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Statistical Characteristics of Solar Wind Dynamic Pressure Enhancements During Geomagnetic Storms

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Abstract

Solar wind dynamic pressure enhancements are known to cause various types of disturbances to the magnetosphere. In particular, dynamic pressure enhancements may affect the evolution of magnetic storms when they occur during storm times. In this paper, we have investigated the statistical significance and features of dynamic pressure enhancements during magnetic storm times. For the investigation, we have used a total of 91 geomagnetic storms for 2001-2003, for which the Dst minimum (Dst_{min}) is below −50 nT. Also, we have imposed a set of selection criteria for a pressure enhancement to be considered an event: The main selection criterion is that the pressure increases by $\geq$ 50% or $\geq$ 3 nPa within 30 min and remains to be elevated for 10 min or longer. For our statistical analysis, we define the storm time to be the interval from the main Dst decrease, through Dst_{min}, to the point where the Dst index recovers by 50%. Our main results are summarized as follows. (i)$\sim$ 81% of the studied storms indicate at least one event of pressure enhancements. When averaged over all the 91 storms, the occurrence rate is $\sim$ 4.5 pressure enhancement events per storm and $\sim$ 0.15 pressure enhancement events per hour. (ii) The occurrence rate of the pressure enhancements is about three times higher for CME-driven storm times than for CIR-driven storm times. (iii) Only 21.1% of the pressure enhancements show a clear association with an interplanetary shock. (iv) A large number of the pressure enhancement events are accompanied with a simultaneous change of IMF B_y and/or B_z: For example, 73.5% of the pressure enhancement events are associated with an IMF change of either $|\Delta B_z| > 2$ nT or $|\Delta B_y| > 2$ nT. This last finding suggests that one should consider possible interplay effects between the simultaneous pressure and IMF changes in many situations.

Keywords: solar wind, solar wind dynamic pressure enhancements, magnetic storms

1. Introduction

It is generally accepted that occurrence of magnetic storms is critically dependent on solar wind conditions. It is well known that a prolonged southward interplanetary magnetic field (IMF) is the key condition for causing geomagnetic storms (e.g., Kamide et al. 1998). Major storms are most

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often associated with a coronal mass ejection (CME) or corotating interaction region (CIR) that includes a major interval of southward IMF conditions.

How the state of dynamic pressure P_{dyn} or its change can affect the evolution of magnetic storms is an interesting question, and there are some relevant reports available in the literature. Traditionally, the pressure effect on the Dst index has been taken into account by the equation, Dst* = Dst $-b\sqrt{P_{dyn}} + c$, where b and c are constants (Burton et al. 1975). Fenrich & Luhmann (1998) suggested that the ring current injection rate would increase during a period of enhanced dynamic pressure. Wang et al. (2003) empirically studied the effect of solar wind dynamic pressure on the decay and injection of the ring current on the basis of the Dst index. They reported that the ring current decay time is shorter for a higher dynamic pressure state for northward IMF conditions and the ring current injection rate increases with dynamic pressure during southward IMF. Kim et al. (2005) suggested that a higher dynamic pressure state can sometimes be an important cause of ring current ion loss through the magnetopause.

It is often the case that solar wind dynamic pressure increases abruptly. The effect of such an abrupt pressure increase on various types of magnetospheric phenomena has long been a subject of active research. The types of effects include ground magnetic disturbances (e.g., Russell et al. 1994, and references therein), a geosynchronous magnetic field response (e.g., Wing et al. 2002, Lee et al. 2004, and references therein), a geosynchronous energetic particle disturbance (e.g., Li et al. 2003, Lee et al. 2005), a response throughout the magnetotail (e.g., Nakai et al. 1991, Kawano et al. 1992, Fairfield & Jones 1996, Collier et al. 1998, Ostapenko & Maltsev 1998, Kim et al. 2004), an auroral disturbance (e.g., Lyons et al. 2000, 2005, Zesta et al. 2000, Chua et al. 2001, Boudouridis et al. 2003), a polar cap convection change (e.g., Lukianova 2003), dayside magnetic reconnection (e.g., Boudouridis et al. 2007, Sibeck & Croley 1991), substorm triggering (Zhou & Tsurutani 2001, Lee et al. 2007a) and an energetic neutral atom response (Lee et al. 2007b).

Also, some of other previous papers indicate potential relevance of abrupt increases of the dynamic pressure to the storm evolution. For example, Shi et al. (2006) statistically investigated the effect of abrupt dynamic pressure enhancements on the dawn-to-dusk ring current asymmetry. They reported that a solar wind dynamic pressure enhancement during storm intervals can increase the ring current asymmetry. Also Lee et al. (2004) suggested the possibility that sawtooth injections during magnetic storms are a direct response to successive solar wind dynamic pressure enhancements, which therefore implies the possible direct influence of dynamic pressure changes on the storm evolution.

Another important effect related to P_{dyn} enhancement is substorm triggering under certain conditions. The P_{dyn} trigger has been discussed by many researchers (e.g., Heppner 1955, Schieldge & Siscoe 1970, Kawasaki et al. 1971, Burch 1972, Kokubun et al. 1977, Zhou & Tsurutani 2001, Liou et al. 2003, Lyons et al. 2005, Lee et al. 2005). Although there has yet to be a realistic determination of the precise magnitude and length of the P_{dyn} enhancement required for triggering a substorm as a function of the preceding IMF B_z and P_{dyn}, it seems clear that prolonged and/or strong southward IMF is generally a favorable condition for a P_{dyn} enhancement to trigger a substorm. Since the condition is what is generally expected during storm times and triggered substorms during storms can be an important contributor to the storm construction from the viewpoint of the storm-substorm relationship, one need to clarify the role and importance of P_{dyn} enhancements during storm times.

For a firm establishment of the role of dynamic pressure enhancements during magnetic storms, it is worthwhile to evaluate the statistical significance and features of dynamic pressure enhancements during storm times. To the authors' knowledge, there is no previously reported work on this topic that has been done thoroughly and in a systematic way. In the present paper, we report the statistical significance and features of solar wind dynamic pressure enhancements as obtained from

Table 1. Number of Storms Studied.

YEAR	Storm Number
2001	27
2002	35
2003	29
Total	91

a total of 91 geomagnetic storms for 2001-2003. Specifically, we aim to address several questions including (i) how often abrupt pressure enhancements occur during storm times, (ii) whether the pressure enhancements are primarily due to an interplanetary shock or not, (iii) whether the occurrence rate of pressure enhancements depends on types of storm drivers (such as CME or CIR, for example), and (iv) whether or how often a dynamic pressure enhancement is accompanied with a simultaneous IMF change(s). We briefly describe the methodology used in section 2. In section 3, we present our statistical analysis results including the answers to the questions raised above. Finally, summary and discussion are given in section 4.

2. Methodology

This study is based on a total of 91 storm intervals obtained from the CDAWeb site (http://cdaweb.gsfc.nasa.gov). These events occurred in 2001 through 2003 (See Table 1 for a summary). As a selection criterion, we required that the Dst index exhibits a typical main phase decrease followed by a recovery phase increase and its minimum value is less than –50 nT. As a part of our research purposes, we want to evaluate statistical dependence of pressure events on different types of storms (in particular, CME-driven storms and CIR-driven storms). Inclusion of year 2003 is meaningful since this is the year that is dominated by $\sim$ 27-day recurring, long-lasting, well-defined coronal hole streams, the corotating interaction region of which sometimes causes storms (e.g., Lee et al. 2006). For the year 2003, however, CME-driven storms are rare while for years before 2003, we find many CME-driven storms as well as CIR-driven storms. Our choice of year 2001-2003 results in similar numbers of storms driven by CME and those by CIR (as shown in Figure 6 and discussed in section 3.3). This makes it adequate to compare statistics on pressure events between two different types of storms.

For each storm, we define "storm time interval" to be the interval from the main Dst decrease, through Dst_{min}, to the point where the Dst index recovers by 50%. This definition of the storm time interval thus includes some substantial portion of the Dst recovery phase (See more discussion in the last section) but excludes Storm Sudden Commencement (SSC) due to a dynamic pressure increase that sometimes exists prior to the main decrease of the Dst index for some storms. For the storm time interval of each storm, we have investigated solar wind dynamic pressure enhancement events using the solar wind data at 1 min time resolution from ACE that are time-shifted to X= +15RE by the Weimer mapping technique (Weimer et al. 2003, 2003, Weime 2004). It is known that the ACE particle analyzers sometimes saturate during the passage of intense interplanetary clouds causing data gaps. The storm list that we have used for this study excluded storms that include an interval of such data gap during the storm time interval.

