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Statistical comparison of interplanetary conditions causing intense geomagnetic storms (Dst ≤ −100 nT)

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[1] It is well known that intense southward magnetic field and convection electric field (V × B) in the interplanetary medium are key parameters that control the magnitude of geomagnetic storms. By investigating the interplanetary conditions of 82 intense geomagnetic storms from 1998 to 2006, we have compared many different criteria of interplanetary conditions for the occurrence of the intense geomagnetic storms (Dst ≤ −100 nT). In order to examine if the magnetosphere always favors such interplanetary conditions for the occurrence of large geomagnetic storms, we applied these conditions to all the interplanetary data during the same period. For this study, we consider three types of interplanetary conditions as follows: B_z conditions, E_y conditions, and their combination. As a result, we present contingency tables between the number of events satisfying the condition and the number of observed geomagnetic storms. Then we obtain their statistical parameters for evaluation such as probability of detection yes, false alarm ratio, bias, and critical success index. From a comparison of these statistical parameters, we suggest that three conditions are promising candidates to trigger an intense storm: $B_z \leq -10$ nT for >3 h, $E_y \geq 5$ mV/m for >2 h, and $B_z \leq -15$ nT or $E_y \geq 5$ mV/m for >2 h. Also, we found that more than half of the "miss" events, when an intense storm occurs that was not expected, are associated with sheath field structures or corotating interacting regions. Our conditions can be used for not only the real-time forecast of geomagnetic storms but also the survey of interplanetary data to identify candidate events for producing intense geomagnetic storms.

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1. Introduction

[2] Geomagnetic storms are initiated when energy is transferred from the solar wind into the Earth's magnetosphere, a process that appears to be controlled by the rate of magnetic reconnection between the southward component of the interplanetary magnetic field (IMF) and magnetospheric fields [*Dungey*, 1961]. Such storms may lead to the intensification of the ring current due to the injection of energetic ions from the plasma sheet largely by convection driven by the dawn-to-dusk component of the convective electric field, $E_y = V_x B_z$. Here V_x is the radial component of the solar wind velocity and B_z is the north-south component of the IMF. Development of the ring current during storms may be measured by the *Dst* geomagnetic index which is frequently used as an indication of the relative strengths of geomagnetic storms [e.g., *Gonzalez et al.*, 1994].

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[3] The magnitudes of the southward IMF B_z and the convection electric field E_y are known to be important parameters causing intense geomagnetic storms (Dst ≤ −100 nT) [*Gonzalez and Tsurutani*, 1987; *Tsurutani et al.*, 1988; *Gonzalez et al.*, 1994; *Alves et al.*, 2006]. From a statistical study, *Wang et al.* [2003] found that during intense storms in 1998–2001, the value of E_y averaged between the times of first southward IMF turning and $Dst_{\min}$ was well correlated with the value of $Dst_{\min}$. *Echer et al.* [2008] investigated the correlation of $Dst_{\min}$ with peak values of B_z, E_y, positive and negative IMF B_y values, total magnetic field, dynamic pressure, density, and velocity. The best correlation was found for B_z and E_y.

[4] Using B_z and E_y components, several authors have statistically studied the interplanetary criteria causing intense geomagnetic storms [*Gonzalez and Tsurutani*, 1987; *Wang et al.*, 2003; *Echer et al.*, 2008]. *Gonzalez and Tsurutani* [1987] studied the interplanetary cause for 10 intense magnetic storms that occurred from 16 August 1978 to 28 December 1979. They found that a necessary interplanetary condition for the intense geomagnetic storms is $B_z < -10$ nT or $E_y > 5$ mV/m persisting for more than 3 h. *Wang et al.* [2003] investigated the influence of the averaged convection electric field ($\overline{E_y}$) and its duration for 35 intense geomagnetic storms during

Table 1. Contingency Table

Condition	Observation Yes	No	Remarks
Yes	a	b	a = hits, b = false alarm
No	c	d	c = misses, d = correct nulls

1998–2001. They found that $B_z \leq -6$ nT persisting for more than 2 h, or $E_y \geq 5$ mV/m persisting for at least 3 h, were associated with these intense storms. *Echer et al.* [2008] found that 70% of the 90 intense storms during 1996–2006 satisfied the criterion of $E_y \geq 5$ mV/m for at least 3 h. They also showed that around 90% of the storms followed the criteria: $E_y \geq 3$ mV/m for at least 3 h.

[5] The purpose of this study is to identify criteria for B_z, E_y, and their combination that have the highest association rate with intense geomagnetic storms. In particular, we consider 45 criteria which we first apply to all the near-Earth solar wind data from 1998 to 2006. As a result, we find interplanetary events satisfying each condition. Then we make contingency tables between the number of events satisfying the condition and the number of observed geomagnetic storms and evaluate statistical parameters such as probability of detection yes (PODy), false alarm ratio (FAR), bias, and critical success index (CSI), to be described below. By comparing the statistical parameters, we determine promising conditions for the occurrence of intense geomagnetic storms. The paper is organized as follows. The method of our analysis is given in section 2. We present the results of our study in section 3. These are summarized and discussed in section 4.

