

Statistical study of ICMEs and their geoeffectiveness during the rising phases of Solar Cycles 23, 24, and 25

XinYue Chen¹, ChengLong Shen^{2,3*}, YuTian Chi^{4,5*}, DongWei Mao¹, ZhiYong Zhang¹, JunYan Liu¹, ChenXi Zhai¹, and YuMing Wang^{2,3}

¹CAS Key Laboratory of Geospace Environment, Department of Geophysics and Planetary Sciences, University of Science and Technology of China, Hefei 230026, China;

²Deep Space Exploration Laboratory/School of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, China;

³CAS Center for Excellence in Comparative Planetology, University of Science and Technology of China, Hefei 230026, China;

⁴Institute of Deep Space Sciences, Deep Space Exploration Laboratory, Hefei 230026, China;

⁵National Key Laboratory of Deep Space Exploration, Hefei 230000, China

Key Points:

- Although the sunspot numbers during the rising phase of Solar Cycle 25 are more comparable to those of Solar Cycle 23 and clearly higher than those of Solar Cycle 24, the numbers of ICMEs (Interplanetary Coronal Mass Ejections) and ICME groups during the rising phase of Solar Cycle 25 appear more similar to those of Solar Cycle 24.
- The numbers of geomagnetic storms and intense geomagnetic storms during Solar Cycle 25 are intermediate between those of the previous two cycles, which is consistent with the overall level of solar activity.
- The average values of the magnetic field strength, southward magnetic field component, and dawn–dusk electric field of ICMEs during Solar Cycle 25 are the highest among the three periods. These parameters are key factors influencing the geoeffectiveness of ICMEs.

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Abstract: As Solar Cycle 25 appears to approach the declining phase, to objectively evaluate the activity intensity during its rising phase and conduct a comparative analysis, we extend the catalog of Interplanetary Coronal Mass Ejections (ICMEs) from 2016 to 2025. Subsequently, we systematically compare and analyze the parameter characteristics and geoeffectiveness of ICMEs during the rising phase of Solar Cycle 25 with those of the previous two solar cycles. Overall, from 1995 to 2025, we identify 657 ICME events, which are classified into 530 groups and are associated with a total of 325 geomagnetic storms, including 103 intense geomagnetic storms. The annual occurrence frequencies of ICMEs, the number of ICME groups and their associated geomagnetic storms are largely synchronized with the variations in sunspot numbers. The sunspot numbers during the rising phase of Solar Cycle 25 are comparable to those of Solar Cycle 23 and clearly higher than those of Solar Cycle 24. Compared with the previous two solar cycles, Solar Cycle 25 exhibits the smallest number of ICMEs during its rising phase. The numbers of geomagnetic storms and intense geomagnetic storms during this period fall between those of the two preceding cycles, consistent with the overall variation in solar activity. Although the number of intense geomagnetic storms during the rising phase of Solar Cycle 25 is relatively small, their intensities are remarkably high, with several extremely intense storm events observed. During the rising phase of Solar Cycle 25, the average values of the magnetic field strength, southward magnetic field component, and dawn–dusk electric field of ICMEs are the highest among the three periods. They are key parameters influencing the geoeffectiveness of ICMEs. Overall, the geoeffectiveness of ICMEs during the rising phase of Solar Cycle 25 is intermediate between those of the previous two cycles.

Keywords: Interplanetary Coronal Mass Ejections; geomagnetic storms; geoeffectiveness

First author: X. Y. Chen, chenxinyue@mail.ustc.edu.cn

Correspondence to: C. L. Shen, clshen@ustc.edu.cn

Y. T. Chi, ytchi@mail.ustc.edu.cn

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1. Introduction

Coronal mass ejections (CMEs) are massive eruptions of magnetized plasma from the solar atmosphere propagating into the heliosphere, during which a large amount of mass and energy is released into the interplanetary medium (Howard et al., 1985; St. Cyr et al., 2000; Gopalswamy, 2006). The interplanetary counter-

parts of CMEs are known as the interplanetary coronal mass ejections (ICMEs) (Plunkett et al., 2001; Russell et al., 2005). ICMEs can be identified from in-situ observations using the following criteria: enhanced magnetic field strength, smooth rotation of the magnetic field direction, relatively low proton temperature, low proton plasma β , bidirectional flows of electrons and low-energy protons, high ion charge states and compositional anomalies, low charge states, singly charged He^+ , bidirectional flows of cosmic-ray energetic (1 MeV) particles, bidirectional solar wind electron heat flux events (BDEs), and one- or two-step Forbush decreases as observed by ground-based instruments (Wu and Lepping, 2011). When an ICME arrives at Earth, its southward magnetic field component can trigger magnetic reconnection on the dayside magnetosphere, opening closed magnetic field lines and allowing the direct injection of solar wind momentum, energy, and energetic particles into the magnetosphere. This process can lead to severe geomagnetic disturbances, disrupt the near-Earth space environment, and pose significant threats to both space-based and ground-based technological systems (Gonzalez et al., 1994; Lakhina and Tsurutani, 2016; Gonzalez et al., 1999; Feynman and Gabriel, 2000; Huttunen et al., 2005). Therefore, investigating the parameters of ICMEs, as well as their geoeffectiveness, is of great importance for advancing space weather forecasting.

Many studies have systematically analyzed the geoeffectiveness of ICMEs during Solar Cycles 23 and 24. Alexakis and Mavromichalaki (2019) performed a detailed study on the geoeffectiveness of 502 ICMEs from 1996 to 2017 and confirmed that the southward magnetic field component and the dawn–dusk electric field were the most critical factors in causing geomagnetic storms. Lawrance et al. (2020) examined the relationships between ICME characteristics and geoeffectiveness during the declining phases of Solar Cycles 23 and 24, finding that ICMEs appeared to be more geoeffective in the declining phase than in the rising phase. Sun XY et al. (2024) investigated the interplanetary origins of 384 geomagnetic storms from 1996 to 2023 and performed a statistical analysis of the correlations between storm intensity and various solar wind parameters. Zhang ZY et al. (2023) compared the number and key parameters of ICMEs during Solar Cycles 23 and 24. In addition, a velocity-corrected cylindrical force-free flux rope model was applied to fit I-ICME events, and the fitted parameters, including the total magnetic flux, flux rope radius, and axial magnetic field strength, were systematically compared. They concluded that the weaker geomagnetic activity during Solar Cycle 24 relative to Solar Cycle 23, can be attributed to the smaller number of M-ICMEs, the lower propagation speeds of ICMEs, and the absence of ICME events with significant southward magnetic fields during Solar Cycle 24.

As Solar Cycle 25 appears to approach the declining phase, renewed attention has been drawn to the geoeffectiveness of ICME events during this cycle. Many research results have predicted that the peak sunspot number of Solar Cycle 25 is significantly higher than that of Solar Cycle 24, yet remains lower than that of Solar Cycle 23 (Prasad et al., 2022; McIntosh et al., 2023). In recent years several intense geomagnetic storms have indeed been observed (Tulasi Ram et al., 2024; Pierrard et al., 2025; Kumar et al., 2025). These developments naturally raise an impor-

tant question: how geoeffective are ICME events in Solar Cycle 25 compared with those in previous cycles? A systematic investigation of the ICME–geomagnetic storm relationship during Solar Cycle 25 is therefore timely and necessary, providing an opportunity to assess whether the geoeffectiveness of ICMEs follows the expected solar cycle dependence or exhibits distinct characteristics in the current cycle.

