0254-6124/2012/32(3)-312–09 *Chin. J. Space Sci.* 空间科学学报

Li Zheng, Wei Fengsi, Feng Xueshang, Guo Jianpeng, Xu Xiaojun. A prediction method for $\Delta f_0F_{2\,\min}$ of a single station from interplanetary parameters based on statistical study. *Chin. J. Space Sci.*, 2012, **32**(3): 312-320

A Prediction Method for $\Delta f_0F_{2\min}$ of a Single Station From Interplanetary Parameters Based on Statistical Study*

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Abstract Using 86 CME-interplanetary shock events, the correlation between the peak values of (a) the solar wind parameters (B_z, E_y, $P_{\rm dyn}$) and the geomagnetic indices (SYM-H, ASY-H, Kp), (b) the coupling functions (Borovsky, Akasofu, Newell) and the geomagnetic indices, (c) the solar wind parameters/coupling functions/geomagnetic indices and the ionospheric parameter ($\Delta f_0F_{2\min}$), are investigated. The statistical results show that in group (a), $B_{z\,\min}$ and SYM-$H_{\min}$ have the best correlation, that in group (b), the best correlation is between the peak values of Akasofu function ($A_{\min}$) and SYM-$H_{\min}$, and that in group (c), the best correlation is between $Kp_{\max}$ and $\Delta f_0F_{2\min}$. Based on the statistical results, a method for predicting f_0F_2 of a single station is attempted to be set up. The input is modified $B_{z\,\min}$ and the outputs are SYM-$H_{\min}$ and $\Delta f_0F_{2\min}$. Then 25 CME-IPS events that caused geomagnetic storms in 1998 and 2009 are used to check the prediction method. The results show that our method can be used to predict SYM-$H_{\min}$ and $\Delta f_0F_{2\min}$.

Key words Interplanetary parameter, Coupling function, Geomagnetic index, Ionospheric strom, Correlation coefficient

0 Introduction

The upper atmosphere of the Earth, beginning at about 50 km altitude, is partially ionized by ultraviolet and X-ray radiation from the Sun. The region is termed the ionosphere. Ionospheric storms which are distinguished from the Travelling Ionospheric Disturbances (TIDs), usually refer to intense changes of the Total Electron Content (TEC) of the ionosphere and ionospheric critical frequency (f_0F_2), which persist from several hours to days and are associated with geomagnetic disturbances[1−3]. Ionospheric storms are often described as positive storms when f_0F_2 is increased and as negative storms when f_0F_2 is significantly reduced.

Establishing the models of ionosphere is an important work for space weather investigation. Over the last three decades, many ionospheric models have been set up with the development of technology both in detecting and computing, which can be

* Supported by the National Natural Science Foundation of China (40890162, 40704030, 40674084) and the Specialized Research Fund for State Key Laboratories

Received March 1, 2011. Revised December 14, 2011

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described as theoretical models[4−6] and empirical models[7−13]. Since the theoretical models are not responsible for real-time prediction at present[14], the ionospheric empirical models are getting more attention and development[15]. These empirical models obtain some good results in predicting the tendency of ionospheric parameters' variation during geomagnetic disturbances. But they often get poor results in predicting the intensity of ionospheric storms, which are important and irreplaceable in ionosphere prediction. Wang and Wei[16] studied the correlation between the interplanetary shock's energy and the intensity of ionospheric negative storm using the ionosonde station of Manzhouli, but they did not associate their work with magnetosphere.

In this paper, we calculate the peak values of some interplanetary parameters, coupling functions, geomagnetic indices and ionospheric parameters, and investigate the correlations between them for the 86 CME-IPS events from 1999 to 2008. Based on the statistical results, we establish an empirical method to predict the intensity of geomagnetic storms and ionospheric negative perturbations using interplanetary parameters. And then we select 25 CME-IPS events in 1998 and 2009 to check the prediction method and analyze the deviations between the predictions and observations.

