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Solar cycle distribution of major geomagnetic storms *

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Abstract We examine the solar cycle distribution of major geomagnetic storms ($Dst \leq -100$ nT), including intense storms at the level of -200 nT$< Dst \leq -100$ nT, great storms at -300 nT$< Dst \leq -200$ nT, and super storms at $Dst \leq -300$ nT, which occurred during the period of 1957–2006, based on Dst indices and smoothed monthly sunspot numbers. Statistics show that the majority (82%) of the geomagnetic storms at the level of $Dst \leq -100$ nT that occurred in the study period were intense geomagnetic storms, with 12.4% ranked as great storms and 5.6% as super storms. It is interesting to note that about 27% of the geomagnetic storms that occurred at all three intensity levels appeared in the ascending phase of a solar cycle, and about 73% in the descending one. Statistics also show that 76.9% of the intense storms, 79.6% of the great storms and 90.9% of the super storms occurred during the two years before a solar cycle reached its peak, or in the three years after it. The correlation between the size of a solar cycle and the percentage of major storms that occurred, during the period from two years prior to maximum to three years after it, is investigated. Finally, the properties of the multi-peak distribution for major geomagnetic storms in each solar cycle is investigated.

Key words: Sun: sunspots — Sun: activity — Sun: solar-terrestrial relations

1 INTRODUCTION

A geomagnetic storm is a disturbance in the Earth's magnetic field caused by interactions between materials ejected from the Sun and the magnetosphere. Major geomagnetic storms are among the most important space weather phenomena. What determines the physical laws describing the solar cycle distribution of major geomagnetic storms? Newton & Milsom (1954) investigated the solar cycle distribution of great geomagnetic storms that occurred during the period 1878–1952. They reported that most of the largest geomagnetic storms did not occur exactly at the peak phase of the

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cycles, but rather in periods a few years away from the peak on either side. Gupta & Basu (1965) investigated the outstanding solar-terrestrial events that occurred during 1956–1963 and pointed out that all types of outstanding solar-terrestrial events occurred most frequently either in the ascending or in the descending phase or in both of these phases of the solar cycle, avoiding the peak phase. The period studied in their paper was only 8 yr within a solar cycle. Gonzalez et al. (1990) studied the solar cycle distribution of intense geomagnetic storms that occurred during 1965–1985. They pointed out that a dominant dual-peaked distribution exists in the variability of these storms, with one peak occurring at the late ascending phase of the cycle or at the solar maximum and the other at the early descending phase of the cycle. Gonzalez et al. (1990) also investigated the distribution of intense geomagnetic storms with $aa > 100$ nT during 1880–1965. The results show that the solar cycle distribution of intense geomagnetic storms has a dual-peaked structure and the average separation of the peaks from the solar maximum is about eight months ahead of the first peak and about 25 months after the second one. Recent studies have indicated that geomagnetic storms mainly occur either in the spring or autumn; in addition they may also occur in a dual-peaked manner (Gonzalez et al. 2011; Echer et al. 2011). The two peaks in solar activity represent a well-known phenomenon and the gap between the two peaks is called the Gnevyshev gap. The gap is usually 2–3 yr (Gnevyshev 1967). Le et al. (2012) analyzed the solar cycle distribution of great geomagnetic storms. Their results show that about 73% of great geomagnetic storms occurred in the descending phase of the solar cycle, and 83% of great geomagnetic storms occurred in the two years before the solar cycle peak and in the three years after it. The major geomagnetic storms studied in this paper are intense geomagnetic storms at the level of -200 nT$< Dst \leq -100$ nT, great geomagnetic storms at -300 nT$< Dst \leq -200$ nT, and super geomagnetic storms at $Dst \leq -300$ nT.

What is the ratio of major geomagnetic storms at different levels to the total major geomagnetic storms that occurred during 1957–2006? What properties relate the solar cycle distribution to major geomagnetic storms? How can we describe the dual-peak distribution in each solar cycle for the major geomagnetic storms? In order to answer these questions, the major geomagnetic storms that occurred during 1957–2006 are analyzed. The major geomagnetic storm data are compared with the smoothed monthly mean sunspot numbers (SMMSNs) so that we can rigorously analyze the solar cycle distribution of major geomagnetic storms.