To investigate the geoeffectiveness of ICMEs during Solar Cycle 25, we need to expand the existing ICME event list to 2025. Section 2 describes the methods for identifying and classifying ICMEs and the geomagnetic storms caused by ICME groups. Section 3 discusses the annual distributions of the numbers of ICMEs, ICME groups, and geomagnetic storms caused by ICME groups. Based on the ICME catalog from 1995 to 2025, Section 4 compares the parameter characteristics and geoeffectiveness of ICMEs in the rising phase of Solar Cycles 23, 24 and 25. Section 5 examines the distributions of the occurrence frequency and intensity of geomagnetic storms caused by ICMEs during different solar cycles. Finally, Section 6 presents the conclusion and discussion.

2. ICME's Identification and Classification

Different studies have adopted various criteria for identifying ICMEs, leading to discrepancies in the identified events. In this study, we follow the method of Chi YT et al. (2016) and use the following criteria to identify ICMEs: i) enhanced magnetic field strength, ii) smooth rotation of the magnetic field direction, iii) decreasing solar wind speed, iv) low proton temperature, v) low proton plasma β , and vi) bidirectional electron flows. A structure is identified as an ICME when it meets at least three of the above criteria. The boundaries of an ICME are determined based on the obvious changes or discontinuities in the corresponding solar wind parameters.

Figure 1 shows two examples of ICMEs, the light purple shaded area marks the ejection region of the ICME structure. The left panel presents a non-MC ICME with a shock, characterized by a decrease in solar wind speed, low proton temperature, and low plasma β . The red vertical line marks the shock driven by this ICME. After the shock, the magnetic field strength, solar wind speed, proton number density, and proton temperature increase significantly. The right panel shows a typical MC, which exhibits enhanced magnetic field strength, a large and smooth rotation of the magnetic field vector, and low values of proton temperature and plasma β . We identified a total of 657 ICME events between 1 January 1995 and 31 December 2025. Among them, 250 events (38%) are classified as MCs, and 300 events (46%) are associated with upstream shocks.

Richardson and Cane's catalog (RC catalog) (Richardson and Cane, 2010) is fairly comprehensive and has been updated to November 7, 2025, thus we compared our catalog with the RC catalog. During the period from January 1996 to October 2025, our catalog contains 638 ICMEs, while the RC catalog contains 619 ICMEs. There are 498 overlapping ICME events between these two catalogs. This means that approximately 78% of the events in our catalog are recorded in the RC catalog, and similarly, about 80% of the events in the RC catalog are listed in our catalog. These results

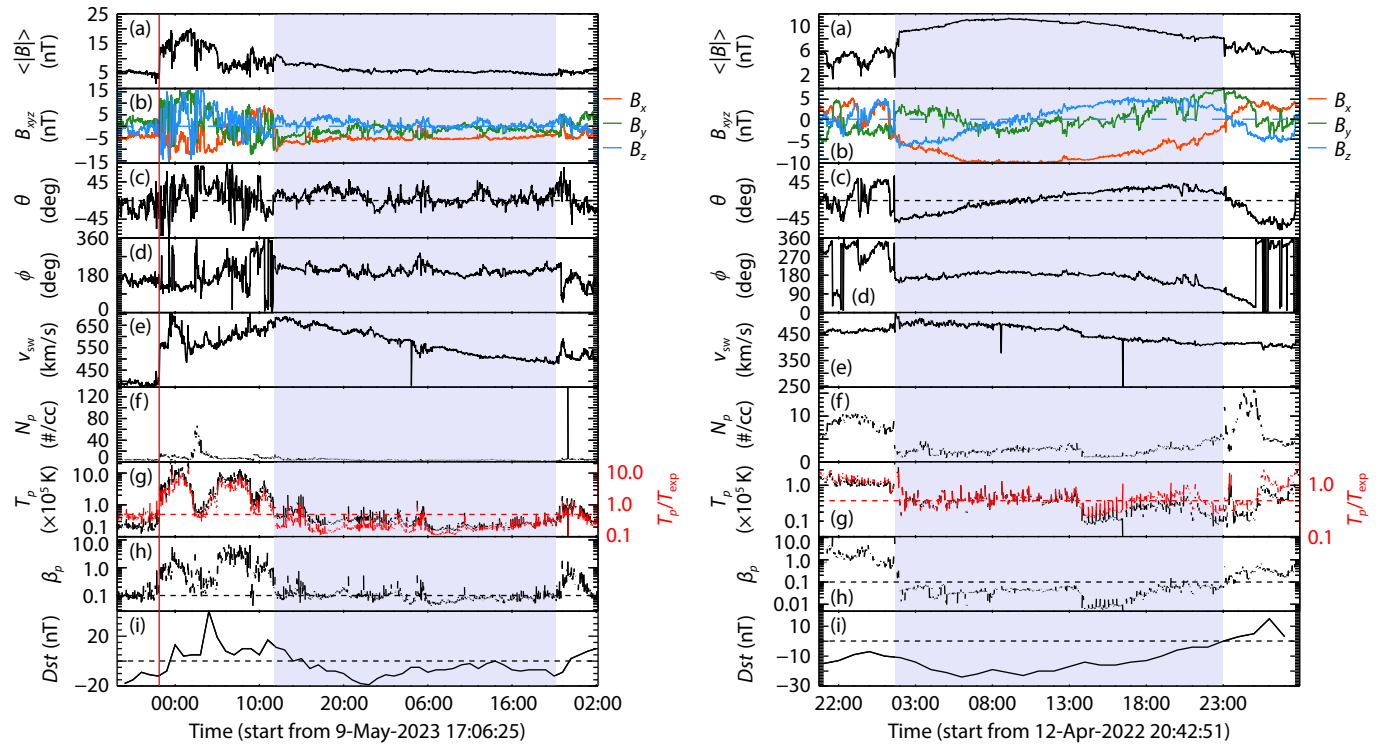


Figure 1. Two examples of ICMEs: the left one is a non-MC ICME with a shock, and the right one is an MC. From top to the bottom, they are the magnetic-field strength $\langle B \rangle$, the vector magnetic field in Geocentric Solar Ecliptic (GSE) coordinate system, the elevation θ and azimuth ϕ of field direction in GSE coordinate system from *Wind*, solar-wind speed v , proton density N_p , proton temperature T_p , and the ratio of proton thermal pressure to magnetic pressure β from *Wind* observations. The last panel indicates the Dst index. The light purple shaded area marks the ejection region of the ICME structure. The red vertical line marks the shock driven by the ICME.

indicate a high degree of consistency between the two catalogs.

Previous studies have shown that the interaction between multiple CMEs can enhance the magnetic field in the ICMEs (Wang YM et al., 2003b; Lugaz et al., 2017; Shen CL et al., 2018; Chi YT et al., 2018; Shen CL et al., 2021). As a special type of multiple ICMEs interaction, the interaction between previous ICMEs and following shocks can also significantly enhance the southward magnetic field component in the ICMEs (Wang YM et al., 2003a; Xu MJ et al., 2019; Liu YD et al., 2020; Scolini et al., 2020; Chi YT et al., 2020). Therefore, when studying the geoeffectiveness of ICMEs, we cannot focus solely on individual ICMEs. Instead, it is necessary to categorize ICMEs into groups based on whether they interact with each other. According to the criteria from Shen CL et al. (2017), all ICME events observed by the *Wind* spacecraft can be divided into two categories: Isolated-ICME (I-ICME) groups and Multiple-ICMEs (M-ICMEs) groups. When the time interval between two or more ICMEs is less than 6 hours, or when the shock driven by a subsequent ICME propagates into the ejection region of a preceding ICME, they are grouped together as an M-ICMEs group. Following their classification criteria, we categorize a total of 657 ICME groups observed between 1995 and 2025 into 530 groups, with the following distribution: 425 groups (80%) are I-ICME groups, 105 groups (20%) are M-ICMEs groups.