1 Observations

We select 86 IP shocks that occurred during the period of 1999—2008 and produced geomagnetic storms ($Dst \leqslant -50\,\mathrm{nT}$) from a list of CME-associated shocks, which is compiled using the events reported in the literature[17−23], supplemented with the shock list obtained from the Proton Monitor (PM) instrument on board the SOHO mission*. The variables that we choose include the characteristic quantities of solar wind as well as geomagnetic indices and ionospheric parameter, including the north-south component of interplanetary magnetic field B_z, the Y component of the electric field E_y, and the dynamic pressure $P_{\rm dyn}$. These parameters are available from the 1 min averaged OMNI database (spacecraft-interspersed, near-Earth solar wind data) at 1 AU (geocentric solar magnetospheric coordinates).

For each of the 86 events, we calculate three coupling functions: Borovsky function[24−25], Akasofu function[26] and Newell function[27]. They are often written as

$$\begin{aligned} R =&0.4\mu_0^{1/2}\sin(\theta/2)\rho v^2(1+0.5M_{\rm ms}^{-2})\cdot \\ &(1+\beta_{\rm s})^{-1/2}[C\rho+(1+\beta_{\rm s})^{-1/2}\rho_{\rm m}]^{-1/2}\cdot \\ &[(1+\beta_{\rm s})^{1/2}+1]^{-1/2}, \end{aligned} \tag{1}$$

$$\varepsilon =\frac{4\pi}{\mu_0} l_0^2 v B^2 \sin^4\frac{\theta}{2}, \tag{2}$$

$$F_{\rm N} = v^{4/3}B_{\rm T}^{2/3}\sin^{8/3}(\theta/2), \tag{3}$$

respectively. The variables $\theta, \rho, B, B_{\rm T}, v, l_0$ on the right-hand side are given in SI units and denote the IMF clock angle, mass density, the solar wind magnetic field magnitude, the solar wind magnetic field magnitude perpendicular to the Sun-Earth line, the solar wind velocity, and the scaling factor, respectively. The scaling factor l_0 was empirically determined to be $7\,R_{\rm e}$. Besides, the variables $\beta_{\rm s}$, $M_{\rm ms}$, C in Equation (1) are the plasma beta of the magnetosheath near the nose of the magnetosphere

$$\beta_{\rm s} = 3.2\times10^{-2}M_{\rm A}^{1.92}, \tag{4}$$

the magnetosonic Mach number of the solar wind

$$M_{\rm ms} = v/[(B/4\pi\rho)+2P/\rho]^{1/2}, \tag{5}$$

and the compression ratio of the bow shock

$$C = \{(1/4)^6 + [1/(1+1.38\ln M_{\rm A})]^6\}^{-1/6}, \tag{6}$$

where P is the particle pressure (thermal plus kinetic) in the upstream solar wind and $M_{\rm A}$ is the Alfvén Mach number:

$$M_{\rm A} = v(4\pi\rho)^{1/2}/B. \tag{7}$$

The Geomagnetic activity indices, SYM-H, ASY-H and Kp, are obtained from the World Data

* http://umtof.umd.edu/pm/FIGS.HTML, http://www.gi.alaska.edu/pipermail/gse-ff

Center for Geomagnetism, Kyoto*. Besides, the values of f_0F_2 of the single ionosonde station, Millstone Hill (42.6°N, 288.5°E) during 1999−2008 are obtained from the SPIDR (Space Physics Interactive Data Resource) network of the National Geophysical Data Center. In our investigations, Δf_0F_2 is used to describe the response of the F_2 region to geomagnetic storms, that is, the relative deviations of the critical frequency from the quiet level:

$$\Delta f_0F_2 = \frac{f_0F_2 - f_0F_{2\text{med}}}{f_0F_{2\text{med}}} \times 100\%. \tag{8}$$

Here f_0F_2 is the critical frequency (15 min resolution) and $f_0F_{2\text{med}}$ represents the monthly median of f_0F_2. Since ionospheric positive storms usually have shorter duration, less prominent and weaker correlations with geomagnetic storms than negative storms[28], and are hard to identify especially when the f_0F_2 data are partly missed, in this paper we only investigate ionospheric negative storms. In the following discussions, we consider an ionospheric disturbance as a negative storm when Δf_0F_2 is less than −15% and the negative disturbances persist over 4 hours.