SMMSNs are used to indicate the level of solar activity in this paper. The period from the start of a solar cycle to its peak constitutes the ascending phase of the solar cycle. The period from the time one month after the solar cycle's peak to its end is the descending phase of the solar cycle. Section 2 illustrates the distribution of major geomagnetic storms that occurred in 1957–2006 with a figure. Section 3 gives the statistical analysis of major geomagnetic storms. Section 4 is a discussion and Section 5 is the conclusion.

2 THE MAJOR GEOMAGNETIC STORMS IN 1957–2006

The Dst index for each major storm can be obtained from the World Data Center for Geomagnetism, Kyoto (*http://wdc.kugi.kyoto-u.ac.jp/dstdir*). During the period of 1957–2006, 387 major geomagnetic storms were identified. In Figure 1, solar cycle 19 is depicted with the major geomagnetic storms that occurred since 1957 January 1, because the Dst index has only been available since 1957. It shows the distribution of major geomagnetic storms in solar cycles 19–23, giving a direct view of how solar cycle distributions are related to major geomagnetic storms.

3 STATISTICAL ANALYSIS OF MAJOR GEOMAGNETIC STORMS

The ratio of major storms at different levels to total major geomagnetic storms is shown in Table 1. From Table 1, we can see that 82% of them are intense storms, 12.4% are great geomagnetic storms, and 5.6% are super geomagnetic storms, suggesting that most of the major storms are intense ones, with the rest being some great geomagnetic storms and a few super geomagnetic storms.

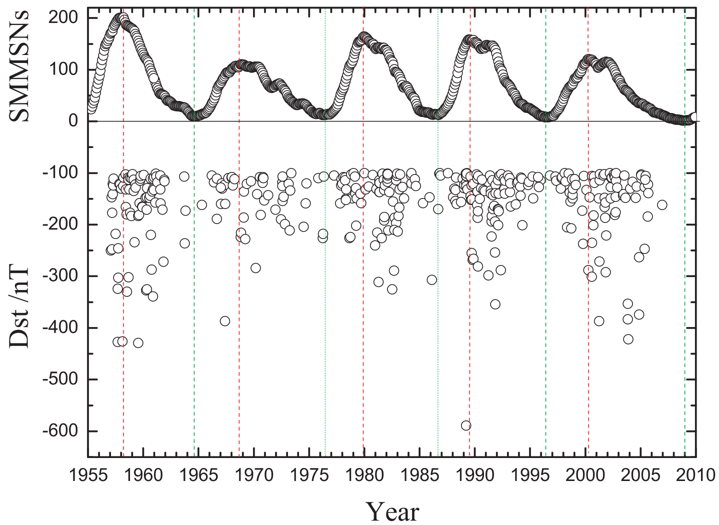

Fig. 1 SMMSNs and the major geomagnetic storms that occurred during 1957–2006. The red vertical dashed lines indicate the time corresponding to solar cycle peaks, while the green vertical lines indicate the minimum of each solar cycle.

Table 1 The ratios of the three kinds of major geomagnetic storms that occurred during 1957–2006.

Storm levels	Intense geomagnetic storm	Great geomagnetic storms	Super geomagnetic storms
Dst value	-200 nT $< Dst \leq -100$ nT	-300 nT $< Dst \leq -200$ nT	$Dst \leq -300$ nT
Number	$N_{\rm it} = 316$	$N_{\rm gt} = 49$	$N_{\rm st} = 22$
Total number		$N_{\rm t} = N_{\rm it} + N_{\rm gt} + N_{\rm st} = 387$	
Ratio	$\text{Ratio(i)} = N_{\rm it}/N_{\rm t} = 81.7\%$	$\text{Ratio(g)} = N_{\rm gt}/N_{\rm t} = 12.7\%$	$\text{Ratio(s)} = N_{\rm st}/N_{\rm t} = 5.6\%$

Notes: $N_{\rm it}$, $N_{\rm gt}$ and $N_{\rm st}$ indicate the total number of intense geomagnetic storms, great geomagnetic storms and super geomagnetic storms that occurred during 1957–2006, respectively. $N_{\rm t}$ is the total number of major geomagnetic storms ($Dst \leq -100$ nT) that occurred during 1957–2006. Ratio(i), Ratio(g) and Ratio(s) are the ratios for intense, great and super storms, respectively.