Figure 2 presents three typical examples of I-ICMEs and M-ICMEs. The upper-left panel shows an I-ICME group that occurred on 23–24 April 2023. This ICME exhibited a clear MC structure and

lasted for 18 hours. The shock driven by this ICME was first recorded at 17:02 UT on 23 April 2023. About eight hours later, the main body of the ICME reached Earth. No other ICMEs were recorded by the *Wind* spacecraft within six hours before or after this event. Therefore, it was classified as an I-ICME group. The southward magnetic field components in the sheath region and MC region of this ICME caused an extremely intense geomagnetic storm, with the Disturbance Storm Time (Dst) index peaking at -213 nT. The upper-right panel shows an M-ICMEs group that occurred on 7–8 October 2024, in which case there were interactions between these ICMEs. In this case, the first ICME lasted from 07:30 to 20:05 UT on 7 October 2024. Approximately 2.5 hours later, another ICME was detected, lasting about 12.5 hours. Between these two ICMEs, in situ observations revealed a distinct interaction region characterized by low magnetic field intensity, increased proton number densities, and enhanced proton temperatures. This M-ICMEs group caused an intense geomagnetic storm, with the Dst index reaching a peak value of -148 nT. The lower panel shows an M-ICMEs group that occurred on 18–19 September 2023, in which case the preceding ICME interacted with the shock. The first ICME lasted from 01:51 to 15:51 UT on 18 September 2023 and exhibited distinct MC characteristics. A shock driven by the second ICME was detected at 12:51 UT on 18 September 2023, indicating that the shock had propagated into the ejecta region of the first ICME. This shock compressed the first ICME, significantly enhancing its magnetic field strength, solar wind speed, proton density, and proton temperature. In the shock-

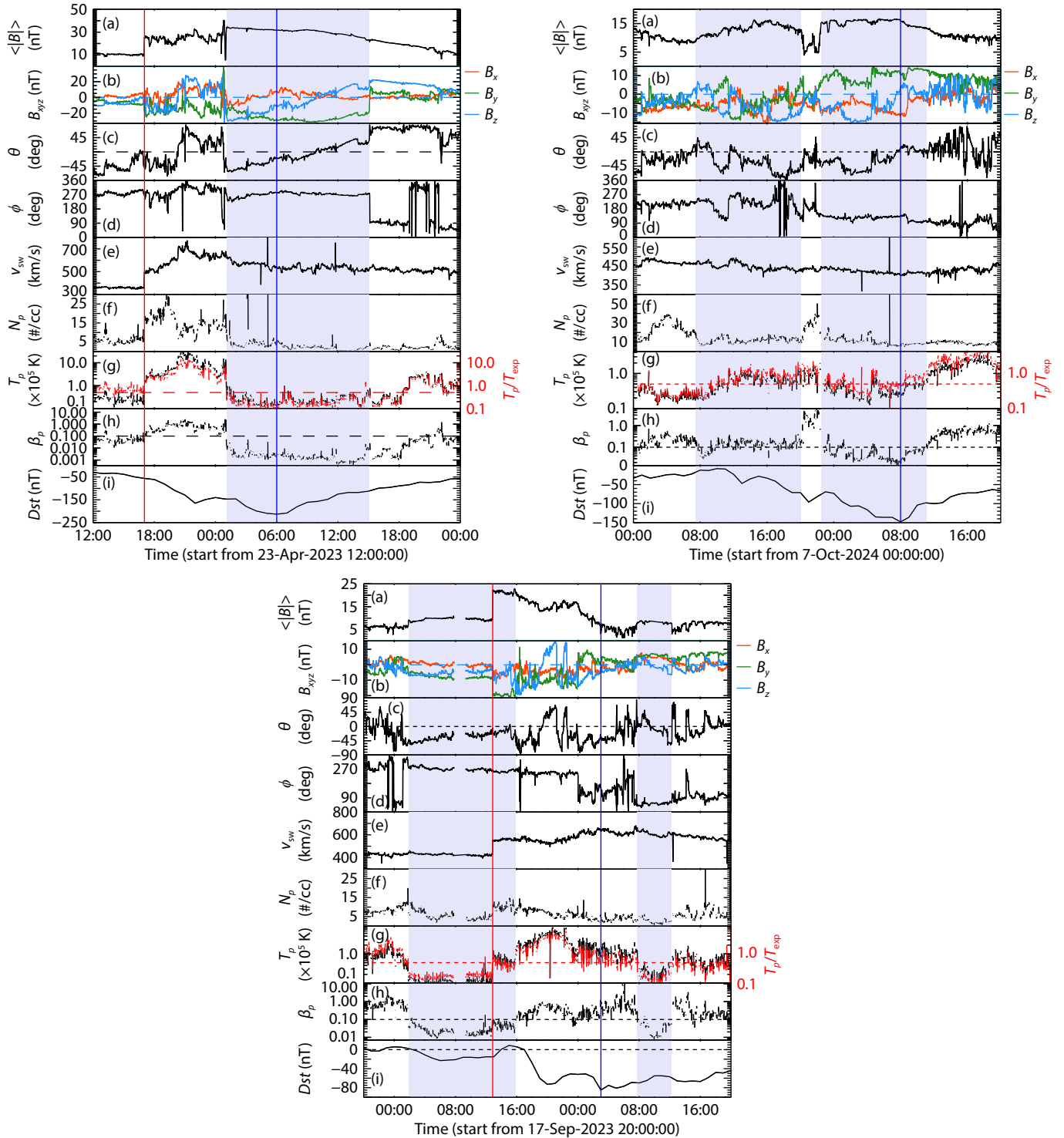


Figure 2. Three typical examples of I-ICMEs and M-ICMEs. The panels are the same as in Figure 1. The light purple shaded area marks the ejection region of the ICME structure. The red vertical line shows the time of the shock driven by the ICME. The blue vertical line shows the peak time of the Dst index.

sheath region of the second ICME, the Dst index peaked at -85 nT. This M-ICMEs group caused a moderate geomagnetic storm.

To investigate the geoeffectiveness of ICME groups, we utilized the Dst index provided by the WDC to determine whether an ICME group caused a geomagnetic storm. According to the defini-

tion of Shen CL et al. (2017), an ICME group was considered associated with a geomagnetic storm if the storm's main phase correlated with the ICME group, the peak Dst time aligned closely with the end of the group, and no subsequent structures significantly influenced the storm's main phase. If the minimum Dst index (Dst_{min}) associated with the ICME group is less than or equal to

–30 nT, the ICME group is deemed to have caused a geomagnetic storm. Among 530 ICME groups, 325 (61%) caused geomagnetic storms, including 86 (26%) weak geomagnetic storms ($-50 < Dst_{min} \leq -30$ nT), 136 (42%) moderate geomagnetic storms ($-100 < Dst_{min} \leq -50$ nT), and 103 (32%) intense geomagnetic storms ($Dst_{min} \leq -100$ nT). Most (74%) of the geomagnetic storms caused by ICME groups were moderate or intense geomagnetic storms.

Table 1 presents the numbers and proportions of different levels of geomagnetic storms caused by different types of ICME groups. The proportions of I-ICMEs and M-ICMEs responsible for geomagnetic storms, weak geomagnetic storms and moderate geomagnetic storms are all close to 4:1, which is consistent with the overall distribution of I-ICMEs and M-ICMEs among all ICME groups. The last row of Table 1 reveals that 46% of intense geomagnetic storms are caused by M-ICMEs groups. This proportion is much higher than those for all ICME groups (20%), all geomagnetic storms (26%), weak geomagnetic storms (20%), and moderate geomagnetic storms (16%). This indicates that M-ICMEs are more likely to cause intense geomagnetic storms, in agreement with previous studies (Lugaz et al., 2015; Shen CL et al., 2017; Xu MJ et al., 2019).