The peak values of those parameters and functions mentioned above in each of the 86 events are used for our study later in this paper.

2 Statistical Results

The correlation coefficient R between the peak values of the parameters and functions of the 86 events is shown in Table 1. For brevity, $B_{\max}$, $A_{\max}$, and $N_{\max}$ are used to represent the maximum of Borovsky function, Akasofu function and Newell function, respectively. For the purposes of convenience and chain-study of interplanetary disturbances-geomagnetic disturbances-ionospheric disturbances, we divide their peak values into three groups, namely geomagnetic indices against solar wind parameters, geomagnetic indices against coupling functions, and ionospheric parameters against solar wind parameters/coupling functions/geomagnetic indices. Then we draw the histograms of the correlation coefficients for the three groups, shown as Figure 1(a), (b) and (c), respectively.

From Figure 1(a) we find that the correlation between $B_{z\,\min}$ and geomagnetic indices is, in general, a bit better than the correlation between $E_{y\,\max}$ and geomagnetic indices, while the correlation between $P_{\text{dyn,max}}$ and geomagnetic indices is the worst. Especially, $B_{z\,\min}$ and SYM-$H_{\min}$ have the strongest correlation, with the coefficient $R = 0.83$.

Table 1 Parameters and their correlation coefficients for the 86 CME-IPS events from 1999 to 2008

parameters	correlation coefficient R
$B_{z\,\min}$, SYM-$H_{\min}$	0.83
$B_{z\,\min}$, ASY-$H_{\max}$	0.71
$B_{z\,\min}$, $Kp_{\max}$	0.73
$E_{y\,\max}$, SYM-$H_{\min}$	0.82
$E_{y\,\max}$, ASY-$H_{\max}$	0.68
$E_{y\,\max}$, $Kp_{\max}$	0.77
$P_{\text{dyn,max}}$, SYM-$H_{\min}$	0.42
$P_{\text{dyn,max}}$, ASY-$H_{\max}$	0.36
$P_{\text{dyn,max}}$, $Kp_{\max}$	0.61
$B_{\max}$, SYM-$H_{\min}$	0.74
$B_{\max}$, ASY-$H_{\min}$	0.68
$B_{\max}$, $Kp_{\max}$	0.73
$A_{\max}$, SYM-$H_{\min}$	0.81
$A_{\max}$, ASY-$H_{\max}$	0.67
$A_{\max}$, $Kp_{\max}$	0.68
$N_{\max}$, SYM-$H_{\min}$	0.78
$N_{\max}$, ASY-$H_{\max}$	0.72
$N_{\max}$, $Kp_{\max}$	0.76
$B_{\min}$, $\Delta f_0F_{2\min}$	0.43
$E_{y\,\max}$, $\Delta f_0F_{2\min}$	0.42
$P_{\text{dyn,max}}$, $\Delta f_0F_{2\min}$	0.33
$B_{\max}$, $\Delta f_0F_{2\min}$	0.30
$A_{\max}$, $\Delta f_0F_{2\min}$	0.38
$N_{\max}$, $\Delta f_0F_{2\min}$	0.34
SYM-$H_{\min}$, $\Delta f_0F_{2\min}$	0.46
ASY-$H_{\max}$, $\Delta f_0F_{2\min}$	0.30
$Kp_{\max}$, $\Delta f_0F_{2\min}$	0.51

Note For brevity, $B_{\max}$, $A_{\max}$, and $N_{\max}$ are used to represent the maximum of Borovsky function, Akasofu function and Newell function, respectively.