One needs to impose a set of selection criteria for a dynamic pressure increase. We have imposed the following criteria, which are motivated by the recent works by Lee et al. (2004, 2007a) and Lyons et al. (2005) to some extent: (i) the dynamic pressure increases by $\geq$ 50% or by $\geq$ 3 nPa, (ii) the

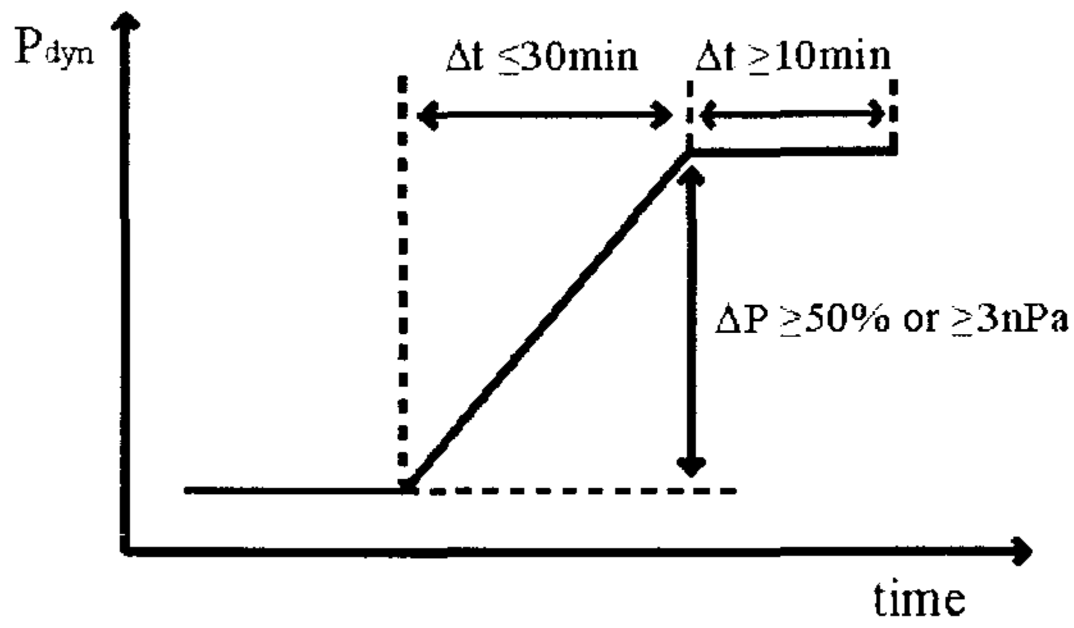

Figure 1. Sketch of the selection criteria for dynamic pressure enhancement events.

transition time over which the pressure reaches to a peak value is less than 30 minutes, (iii) the dynamic pressure remains to be elevated for at least 10 minutes, and (iv) successive increase events are considered to be separate events only when they are separated by 10 min or longer. Figure 1 shows a sketch of the criteria. The quite loose conditions (i) and (ii) allow us to include events of a very weak increase of the dynamic pressure. The motivation for this is that we want to not exclude the possibility that even a weak increase of the dynamic pressure can still be important under certain conditions as suggested by Lee at al. (2004). The statistical results presented below will show how statistically the identified pressure enhancement events are distributed with regard to the pressure change amount or the time rate of the pressure change. By the condition (iii), we want to exclude the cases of too short-lasting pressure enhancements. In the conditions (i) and (iii), the pressure increase amount is estimated based on an average value over 10 min before the start of the pressure increase and an average value over $>$ 10 min of the elevated pressure interval. Within an interplanetary could causing storms, pressure spikes $\gg$ 3 nPa but lasting only a few to several minutes often occur on the background of enhanced pressure. While such pressure spikes by themselves are of interest for another research topic, our 10 min average technique used here smoothed away them without identifying each spike. Based on the criteria, we have developed a computer program of an automatic detection of a dynamic pressure increase. The results were visually confirmed.

Figure 2 shows an example of storm event that occurred on May 11-12, 2002. In Figure 2a, it is shown that the storm starts at $\sim$ 11 UT on May 11, the Dst index becomes minimum, $\sim$ -110 nT, at $\sim$ 19 UT on May 11 as indicated by dotted line through all panels, and it recovers by 50% at $\sim$ 10 UT on May 12. Figure 2b to 2f show the Weimer mapped IMF and solar wind data for this interval. According to the selection criteria above, we have identified nine dynamic pressure enhancement events as marked by vertical dotted lines with numbers in panel (f). Note that these pressure enhancements are primarily due to enhancements of the solar wind density as shown in panel (e). Also note that the IMF B_y and B_z changes are significant in association with some of the pressure enhancement events, which we will discuss further below.

3. Statistical results

3.1 How often do pressure enhancements occur?

Statistically, we have found that, out of the 91 storms studied here, 74 storms ($\sim$ 81%) are accompanied with at least one event of P_{dyn} enhancement during each storm time and the other 17

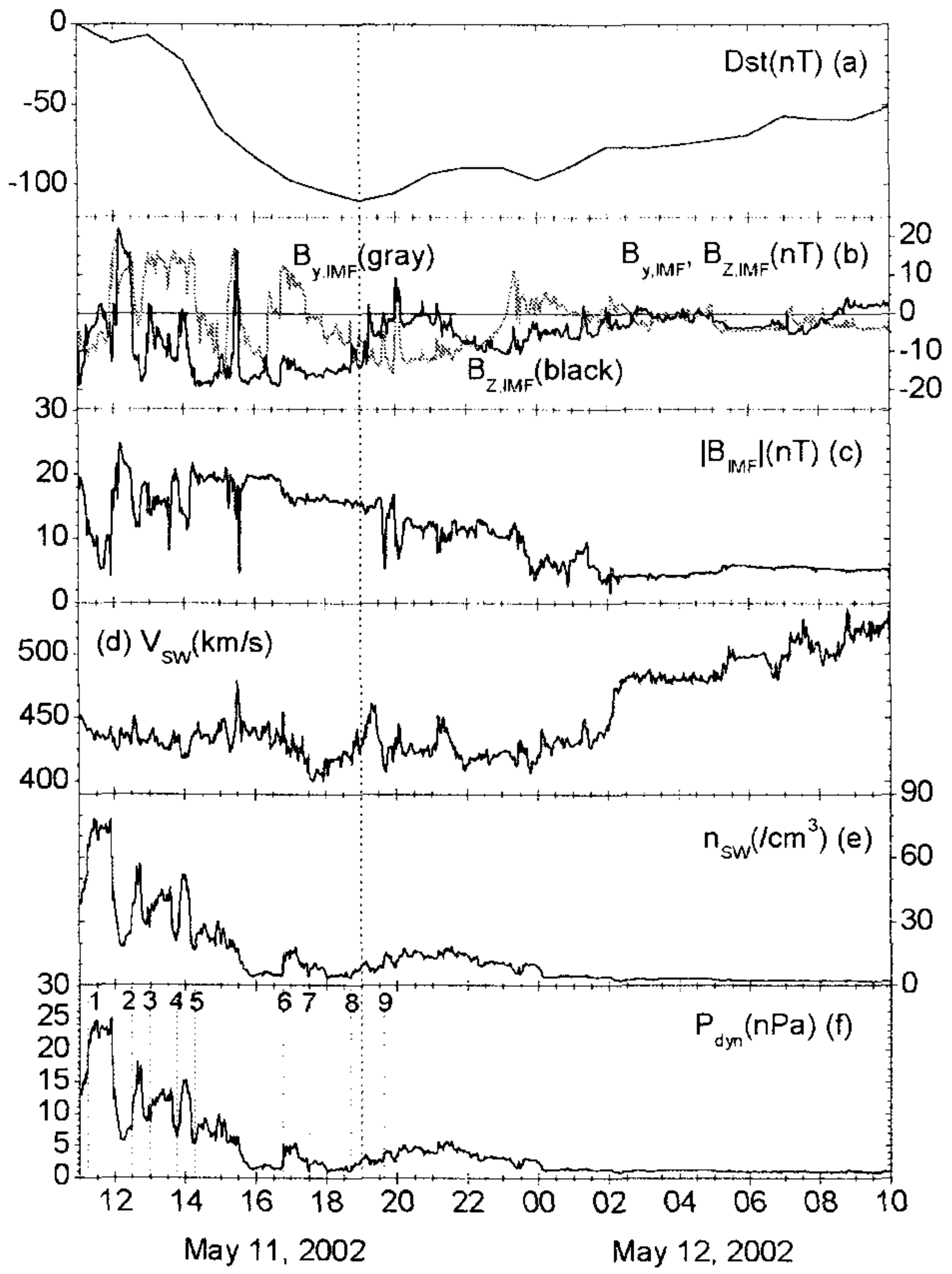

Figure 2. (a) Dst index, (b) IMF B_y, and B_z, (c) IMF $|B|$ data , (d) solar wind velocity, (e) solar wind density, and (f) dynamic pressure from ACE on 11-12 May, 2002. The solar wind/IMF data are presented as time-shifted by the Weimer mapping. The long dotted vertical line through all panels indicates the Dst minimum time, and the shorter dotted vertical lines in panel (f) mark the identified pressure enhancement events based on the criteria described in text.