3. Annual Distributions of the Numbers

Panel (a) in Figure 3 displays the annual occurrence frequency of ICMEs and the yearly average sunspot number from 1995 to 2025. The correlation coefficient of them is 0.79, which shows a good correlation. A comparison of the peak sunspot numbers indicates that the overall intensity of Solar Cycle 25 is lower than that of Solar Cycle 23 but significantly higher than that of Solar Cycle 24. Panel (b) in Figure 3 displays the annual numbers of different ICME types. The panel shows that most M-ICMEs occurred around solar maximum periods. During the late rising, maximum, and early declining phases of Solar Cycles 23, 24, and 25 (specifically, 1998–2005, 2011–2015, and 2022–2025), a total of 91 M-ICMEs were recorded, accounting for 87% of the total M-type groups. During solar minimum periods, very few M-ICMEs were observed. Specifically, no M-ICME events were recorded at 1 AU during the periods from 2006 to 2009 and from 2020 to 2021.

Panel (c) in Figure 3 show the annual numbers of geomagnetic storms and intense geomagnetic storms caused by ICME groups. The analysis indicates that the variations in the number of geomagnetic storms and intense geomagnetic storms exhibit a synchronous trend with the changes in sunspot numbers. Specifically, during the rising phase of the solar cycle, the numbers of geomagnetic storms and intense geomagnetic storms caused by ICME groups increase significantly. While during the declining phase, the numbers decrease markedly. In the periods of 2006–

2009 and 2020–2021, no intense geomagnetic storms occurred. Furthermore, the numbers of geomagnetic storms and intense geomagnetic storms caused by ICME groups during the solar maximum are significantly higher than those during the solar minimum. The correlation coefficients between sunspot numbers and the number of geomagnetic storms, the number of intense geomagnetic storms are 0.77 and 0.73 respectively. These results confirm that the annual number of geomagnetic storms is influenced by solar activity, consistent with the findings of Hajra et al. (2021). Notably, Qiu SC et al. (2022) reported that during Solar Cycle 24, the annual distributions of geomagnetic storms and sunspot numbers both exhibit a double-peak structure, with a positive correlation between them. Consistently, panel (c) in Figure 3 shows that the numbers of geomagnetic storms and intense geomagnetic storms caused by ICME groups also display a double-peak distribution during Solar Cycle 24, with peaks in 2012 and 2015.

4. The Comparison of the Parameters

For all ICME events, we calculated the average values of magnetic field strength $\langle B \rangle$, southward magnetic field component $\langle B_s \rangle$, solar wind speed $\langle v \rangle$, dawn-dusk electric field $\langle vB_s \rangle$, proton temperature $\langle T_p \rangle$, and proton number density $\langle N_p \rangle$ in both the ejecta and sheath regions. The updated data are available on the website (http://space.ustc.edu.cn/dreams/wind_icmes/index.php).

Currently, we are in the maximum phase of Solar Cycle 25. To compare geomagnetic activity across different solar cycles, we selected three comparable intervals from Solar Cycles 23, 24 and 25. According to the smoothed monthly mean sunspot number minima published by the SILSO, Solar Cycles 22, 23 and 24 ended in August 1996, December 2008, and December 2019, respectively. We define the subsequent month as the beginning of Solar Cycles 23, 24 and 25. For Solar Cycle 23 (September 1996–December 2008), the interval from 1 September 1996 to 31 August 2002 was chosen as the first period, denoted as Period I. For Solar Cycle 24 (January 2009–December 2019), the interval from 1 January 2009 to 31 December 2014 was chosen as the second period, denoted as Period II. For Solar Cycle 25 (January 2020–present), the interval from 1 January 2020 to 31 December 2025 was chosen as the third period, denoted as Period III. Each period corresponds to the first six years after the start of the respective solar cycle.

Figures 4 and 5 display the distributions of magnetic field and solar wind plasma parameters within the ejecta regions of all ICMEs and of the ICMEs that caused geomagnetic storms during Periods I, II, and III respectively. Panels (a)–(f) display the distribu-

Table 1. The numbers and percentages of different ICME groups that caused different geomagnetic storms.

	I-ICMEs	M-ICMEs	Total
All groups	425(80%)	105(20%)	530
Geomagnetic storms	240(74%)	85(26%)	325
Weak geomagnetic storms	69(80%)	17(20%)	86
Moderate geomagnetic storms	115(84%)	21(16%)	136
Intense geomagnetic storms	56(54%)	47(46%)	103

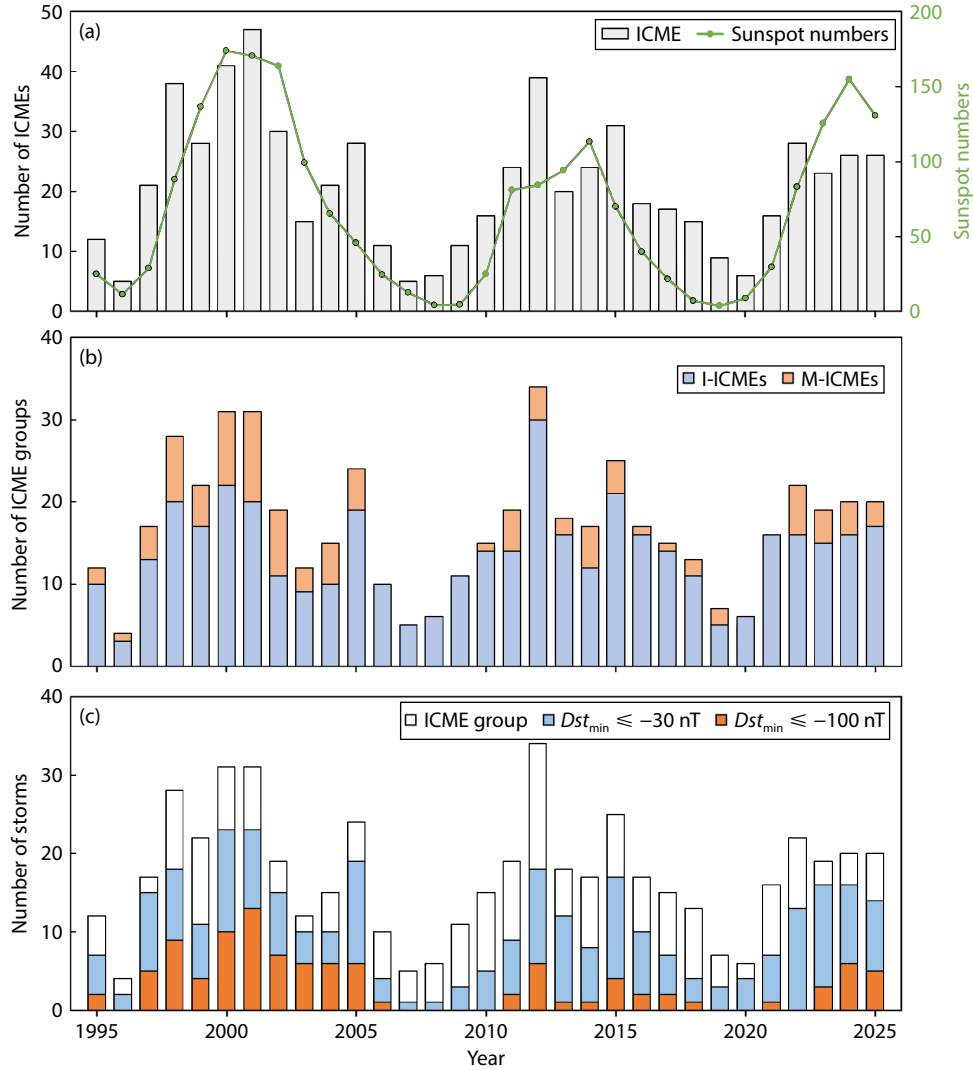


Figure 3. (a) The yearly occurrence frequency of ICMEs (grey bars). The green line and symbols show the yearly average sunspot numbers. (b) The annual number of different ICME types from 1995 to 2025. The light blue and light orange bars show the numbers of I-ICMEs and M-ICMEs groups respectively. (c) The solar cycle variation of the annual numbers of geomagnetic storms (blue bars) and intense geomagnetic storms (orange bars) caused by ICME groups (white bars).

