

Polar Cap Potential Saturation and Ionospheric Convection Patterns during Superstorms*

DU Aimin^{1,2} LUO Hao^{1,2} GE Yasong^{1,2}
ZHANG Ying¹ XU Wenyao^{1,2}

¹(Key Laboratory of Deep Petroleum Intelligent Exploration and Development, Institute of Geology and Geophysics,
Chinese Academy of Sciences, Beijing 100029)

²(College of Earth and Planetary Sciences, University of Chinese Academy of Sciences,
Chinese Academy of Sciences, Beijing 100029)

Abstract Five super intense magnetic storms (with minimum $Dst < -200$ nT) were examined to investigate the relationship between Polar Cap Potential (PCP) saturation and ionospheric convection patterns. A quantitative method was used to determine whether or not PCP was saturated by applying both linear and nonlinear (exponential) fits for each event. The results showed that PCP saturation occurred for two of five. The two events with saturation had distorted ionospheric convection patterns (D-CONV) with asymmetric vortices, while the other three events without PCP saturation had well-known standard convection (S-CONV) with quasi-symmetric twin vortices. The authors conclude that sporadic midnight sector substorm electric fields may contribute to the asymmetric convection patterns and PCP saturation, in agreement with previous speculations. Further analyses are needed to confirm this hypothesis.

Key words

Classified index

0 Introduction

The Polar Cap Potential (PCP) in the ionosphere has long been considered an indicator for the amount of energy flowing into and through the Magnetosphere-Ionosphere (M-I) system^[1]. Studies have shown that the PCP reaches an upper limit, or saturates, during geomagnetic storms when the solar wind electric field becomes increasingly large. Numerous observational, theoretical, and modeling studies of the PCP have seemingly confirmed that saturation does indeed occur. Many mechanisms for saturation have been suggested, however there

is no direct observational evidence confirming any single cause^[1,2]. On the other hand, extremely large storms such as the Carrington event with $Dst \approx -1760$ nT, have occurred in the past^[3]. Lopez *et al.*^[4] has suggested a scenario where the PCP saturates but the ring current injection does not.

Previous studies indicate that PCP saturation is the effect of solar wind-magnetosphere-ionosphere coupling^[5–9]. A portion of the dawn-dusk solar wind electric field along the reconnection line on the dayside magnetopause maps into the high-latitude ionosphere^[1,10]. The dayside reconnection rate is related

* Supported by the Deep Earth Probe and Mineral Resources Exploration-National Science and Technology Major Project (2024ZD1002502) and the National Natural Science Foundation of China (42374217, 42330207, 42274224)

Received December 20, 2025. Revised September 8, 2026

©The Author(s) 2026. This is an open access article under the CC-BY 4.0 License
(<https://creativecommons.org/licenses/by/4.0/>)

to the feedback of the region-1 Field-Aligned Currents (FAC), including Pedersen conductance in the ionosphere^[5,7]. The reconnection rate is also controlled by solar wind ram pressure^[7,11]. Kan *et al.*^[9] pointed out the important role that oval ionospheric conductivity plays in this process. Previous studies have suggested that nightside reconnection in the plasma sheet, in addition to the dayside reconnection process, may govern the nonlinear process of PCP saturation, and that the nightside potential and resistance contribute to the nonlinear relationship between the PCP and the Interplanetary Electric Field (IEF)^[1,6]. It has also been noted in earlier simulations that the reported PCP saturation examples and simulation conditions were typically selected when the Interplanetary Magnetic Field (IMF) remained steady for several hours^[2,11]. The above authors suggested that an important factor controlling PCP saturation may be a longer magnetospheric response time to the steady southward IMF. In this study, we examine the PCP variations under both steady and unsteady solar wind driving based on five superstorm events, with the aim of providing observational clues to this issue rather than offering a definitive solution.

When the IMF B_z in the solar wind turns southward, dayside magnetic reconnection at the magnetopause takes place^[12]. The solar wind dawn-to-dusk electric field E maps into the polar cap ionospheres. An antisunward $\mathbf{E} \times \mathbf{B}$ drift of plasma is formed along the noon-midnight direction in the F-region ionosphere. The flows return to local noon from the nightside along the dawn- and dusk-auroral oval, respectively. This is the standard

two-cell pattern of the PCP (or convection) distribution, shown in Figure 1(a). This process results from a “directly driven” process as discussed by Akasofu^[13] and Rostoker *et al.*^[14]. During magnetic storms, the PCP configuration often exhibits a pattern like that in Figure 1(b) in which the convection pattern is disturbed and is significantly different from that in Figure 1(a). This difference is believed to be caused by the presence of equatorward electric fields in the midnight sector associated with substorm expansion phases^[15,16]. This is called as the “unloading process”. The equatorward electric field appears as a one-cell pattern around the midnight sector. A pattern combining a standard two-cell and a one-cell in the midnight sector will result in a complicated configuration like that in Figure 1(b).