storms ($\sim$ 19%) show no P_{dyn} enhancement event. The 74 storms together indicate a total of 407 P_{dyn} enhancement events. This means that an average occurrence rate per storm (considering all the 91 storms) is $\sim$ 4.5 (It becomes $\sim$ 5.5 per storm when averaged over only the 74 storms showing at least one P_{dyn} enhancement). Also, since we find that the total storm time duration as summed over all the 91 storms are 2668 hrs, this implies that an average occurrence rate per hour is $\sim$ 0.15: On the average one P_{dyn} enhancement event occurs every $\sim$ 6.5 hrs during the storm time. A summary is given in Table 2.

Figure 3 shows the number of storms vs. the number of P_{dyn} enhancement events per storm. It is seen that the majority of the storms indicate 4 or less of P_{dyn} enhancement events during each storm time. But it also shows that for 15 storms the occurrence of P_{dyn} enhancement events is 10 or larger, implying that P_{dyn} enhancements occur quite frequently for some magnetic storms. On the other hand, Figure 4 demonstrates that there is no meaningful correlation between the number of P_{dyn} enhancement events and the duration of each storm. There seems to be a weak tendency that the number of P_{dyn} enhancement events increases with the storm intensity (Dst_{min}), but the

Table 2. Summary of Statistical Results.

Description of statistics	Statistics
Total storm time interval summed over all storms	2668hrs
Total number of storms	91
- Storms with at least one P_{dyn} enhancement	- 74 (81%)
- Storms without a P_{dyn} enhancement	- 17 (19%)
Total number of P_{dyn} enhancements identified	407
- Events associated with fast forward shock	- 19 (4.6%)
- Events associated with slow forward shock	- 67 (16.5%)
- Events associated with no obvious shock	- 321 (78.9%)
Average occurrence rate per storm (for all 91 storms)	4.5 (#/storm)
= total number of P_{dyn} enhancements / total number of storms	
Average occurrence rate per hr (for all 91 storms)	0.15 (#/hr)
= total number of P_{dyn} enhancements / total storm time interval summed over all storms	

correlation is not too strong.

The statistics shown in Figure 5 demonstrates how statistically the identified pressure enhancement events are distributed with regard to pressure change amount (in plots (a) and (b)) and time scale or rate of the pressure change (in plots (c) and (d)). First, Figure 5a shows the distribution of the P_{dyn} enhancement events as a function of relative change (in %). It indicates that 59.2% of the P_{dyn} enhancement events correspond to an increase by 50-100% and 31.5% an increase by >100%. Note that the other 9.3% are the cases of <50% and are included as they meet the criterion that the increase be 3 nPa. Figure 5b shows the distribution of the P_{dyn} enhancement events as a function of absolute change (in nPa). It indicates that only $\sim$ 34.6% of the P_{dyn} enhancement events correspond to an increase by $\geq$ 3 nPa. The other $\sim$ 65.4% of the events do not meet the criterion of 3nPa increase but do meet the criterion of $\geq$ 50% increase. In other words, many of the identified P_{dyn} enhancement events are characterized by an absolute increase of $<$ 3 nPa and a relative percentage increase of $\geq$ 50%. Whether or not a relative increase of the pressure can be more important than an absolute increase warrants a future in-depth study. It is interesting to note the attempt by Lee et al. (2004) that they associate some of the teeth of sawtooth injection events during storm times with a dynamic pressure change for which the absolute increase is small but the corresponding relative increase is not.

How fast the pressure increases, i.e., the transition time, can also be an important factor to consider when studying the effect on the magnetosphere. Figure 5c shows the statistics of the P_{dyn} enhancement events as sorted by the transition time Δt. Although our criterion above was to allow the transition time of up to 30 min, the vast majority of our events correspond to a transition time of $\sim$ 10 min or less. Based on this data, Figure 5d shows the statistics of the P_{dyn} enhancement events as a function of the time rate of the pressure increase dP_{dyn}/dt (given in nPa/min). We note that there is some substantial number of events for which dP_{dyn}/dt is quite low: dP_{dyn}/dt is less than 0.2 nPa/min for $\sim$ 25.0% and less than 0.4 nPa/min for $\sim$ 50.8% of the total P_{dyn} enhancement events. Obviously, at least two interesting questions arise: (i) Whether dP_{dyn}/dt is more important or more meaningful in any aspect than P_{dyn}, and (ii) whether such a small value of dP_{dyn}/dt can still be a significant effect during storm times. These questions are beyond the scope of the main purpose of the present paper and are left as a future work.

3.2 How many of the pressure enhancements are due to an interplanetary shock?

Based on the solar wind speed, density, temperature, and magnetic field magnitude, we have checked whether or not the identified P_{dyn} enhancement events are interplanetary shock-associated.

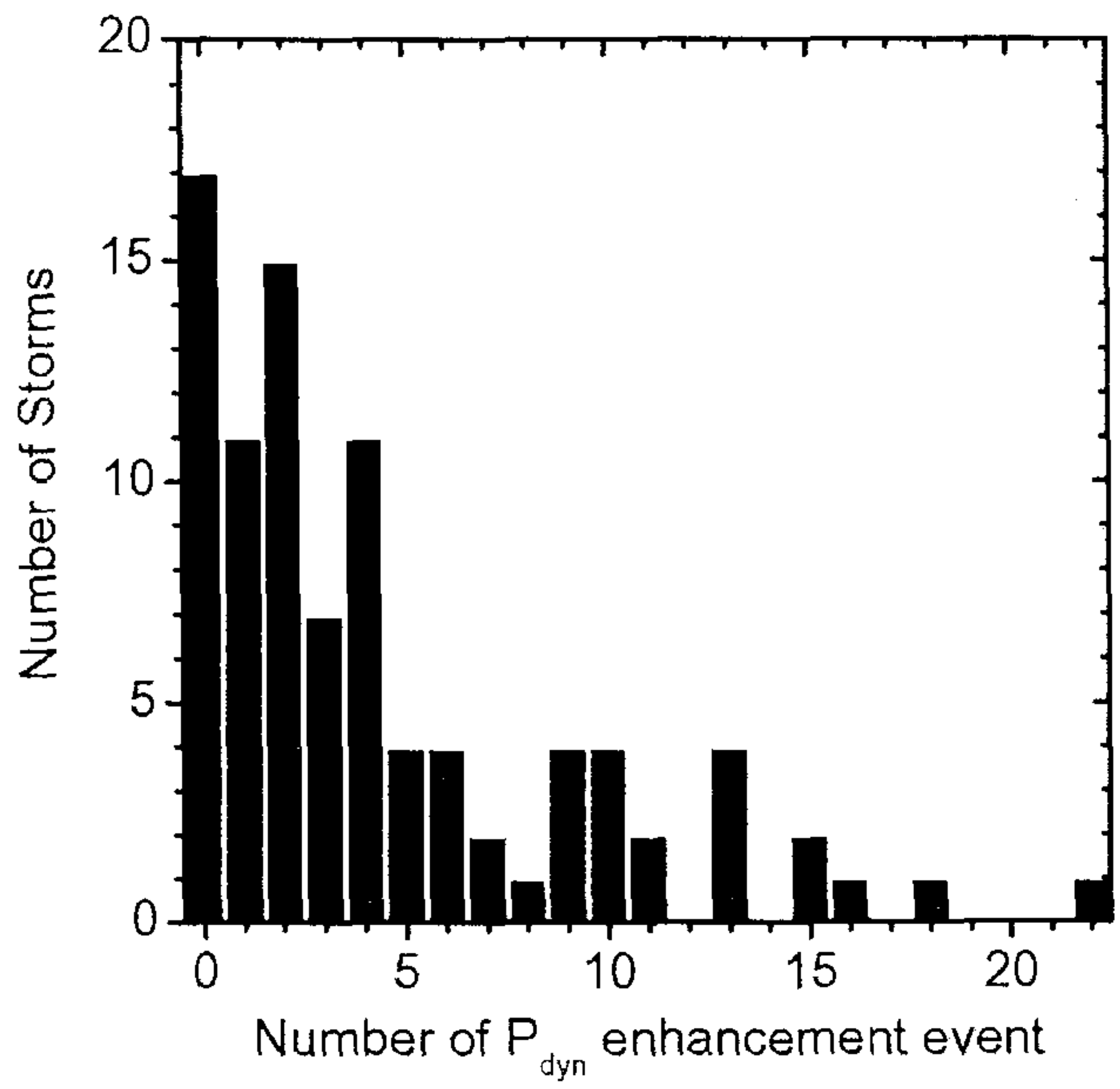

Figure 3. Statistics showing the number of storms versus the number of dynamic pressure enhancements per storm.

