( $CC=-0.6$ ) is stronger on the convection electric field than the rate of open magnetic flux and the reconnection electric field ( $CC=-0.5, -0.49$ ). Thus, the contribution of the convection electric field to the CME-driven storms is likely to be larger than those of the dayside magnetic reconnection  $d\phi/dt$  and  $E_{KL}$ . However, the CIR-driven storms have nearly the same dependence on the three parameters ( $CC=-0.42, -0.44, -0.48$ ), thereby suggesting that the convection electric field and the dayside magnetic reconnection have nearly the same contributions to the development of CIR-driven storms.

During these storms, the substorm intensity relies largely on IMF  $B_z$ , the rate of open magnetic flux, and the reconnection electric field. The solar wind velocity or convection electric field contribution is relatively small for substorms. Although magnetospheric substorms mainly occur in the nightside magnetosphere [Baker et al., 1996; Duan et al., 2011] substorm activity

can promote the ring current through injections of hot and energetic particles as suggested by previous observations [He et al., 2016]. According to our statistical analysis, we found a moderate correlation between the intensity of substorms ( $AE$ ) and both CME-driven and CIR-driven storms (*SYM-H*), with correlation coefficients of  $-0.51$  and  $-0.5$  respectively.

This confirms that both substorms and enhanced convection contribute to enhancement of a storm-time ring current [Lui et al., 2001].

## SUMMARY AND CONCLUSIONS

By analyzing the correlation coefficients between geomagnetic indices *SYM-H*,  $AE$ , single solar wind parameters, and energy coupling functions for 131 CME-driven and 161 CIR-driven storms we have found that the CME-driven storms stronger depend on the solar wind velocity  $V_{sw}$  and the convective electric field  $V_{sw}B$  than other parameters, whereas the CIR-driven storms have nearly the same dependence on the solar wind electric field, the rate of open magnetic flux  $d\phi/dt$ , and the reconnection electric field  $E_{KL}$ . The different dependence indicates that the convection electric field driven by high-speed solar wind play a dominant role in the development of the CME-driven storms but the convection electric field contribution to the CIR-driven storms may be comparable to that of the dayside magnetic reconnection.

Interestingly, storms of the two types have moderate dependence on the substorm intensity  $AE$ , suggesting that substorm activity promotes the enhancement of geomagnetic storms to some extent. This conclusion is in line with the results obtained in [Gonzalez et al., 1994; Boroyev, Vasiliev, 2020]. The substorm intensity relies strongly on IMF  $B_z$ , rate of open magnetic flux, and reconnection electric field, but their dependence on the solar wind velocity and the solar wind electric field are relatively weak. This indicates that the dayside magnetic reconnection plays a crucial role in the solar wind energy transfer to Earth's magnetosphere and the energy storage and release in the magnetotail during substorms.

The data sets for this study were obtained from the OMNI database [[https://omniweb.gsfc.nasa.gov/form/omni\\_min.html](https://omniweb.gsfc.nasa.gov/form/omni_min.html)]. We sincerely acknowledge all teams for the OMNI database. We also thank Center for Space Magnetism, Kyoto University for providing  $Dst$  index data.

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