The main phase of an intense magnetic storm is typically accompanied by intense substorms (but not always for weak storms driven by magnetic clouds^[10]). The PCP pattern during a storm main phase thus typically includes the above two processes.

In this paper, the PCP patterns generated by the Assimilative Mapping of Ionosphere Electrodynamics (AMIE) model during five super-storms are examined. The purpose of our effort is first to determine quantitatively if PCP saturation occurs, and secondly to identify possible effects associated with substorm electric fields.

1 Data and Methods

The PCP data used in this study are derived from the AMIE procedure. AMIE is an assimilation algorithm

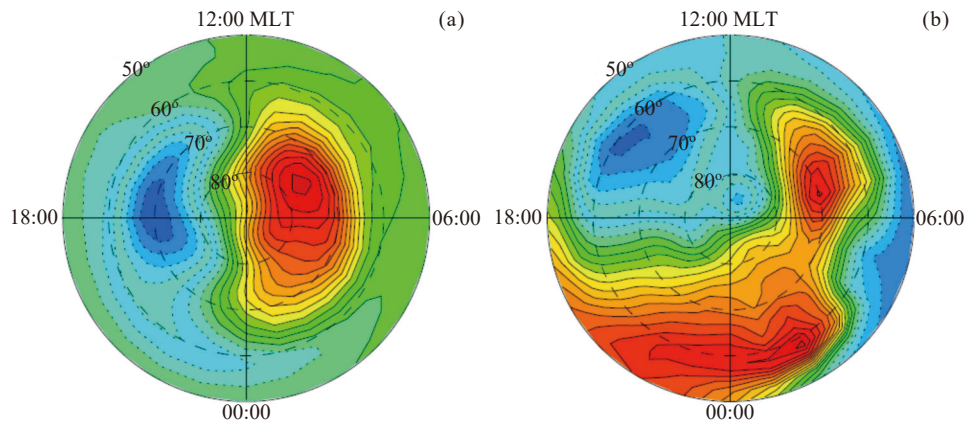


Fig. 1 (a) Standard two-cell pattern in the polar cap potential distribution, (b) the distorted one-cell pattern in the polar cap potential distribution

that combines diverse types of observations, including ground-based magnetometers, ion drift meters from DM-SP satellites, and coherent/incoherent scatter radars, to produce self-consistent global maps of high-latitude ionospheric electric fields, electric potentials, currents, and conductances. The procedure obtains optimal estimates of electrodynamic patterns through an optimally constrained, weighted least-squares fit of the electric potential distribution to all relevant data. Details of the AMIE procedure were described by Richmond *et al.*^[17,18]. In this study, we use the AMIE-derived electric potential maps with 1-min time resolution for magnetic latitudes above 50° to estimate the PCP values, which are calculated as the difference between the maximum and minimum of the electric potential over the high-latitude region.

The IMF and solar wind plasma data used to compute the IEF are obtained from the ACE and WIND satellites. The IEF is quantitatively defined as $E_1 = \mathbf{V} \times \mathbf{B}_z$ (here), where $\mathbf{V}$ is the solar wind speed, $\mathbf{B}_z$ is the north-south component of the IMF in Geocentric Solar Magnetospheric (GSM) coordinates, and E_1 represents IEF, in units of $\text{mV} \cdot \text{m}^{-1}$. The IMF and solar wind data are taken at 1-min resolution and are time-shifted to account for the propagation delay from the satellite location at the L1 point to the Earth's magnetopause. The data are publicly available through the CDAWeb*. The SYM-H index, used as a measure of ring current intensity, is obtained from the World Data Center for Geomagnetism at Kyoto University**.

To examine the relationship between the PCP and the IEF more clearly, we applied a binning and smoothing procedure to the original 1-min resolution data in the

PCP-IEF scatter plots. The procedure is as follows. First, the IEF data are divided into consecutive bins with a window width of $0.5 \text{ mV} \cdot \text{m}^{-1}$. Within each bin, the mean values of both IEF and the corresponding PCP are calculated, yielding a set of binned mean data points. Second, a five-point boxcar smoothing is applied to these binned mean points to reduce residual scatter. The resulting smoothed points are shown as black dots in Figure 4, representing the mean PCP values as a function of the mean IEF. The original 1-min data are shown as grey dots in the background for comparison.

2 Results

2.1 Standard and Distorted Convection Patterns during Geomagnetic Storms

Five super intense storms with the minimum $Dst < -200 \text{ nT}$ were examined. Their dates of occurrence and minimum Dst values are listed in Table 1. These storms can be sorted into two categories. The first type is governed by the directly driven process throughout the main phase of the storm. The PCP pattern appears as two quasi-symmetric vortices shown in Figure 1(a) and is referred to in this paper as the Standard Convection (S-CONV) pattern.