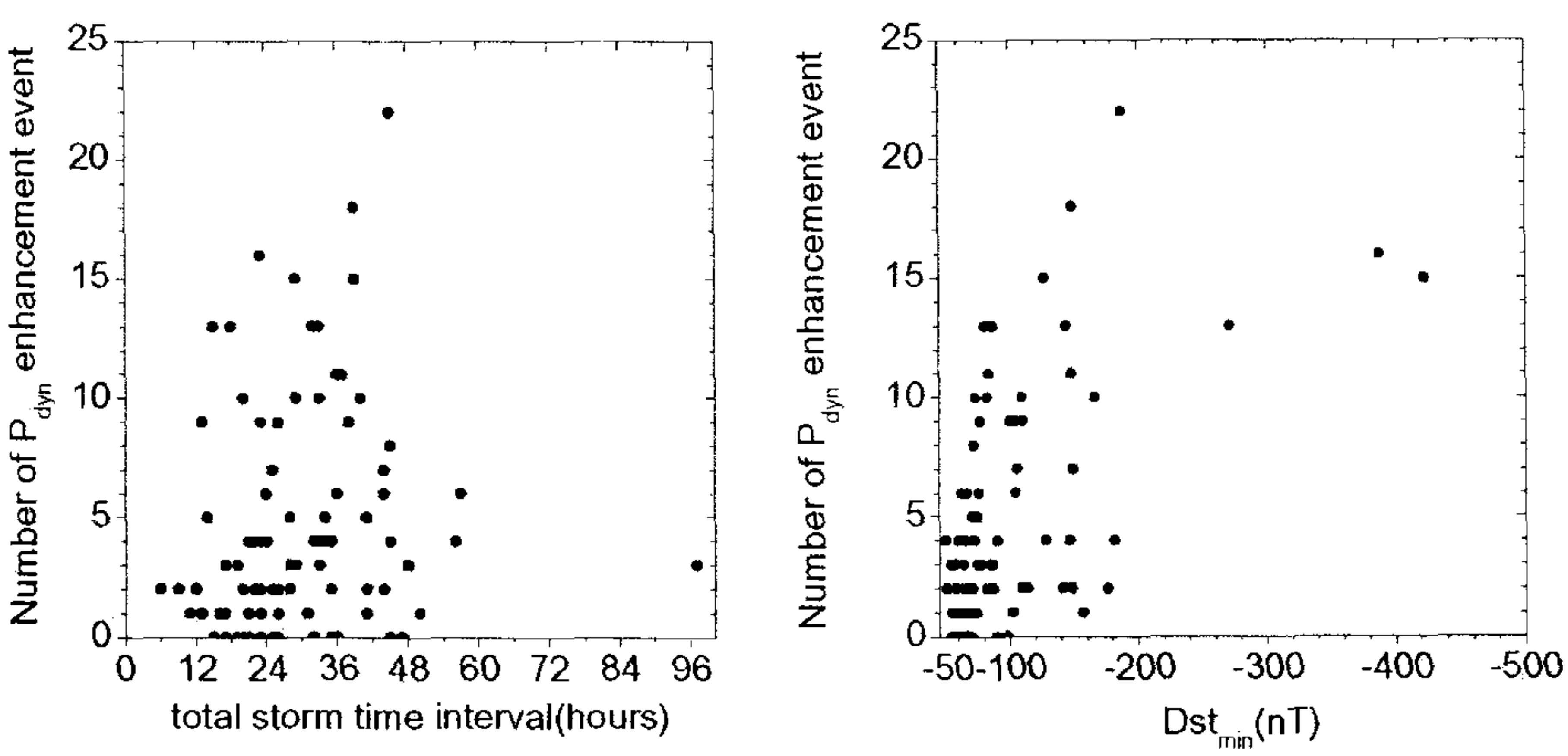

Figure 4. Number of pressure enhancement events vs. storm time duration and Dst_{min}.

We find that out of the 407 P_{dyn} enhancement events, only 19(4.6%) and 67(16.5%) events are clearly associated with a fast forward shock and a slow forward shock, respectively. The remaining 78.9% of the P_{dyn} enhancement events are not related to an interplanetary shock. A summary of these statistics is given in Table 2. It should be noted that these statistical numbers are obtained

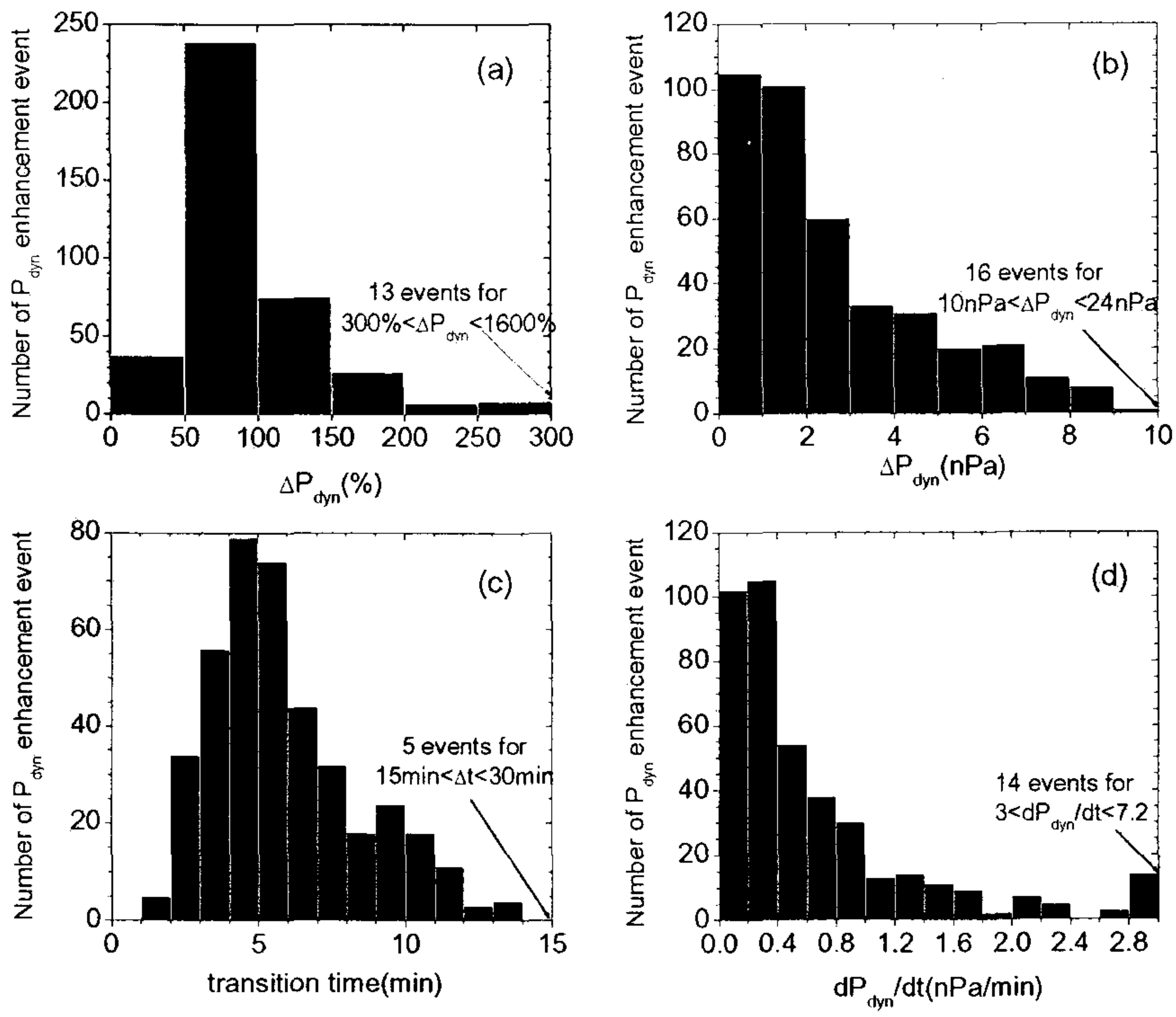

Figure 5. Statistics on dynamic pressure enhancement amount (a) in percentage and (b) in nPa. The cases of large values are separately indicated for the sake of convenience. (c) Statistics of the transition time and (d) statistics of the pressure increase rate in time.

without including the storm sudden commencement events which are usually caused by a shock-associated P_{dyn} enhancement as mentioned above in Section 2.