Table 2 The ratio of intense storms in the ascending and descending phases of the five solar cycles.

Solar cycle	$N_{\rm ia}$	$N_{\rm id}$	$N_{\rm ia} + N_{\rm id}$
19	9	52	61
20	14	28	42
21	19	42	61
22	24	60	84
23	20	48	60
Total	$N_{\rm iat} = 86$	$N_{\rm idt} = 230$	$N_{\rm it} = N_{\rm iat} + N_{\rm idt} = 316$
Ratio	$\text{Ratio(ia)} = N_{\rm iat}/N_{\rm it} = 27.2\%$	$\text{Ratio(id)} = N_{\rm idt}/N_{\rm it} = 72.8\%$	

Notes: $N_{\rm ia}$ and $N_{\rm id}$ indicate the number of intense geomagnetic storms in the ascending and descending phases of each solar cycle, respectively. $N_{\rm iat}$ and $N_{\rm idt}$ indicate the total number of intense geomagnetic storms in the ascending and descending phases, respectively, and $N_{\rm it}$ indicates the total number of intense geomagnetic storms that occurred during 1957–2006. Ratio(ia) and Ratio(id) indicate the ratio of intense geomagnetic storms that occurred in the ascending and descending phases of the solar cycles, respectively.

Table 3 The ratio of great storms in the ascending and descending phases of the five solar cycles.

Solar cycle	N_{ga}	N_{gd}	$N_{\mathrm{ga}}+N_{\mathrm{gd}}$
19	8	11	19
20	3	6	9
21	3	10	13
22	1	11	12
23	4	14	18
Total	$N_{\mathrm{gat}}=19$	$N_{\mathrm{gdt}}=52$	$N_{\mathrm{gt}}=N_{\mathrm{gat}}+N_{\mathrm{gdt}}=71$
Ratio	$\mathrm{Ratio(ga)}=N_{\mathrm{gat}}/N_{\mathrm{gt}}=26.8\%$	$\mathrm{Ratio(gd)}=N_{\mathrm{gdt}}/N_{\mathrm{gt}}=73.2\%$	

Notes: N_{ga} and N_{gd} indicate the number of great geomagnetic storms in the ascending and descending phases of each solar cycle, respectively. N_{gat} and N_{gdt} indicate the total number of great geomagnetic storms in the ascending and descending phases, respectively, and N_{it} indicates the total number of great geomagnetic storms that occurred during 1957–2006. Ratio(ga) and Ratio(gd) indicate the ratio of great geomagnetic storms that occurred in the ascending and descending phases of the solar cycles, respectively.

Table 4 The ratio of three kinds of major storms occurring in the two years before the solar cycle peak and in the three years after it during the period of 1957–2006.

Storm intensity	-200 nT $< Dst \leq -100$ nT		-300 nT $< Dst \leq -200$ nT		$Dst \leq -300$ nT	
Number	N_{i23}	N_{it}	N_{g23}	N_{gt}	N_{s23}	N_{st}
	243	316	39	49	20	22
Ratio	$N_{\mathrm{i23}}/N_{\mathrm{it}}=76.9\%$		$N_{\mathrm{g23}}/N_{\mathrm{gt}}=79.6\%$		$N_{\mathrm{s23}}/N_{\mathrm{st}}=90.9\%$	

Notes: N_{i23} indicates the total number of intense geomagnetic storms that occurred in the two years before the solar cycle peak and the three years after it, and N_{it} indicates the total number of intense geomagnetic storms occurring during 1957–2006. N_{g23} indicates the number of the great geomagnetic storms that occurred in the two years before the solar cycle peak and in the three years after it, and N_{gt} indicates the total number of great geomagnetic storms occurring during 1957–2006. N_{s23} indicates the total number of geomagnetic storms that occurred in the two years before the solar cycle peak and in the three years after it. N_{st} indicates the total number of super geomagnetic storms that occurred during 1957–2006.