Figure 2 shows an example of an S-CONV type storm. The upper three panels show the IEF, the PCP values and the SYMH index, respectively, from 11 April 15:00 UT to 12 April 01:00 UT in 2001. The IEF is quantitatively equal to $\mathbf{V} \times \mathbf{B}_z$, where $\mathbf{V}$ is solar wind speed and $\mathbf{B}_z$ is the z component of IMF, which are observed by ACE/WIND satellite. The PCP values are obtained from output of the AMIE code***. The SYM_H

Table 1 List of five super intense storms with the minimum $Dst < -200 \text{ nT}$

Storm type	Date	Minimum Dst / nT
S-CONV	11 April 2001	-280
S-CONV	22 October 1999	-228
S-CONV	15 July 2000	-327
D-CONV	6 April 2000	-320
D-CONV	24 November 2001	-234

* <https://cdaweb.gsfc.nasa.gov/>

** <https://wdc.kugi.kyoto-u.ac.jp/>

*** <http://amie.engin.umich.edu/~amie/data/>

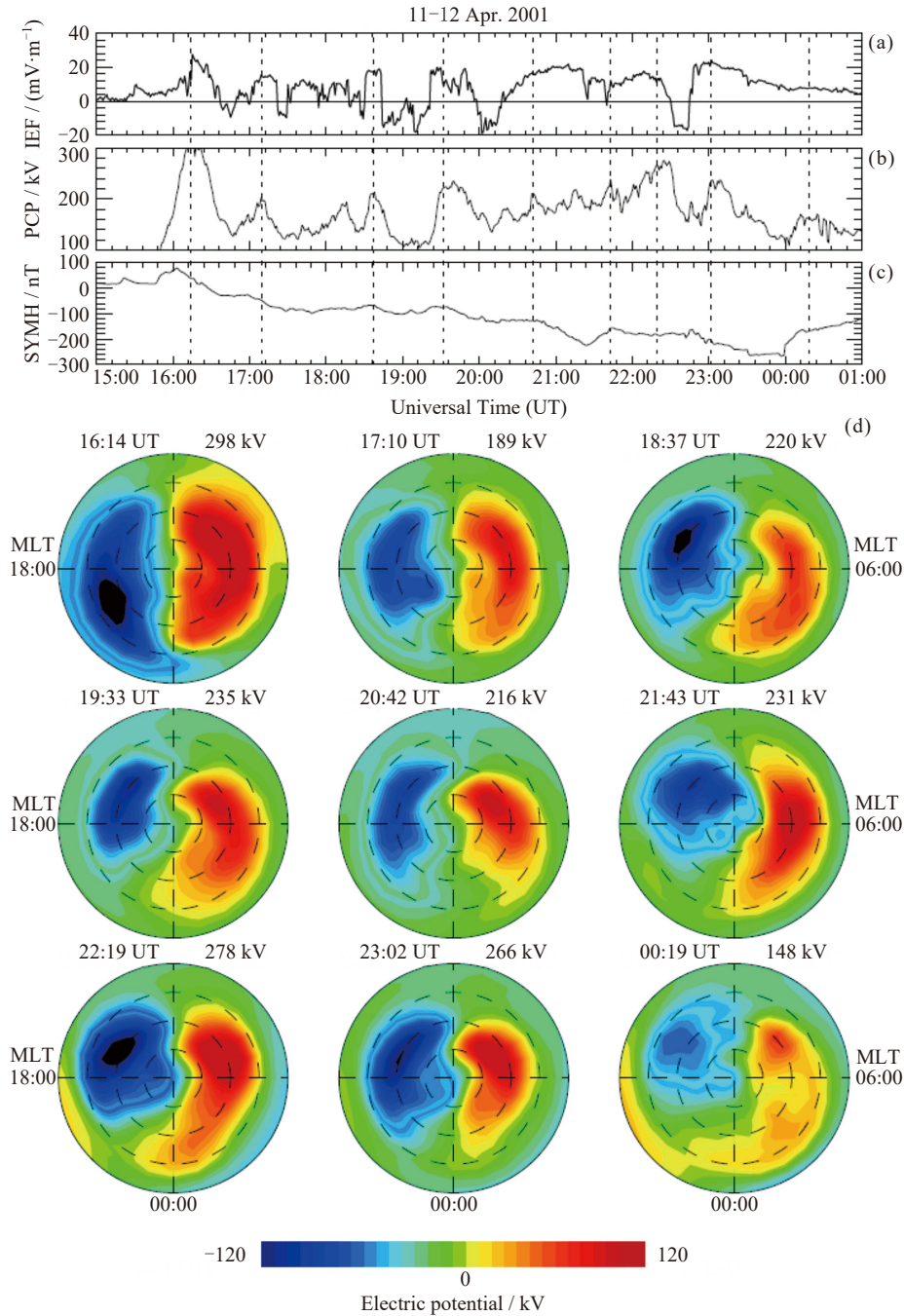


Fig. 2 IEF, PCP values, SYM_ H index, and nine patterns of global electric potential from 11 April 15:00 UT to 12 April 01:00 UT in 2001. Each PCP pattern is corresponding to a peak value of PCP in each hour marked by the vertical dash line

index is taken from the WDC-C2 at Kyoto University.