3.3 Does the pressure enhancement occurrence rate depend on storm-driver types?

In order to determine the extent to which the occurrence rate of P_{dyn} enhancements can differ between storms of different storm-driver types, we have categorized the 91 storms into CME-driven, CIR-driven, High-speed stream-associated, and unidentified types. Here what we mean by "High-speed stream-associated types" is simply storms that indicate Dst less than –50 nT during the high-speed interval that usually follows the main CIR interval. We have distinguished them for the sake of convenience by noting that the Dst index sometimes decreases below –50 nT during high-speed streams following the CIR while CIR itself can sometimes lead to a modest storm.

The result is shown in Figure 6a which indicates that 36.3% (33 events) of our studied storms are CME-driven storms, 38.5% (35 events) are CIR-driven storms, only 3.3% are High-speed stream-associated, and the remaining 21.9% are unidentified types. Now the question is "is there any tendency that P_{dyn} enhancements occur more frequently during storms of a particular driver type?" An answer to this question is summarized in Figure 6b which indicates that 62.7% (255 events) out of all P_{dyn} enhancement events identified are found during the CME-driven storm times while 22.1% (90 events) during the CIR-driven storm times. The total storm time interval is 912 hrs as summed

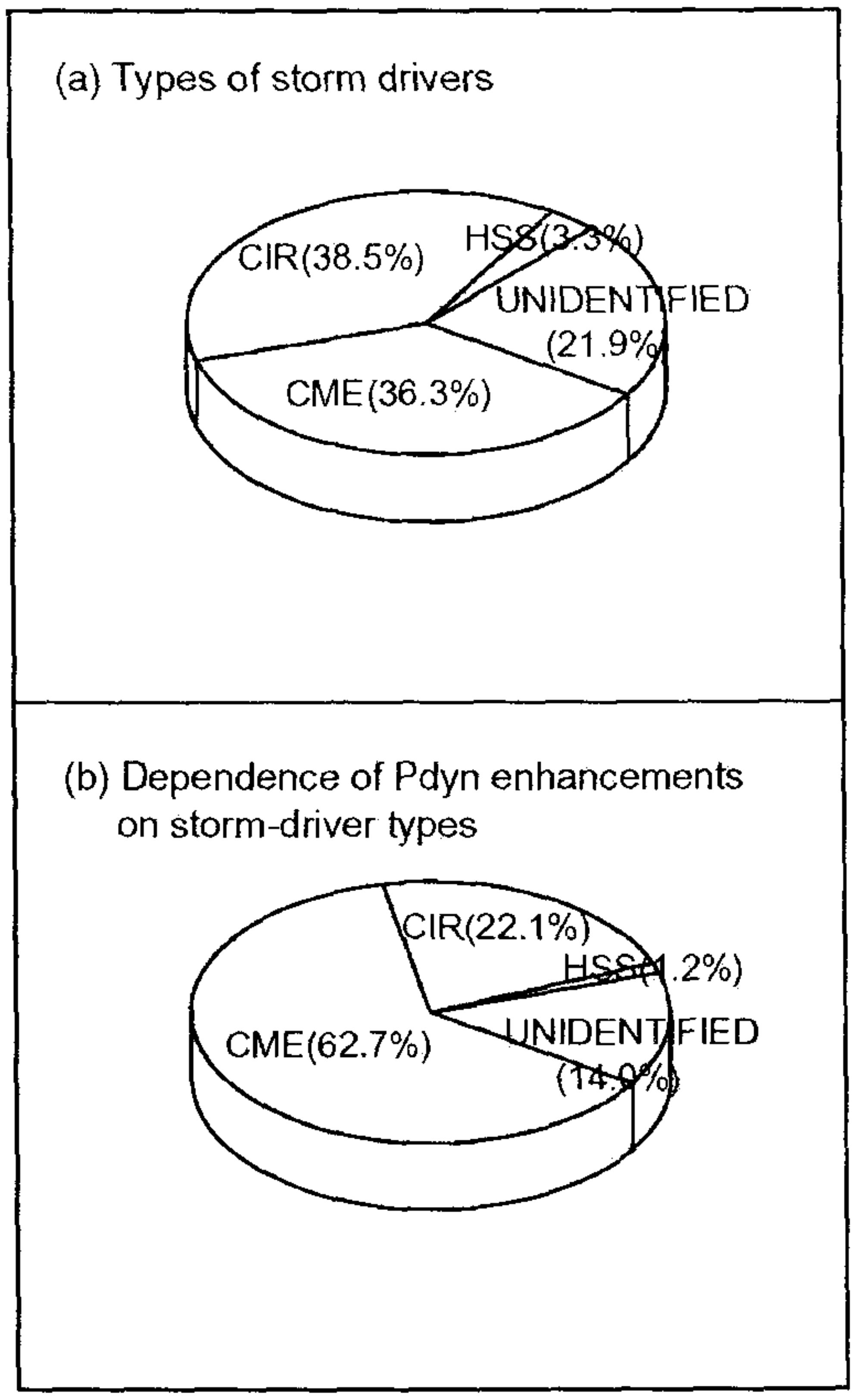

Figure 6. (a) Statistics of driver types of the storms studied in the present work and (b) statistics of dependence of the dynamic pressure enhancements on types of the storm-driver.

over the 33 CME-driven storms and 1050 hrs over the 35 CIR-driven storms, respectively. Therefore an average occurrence rate of P_{dyn} enhancement events is 0.28/hr for the CME-driven storm times and 0.09/hr for the CIR-driven storm times, respectively. Namely, the occurrence rate is about three times higher for the CME-driven storm times than for the CIR-driven storm times. Figure 7 shows more specifically the statistics by distinguishing between CME-driven and CIR-driven types. The average storm time interval per storm is 27.6 hrs for the CME-driven storms, and similarly 30 hrs for the CIR-driven storms. The average number of P_{dyn} enhancements per storm is 7.7 and 2.6 for the CME-driven and CIR-driven storm times, respectively. Use of these numbers actually gives the same occurrence rates mentioned above. On the other hand, only 1.2% events of the P_{dyn} enhancements occurred during the storms associated with high-speed streams, and for the remaining 14% of P_{dyn} enhancement events, no definite determination could be made.

3.4 What is the IMF condition at the time of pressure enhancements?

We have also examined the IMF conditions associated with each pressure enhancement event. First, we have checked the preceding IMF B_z condition over an interval of 10 min prior to each pressure enhancement event. The result is shown in Figure 8 which indicates that 69.5% of the pressure