Table 2. The overall average values of the ejection region parameters for all ICMEs and ICMEs that caused geomagnetic storms across different periods.

	All ICMEs			Storm-driving ICMEs		
	Period I	Period II	Period III	Period I	Period II	Period III
B (nT)	12.02	9.57	12.92	13.09	11.35	14.34
B_s (nT)	4.87	3.80	5.38	5.86	5.44	6.42
vB_s (mV/m)	2.32	1.56	2.91	2.76	2.19	3.56
v (km/s)	453	411	463	464	434	481
T_p (10^5 K)	0.68	0.41	0.48	0.74	0.56	0.49
N_p (cm^{-3})	6.95	6.26	6.79	6.88	7.06	6.84

tions of $\langle B \rangle$, $\langle B_s \rangle$, $\langle v \rangle$, $\langle vB_s \rangle$, $\langle T_p \rangle$, and $\langle N_p \rangle$ respectively. The arrows at the top of each panel indicate the overall average values for the corresponding period, with the specific numerical values listed in

Table 2. The parameter distributions in Figures 4 and 5 exhibit several common characteristics as follows:

- Except for $\langle T_p \rangle$, the average values of all parameters in Period II

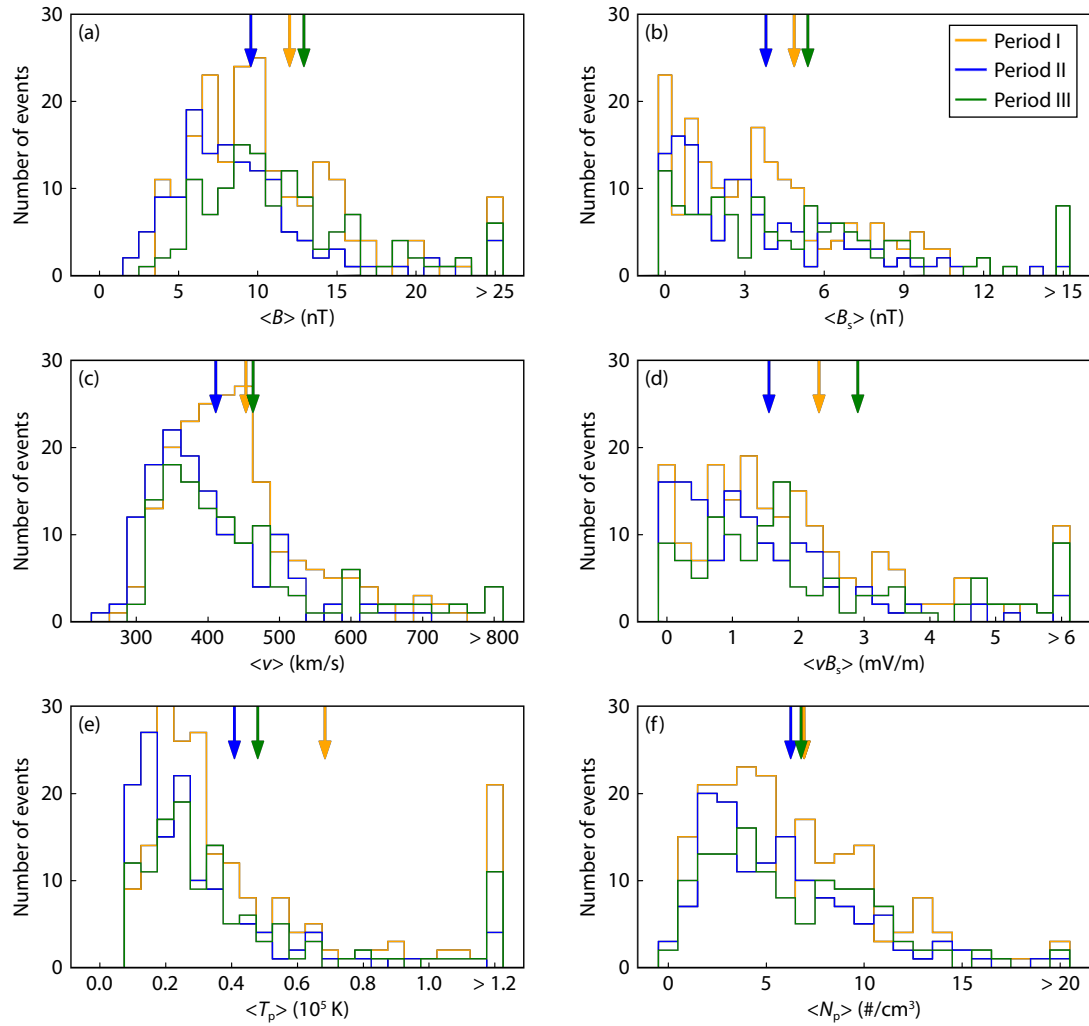


Figure 4. Comparison of the parameters between the ejecta regions of ICMEs during Period I, II, and III. The blue, orange and green arrows show the average values for the ICME ejecta regions during Period I, II, and III respectively.

are the smallest among the three periods. This is consistent with the generally lower level of solar activity during Solar Cycle 24.

- In the low-value ranges of $\langle B \rangle$ (< 15 nT), $\langle B_s \rangle$ (< 6 nT), and $\langle vB_s \rangle$ (< 3 mV m $^{-1}$), the number of events in Period I is significantly larger than that in Periods II and III. In the high-value ranges of these parameters, the number of events in Period III is comparable to that in Period I and considerably larger than that in Period II. The average values of $\langle B \rangle$, $\langle B_s \rangle$, and $\langle vB_s \rangle$ in Period III are the highest among the three periods. Although Period III contains the fewest ICMEs, it has a larger proportion of high-intensity events, leading to stronger average magnetic field strength, southward magnetic field component, and dawn–dusk electric field. This suggests that during Solar Cycle 25, despite the overall weaker solar activity, the magnetic structures of ICMEs may be more efficient in generating geoeffectiveness.

- The distributions of $\langle v \rangle$ are concentrated around 400 km/s. The average solar wind speeds across the three periods are similar, all close to the typical solar wind value (440 km/s). The average $\langle v \rangle$ in Period I is slightly lower than that in Period III and higher than that in Period II.

- The average value of $\langle T_p \rangle$ in period I is significantly higher than those in periods II and III. The average values of $\langle N_p \rangle$ in period I, II and III are very close.

Comparing Figures 4 and 5, we find that in the high-value ranges of $\langle B \rangle$, $\langle B_s \rangle$, and $\langle vB_s \rangle$, the number of ICMEs that cause geomagnetic storms remains nearly unchanged relative to all ICMEs. However, in the low-value ranges of these parameters, the number of ICMEs that cause geomagnetic storms decreases markedly. This indicates that the higher the magnetic-field-related parameters of an ICME, the greater its likelihood of causing a geomagnetic storm. The Table 2 also shows that the average values of $\langle B \rangle$, $\langle B_s \rangle$, and $\langle vB_s \rangle$ of ICMEs that cause geomagnetic storms are significantly higher than those of all ICMEs, demonstrating that these parameters are key factors influencing the geoeffectiveness of ICMEs.