Shown in Tables 2 and 3 are the statistical occurrences of major geomagnetic storms in the ascending or descending phase of the solar cycles. Table 2 presents the numbers and percentages of intense geomagnetic storms that occurred during the ascending or descending phases of the solar cycles. From Table 2, it is evident that 27.2% of the intense storms occurred in the ascending phase, and 72.8% in the descending one. Table 3 shows that 26.8% of the great storms occurred in the ascending phase, and 73.2% in the descending one. The statistical result shows that most major geomagnetic storms occurred in the descending phase of a solar cycle.

Table 4 depicts the occurrences of major geomagnetic storms at three intensity levels appearing in the two years before the solar cycle's peak and in the three years after it, with a respective probability of 76.9%, 79.6% and 90.9%, suggesting that most major geomagnetic storms occur in the two years before the solar cycle peak and in the three years after it, and that the probability of occurrence during that period becomes larger as the storm intensity increases.

To understand the relationship between the occurrence patterns of major geomagnetic storms occurring during the period from the two years before the solar cycle peak to the three years after it and the amplitude of a solar cycle, we examined the statistics associated with each solar cycle recorded during 1957–2006. One can see from Table 5 where statistical results are given that solar cycle 19 is the strongest cycle among the five with a maximum amplitude of 201.3. As a result, 96.7% of the intense geomagnetic storms occurred in the two years before a solar cycle peak and in the three years after it. Table 5 shows that the amplitude for solar cycles 20, 21, 22 and 23 are 110.6, 164.5, 158.5 and 120.8, respectively, and the probability of occurrence for intense geomagnetic storms in

Table 5 The ratios of two kinds of major storms occurring in the two years before a solar cycle peak and in the three years after it for each solar cycle.

Solar cycle	Amplitude	-200 nT$< Dst \leq -100$ nT		Ratio	$Dst \leq -200$ nT		Ratio
		N_{i23}	N_{it}	$N_{\mathrm{i23}}/N_{\mathrm{it}}$	N_{OSE23}	N_{OSEt}	$N_{\mathrm{OSE23}}/N_{\mathrm{OSEt}}$
19	201.3	59	61	96.7%	18	19	94.7%
20	110.6	28	42	66.7%	5	9	55.6%
21	164.5	46	61	75.4%	11	13	84.6%
22	158.5	64	84	76.2%	11	12	91.7%
23	120.8	46	68	67.6%	14	18	77.8%

Notes: N_{i23} indicates the number of intense geomagnetic storms occurring in the two years before a solar cycle peak and in the three years after it. N_{it} is the total number of intense geomagnetic storms occurring in each solar cycle. N_{OSE23} indicates the number of outstanding Sun-Earth connection events occurring in the two years before a solar cycle peak and in three years after it. N_{OSEt} is the total number of outstanding Sun-Earth connection events that occurred in each solar cycle.

the two years before the solar cycle peak and in the three years after it is 66.7%, 75.4%, 76.2% and 67.6%, respectively.