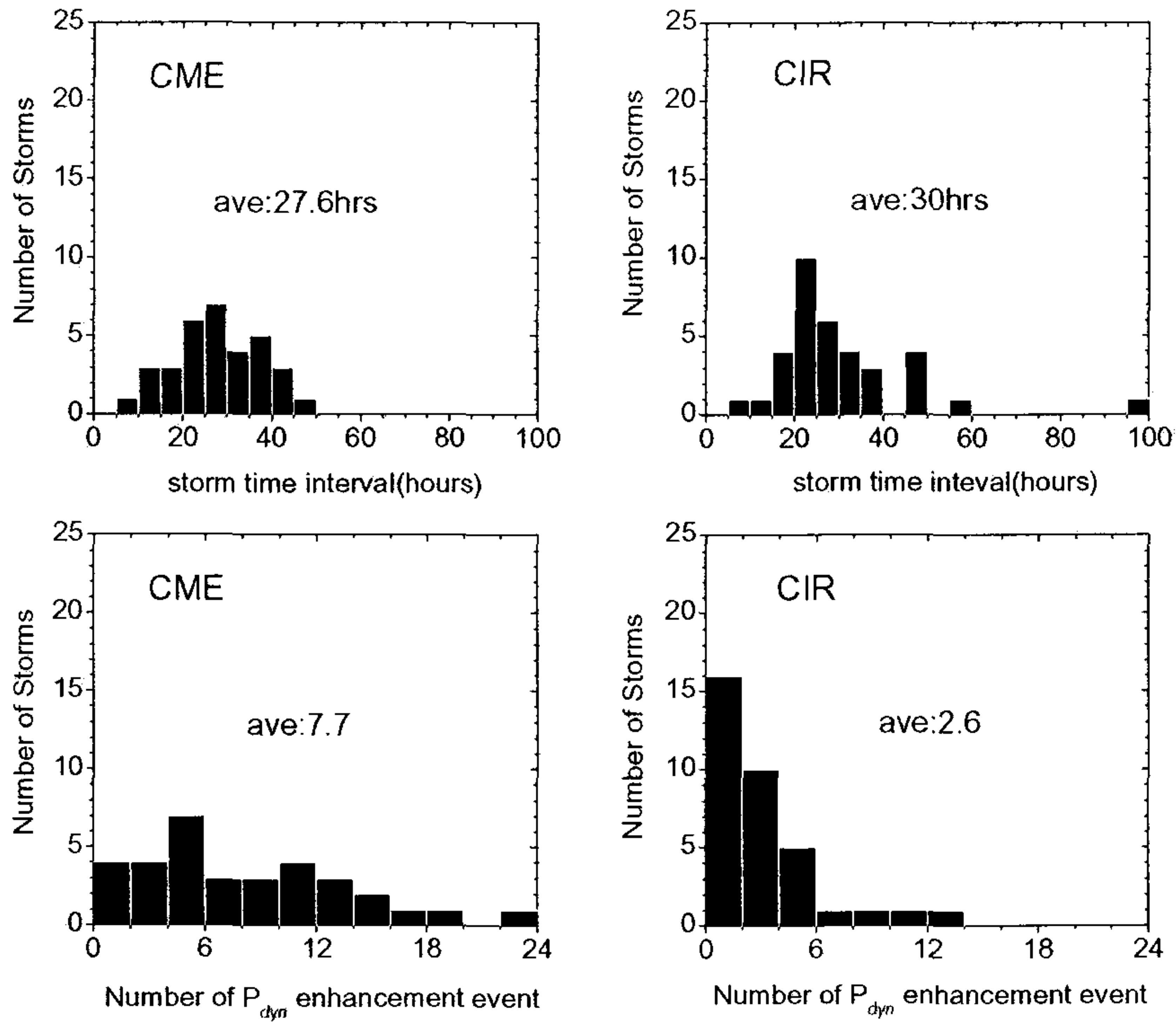

Figure 7. (Top panels) Statistics of the storm time interval and (Lower panels) the number of P_{dyn} enhancements by distinguishing between CME-driven and CIR-driven storms. The average storm time interval per storm is indicated in top panels, 27.6 hrs for the CME-driven storms, and 30 hrs for the CIR-driven storms. The average number of P_{dyn} enhancements per storm is indicated in lower panels, 7.7 and 2.6 for the CME-driven and CIR-driven storm times, respectively.

enhancement events are associated with a preceding southward IMF condition. This relatively large percentage is of course not surprising as we deal with storm times that are usually associated with southward IMF conditions.

More interestingly, we have checked whether or not the IMF B_y and/or B_z change at the same time as each pressure enhancement. Figure 9a shows the scatter plot of all the P_{dyn} enhancement events in the domain defined by changes of IMF B_y and B_z at the time of each P_{dyn} enhancement. One can see that a large number of the P_{dyn} enhancement events are accompanied with a non-zero change of IMF B_y and/or B_z. Figure 9b shows similar results using only the pressure enhancements that are associated with a preceding southward IMF condition. The same data are presented as histograms in Figure 10. As an example, we find from Figure 10a that 73.5% of the P_{dyn} enhancement events are associated with an IMF change of either $|\Delta B_z| > 2$ nT or $|\Delta B_y| > 2$ nT. Also from Figure 10b it is found that 71% of the P_{dyn} enhancement events that are associated with a preceding southward IMF condition indicate a simultaneous IMF change of either $|\Delta B_z| > 2$ nT or $|\Delta B_y| > 2$ nT.

Note that the events associated with a shock are marked by open circle in Figure 9. It is worth-

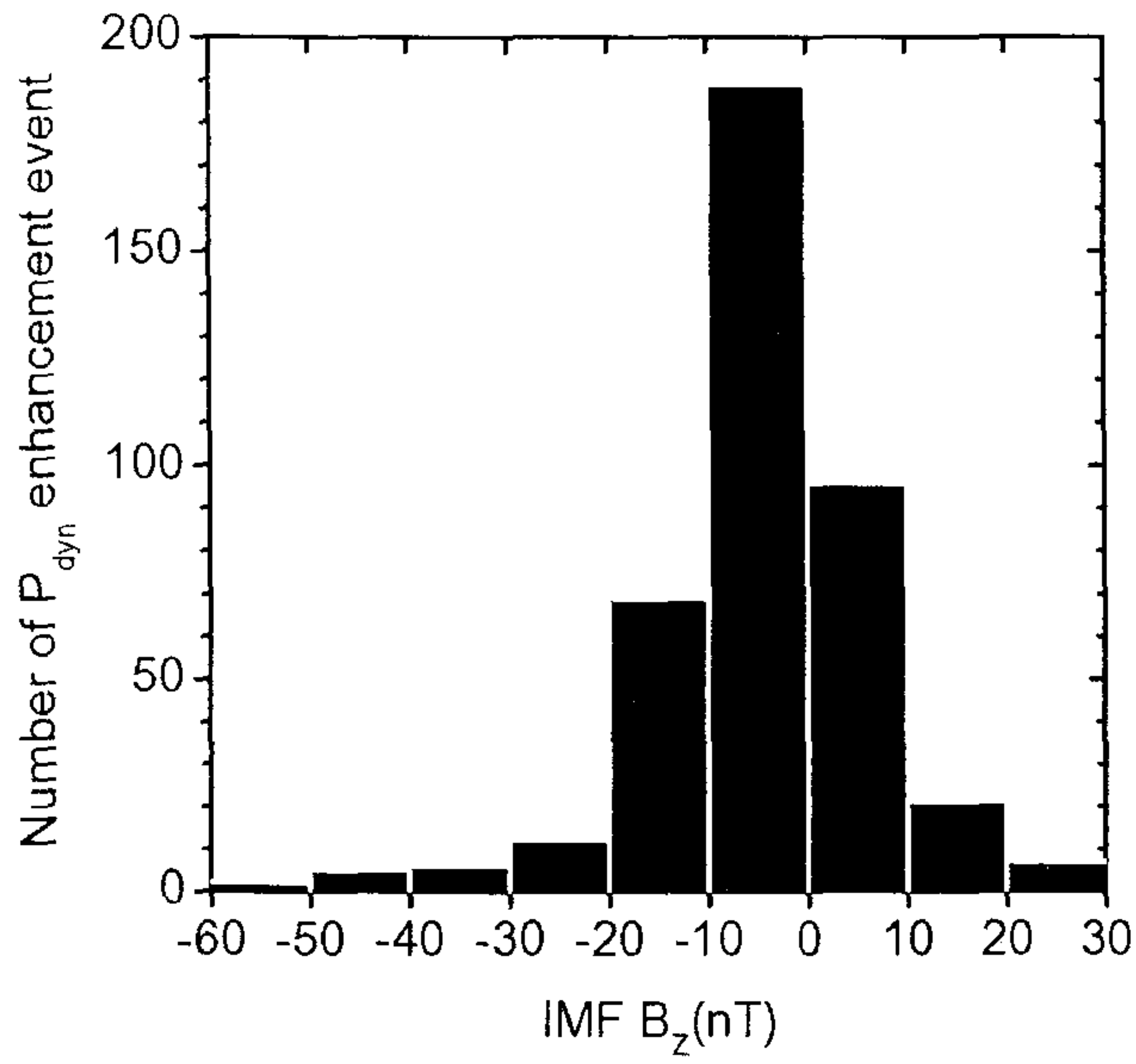

Figure 8. Statistics on IMF B_z condition averaged over 10 min prior to each dynamic pressure enhancement event.

while to note that the simultaneous pressure and IMF changes are not necessarily due to an interplanetary shock as we have already shown above that the pressure enhancements due to a shock are not the majority of the identified events. But by distinguishing the statistics between the shock-associated pressure enhancements and those not associated with a shock as shown in Figure 11, we find that a modestly larger percentage of the P_{dyn} enhancement events are accompanied with a larger change in IMF B_y or B_z when the P_{dyn} enhancement is due to a shock than when it is not. For example, 84.9% of the P_{dyn} enhancement enhancement events that are shock-associated indicate a change of >2 nT in either IMF B_y or B_z while the percentage becomes $\sim$ 70.4% for the P_{dyn} enhancement events that are not shock-associated. We find a similar difference when using only the P_{dyn} enhancement events under the preceding southward IMF condition (i.e., 85.7% vs. 66.8%). Note that in Figure 9-11, we have separately presented the statistics of the P_{dyn} enhancement events associated with a preceding southward IMF condition, considering that the possible interplay effect between the simultaneous pressure and IMF changes may be more meaningful under preceding southward IMF conditions (See more discussion below).