2. Data and Methodology

2.1. Data

[6] In this study we used 16 s magnetic field and 64 s solar wind velocity observations made in 1998–2006 by the ACE spacecraft, located in a halo orbit about the L1 libration point ~1.5 million km upstream of the Earth. The ACE spacecraft data were obtained from the Coordinated Data Analysis Web (CDAWeb) page of NASA's Goddard Space Flight Center (available at http://cdaweb.gsfc.nasa.gov/cdaweb/). The magnetic field and solar wind velocity vectors are given in the Geocentric Solar Magnetospheric (GSM) coordinate system. The convection electric field is calculated by $E_y = V_x B_z$.

2.2. Contingency Table

[7] For a statistical comparison of the interplanetary conditions, we present contingency tables. The tables can provide us with the information of success or failure according to a certain criterion [*Smith et al.*, 2000; *Kim et al.*, 2005]. Table 1 is a general form of the contingency table. "Yes condition" is made whenever an interplanetary event is selected according to each criterion and "Yes observation" is made whenever an intense geomagnetic storm is observed. In this table, "a" is the number of hits that, in the table's entry position, mean "Yes condition" and "Yes observation." A "hit" is defined as an overlap between the interplanetary event and the main phase of the storm. The letter "b" is the number of false alarms. This means that an interplanetary event was identified, but no storm occurred. The letter "c" is the number of misses. A "miss" means that no interplanetary event meeting the condition was identified, but an intense storm occurred. The letter "d" is the number of correct nulls.

2.3. Interplanetary Conditions and Events Selection

[8] For this study, we consider three types of interplanetary conditions as follows: B_z conditions, E_y conditions, and their combination. The second columns of Tables 2, 3, and 4 show interplanetary conditions of these three types, respectively. The conditions are a combination of thresholds on B_z or E_y and the duration of the interval during which this threshold is exceeded.

[9] We searched interplanetary events satisfying each interplanetary condition. By considering fluctuations of B_z and E_y data, we selected the interplanetary events by the following procedure. First, we checked B_z and E_y data during one 30 min interval. If the number of data points of B_z, E_y, and B_z or E_y satisfying a given interplanetary condition is more than 50% during this interval, then the interval would be identified as meeting the condition ("Yes"). Otherwise this interval is identified as "No." The next 30 min interval is then examined in the way, and so on. If "Yes" intervals are separated by two or fewer "No" intervals, then these intervals are regarded as part of the same "event." Finally, we obtained events for each interplanetary condition. The third column of Tables 2, 3, and 4 show the number of the interplanetary events. If there are more than two interplanetary events in the main phase (the interval of large decrease of *Dst*) of a geomagnetic storm, we used the event, closest to *Dst* minimum, for the comparison between interplanetary parameters and geomagnetic storms.

3. Results

[10] In this study, we use 82 intense geomagnetic storms (*Dst* ≤ −100 nT) from 1998 to 2006 that were identified by

Table 2. Summary of Interplanetary Conditions, the Numbers of Interplanetary Events, the Numbers in Contingency Tables, and Statistical Parameters for B_z Conditions

Case	Condition	Event	Hits	False Alarm	Misses	PODy	FAR	Bias	CSI
1	$B_z \leq -15$ nT, t >3 h	24	24	0	58	0.29	0.00	0.29	0.29
2	$B_z \leq -15$ nT, t > 2 h	37	31	6	51	0.37	0.16	0.45	0.35
3	$B_z \leq -15$ nT, t > 1 h	55	44	11	38	0.53	0.20	0.67	0.47
4	$B_z \leq -10$ nT, t > 3 h	73	55	18	27	0.67	0.24	0.89	0.55
5	$B_z \leq -10$ nT, t > 2 h	106	63	43	19	0.76	0.40	1.29	0.50
6	$B_z \leq -10$ nT, t > 1 h	237	71	166	11	0.86	0.70	2.89	0.28
7	$B_z \leq -5$ nT, t > 3 h	316	73	243	9	0.89	0.76	3.85	0.22
8	$B_z \leq -5$ nT, t > 2 h	484	76	408	6	0.92	0.84	5.90	0.15
9	$B_z \leq -5$ nT, t > 1 h	861	80	781	2	0.97	0.90	10.5	0.09

Table 3. Summary of Interplanetary Conditions, the Numbers of Interplanetary Events, the Numbers in Contingency Tables, and Statistical Parameters of E_y Conditions