In Figure 2, the IEF changes polarity between $\sim 30 \text{ mV} \cdot \text{m}^{-1}$ and $\sim -20 \text{ mV} \cdot \text{m}^{-1}$ with period of tens of minutes. The values of the PCP are estimated by differencing the maximum and minimum of the electric potential in the high-latitude ionosphere (magnetic latitude $> 50^\circ$). Figure 2 (d) shows nine patterns of the global elec-

tric potential. Each pattern corresponds to time marked by the vertical dashed line in Figure 2. One can note a clear quasi-symmetric two-cell pattern throughout the main phase of the storm.

Two storms on 6 April 2000 and 24 November 2001 have the disturbed potential pattern (D-CONV) characterized by asymmetric vortices. As an example,

from the top to the bottom, Figure 3 shows the IEF, PCP, SYM_H index and PCP patterns, respectively, for the 6 April 2000 storm. It is noted that the IEF values are positive and stable. In the PCP patterns, a new potential cell started to form at lower latitude in the pre-midnight sector at $\sim 18:26$ UT. This new potential cell expanded and was stronger than the dawnside potential cell. Some-

times the midnight potential cell extended to the dusk sector as a potential plume at 20:23 UT. Plumes have been suggested to be related to shielding electric fields in magnetospheric convection patterns^[19–22]. The shielding electric field will screen out the convection field^[22]. In the latter portion of the storm main phase, the new midnight sector cell becomes the main contributor to the