4. Summary and Discussion

In this paper, we have investigated statistical features of solar wind dynamic pressure enhancements during storm times. Our analysis is based on a total of 91 geomagnetic storms for 2001-2003 for which the Dst index decreases below −50 nT, and the requirement that the pressure enhancement is $\geq$ 50% or $\geq$ 3nPa within a time scale of 30 min (but vast majority of our identified events turned out to correspond to a time scale of 10 min or less).

Our main results can be summarized as follows. (i) $\sim$ 81% of the studied storms indicate

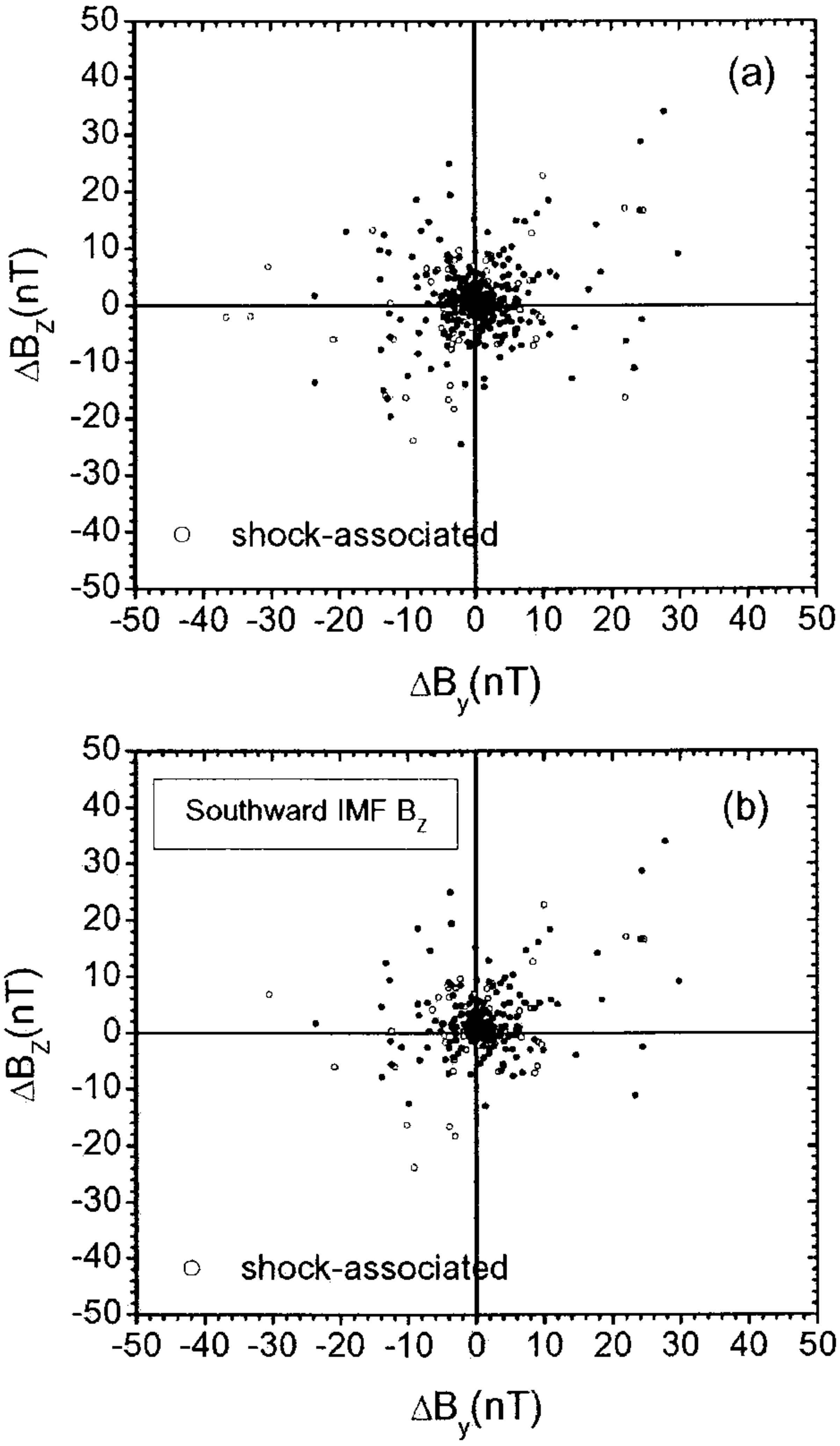

Figure 9. (a) Scatter plot of all dynamic pressure enhancement events in the domain defined by ΔB_y (IMF B_y change) and ΔB_z (IMF B_z change). (b) Similar plot but only for the pressure events when the preceding IMF B_z is southward. Open circles represent the pressure events associated with an interplanetary shock.

at least one event of P_{dyn} enhancements. When averaged over all the 91 storms, the occurrence rate is $\sim 4.5 P_{dyn}$ enhancement events per storm and 0.15 P_{dyn} enhancement events per hr. This occurrence rate is not insignificant considering the expectation that a P_{dyn} enhancement can likely trigger a substorm during the storm time, therefore affecting the storm evolution to some extent.

However we caution the readers to note that the occurrence rate can differ depending on how one defines the storm time. First, one could limit the study to the storm main phase only, but we find that for many storms the main phase is too short, and more importantly we see no reason to exclude

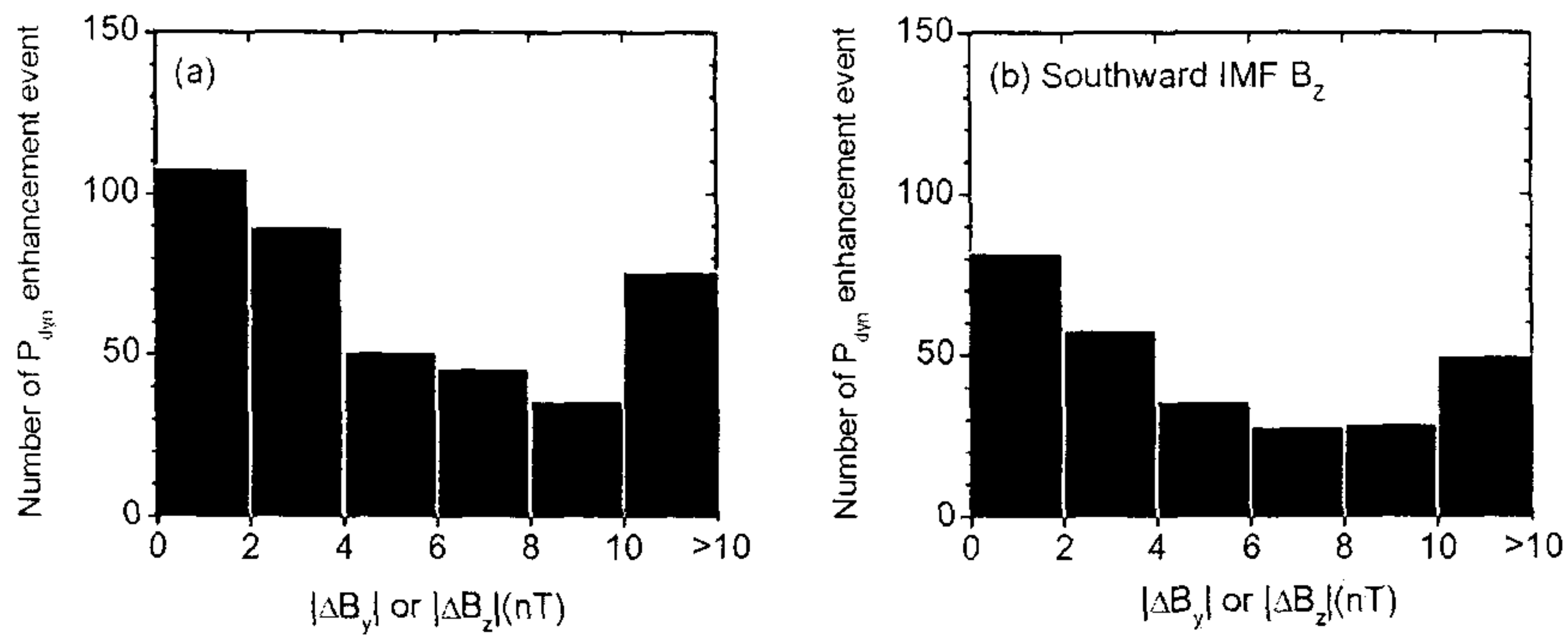

Figure 10. (a) Histogram of dynamic pressure enhancement events that are accompanied by a simultaneous ΔB_y or ΔB_z. (b) Similar plot but only for the pressure events when the preceding IMF B_z is southward.