Case	Condition	Event	Hits	False Alarm	Misses	PODy	FAR	Bias	CSI
1	$E_y \geq 7$ mV/m, t > 3 h	24	24	0	58	0.29	0.00	0.29	0.29
2	$E_y \geq 7$ mV/m, t > 2 h	38	35	3	47	0.42	0.07	0.46	0.41
3	$E_y \geq 7$ mV/m, t > 1 h	56	47	9	35	0.57	0.16	0.68	0.51
4	$E_y \geq 5$ mV/m, t > 3 h	57	50	7	32	0.60	0.12	0.69	0.56
5	$E_y \geq 5$ mV/m, t > 2 h	87	62	25	20	0.75	0.28	1.06	0.57
6	$E_y \geq 5$ mV/m, t > 1 h	126	70	56	12	0.85	0.44	1.53	0.50
7	$E_y \geq 3$ mV/m, t > 3 h	163	67	96	15	0.81	0.58	1.98	0.37
8	$E_y \geq 3$ mV/m, t > 2 h	239	76	163	6	0.92	0.68	2.91	0.31
9	$E_y \geq 3$ mV/m, t > 1 h	438	80	358	2	0.97	0.81	5.34	0.18

Echer et al. [2008]. By applying forty-five criteria to all ACE solar wind data during the same period and using the 82 storm events, we made a contingency table for each condition indicating the number of interplanetary events satisfying the condition and the number of interplanetary events associated or not associated with the geomagnetic storms.

[11] Figure 1 shows the interplanetary (B_z and the y component of the convection electric field) and geomagnetic (*Dst*) data for two cases (hit and false alarm) when the condition of Case 10 of Table 4 ($B_z \leq -10$ nT or $E_y \geq 7$ mV/m for >3 h) is applied. In Figure 1, the interplanetary event interval is marked with the dash dotted vertical lines and by the arrow bar. The dotted horizontal lines indicate the thresholds for B_z and E_y. As seen in Figure 1a, there was an interplanetary event satisfying the Case 10 of Table 4 as well as there was an intense geomagnetic storm ($Dst_{\min} = -173$ nT) of 22 September 1999. Here the time interval of the interplanetary event is well overlapped with the main phase of the storm. Therefore, this event was identified as "hit." As seen in Figure 1b, the interplanetary event was selected, but no the intense geomagnetic storm occurred. At this time, the $Dst_{\min}$ is −62 nT. Therefore, this event was identified as "false alarm." Regarding miss events, we will present their representative examples and discuss in detail their main characteristics in section 4.

[12] The results of the three types of interplanetary conditions are summarized in the forth to tenth column of Tables 2, 3, and 4. They include the numbers of interplanetary events, the numbers in contingency tables (hits, false alarm, and misses), and statistical parameters (PODy, FAR, bias, and CSI). Here the number of correct nulls (no interplanetary event and no geomagnetic storm) is not indicated because such events are too many and not of interest. We estimated several statistical parameters from the numbers in the contingency tables: (1) PODy, the probability of detection yes, is the number of "hits" divided by the sum of the numbers of hits and misses, (2) FAR, the false alarm ratio, is the number of false "Yes" conditions divided by the sum of the numbers of hits and false "Yes" conditions, (3) bias is the ratio of "Yes condition" to "Yes observation", and (4) CSI, the critical success index, is the ratio of the number of correct

Table 4. Summary of Interplanetary Conditions, the Numbers of Interplanetary Events, the Numbers in Contingency Tables, and Statistical Parameters of the Combined B_z and E_y Conditions