When a coronal mass ejection (CME) or several successive eruptions of CMEs finally reach the magnetosphere and trigger a geomagnetic storm at the level of $Dst \leq -200$ nT, the event is defined as an outstanding Sun-Earth connection event in this paper. One can see from Table 5 that a very strong solar cycle would show more intense, outstanding Sun-Earth connection events in the two years before a solar cycle reaches its peak and in the three years after it. For example, solar cycle 19 stands out as the strongest among the five cycles, as 96.7% of the intense geomagnetic storms and 94.7% of the outstanding Sun-Earth connection events took place in the two years before the solar cycle peak and in the three years after it. As a result, very few intense geomagnetic storms and outstanding Sun-Earth connection events could be spotted at times other than in this period. By contrast, when a solar cycle is weak, as in cycle 20 where only nine outstanding Sun-Earth connection events were recorded, outstanding Sun-Earth connection events become a rare phenomenon. In solar cycle 20, only 55.6% of the outstanding Sun-Earth connection events appeared in the two years before the cycle peak and in the three years after it, indicating that a weak cycle is associated with fewer and more sporadic occurrences of outstanding Sun-Earth connection events, and that a considerable part of outstanding Sun-Earth connection events tend to occur later than three years after the solar cycle peak. 66.7% and 67.6% of the intense geomagnetic storms occurred during the period from two years prior to maximum to three years after it for solar cycles 20 and 23 respectively, indicating that about 1/3 of intense geomagnetic storms took place outside the period of the two cycles.

Is there any correlation between the maximum amplitude of a solar cycle and the percentage of intense or outstanding Sun-Earth connection events occurring during the period from two years prior to maximum to three years after it? In order to answer this question, we calculate the two correlation coefficients shown in Figures 2 and 3, respectively. We can see from Figures 2 and 3 that there is a very good correlation between the maximum amplitude of a solar cycle and the percentage of intense or outstanding Sun-Earth connection events occurring during the period from two years prior to the maximum to three years after it.

Gonzalez et al. (2011) pointed out that the solar cycle distribution of superintense storms (defined as $Dst \leq -250$ nT) has a dual-peak distribution structure; the gap between the two peaks for superintense storms ranged from 2 yr to 4 yr, which can be seen from figure 5 in Gonzalez et al. (2011). Gonzalez et al. (1990) investigated the dual-peak solar cycle distribution of intense geomagnetic storms. The separation is the gap between the first peak of intense geomagnetic and the sunspot number peak or the gap between the second peak of intense geomagnetic and the sunspot number peak. The average separation of the two peaks from the solar maximum is about eight months before

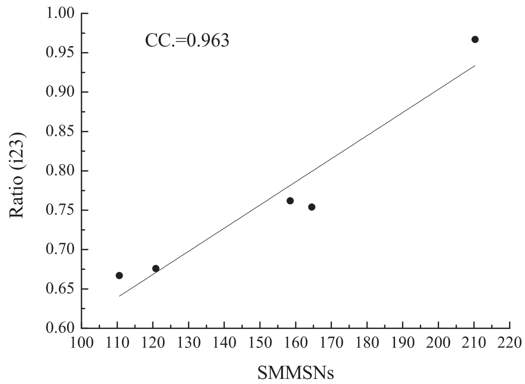

Fig. 2 Correlation coefficient (CC.) between the amplitude of a solar cycle and the ratio of intense geomagnetic storms occurring during the period from two years prior to the maximum to three years after it.

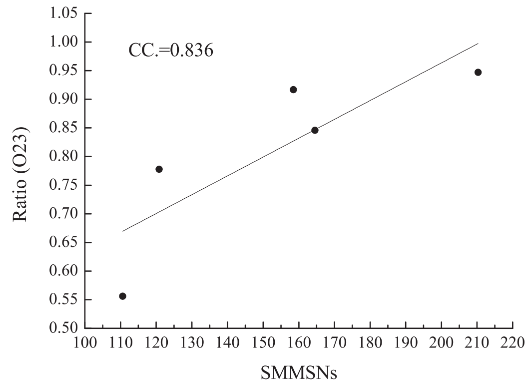

Fig. 3 Correlation coefficient (CC.) between the amplitude of a solar cycle and the ratio of outstanding Sun-Earth connection events occurring during the period from two years prior to the maximum to three years after it.