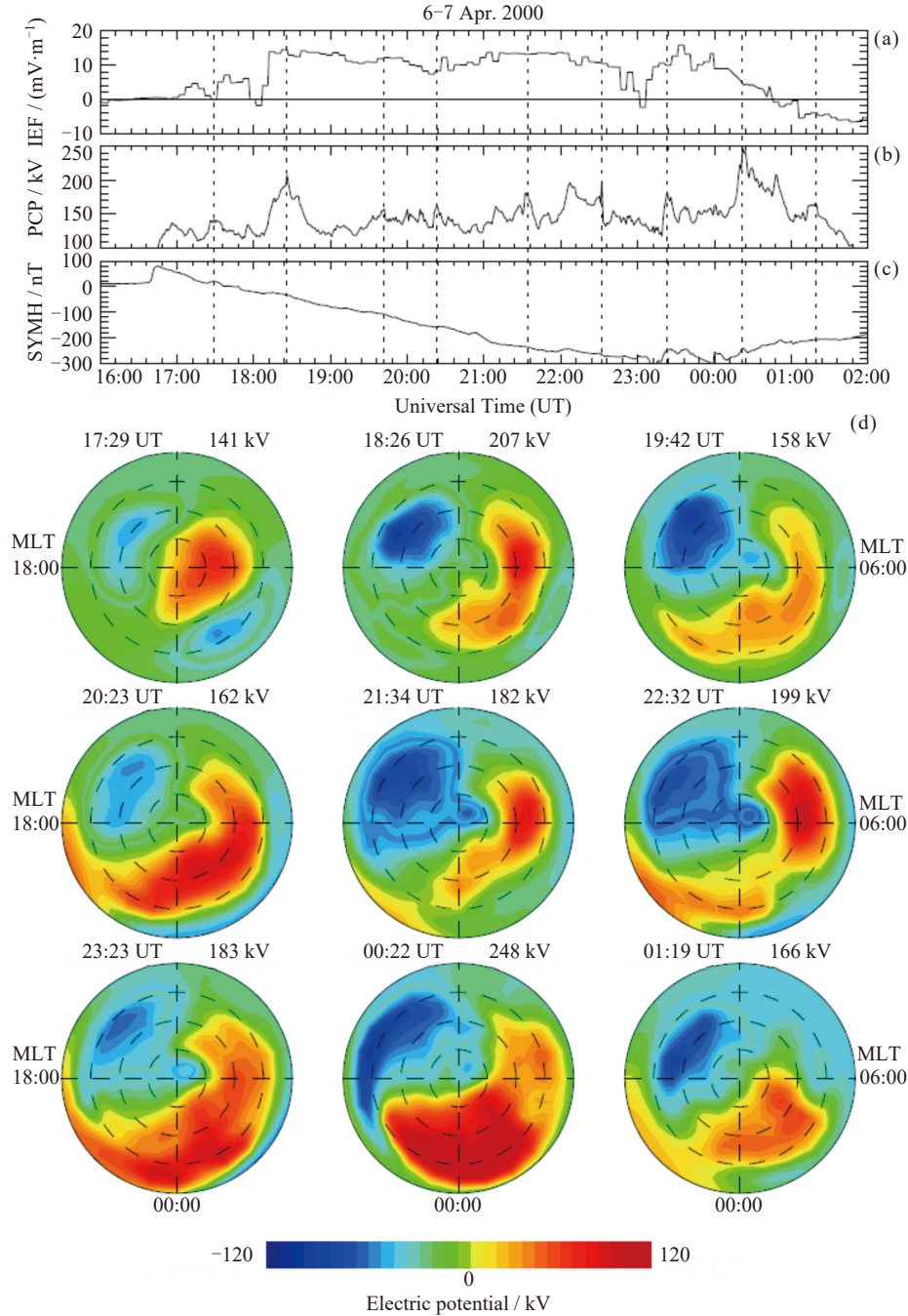


Fig. 3 IEF, PCP values, SYM_H index, and nine patterns of global electric potential from 6 April 16:00 UT to 7 April 02:00 UT in 2000. Each PCP pattern is corresponding to a peak value of PCP in each hour marked by the vertical dash line

PCP (the PCP value was ~ 218 kV in the midnight sector and ~ 120 kV in the dawn sector).

2.2 Examination of the PCP Saturation

In order to identify whether or not PCP saturation occurred during the storm main phases, two types of fitting function, linear and nonlinear, are applied to fit the relationship between PCP and IEF for all of five storm events. If the correlation coefficient (c.c.) in the nonlinear (exponential) fitting is larger than that in the linear fitting, we argue that saturation did in fact occur. If the c.c. of the nonlinear (exponential) fitting is not larger than that for the linear fitting, we assume that no saturation occurred.

For nonlinear fitting, an exponential function is defined by the following functional form:

$$P_{pcp} = P_s(1 - e^{-k(E_I - E_{I0})}). \quad (1)$$

In the above expression, P_s , k , and E_{I0} are the parameters to be solved by the fit. P_s represents PCP saturation value. If assuming that saturation starts when $P_{pcp} = 0.8P_s$ the E_I value at the onset of PCP satura-

tion IEF_s , defined as E_{Is} , can be calculated by the following relationship:

$$E_{Is} = E_{I0} - \ln(0.2)/k = E_{I0} + 1.6095/k. \quad (2)$$

A linear fit is defined as

$$P_{pcp} = A \times E_I + B, \quad (3)$$

simply indicating a linear variation of PCP with E_I .

For the remaining three events (22 October 1999, 15 July 2000, and 24 November 2001), the AMIE-derived convection patterns (not shown but available from the AMIE database) are examined. The 22 October 1999 and 15 July 2000 events exhibit quasi-symmetric twin-vortex patterns throughout the main phase, similar to the 11 April 2001 event shown in Figure 2, and are therefore classified as S-CONV. In contrast, the 24 November 2001 event shows a pronounced asymmetric potential structure with a dominant midnight-sector cell, consistent with the D-CONV classification of the 6 April 2000 event shown in Figure 3. These classifications are further supported by the distinct PCP-IEF fitting behavior shown in Figure 4 (left three panels for S-