* http://swdcwww.kugi.kyoto-u.ac.jp/index.html

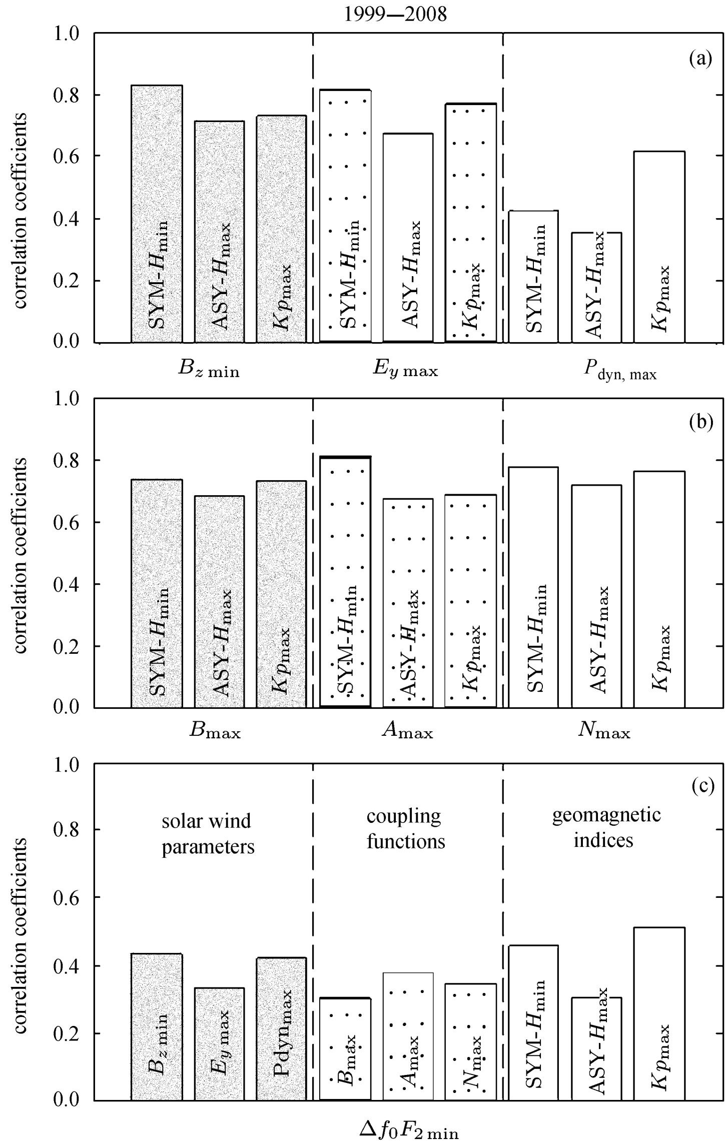

Fig. 1 Histograms of the correlation coefficients between the peak values of (a) interplanetary parameters and geomagnetic indices, (b) coupling functions and geomagnetic indices, (c) f_0F_2 and interplanetary parameters/coupling functions/geomagnetic indices, for the 86 CME-IPS events from 1999 to 2008

For group (b) from Figure 1(b), in general, the geomagnetic indices are better correlated with the coupling functions, and all the coefficients are bigger than 0.67. Among these results, the correlation between A_{max} and SYM-H_{min} is the strongest one with the correlation coefficient $R = 0.81$.

In general, there is no strong correlation between $\Delta f_0F_{2\mathrm{min}}$ and solar wind parameters/coupling functions/geomagnetic indices. And the biggest coefficient is 0.51 between $\Delta f_0F_{2\mathrm{min}}$ and Kp_{max} as shown by Figure 1(c). Figure 2 plots $\Delta f_0F_{2\mathrm{min}}$ against SYM-H_{min}, (a) of all the 86 events, (b) for the events of $-200\,\mathrm{nT} \leqslant$ SYM-$H_{\mathrm{min}} \leqslant -50\,\mathrm{nT}$. From Figure 2 we find that although the coefficient R is 0.46 of all the events, it reaches 0.59 for the events of $-200\,\mathrm{nT}$ $\leqslant$SYM-$H_{\mathrm{min}} \leqslant -50\,\mathrm{nT}$.