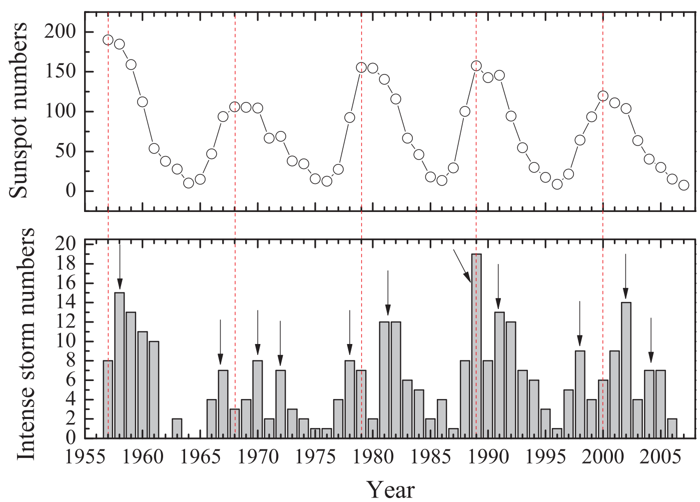

Fig. 4 Comparison between the yearly number of intense geomagnetic storms and sunspot numbers. The vertical dashed lines indicate the solar maximum of five solar cycles. Each down arrow in the lower panel indicates a peak in the yearly intense storm numbers.

the solar maximum for the first peak of the intense geomagnetic storm and about 25 months after the solar maximum for the second peak of intense geomagnetic storm.

Is there always a dual-peak distribution in each solar cycle for the intense or outstanding Sun-Earth connection events that occurred during 1957–2006? How long is the gap between the two peaks for each solar cycle? In order to answer these questions, a comparison between the yearly number of intense geomagnetic storms and yearly mean sunspot numbers is shown in Figure 4. We can see from Figure 4 that intense geomagnetic storms have a dual-peak distribution in solar cycles 21–22. The yearly number of intense geomagnetic storms in solar cycles 20 and 23 has three peaks.

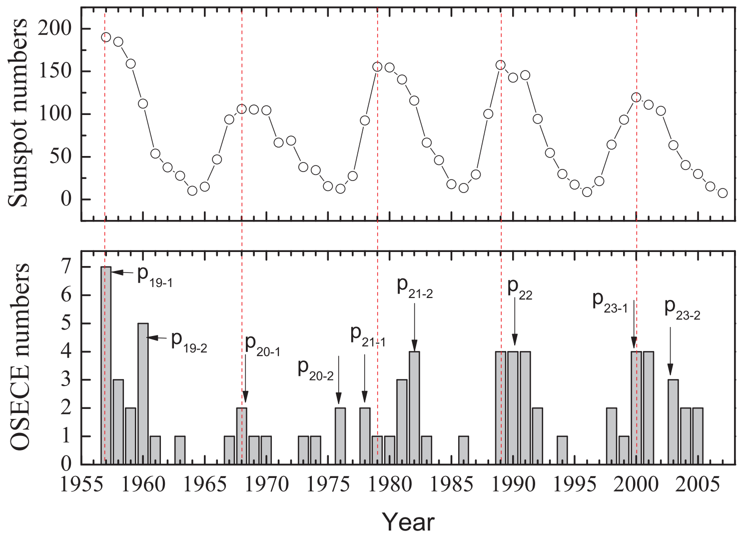

Fig. 5 Comparison between the yearly number of outstanding Sun-Earth connection events and sunspot numbers. The vertical dashed lines indicate the solar maximum for five solar cycles. The OSECE number is the number of outstanding Sun-Earth connection events. The P_{19-1} and P_{19-2} indicate the first and second peak in solar cycle 19, respectively. The rest can be understood in the same manner.

The first peak in yearly number of intense geomagnetic storms occurred one year before the solar cycle maximum in solar cycles 20, 21 and 23, but only in solar cycle 22 did the first peak in yearly number of intense geomagnetic storms occur at the solar maximum. The second peak for solar cycles 20 to 23 all occurred 2 yr after the solar maximum. The gap between the the first and second peaks for intense geomagnetic storms is 1–3 yr, which matches that of sunspot numbers. Because solar cycle 19 started in April 1954, data about major geomagnetic storms studied in this paper for solar cycle 19 do not include all the intense geomagnetic storms that occurred during that cycle. Perhaps this is the reason why cycle 19 shows only a single peak for intense geomagnetic storms, as shown in Figure 4.