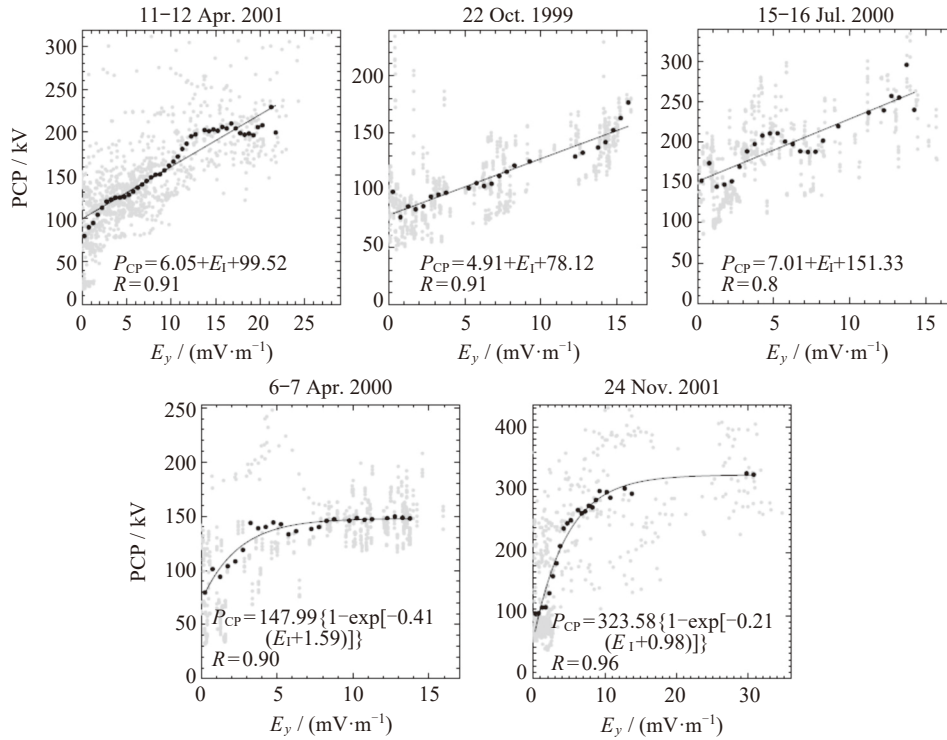


Fig. 4 Relationship between PCP and IEF for five storms. The grey dots are from the original PCP and IEF data with a 1-min time resolution. The black points are binned ($0.5 \text{ mV} \cdot \text{m}^{-1}$ window) and five-point boxcar-smoothed mean values of PCP and IEF, representing the mean PCP as a function of the mean IEF. The black lines or curves indicate linear fits and nonlinear (exponential) fits to the black data points

CONV versus right two panels for D-CONV).

Figure 4 shows the relationship between the PCP and the IEF for the five super storms. The grey dots are from the original PCP and IEF data with 1-min time resolution. The black points are smoothed mean IEF values. They are created by first calculating the mean values using a window of $0.5 \text{ mV} \cdot \text{m}^{-1}$ (for IEF) width. A smoothed five-point boxcar average was then calculated. The black lines or curves indicate linear fits and nonlinear fits for the black data points. The parameters and correlation coefficients are also listed in each panel.

It is noted that there are high correlation coefficients for the linear fits for the first three S-CONV types of super storms. Nonlinear fitting does not work for those events. We thus conclude that there was no PCP saturation for these three events.

For the other two D-CONV type of storms, there are much higher correlation coefficients for nonlinear fitting, $R = 0.90$ and 0.96 for the 6 April 2000 event and for the 24 November 2001 event, respectively. Their saturated values are $P_s = 148$ and 323 kV , and the starting saturation values $E_{Is} = 5.5$ and $8.6 \text{ mV} \cdot \text{m}^{-1}$, respectively.

3 Summary

The major findings of this study are as follows.

(1) PCP saturation may or may not occur during super storms with $Dst \leq -200 \text{ nT}$. Although the Dst index and IEF have similar intensities for all five super storms, some were determined to have PCP saturation and others not.

(2) PCP saturation occurred for two of the five super storms (6 April 2000 and 24 November 2001). The PCP saturation values were $P_s = 148 \text{ kV}$ and 323 kV with IEF_s of $5.5 \text{ mV} \cdot \text{m}^{-1}$ and $8.6 \text{ mV} \cdot \text{m}^{-1}$, respectively. We note that neither the two P_s nor the IEF_s values are similar to each other. We will discuss this later. It was also found that these two storms had asymmetric convection patterns (were of the D-CONV type), while the other three events had symmetric convection patterns (of the S-CONV type).

4 Discussion and Conclusion

Based on the time series of driving parameters present-

ed in Figures 2 and 3, we systematically compare the solar wind driving conditions between the S-CONV and D-CONV events. The key differences are as follows.

(1) Stability of the IEF. For the S-CONV event (*e.g.*, 11 April 2001, Figure 2), the IEF exhibits pronounced short-period oscillations, alternating between southward and northward polarities, without forming a steady southward driving that lasts for several hours. In contrast, for the D-CONV event (*e.g.*, 6 April 2000, Figure 3), the IEF remains persistently southward ($\text{IEF} \approx 10 - 20 \text{ mV} \cdot \text{m}^{-1}$) for more than 6 hours during the storm main phase. Such a steady and sustained driving may allow the dayside reconnection rate and the polar cap ionospheric potential to accumulate gradually, eventually entering the nonlinear saturation regime^[5,11]. Conversely, oscillatory driving may interrupt this accumulation process, keeping the PCP-IEF relationship in an approximately linear response range. The frequent polarity reversals of the IEF (with periods of tens of minutes) observed in the S-CONV events (Figure 2) may also be attributed to large-amplitude Alfvén waves in the solar wind. Such Alfvénic fluctuations are common in high-speed solar wind streams, particularly during the declining phase of the solar cycle, and are characterized by quasi-constant magnetic field magnitude with significant B_z oscillations on timescales of minutes to hours^[23]. Recent studies have further demonstrated that interplanetary Alfvén waves can directly trigger dayside magnetopause reconnection, thereby modulating the solar wind-magnetosphere-ionosphere coupling efficiency^[24]. The persistent IEF oscillations in the S-CONV events may thus reflect the intermittent nature of such Alfvén-wave-dominated solar wind driving, which prevents the magnetosphere-ionosphere system from reaching a steady state required for PCP saturation.