To further quantitatively investigate the effects of $\langle B_s \rangle$ and $\langle vB_s \rangle$ on the occurrence probability and intensity of geomagnetic storms, we calculated the number of ICMEs within different $\langle B_s \rangle$ and $\langle vB_s \rangle$ intervals, as well as the numbers of geomagnetic storms with different intensities caused by these ICMEs. Figure 6 shows the probabilities of ICMEs causing geomagnetic storms of different

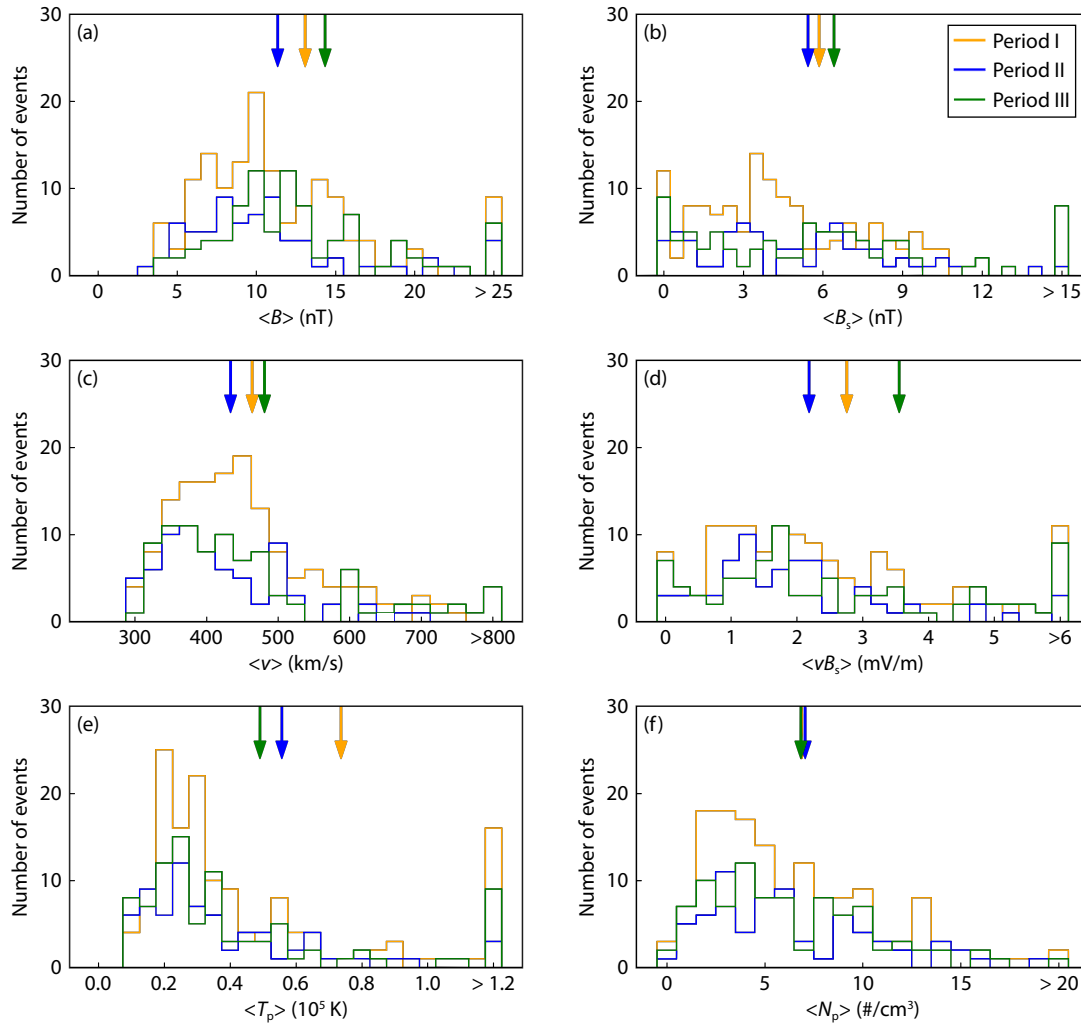


Figure 5. Comparison of the parameters between the ejecta regions of ICMEs that cause geomagnetic storms during Period I, II, and III. The orange, blue and green arrows show the average values for the ICME ejecta regions during Period I, II, and III respectively.

intensities within different $\langle B_s \rangle$ and $\langle vB_s \rangle$ intervals. The overall distribution of the number of ICMEs is indicated by the black dots and solid line. The results show that, for ICMEs with $\langle B_s \rangle$ values between 2–3 nT, the probability of generating a geomagnetic storm exceeds 50%, and the probability of producing an intense geomagnetic storm is about 20%. When $\langle B_s \rangle$ is in the range of 8–10 nT, the probability of generating a geomagnetic storm reaches 100%, and the probability of generating intense geomagnetic storms exceeds 50%. When $\langle B_s \rangle$ is greater than 16 nT, the probability of generating intense geomagnetic storms reaches 100%. For ICMEs with $\langle vB_s \rangle$ values between 1–1.5 mV m^{-1} , the probability of generating geomagnetic storms exceeds 60%, and the probability of generating intense geomagnetic storms is about 18%. When $\langle vB_s \rangle$ is in the range of 6–8 mV m^{-1} , the probability of generating geomagnetic storms reaches 100%, and the probability of generating intense geomagnetic storms exceeds 80%. When $\langle vB_s \rangle$ is greater than 8 mV m^{-1} , the probability of generating intense geomagnetic storms reaches 100%.

Furthermore, we performed a correlation analysis between ICME parameters and the $Dst_{\min}$. The results indicate that the maximum values of $\langle B_s \rangle$ and $\langle vB_s \rangle$ exhibit strong correlations with $Dst_{\min}$,

with correlation coefficients of -0.81 and -0.82 respectively. The mean values of $\langle B_s \rangle$ and $\langle vB_s \rangle$ are also well correlated with $Dst_{\min}$, with correlation coefficients of -0.70 and -0.78 respectively, both of which are smaller than those corresponding to the maximum values. These results further confirm previous studies that, due to the magnetic reconnection between the solar wind magnetic field and the magnetosphere, $\langle B_s \rangle$ and $\langle vB_s \rangle$ play crucial roles on space weather effects (Tsurutani and Gonzalez, 1997; Ji et al., 2010; Paouris and Mavromichalaki, 2017). In general, the stronger the southward magnetic field component and the dawn–dusk electric field within an ICME, the higher the probability of it causing a geomagnetic storm, and the greater the storm intensity.

5. The Comparison of the Geoeffectiveness

The numbers of ICMEs, ICME groups, geomagnetic storms, weak geomagnetic storms, moderate geomagnetic storms and intense geomagnetic storms in Solar Cycles 23 and 24, as well as in Periods I, II, and III, are listed in Table 3. During Solar Cycle 23, a total of 293 ICME events occurred, forming 221 ICME groups. During Solar Cycle 24, 224 ICME events occurred, forming 191 ICME groups, representing decreases of 24% and 14% respectively relative to