Figure 5 presents a comparison between the yearly number of outstanding Sun-Earth connection events and yearly mean sunspot numbers. It can be seen from Figure 5 that outstanding Sun-Earth connection events have a dual-peak distribution in solar cycles 19, 20, 21 and 23 with the first peak occurring in the solar maximum or one year before the solar maximum and the second peak occurring three years after the solar maximum for solar cycles 19, 21 and 23. The second peak of outstanding Sun-Earth connection events for solar cycle 20 occurred eight years after the solar maximum. The gap between the two peaks for outstanding Sun-Earth connection events ranged from two years to eight years, which is different from the one for intense geomagnetic storms.

It should be pointed that outstanding Sun-Earth connection events do not have a dual-peak distribution in solar cycle 22, which indicates that outstanding Sun-Earth connection events do not always have a dual-peak distribution in every solar cycle. Richardson et al. (2006) pointed out that the strongest geomagnetic storm caused by a corotating interaction region is $Dst = -180$ nT. It is evident that outstanding Sun-Earth connection events can only be caused by CMEs. The distribution of the yearly number of outstanding Sun-Earth connection events reveals the distribution of CMEs, which can cause outstanding Sun-Earth connection events.

4 DISCUSSION

The first peak of the outstanding Sun-Earth connection events was in 1968 while the second peak of great geomagnetic storms occurred in the solar minimum (1976); the gap between the two peaks is eight years, much longer than the 2–3 yr reported by Gnevyshev (1977). According to the monthly mean sunspot numbers, the first peak of solar activity in solar cycle 20 is May 1968, while the second peak is March 1970. Obviously, the second peak of sunspot numbers does not match the second peak of the outstanding Sun-Earth connection events.

Because geomagnetic storms at the level of $Dst \leq -200$ nT can only be caused by a single CME or several successive eruptions of CMEs, which interact with each other close to the Sun and form multiple magnetic clouds near the Earth (Zhang et al. 2007 and references therein, Yermolaev & Yermolaev 2008 and references therein), the second peak of outstanding Sun-Earth connection events characterizes the very strong solar events that can cause outstanding Sun-Earth connection events. Obviously, the gap between the two peaks of outstanding Sun-Earth connection events is also one kind of the Gnevyshev gap, which is characterized by very strong solar events that can cause outstanding Sun-Earth connection events. The Gnevyshev gap for outstanding Sun-Earth connection events did not match the Gnevyshev gap for sunspot numbers. Kane (2005) also pointed out that solar wind parameters and geomagnetic indices did not match the sunspot numbers.

Gonzalez et al. (1994) said that solar wind speed, south directed interplanetary magnetic field ($B_{\rm s}$), and duration of the $B_{\rm s}$ have the greatest effects on causing geomagnetic storms. Only the solar wind with southward $B_{\rm s}$ can cause geomagnetic storms. If the sheath, the interplanetary coronal mass ejection or a combination of them has a strong, long duration magnetic field that is directed southward and large, dynamic pressure in the solar wind, then a major geomagnetic storm will happen if such a kind of solar wind structure finally reaches the magnetosphere. The different gaps for different intensities in storms reveal the solar cycle distribution of solar wind conditions that can cause different intensities in geomagnetic storms.

The amplitude of solar cycle 20 is 110.6, which is the weakest among the five cycles studied in this paper. The time of the second peak representing outstanding Sun-Earth connection events in solar cycle 20, shown in Figure 5, indicates that very strong solar eruptions can cause outstanding Sun-Earth connection events and may lead to the second peak of outstanding Sun-Earth connection events occurring around the solar minimum if the solar cycle is weak.

The yearly number of outstanding Sun-Earth connection events has only one peak but the yearly number of intense geomagnetic storms has three peaks in solar cycle 22. We can see from Figure 5 that the yearly number of outstanding Sun-Earth connection events is four in each year during 1989–1991, which indicates that the Sun had very strong eruptions during 1989–1991 and then caused four outstanding Sun-Earth connection events in each year during 1989–1991. This led to the outstanding Sun-Earth connection events having only a single peak distribution in solar cycle 22.