Case	Condition	Event	Hits	False Alarm	Misses	PODy	FAR	Bias	CSI
1	$B_z \leq -15$ nT or $E_y \geq 7$ mV/m, t > 3 h	28	28	0	54	0.34	0.00	0.34	0.34
2	$B_z \leq -15$ nT or $E_y \geq 7$ mV/m, t > 2 h	48	40	8	42	0.48	0.16	0.58	0.44
3	$B_z \leq -15$ nT or $E_y \geq 7$ mV/m, t > 1 h	69	55	14	27	0.67	0.20	0.84	0.57
4	$B_z \leq -15$ nT or $E_y \geq 5$ mV/m, t > 3 h	57	50	7	32	0.60	0.12	0.69	0.56
5	$B_z \leq -15$ nT or $E_y \geq 5$ mV/m, t > 2 h	85	62	23	20	0.75	0.27	1.03	0.59
6	$B_z \leq -15$ nT or $E_y \geq 5$ mV/m, t > 1 h	130	70	60	12	0.85	0.46	1.58	0.49
7	$B_z \leq -15$ nT or $E_y \geq 3$ mV/m, t > 3 h	134	68	66	14	0.82	0.49	1.63	0.45
8	$B_z \leq -15$ nT or $E_y \geq 3$ mV/m, t > 2 h	239	76	163	6	0.92	0.68	2.91	0.31
9	$B_z \leq -15$ nT or $E_y \geq 3$ mV/m, t > 1 h	441	80	361	2	0.97	0.81	5.37	0.18
10	$B_z \leq -10$ nT or $E_y \geq 7$ mV/m, t > 3 h	84	65	19	27	0.70	0.22	0.91	0.58
11	$B_z \leq -10$ nT or $E_y \geq 7$ mV/m, t > 2 h	106	62	44	20	0.75	0.41	1.29	0.49
12	$B_z \leq -10$ nT or $E_y \geq 7$ mV/m, t > 1 h	152	72	80	10	0.87	0.52	1.85	0.44
13	$B_z \leq -10$ nT or $E_y \geq 5$ mV/m, t > 3 h	77	59	18	23	0.71	0.23	0.93	0.59
14	$B_z \leq -10$ nT or $E_y \geq 5$ mV/m, t > 2 h	108	68	40	14	0.82	0.37	1.31	0.55
15	$B_z \leq -10$ nT or $E_y \geq 5$ mV/m, t > 1 h	164	74	90	8	0.90	0.54	2.00	0.43
16	$B_z \leq -10$ nT or $E_y \geq 3$ mV/m, t > 3 h	151	68	83	14	0.82	0.54	1.84	0.41
17	$B_z \leq -10$ nT or $E_y \geq 3$ mV/m, t > 2 h	222	76	146	6	0.92	0.65	2.70	0.33
18	$B_z \leq -10$ nT or $E_y \geq 3$ mV/m, t > 1 h	445	80	365	2	0.97	0.82	5.42	0.17
19	$B_z \leq -5$ nT or $E_y \geq 7$ mV/m, t > 3 h	319	73	246	9	0.89	0.77	3.89	0.22
20	$B_z \leq -5$ nT or $E_y \geq 7$ mV/m, t > 2 h	482	76	406	6	0.92	0.84	5.87	0.15
21	$B_z \leq -5$ nT or $E_y \geq 7$ mV/m, t > 1 h	857	80	777	2	0.97	0.90	10.45	0.09
22	$B_z \leq -5$ nT or $E_y \geq 5$ mV/m, t > 3 h	320	73	247	9	0.89	0.77	3.90	0.22
23	$B_z \leq -5$ nT or $E_y \geq 5$ mV/m, t > 2 h	489	76	413	6	0.92	0.84	5.96	0.15
24	$B_z \leq -5$ nT or $E_y \geq 5$ mV/m, t > 1 h	871	80	791	2	0.97	0.90	10.62	0.09
25	$B_z \leq -5$ nT or $E_y \geq 3$ mV/m, t > 3 h	321	73	248	9	0.89	0.77	3.91	0.22
26	$B_z \leq -5$ nT or $E_y \geq 3$ mV/m, t > 2 h	496	77	419	5	0.93	0.84	6.04	0.15
27	$B_z \leq -5$ nT or $E_y \geq 3$ mV/m, t > 1 h	880	80	800	2	0.97	0.90	10.73	0.09