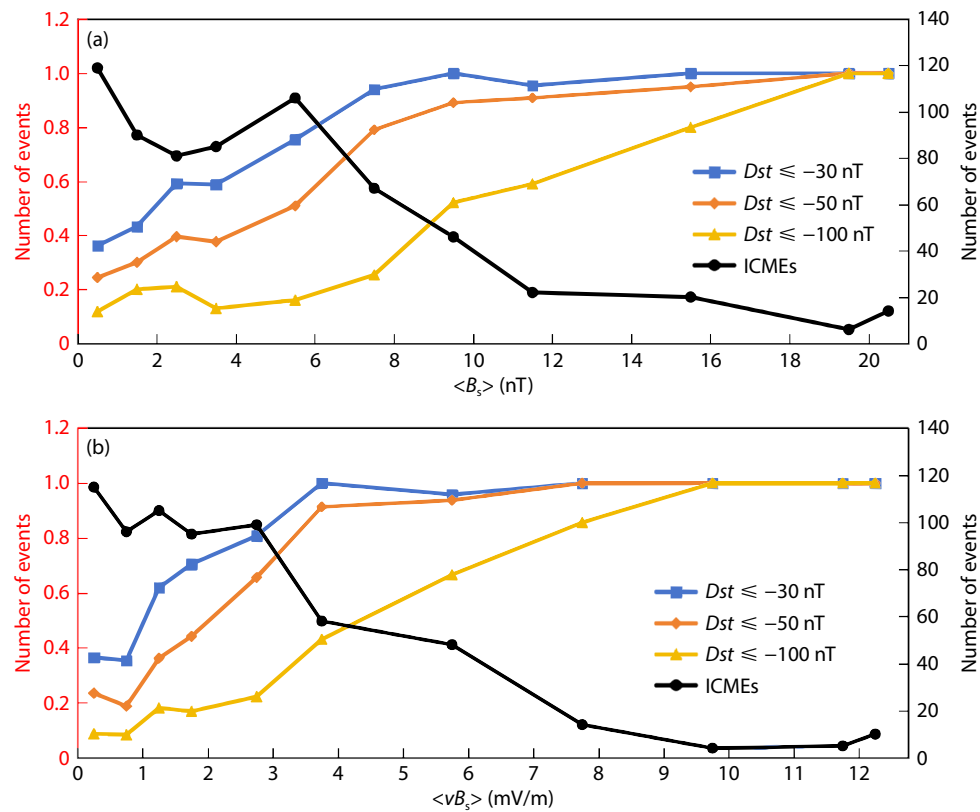


Figure 6. Probability distributions of ICMEs causing geomagnetic storms of different intensities in different $\langle B_s \rangle$ (upper panel) and $\langle vB_s \rangle$ (lower panel) ranges. The black circles and solid lines denote the numbers of ICMEs. The blue, orange, and yellow circles and lines represent the percentages of geomagnetic storms with $Dst \leq -30$ nT, $Dst \leq -50$ nT, and $Dst \leq -100$ nT caused by ICMEs respectively.

Table 3. Comparison of similar periods in different Solar Cycles.

	Solar Cycle 23	Solar Cycle 24	Period I	Period II	Period III
ICMEs	293	224	198	134	125
ICME groups	221	191	141	114	103
Geomagnetic storms	151	96	100	55	70
Weak geomagnetic storms	33(22%)	35(36%)	22(22%)	17(31%)	17(24%)
Moderate geomagnetic storms	51(34%)	42(44%)	33(33%)	28(51%)	38(54%)
Intense geomagnetic storms	67(44%)	19(20%)	45(45%)	10(18%)	15(22%)

Solar Cycle 23. In Period I, there were 198 ICMEs forming 141 ICME groups. In Period II, 134 ICMEs formed 114 ICME groups, reflecting reductions of 32% and 19% respectively compared with Period I. In Period III, 125 ICMEs formed 103 ICME groups, which are 7% and 10% lower respectively than those in Period II.

Through comparison of the corresponding periods of the three solar cycles, we find that the numbers of ICMEs and ICME groups in Period II decrease significantly compared to Period I, and in Period III they decrease slightly compared to Period II. Compared with the previous two solar cycles, the 25th solar cycle exhibits the lowest numbers of ICMEs and ICME groups. Although the sunspot numbers during the rising phase of Solar Cycle 25 are more comparable to those of Solar Cycle 23 and clearly higher than those of Solar Cycle 24, the numbers of ICMEs and ICME groups in Period III appear more similar to those in Period II.

During Solar Cycle 23, ICME groups caused 151 geomagnetic storms with an average intensity of -109 nT and a minimum of -422 nT, including 67 intense geomagnetic storms. During Solar Cycle 24, ICME groups caused 96 geomagnetic storms with an average intensity of -71 nT and a minimum of -223 nT, including 19 intense geomagnetic storms. The geoeffectiveness of ICME groups during Solar Cycle 24 was relatively weak, consistent with the results reported by [Lawrance et al. \(2020\)](#). In Period I, ICME groups caused 100 geomagnetic storms with an average intensity of -104 nT and a minimum of -387 nT, including 45 intense geomagnetic storms. In Period II, ICME groups caused 55 geomagnetic storms with an average intensity of -70 nT and a minimum of -147 nT, including 10 intense geomagnetic storms. In Period III, ICME groups caused 70 geomagnetic storms with an average intensity of -86 nT and a minimum of -406 nT, including 15

intense geomagnetic storms.

In terms of the numbers and proportions of geomagnetic storms and intense geomagnetic storms, the comparison results are: Period I > Period III > Period II, which aligns with the levels of solar activity. Although the number of geomagnetic storms in Period III was lower than that in Period I, the proportion of storms (68%) was relatively high due to the smaller number of ICME groups, approaching the level observed in Period I (71%). The average intensity of geomagnetic storms caused by ICMEs in Period III was higher than that in Period II but lower than that in Period I. Notably, the extreme intensity of geomagnetic storms triggered by ICMEs in Period III reached -406 nT, exceeding the extreme value of -387 nT in Period I and approaching the extreme value of -422 nT recorded during Solar Cycle 23. This event, associated with the multiple ICME events of May 10–11, 2024, has been studied by Lazzús and Salfate (2024), Tulasi Ram et al. (2024), and Pierard et al. (2025).

Figure 7 displays the distribution of the *Dst* index for geomagnetic storms caused by ICMEs during Periods I, II, and III. Based on Figure 7 and Table 3, we have the following findings:

- For intense geomagnetic storms, the number of events in Period I is significantly higher than that in the other two periods across all intensity ranges, and extremely intense storms with *Dst* index below -200 nT occur frequently. In Period I, 45% of the geomagnetic storms are intense geomagnetic storms, which is more than twice the proportion observed in Periods II and III. This reflects the strong geoeffectiveness of Solar Cycle 23.
- In Period II, the number of intense geomagnetic storms is very small, and even no events with *Dst* index below -150 nT are recorded. This indicates that the geoeffectiveness of ICMEs during Solar Cycle 24 is generally weak.
- In Period III, although the total number of intense geomagnetic

storms is not large and only slightly higher than that in Period II, their intensity is much higher, with several extremely intense storms occurring. This suggests that the geoeffectiveness of Solar Cycle 25 is intermediate between that of Cycles 23 and 24.

- For moderate geomagnetic storms, Period III has the largest number, while Period II has the smallest. During Periods II and III, moderate geomagnetic storms account for the highest proportion, exceeding 50%.
- For weak geomagnetic storms, the number of events within the -40 to -30 nT interval in Period III is the same as that in Period I and is significantly higher than that in Period II. In the -50 to -40 nT interval, Period III exhibits the fewest events, whereas Period I has the most.

By comprehensively analyzing the number of ICMEs and the characteristics of geomagnetic storms they caused, we can draw the following conclusions:

- The geoeffectiveness of ICMEs in Solar Cycle 23 is strongest. In Period I, ICMEs caused the largest number of geomagnetic storms, with the broadest distribution and the most concentrated occurrence of intense and moderate geomagnetic storms. This demonstrates that strong solar activity and frequent ICME occurrence lead to more pronounced geoeffectiveness.
- The geoeffectiveness of ICMEs in Solar Cycle 24 is weakest. In Period II, the numbers of intense, moderate, and weak geomagnetic storms are all the lowest, and the average storm intensity is also the weakest. This is consistent with the overall weak magnetic field and plasma parameters of ICMEs during this period, as presented in the previous chapter.
- The geoeffectiveness of ICMEs in Solar Cycle 25 lies between the previous two cycles. Although Period III contains the fewest ICMEs and ICME groups, the proportion of high-intensity ICME events is