Different solar active phenomena, such as sunspot numbers, large sunspot groups, solar flares, solar proton events, CMEs and solar radio, have different periods and different gaps (Storini et al. 2003; Ahluwalia & Kamide 2005; Bazilevskaya et al. 2006; Kane 2008, 2010; Zhang et al. 2012). Sunspots, solar radio, solar flares and CMEs are the solar active phenomena that occur in different layers of the solar atmosphere. The periods for different solar parameters are different (Kane 2010; Norton & Gallagher 2010; Zhang et al. 2012).

There is a big difference between the distribution of outstanding Sun-Earth connection events in a strong solar cycle and the one in a weak solar cycle. The solar cycle distribution of outstanding Sun-Earth connection events can help us to make various decisions, such as selecting a time window to launch satellites to detect enough outstanding Sun-Earth connection events occurring in a strong or weak solar cycle, as mentioned by Le et al. (2012). The amplitude of solar cycle 24 predicted by researchers (Ajabshirizadeh et al. 2011; Chumak & Matveychuk 2010; Du & Wang 2010; Jiang et al. 2007; Wang et al. 2009) is about 90 or even lower. A peak in the SMMSNs for solar cycle 24 is 66.9 (*http://sidc.oma.be*), which occurred in Feb. 2012. This indicates that solar cycle 24 is a very weak cycle and the total number of outstanding Sun-Earth connection events will be small during the cycle. It is evident that 2016 is not a good year to launch a satellite to observe outstanding Sun-Earth connection events.

5 CONCLUSIONS

The statistical analysis of the solar cycle distribution of major geomagnetic storms that occurred during 1957–2006 has resulted in the following conclusions.

(1) Of the 387 major geomagnetic storms at the level of $Dst \leq -100$ nT, intense ones accounted for 82%, great ones accounted for 12.4%, and super ones accounted for 5.6%.
(2) The percentage of intense, great and super geomagnetic storms that occurred in an ascending phase is about 27%, with about 73% appearing in the descending phase, suggesting that most major geomagnetic storms occur in the descending phase of a solar cycle.
(3) Intense, great and super geomagnetic storms, appearing in the two years before the solar cycle peak and in the three years after it, accounted for 76.9%, 79.6% and 90.9% respectively of the total, suggesting that the stronger the major geomagnetic storms, the more storms tend to occur in the two years before the solar cycle peak and in the three years after it. Of them, super geomagnetic storms claimed the most prominent occurrences in the period. There is a good correlation between the size of the solar cycle and the percentage of intense or outstanding Sun-Earth connection events occurring in the period from two years prior to the maximum to three years after it.
(4) When a solar cycle is very strong, such as solar cycle 19, almost all intense geomagnetic storms (96.7%) and outstanding Sun-Earth connection events (94.7%) tend to appear either in the two years before the solar cycle peak or in the three years after it, with rare occurrences seen outside the period. When a solar cycle is weak, such as solar cycle 20, 66.7% of the intense geomagnetic storms would occur in the two years before the solar cycle peak and in the three years after it, suggesting that 33.3% of the intense geomagnetic storms would show up outside the period. In a weak cycle like cycle 20, outstanding Sun-Earth connection events are limited in number, with only nine sporadic occurrences in cycle 20, of which 55.6% of the outstanding Sun-Earth connection events occurred in the two years before the solar cycle peak or in the three years after it, suggesting that 44.4% of the outstanding Sun-Earth connection events would occur outside the period.
(5) Intense geomagnetic storms have a dual-peak or three peak distribution. Outstanding Sun-Earth connection events do not always have a dual-peak distribution in each solar cycle. The gap between the two peaks representing the yearly number of outstanding Sun-Earth connection events ranged from two years to eight years.
(6) The gap between the two peaks for the outstanding Sun-Earth connection events is different from the one for the intense geomagnetic storms that occurred during 1957–2006.

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