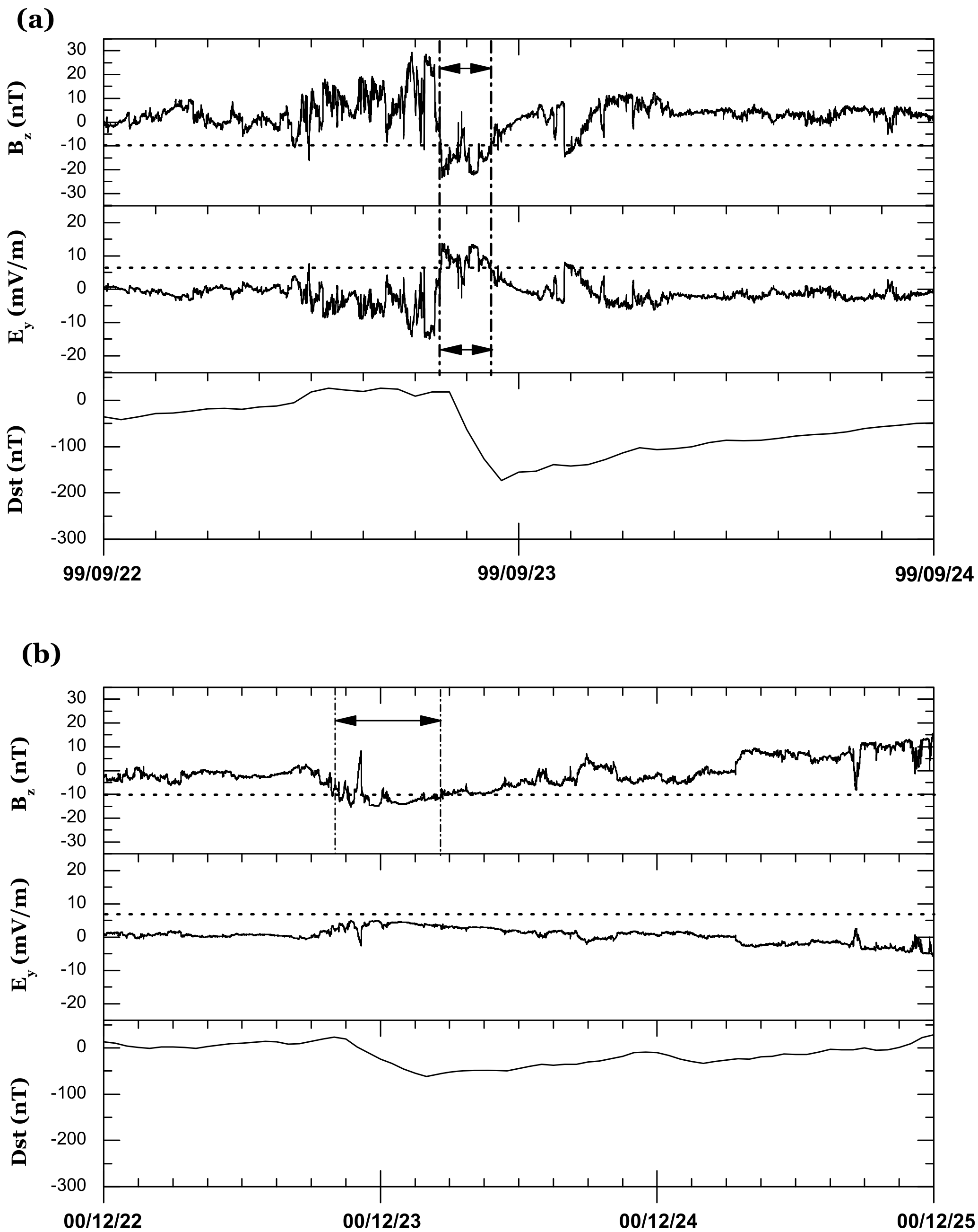

Figure 1. Examples of interplanetary events (bounded by dash-dotted lines) that satisfy Case 10 condition in Table 4 (dotted horizontal lines indicate the thresholds for B_z and E_y). The event in Figure 1a is associated with an intense storm (i.e., is a "hit") while that in Figure 1b is not (a "false alarm").

hits to the total number of cases where an interplanetary event or a storm was present [*Kim et al.*, 2005].

[13] The perfect condition is characterized by PODy = 1, CSI = 1, and FAR = 0. On the other hand, the random condition gives that PODy = 0.5, CSI = 0.33, and FAR = 0.5. Therefore, we think that a pre-condition to be a good condition is as follows: $0.5 \leq \text{PODy} \leq 1$, $0 \leq \text{FAR} \leq 0.5$, and $0.33 \leq \text{CSI} \leq 1$. As shown in Tables 2, 3, and 4, interplanetary conditions satisfying the pre-condition are: Case 3, 4, and 5 in Table 2, Case 3, 4, 5, and 6 in Table 3, Case 3, 4, 5, 6, 7, 10, 11, 13, and 14 in Table 4.

[14] As the climate community have frequently used by *Schaefer* [1990], we also adopt a determining factor as CSI, which is a verification measure of categorical forecast performance. Unlike the POD and the FAR, it takes into account both false alarms and missed events, and is therefore a more balanced score. Thus we have selected three interplanetary conditions as follows: (1) $B_z \leq -10$ nT for >3 h (Case 4 in Table 2); (2) $E_y \geq 5$ mV/m for >2 h (Case 5 in Table 3); and (3) $B_z \leq -15$ nT or $E_y \geq 5$ mV/m for >2 h (Case 5 in Table 4). It is also noted that there are several other conditions having a little smaller CSIs than these conditions. A comparison of CSI values from the different tables suggests that the combined conditions are better predictors of intense storms than conditions based on B_z or E_y individually.

Table 5. Number of Miss Events and Its Dependence on Interplanetary Structures for Three Types of Conditions[a]

Case	sMC	Sheath	SH + MC	CIR	nonMC	nsMC	MC	Total
B_z, Case 4	2	10	2	8	2	2	1	27
E_y, Case 5	4	6	1	6	1	2	0	20
B_z or E_y, Case 5	4	6	1	6	1	2	0	20
Total	10	22	4	20	4	6	1	67

[a]sMC, MC preceded by a fast shock; Sheath, sheath field; SH + MC, sheath field followed by a magnetic cloud; CIR, corotating interaction region; nonMC, ICME that does not shows the signature of a magnetic cloud; nsMC, MC not preceded by a fast shock; MC: ICME that shows the signature of a magnetic cloud.