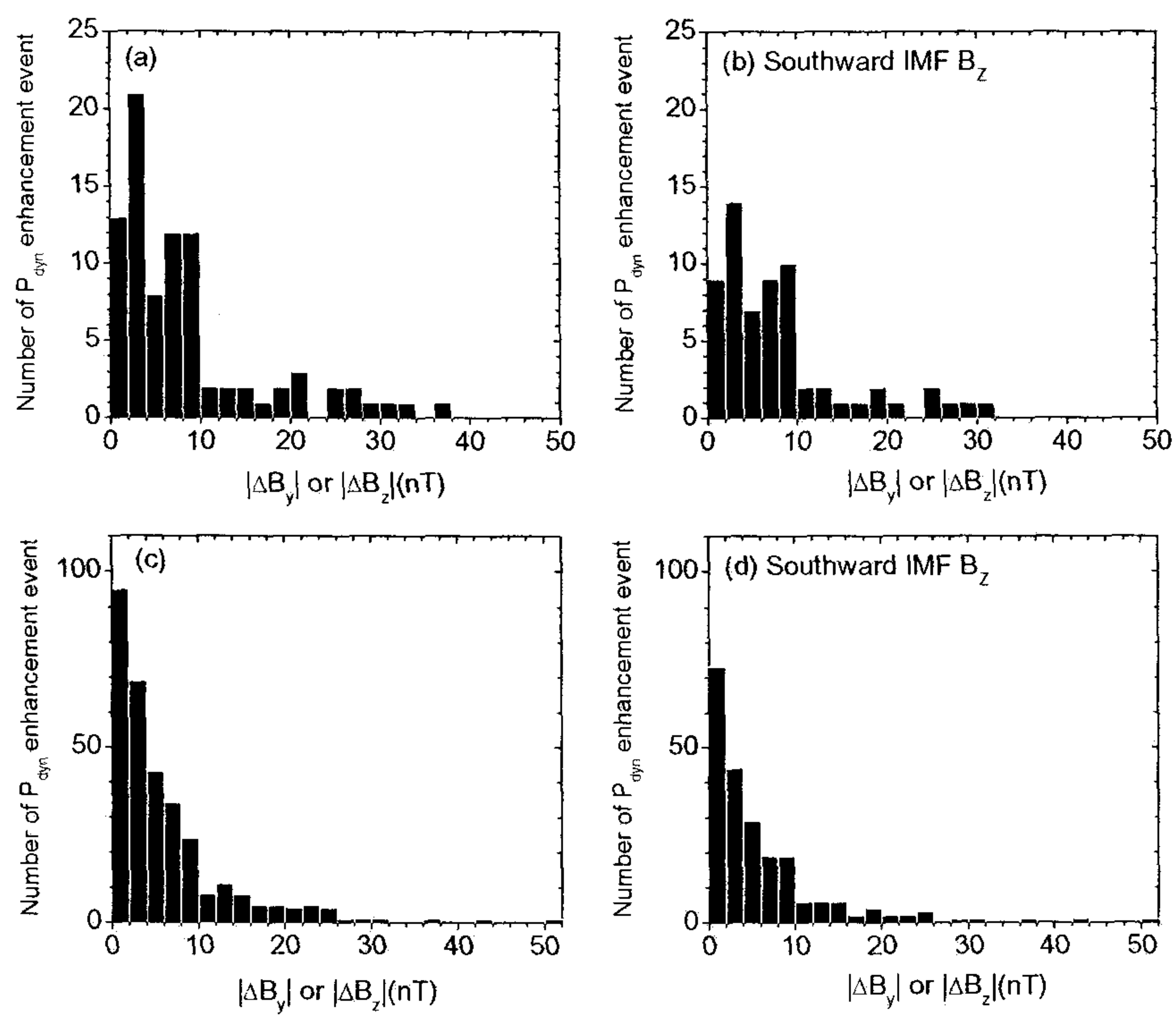

Figure 11. Histogram of dynamic pressure enhancement events that are accompanied by a simultaneous ΔB_y or ΔB_z. (a) For the events associated with a shock and (c) for the events not associated with a shock. (b) and (d) Similar plots but only for the pressure events when the preceding IMF B_z is southward.

the recovery phase from the viewpoint of considering the dynamic pressure effect. Inclusion of the recovery phase to some point should be useful. For some storms, the Dst recovery is characterized by a "fast recovery" followed by a much slower recovery phase (e.g., Jorgensen et al. 2001, and references therein). One could then define the storm time to include the fast recovery phase following the main phase. But we note that it is often practically not easy to distinguish between fast and slow recovery phases without ambiguity for many storms. Thus limiting the study to the storms with a well-defined fast recovery phase only will reduce the number of the storms greatly for our analysis. Also, we see no reason to exclude storms that do not clearly show the two-step recovery phase. For this work, we have defined the storm time to be the interval from the main decrease time of Dst, through Dst_{min}, and to the time of the Dst recovery by 50%. We regard that this definition can still be subjective, but it includes the recovery phase interval to some extent, whether or not the recovery phase is characterized by a well-defined two-step recovery. We leave the issue as a future work how sensitively the result can depend on the definition of the storm time.

Also, one will obtain a different occurrence rate depending on the selection criteria that one sets to identify a P_{dyn} enhancement. We have not attempted to determine the extent to which the result can differ when one uses a set of criteria that are different from our selection criteria. But we do not think that our criteria are unrealistic too much since we have chosen the criteria primarily by referring to the previous works by Lee et al. (2004, 2005, 2007a), Lyons et al. (2005) and Shi et al. (2006).

(ii) The occurrence rate of P_{dyn} enhancements is about three times higher for the CME-driven storm times than for the CIR-driven storm times. This result suggests the possibility that the P_{dyn} enhancement can be an important factor to consider more for the CME-driven storms than for the CIR-driven storms in a statistical sense. Also, it would warrant a future study to see if the solar wind density is indeed more fluctuating when associated with a CME than with a CIR and, if so, examining the responsible mechanism would be interesting.

(iii) Only 21.1% of the P_{dyn} enhancements show a clear association with an interplanetary shock. In other words, the majority of the P_{dyn} enhancements found are caused by other reasons than a shock. However, it should be noted that our definition of the storm time excluded the SSC which is typically caused by a shock-associated P_{dyn} enhancement. Statistics will change if one includes the SSC interval, but our main purpose has been to focus on the P_{dyn} enhancements during the main interval of storms after SSC.

(iv) A large number of the P_{dyn} enhancement events are accompanied with a simultaneous change of IMF B_y and/or B_z: For example, 73.5% of the P_{dyn} enhancement events are associated with an IMF change of either $|\Delta B_z| > 2$ nT or $|\Delta B_y| > 2$ nT. This is significant enough so that it suggests that for many cases one needs to consider the possible interplay effects between the simultaneous pressure and IMF changes.

It has long been considered that a P_{dyn} enhancement can be a substorm trigger under certain conditions. The prolonged southward IMF condition, as for major storm times, seems to be in general the most likely condition for a P_{dyn} enhancement to be a trigger. Our result here suggests that a simultaneous IMF change, depending on the nature of its change, can play a role of suppressing the potential triggering effect by a P_{dyn} enhancement (Lyons et al. 2005, Lee et al. 2007a) or may enhance the possibility of triggering a stronger substorm. In particular, the idea of nullification was suggested by Lyons et al. (2005) that the potential triggering effect by a solar wind variable(s) can be canceled out by the changes in other variables of the solar wind, if sufficiently large. For example, the effect by a dynamic pressure enhancement under prolonged southward IMF conditions, which would alone trigger a substorm, can be nullified by a simultaneous further-southward turning of the IMF B_z and/or by a simultaneous increase of IMF $|B_y|$. Also, another interesting question is whether or not a simultaneous IMF northward turning and pressure enhancement together can lead to a larger or more intense substorm than either of the same IMF turning and pressure enhancement alone would do. All these possibilities warrant further studies. Since the substorms can affect the storm evolution, determination of how effectively the dynamic pressure enhancements affect the storm evolution through substorm triggering will be more reliable when the study considers all the possible interplay effects with a simultaneous IMF change(s).

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