(2) Timescale of the storm main-phase evolution. The SYM- H index decreases at a significantly faster rate in the D-CONV events than in the S-CONV events (compare the third panels of Figures 2 and 3). A more rapid main-phase development is generally associated with stronger magnetotail energy loading and more intense substorm expansion phases, which can generate strong equatorward electric fields in the midnight sector^[15,16]. These electric fields, superimposed on the standard twin-vortex convection, produce the asymmet-

ric potential structures characteristic of the D-CONV type.

(3) Differences in the PCP-IEF response. As shown in Figure 4, all S-CONV events exhibit a predominantly linear PCP-IEF relationship (the linear fit correlation coefficient is higher than the exponential fit for each of these events), while the D-CONV events show a clear nonlinear saturation curve (exponential fit with $R = 0.90$ and 0.96). Notably, the peak IEF ranges overlap between the two types (approximately $15 - 30 \text{ mV} \cdot \text{m}^{-1}$), implying that the peak IEF magnitude alone is not sufficient to determine whether saturation occurs; the temporal pattern of the driving—particularly the duration of steady southward IMF—may be a more critical controlling parameter.

We now ask “why are some super storms not saturated and others saturated”? One possible explanation is that the existence of equatorward electric fields associated with substorms during a storm main phase may screen the convection fields so that the total polar cap potential cannot be enhanced continuously as the interplanetary electric field increases. Many studies have explained the PCP saturation controlled by the dayside reconnection^[5], but the contribution of substorms to the PCP is not clear^[1]. In M-I coupling system, the Region 1 current and ionospheric conductivity affect the PCP^[11]. For D-CONV type storms, the one-cell potential dominates during substorm expansion phases. It is noted that the high potential area is located in midnight sector (as shown in Figure 1b). The formation of this type of cell is related to substorms and it is distorted strongly by enhanced ionospheric conductivities in the midnight sector^[15]. The midnight potential plume is dominated by the equatorward electric field associated with the westward electrojet during the substorm expansion phase and the early recovery phase. We suggest that the superposition of this midnight-sector electric field onto the background dawn-dusk convection field may locally weaken or even cancel the net potential buildup in the polar cap, thereby suppressing the further increase of the total PCP. It should be noted, however, that this interpretation remains qualitative at this stage. A quantitative assessment of how the midnight electric field influences the global PCP value—particularly through the redistribution of high- and low-potential regions—would require

dedicated numerical simulations or higher-resolution observations, which we leave for future work.

Another explanation is that the substorm electric fields are a separate M-I system and at times they dominate the M-I electric field system^[25]. Both explanations provided in this paper bring to a conclusion that substorms play an important role on PCP saturation.

Acknowledgments We appreciate discussions with Mei-Ching Fok. We are extremely grateful to the AMIE data and the CDA Web for access to the ACE, WIND data.

Ethical Approval This article does not contain any studies with human participants or animals performed by any of the authors.

Conflict of Interests The authors declare that there is no conflict of interests.

References

- [1] SHEPHERD S G. Polar cap potential saturation: observations, theory, and modeling[J]. *Journal of Atmospheric and Solar-Terrestrial Physics*, 2007, **69**(3): 234-248
- [2] RAEDER J, LU G. Polar cap potential saturation during large geomagnetic storms[J]. *Advances in Space Research*, 2005, **36**(10): 1804-1808
- [3] TSURUTANI B T, GONZALEZ W D, LAKHINA G S, *et al.* The extreme magnetic storm of 1-2 September 1859[J]. *Journal of Geophysical Research: Space Physics*, 2003, **108**(A7): 1268.
- [4] LOPEZ R E, LYON J G, MITCHELL E, *et al.* Why doesn't the ring current injection rate saturate?[J]. *Journal of Geophysical Research: Space Physics*, 2009, **114**(A2): A02204.
- [5] HILL T W, DESSLER A J, WOLF R A. Mercury and Mars: the role of ionospheric conductivity in the acceleration of magnetospheric particles[J]. *Geophysical Research Letters*, 1976, **3**(8): 429-432
- [6] RUSSELL C T, LUHMANN J G, LU G. Nonlinear response of the polar ionosphere to large values of the interplanetary electric field[J]. *Journal of Geophysical Research: Space Physics*, 2001, **106**(A9): 18495-18504
- [7] SISCOE G L, ERICKSON G M, SONNERUP B U Ö, *et al.* Hill model of transpolar potential saturation: comparisons with MHD simulations[J]. *Journal of Geophysical Research: Space Physics*, 2002, **107**(A6): 1075.
- [8] RIDLEY A J. A new formulation for the ionospheric cross polar cap potential including saturation effects[J]. *Annales Geophysicae*, 2005, **23**(11): 3533-3547
- [9] KAN J R, LI H, WANG C, *et al.* Saturation of polar cap potential: nonlinearity in quasi-steady solar wind-magnetosphere-ionosphere coupling[J]. *Journal of Geophysical Research: Space*