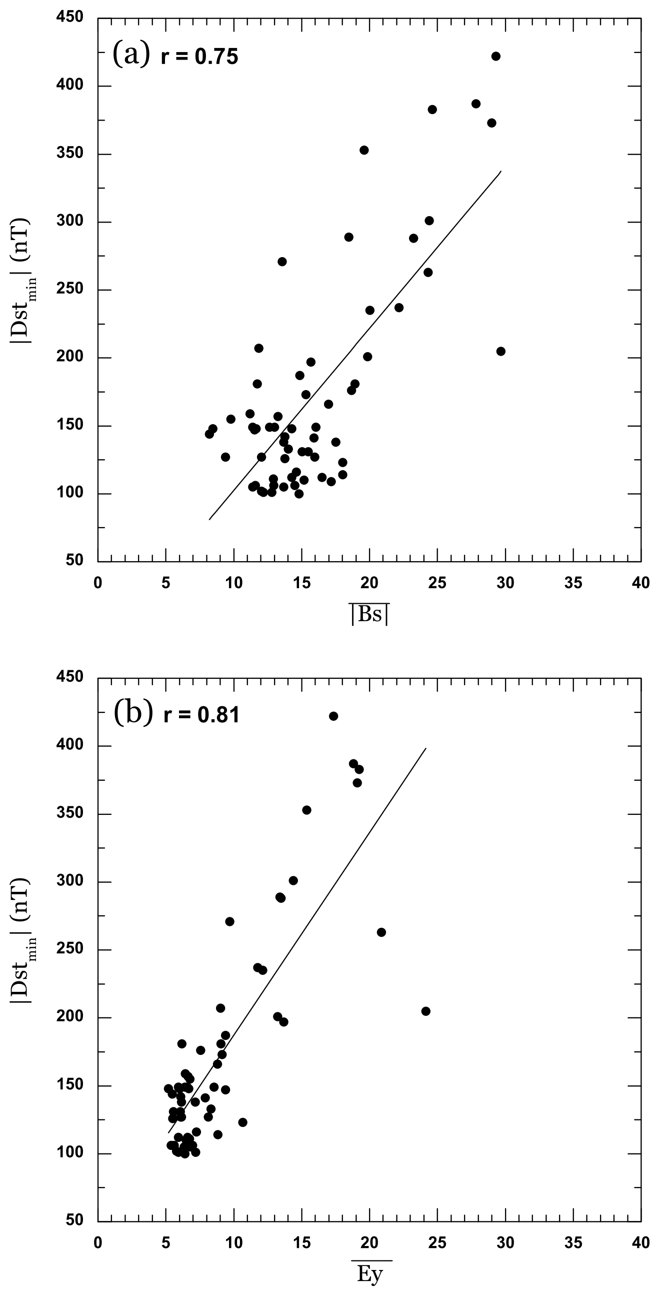

Figure 2. Relationship between $|Dst_{\min}|$ and $\overline{|B_s|}$ and $\overline{E_y}$ for hit events of the Case 5 in Table 4. Here "r" indicates a correlation coefficient.

[15] We examined miss events determined by the above three conditions. Table 5 shows the number of miss events and its dependence on interplanetary structures for three types conditions. These interplanetary structures of miss events were identified by *Echer et al.* [2008]. From Table 5, more than half of the miss events for three cases are sheath or CIR structures.

[16] Figure 2 shows the relationship between $Dst_{\min}$ and interplanetary parameters ($\overline{|B_s|}$ and $\overline{E_y}$) for the hit events of the Case 5 in Table 4. The average values of B_z and E_y were obtained during each interplanetary event interval. Here $B_z > 0$ or $E_y < 0$ data are not included for calculating the average values since only the southward IMF B_s components are significant for geomagnetic storms. The linear fit to data is given by $Dst_{\min} = -16.88 + (11.93)\ \overline{|B_s|}$ and $Dst_{\min} = 37.94 + (14.92)\ \overline{E_y}$. It is found that there are high correlations between two parameters (r = 0.75 for $\overline{|B_s|}$ and r = 0.81 for $\overline{E_y}$) and $Dst_{\min}$. These results imply that large B_z and E_y are very significant for causing the intense geomagnetic storms. These results are consistent with *Gonzalez* [1990], *Wang et al.* [2003], *Srivastava and Venkatakrishnan* [2004], *Tsurutani et al.* [2004], *Kane* [2005], and *Echer et al.* [2008].

[17] Figure 3 shows the relationship between $|Dst_{\min}|$ and $t_{Dst} - t_e$ for the hit events of the Case 5 in Table 4. Here t_{Dst} and t_e is the $Dst_{\min}$ time and the end time of the interplanetary event, respectively. We found that the average value and the standard deviation of $t_{Dst} - t_e$ are 0.12 and 3.31 h, respectively. This indicates that the interplanetary conditions characterized by B_z and E_y end about 0.12 h prior to the start of the recovery phase. That is, the end times of the interplanetary events are approximately consistent with the $Dst_{\min}$ time. We realize that the values are several hours for very strong events larger than Dst ≤ −200 nT, indicating that the recovery phases of such geomagnetic storms already started before the interplanetary condition ends. Since the peak B_s (or E_y) is typically larger for these very strong