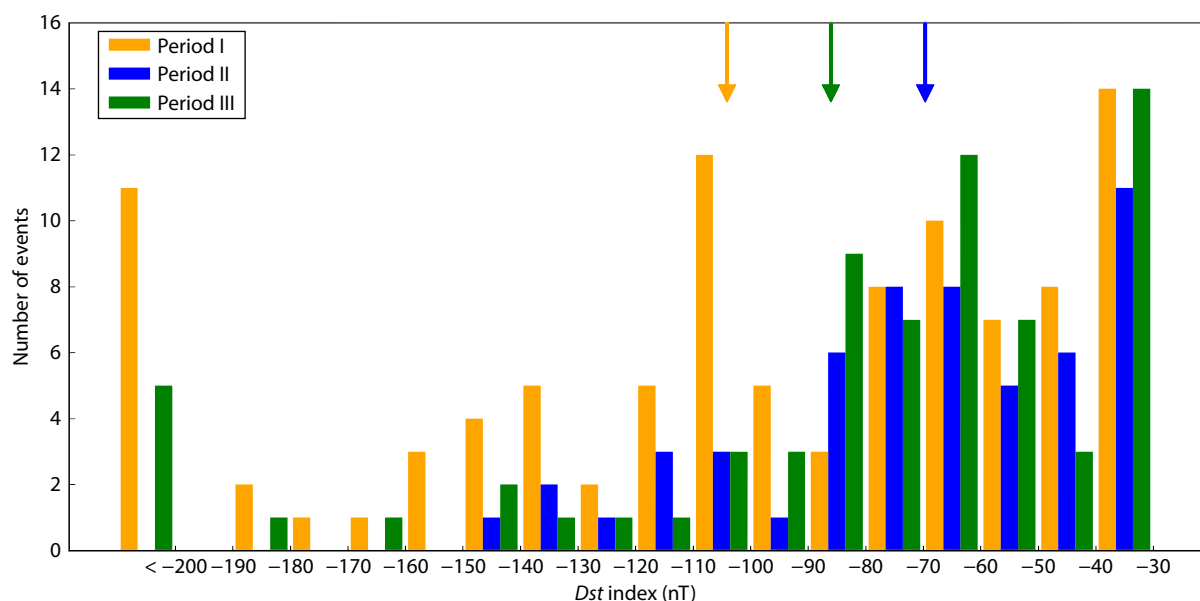


Figure 7. Comparison of the *Dst* index distribution of geomagnetic storms caused by ICMEs in three periods. The orange, blue and green bars represent Period I, II, and III respectively. The arrows at the top indicate the overall average values for the corresponding period.

relatively high. The average values of $\langle B \rangle$, $\langle B_s \rangle$, and $\langle vB_s \rangle$ during this period are the highest among the three periods, which is the fundamental reason for the enhanced geoeffectiveness. These strong-field events exhibit higher magnetic reconnection efficiency and are therefore more likely to cause geomagnetic storms.

6. Conclusion and Discussion

This study utilizes in-situ observations from the *Wind* and *ACE* spacecraft to extend the catalog of ICMEs from 2016 to 2025. Based on the extended ICME catalog and the *Dst* index from the WDC, a comparative analysis of the parameter characteristics and geoeffectiveness of ICMEs in the rising phase of Solar Cycles 23, 24 and 25 is conducted. The main conclusions are summarized as follows:

- (1) From January 1995 to December 2025, a total of 657 ICME events were grouped into 530 ICME groups, of which 80% are I-ICMEs and 20% are M-ICMEs. Approximately 61% of the ICME groups caused geomagnetic storms with $Dst_{\min} \leq -30$ nT. Among all geomagnetic storms, 74% are moderate or intense geomagnetic storms, which is a relatively high proportion.
- (2) Most M-ICMEs occurred near solar maximum. The number of geomagnetic storms and intense geomagnetic storms varies synchronously with the sunspot number. During solar maximum, the number of geomagnetic storms and intense geomagnetic storms caused by ICMEs increase significantly.
- (3) Although the sunspot numbers during the rising phase of Solar Cycle 25 are more comparable to those of Solar Cycle 23 and clearly higher than those of Solar Cycle 24, the numbers of ICMEs and ICME groups during the rising phase of Solar Cycle 25 appear more similar to those of Solar Cycle 24.
- (4) During Period III, the average values of $\langle B \rangle$, $\langle B_s \rangle$ and $\langle vB_s \rangle$ are the highest among the three periods. These parameters are key factors influencing the geoeffectiveness of ICMEs. Higher magnetic field strength-related parameters of ICMEs correspond to a higher probability of causing geomagnetic storms. When the $\langle B_s \rangle$ of an ICME exceeds 16 nT or the $\langle vB_s \rangle$ exceeds 8 mV m^{-1} , the probability of it causing an intense geomagnetic storm reaches 100%.
- (5) The numbers and proportions of geomagnetic storms and intense geomagnetic storms during Period III are both lower than those in Period I but higher than those in Period II, which is consistent with the overall level of solar activity. In Period III, the proportion of moderate geomagnetic storms is the highest, exceeding 50%. Although the number of intense geomagnetic storms in Period III is relatively small and comparable to that in Period II, their intensities are remarkably high, with several extremely intense geomagnetic storms occurring.

Taken together, our research indicates that the geomagnetic effectiveness of ICMEs during the rising phase of Solar Cycle 25 falls between those of the previous two solar cycles. Compared with Solar Cycle 24, ICMEs during the rising phase of Solar Cycle 25 are fewer in number but possess stronger geomagnetic effec-

tiveness. We propose several physical mechanisms to interpret this phenomenon. First, the eruptive source regions exhibit higher magnetic energy density and magnetic shear strength. Recent observations indicate that active regions in Solar Cycle 25, such as the super-active region AR 13664 (Jarolim et al., 2024; Dikpati et al., 2025), are characterized by extremely high magnetic flux concentration and complex magnetic topologies. Such highly sheared magnetic fields can form flux rope structures with larger magnetic flux and higher helicity during eruptions, thereby endowing the resulting ICMEs with stronger initial magnetic field strength. Second, complex interactions among ICMEs serve as a core mechanism for triggering extreme space weather events. During the interaction process, subsequent fast CMEs strongly compress the preceding structures, leading to a substantial increase in magnetic field components and plasma density within both the sheath region and the ejecta. This compression enhancement mechanism significantly improves the magnetic reconnection efficiency at the magnetopause. Consequently, even when the total number of ICME events is relatively small, Solar Cycle 25 still exhibits high geomagnetic coupling efficiency. Finally, the modulation effect of the interplanetary background environment can not be neglected. The interplanetary magnetic field (IMF) of Solar Cycle 25 has recovered remarkably from the historically low level in Solar Cycle 24. This enhanced background IMF, combined with the synergistic compression of High-Speed Streams (HSS) from coronal holes, effectively suppresses the radial expansion and magnetic field decay of ICMEs during their propagation to 1 AU (Heinemann et al., 2024). This allows the ICMEs to maintain a higher degree of structural integrity in their magnetic fields and plasma states, ultimately resulting in superior geomagnetic effectiveness when coupling with Earth's magnetosphere.

In summary, the enhancement of geomagnetic effectiveness in Solar Cycle 25 is driven by the combined influence of enhanced magnetic field strength of source regions and compression mechanisms in interplanetary space. It should be noted that the conclusions of this study are based on observations during the rising phase of Solar Cycle 25. The comprehensive assessment of the geomagnetic effectiveness throughout the entire Solar Cycle 25 still requires further investigation combined with future satellite data in the declining phase and evolutionary models of source region magnetic fields.

Acknowledgments

The ICME list used in this research is sourced from http://space.ustc.edu.cn/dreams/wind_icmes/index.php. Interplanetary magnetic field and solar wind parameters are obtained from the *WIND* satellite (<https://wind.nasa.gov/data.php>). The *Dst* index is retrieved from the World Data Center (WDC) for Geomagnetism (<https://wdc.kugi.kyoto-u.ac.jp/dstidir/>). The sunspot activity data comes from version 2.0 of the Sunspot Number provided by the International Sunspot Index and Long-term Solar Observations (SILSO) (<https://www.bis.sidc.be/silso/datafiles>). This work is supported by grants from the NSFC (42325405, 42474204, 42441808).

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