- Physics*, 2010, **115**(A8): A08226.
- [10] TSURUTANI B, MANNUCCI A, IJIMA B, *et al.* Global day-side ionospheric uplift and enhancement associated with interplanetary electric fields[J]. *Journal of Geophysical Research: Space Physics*, 2004, **109**(A8): A08302.
 - [11] SISCOE G, RAEDER J, RIDLEY A J. Transpolar potential saturation models compared[J]. *Journal of Geophysical Research: Space Physics*, 2004, **109**(A9): A09203.
 - [12] DUNGEY J W. Interplanetary magnetic field and the auroral zones[J]. *Physical Review Letters*, 1961, **6**(2): 47-48
 - [13] AKASOFU S I. What is a magnetospheric substorm?[C]//Proceedings of the A. G. U. Chapman Conference ‘Magnetospheric Substorms and Related Plasma Processes’. Los Alamos: Springer, 1978: 447-460
 - [14] ROSTOKER G, AKASOFU S I, BAUMJOHANN W, *et al.* The roles of direct input of energy from the solar wind and unloading of stored magnetotail energy in driving magnetospheric substorms[J]. *Space Science Reviews*, 1988, **46**(1/2): 93-111
 - [15] KAMIDE Y, KOKUBUN S. Two-component auroral electrojet: importance for substorm studies[J]. *Journal of Geophysical Research: Space Physics*, 1996, **101**(A6): 13027-13046.
 - [16] SUN W, ZHOU X Y, DU A. Quantitative separation of the directly-driven and unloading components of the ionospheric electric field[J]. *Geophysical Research Letters*, 2008, **35**(13): L13104.
 - [17] RICHMOND A D, KAMIDE Y (1988), Mapping electrodynamic features of the high-latitude ionosphere from localized observations: Technique, *J. Geophys. Res.*, 93(A6), 5741–5759, doi:10.1029/JA093iA06p05741.
 - [18] RICHMOND A D (1992), Assimilative mapping ionospheric electrodynamics, *Adv. Space Res.*, 12, 59, 1992.
 - [19] WOLF R A. Calculations of magnetospheric electric fields [M]//MCCORMAC B M. *Magnetospheric Physics*. Dordrecht: Springer, 1974: 167-177
 - [20] FOK M C, WOLF R A, SPIRO R W, *et al.* Comprehensive computational model of Earth’s ring current[J]. *Journal of Geophysical Research: Space Physics*, 2001, **106**(A5): 8417-8424
 - [21] FOK M C, MOORE T E, WILSON G R, *et al.* Global ENA image simulations[J]. *Space Science Reviews*, 2003, **109**(1/2/3/4): 77-103
 - [22] WOLF R A, SAZYKIN S, XING X, *et al.* Direct effects of the IMF on the inner magnetosphere[M]//BURCH J L, SCHULZ M, SPENCE H E. *Inner Magnetosphere Interactions: New Perspectives from Imaging*. Washington: American Geophysical Union, 2005: 127-139
 - [23] TSURUTANI B T, GOLDSTEIN B E, GONZALEZ W D and SUGIURA M (1990), Interplanetary Alfvén waves and auroral (substorm) activity: IMP 8, *J. Geophys. Res.*, 95(A3), 2241–2252, doi:10.1029/JA095iA03p02241.
 - [24] DAI L, HAN Y M, WANG C, *et al.* Geoeffectiveness of interplanetary Alfvén waves. I. Magnetopause magnetic reconnection and directly driven substorms[J]. *The Astrophysical Journal*, 2023, **945**(1): 47.
 - [25] TSURUTANI B T, VERKHOGLYADOVA O P, MANNUCCI A J, *et al.* Oxygen ion uplift and satellite drag effects during the 30 October 2003 daytime superfountain event[J]. *Annales Geophysicae*, 2007, **25**(3): 569-574.
 - [26] LU G, LI W H, RAEDER J, *et al.* Reversed two-cell convection in the Northern and Southern hemispheres during northward interplanetary magnetic field[J]. *Journal of Geophysical Research: Space Physics*, 2011, **116**(A12): A12237.

Author Biography



LUO Hao Professor at Institute of Geology and Geophysics, Chinese Academy of Sciences. He is interested in solar wind-magnetosphere coupling and the resulting geomagnetic storm and substorm processes.
E-mail: luohao@mail.iggcas.ac.cn