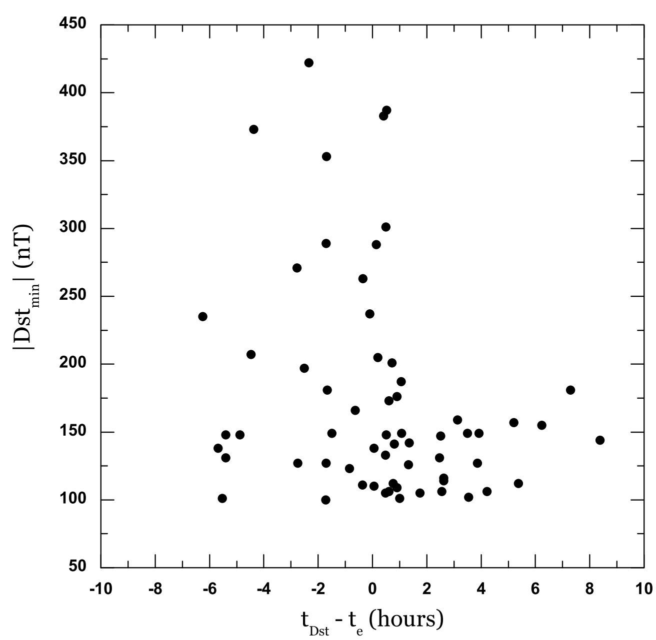

Figure 3. Relationship between $|Dst_{\min}|$ and $t_{Dst} - t_e$ for hit events of the Case 5 in Table 4.

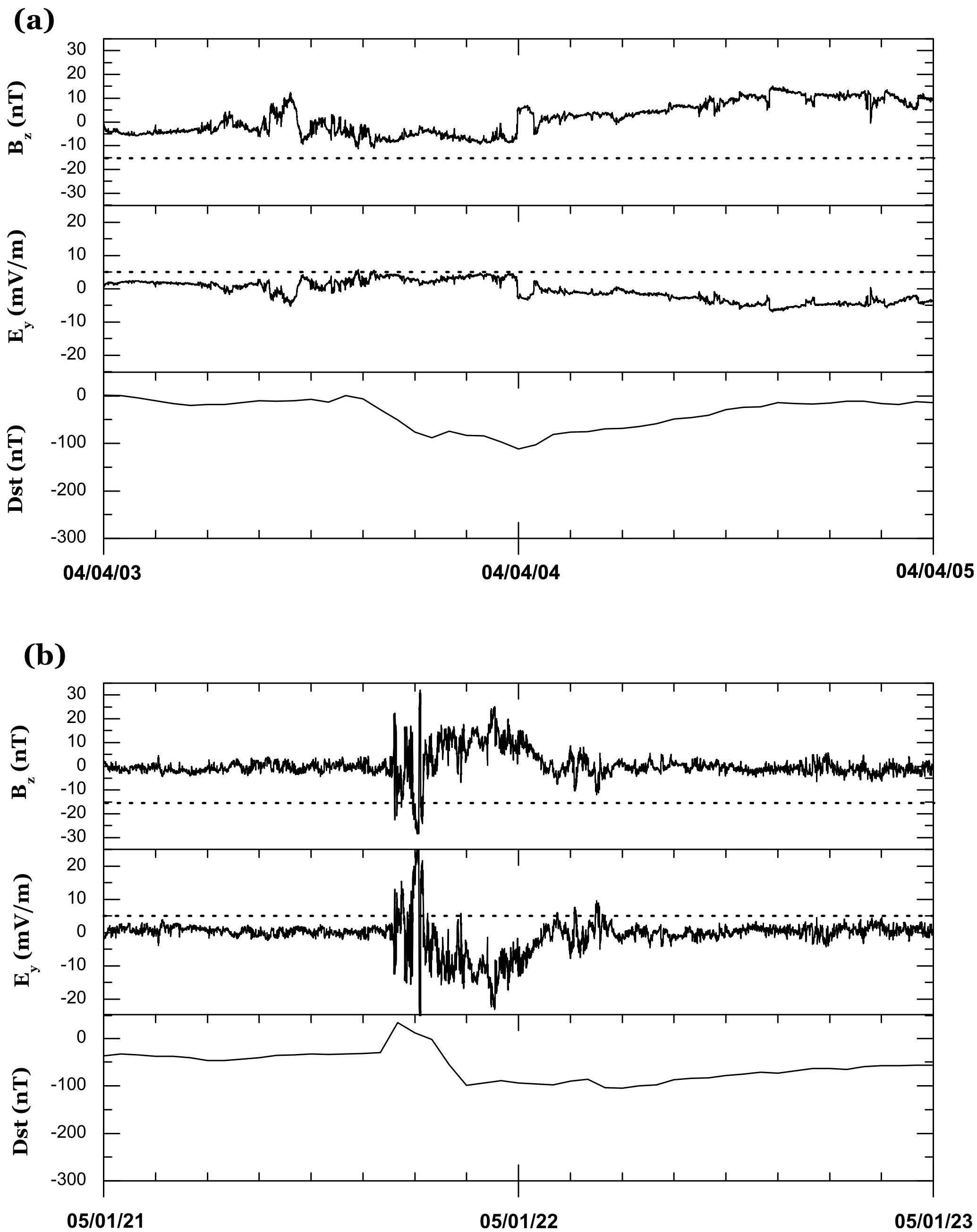

Figure 4. Example of two types of miss events of the Case 5 in Table 4. (a) The first type example that occurred on 4 April 2004. (b) The second type example that occurred on 22 January 2005. The dotted horizontal lines indicate the threshold for B_z and E_y of Case 5, respectively.

storms, possibly it may often take longer for B_s (E_y) to fall below the threshold that defines the end of the interplanetary event than for a weaker storm where this threshold is only just exceeded. This characteristic is reserved for future study.

4. Summary and Discussion

[18] In this paper, we have statistically compared the interplanetary conditions (Tables 2, 3, and 4) that can well cause 82 intense geomagnetic storms. By applying these conditions to interplanetary data (IMF B_z and E_y) from 1998 to 2006, we made contingency tables between the number of events satisfying the condition and the number of observed events as intense geomagnetic storms. We have considered three types of interplanetary conditions as follows: B_z conditions (Table 2), E_y conditions (Table 3), and their combination (Table 4). We obtained the verification statistics from the contingency tables. The main results from this study can be summarized as follows.

[19] First, by comparing statistical parameters (PODy, FAR, and CSI) from the contingency tables, we find the promising interplanetary conditions for three types: (1) $B_z \leq -10$ nT for >3 h (Case 4 in Table 2); (2) $E_y \geq 5$ mV/m for >2 h (Case 5 in Table 3); and (3) $B_z \leq -15$ nT or $E_y \geq 5$ mV/m for >2 h (Case 5 in Table 4). Second, we identified miss

events for each of these three conditions. In each case, more than half of these miss events were associated with sheath field structures or corotating interaction regions. Third, there are high correlations between two interplanetary parameters (r = 0.75 for $\overline{|B_s|}$ and r = 0.81 for $\overline{E_y}$) and *Dst* index (Figure 3) for the Case 5 in Table 4. Fourth, from the relationship between $|Dst_{\min}|$ and $t_{Dst} - t_e$, the average value and the standard deviation of $t_{Dst} - t_e$ are 0.12 and 3.31 h, respectively. This implies that the end times of the interplanetary events should be well consistent with the $Dst_{\min}$ time.

[20] Comparing the statistical parameters of three types, the larger values of CSI suggest that the conditions using combinations of B_z and E_y (Table 4) are better predictors of intense storms than those using B_z or E_y alone (Tables 2 and 3). Also, we found that the values of CSI for E_y conditions are a little larger than those of B_z.

[21] We have examined in detail the solar wind data of all miss events in Table 5. Their characteristic can be classified as the following two types. First type corresponds to a case that the values of B_z or E_y are lower than their thresholds. Figure 4a shows an example of first type that occurred on 4 April 2004 ($Dst_{\min} = -112$ nT). As shown in Figure 4a, the miss events of this type appear to be a little smaller than their thresholds. Not only just below the threshold, but this situation is maintained over a number of hours. By reducing the thresholds, some of the miss events were included as hit events. But, we can see that the lower thresholds give the lower values of CSI (see Tables 2, 3, and 4). In the second type of "miss" event, the B_z and E_y components show highly fluctuating structures [*Tsurutani et al.*, 1995; *Tsurutani et al.*, 2006]. Figure 4b shows an example of the second type that occurred on 22 January 2005. As shown in Figure 4b, B_z and E_y far exceed their thresholds but because of the highly fluctuating field direction, the criteria for duration are not met. While the numbers of the miss events for the first type are 5, 12, and 12 for three types of conditions (B_z, and E_y, and their combination), those for the second type are 22, 8, and 8, respectively. In the case of B_z condition, most of the miss events corresponds to the second type. On the other hand, for the E_y and combined B_z and E_y conditions, around 60% of the miss events are of the first type, and ~40% of the second type.

[22] Our main purpose is to find the interplanetary conditions causing the intense geomagnetic storms. Therefore, our research is contrasted with the real-time forecast model studied by *Burton et al.* [1975] and *O'Brien and McPherron* [2000] who treated time and magnetic and electric field variations. Our conditions can be used for not only the real-time forecast of geomagnetic storms but also the survey of interplanetary data to identify candidate events for producing intense geomagnetic storms. Especially, this study is the first attempt to statistically compare interplanetary conditions causing intense geomagnetic storms by making contingency tables and comparing statistical parameters. In addition we applied the conditions to whole data sets from 1998 to 2006 in an automatic and objective way in which interplanetary events are selected according to the criteria.

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