3 Prediction Method

Based on the statistical results above, we attempt to set up a method to predict SYM-$H_{\min}$ and $\Delta f_0F_{2\min}$ during the disturbances. The method has two steps. Firstly, we input the peak value of the solar wind parameter and output the peak value of geomagnetic index. Secondly, we used the peak value of geomagnetic index obtained above to predict $\Delta f_0F_{2\min}$.

3.1 Formula of Prediction Method

Taking the time-weighted accumulations geomagnetic indices[7,11,15] as reference, we input the time-weighted accumulation $B_{z\min}^{\text{new}}$ instead of $B_{z\min}$ for the method. The $B_{z\min}^{\text{new}}$ matrix consists of a consist number 1 and nine B_z data for each of the 86 events. The time interval of every two adjacent B_z data is 10 min, and the seventh data is $B_{z\min}$, that is $B_{z\min}^{\text{new}} = [1, B_{z\min(-50)}, B_{z\min(-40)}, B_{z\min(-30)}, B_{z\min(-20)}, B_{z\min(-10)}, B_{z\min}, B_{z\min(+10)}, B_{z\min(+20)}, B_{z\min(+30)}]'$. Here $B_{z\min(i)}$ is the B_z value that is at the intervals of i minutes depart from $B_{z\min}$. The time-weighted coefficient a is obtained from the least square method for $B_{z\min}^{\text{new}}$ and SYM-$H_{\min}$ in the 86 events and is determined to be A = [16.1056, 2.5685, −1.1525, −0.7879, 0.2012, 0.3647, 5.6180, 0.8525, 1.1341, −0.2488]. Therefore, the empirical formula for $B_{z\min}^{\text{new}}$ to predict the peak value of geomagnetic index is shown as:

$$\text{SYM-}H_{\min}^{\text{new}} = AB_{z\min}^{\text{new}}. \tag{9}$$

Here SYM-$H_{\min}^{\text{new}}$ is the prediction result from using $B_{z\min}^{\text{new}}$.

The dependences of $B_{z\min}$ on SYM-$H_{\min}$ and SYM-$H_{\min}^{\text{new}}$ on SYM-$H_{\min}$ are given in Figure 3(a) and (b), respectively. From Figure 3 we find that the correlation coefficient becomes higher from 0.83 to 0.89 after using the least square method. Besides, the envelops of the plots in Figure 3(b) are more convergent, and the deviations are also smaller especially for super geomagnetic storms.

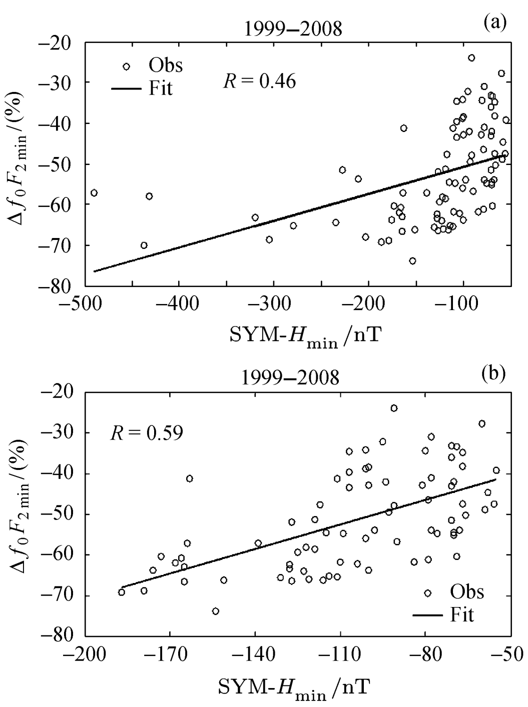

Fig. 2 Dependence of $\Delta f_0F_{2\min}$ on SYM-$H_{\min}$ during 1999–2008 for the geomagnetic storms of (a) SYM-$H_{\min} \leqslant -50$ nT, (b) -200 nT $\leqslant$ SYM-$H_{\min} \leqslant -50$ nT

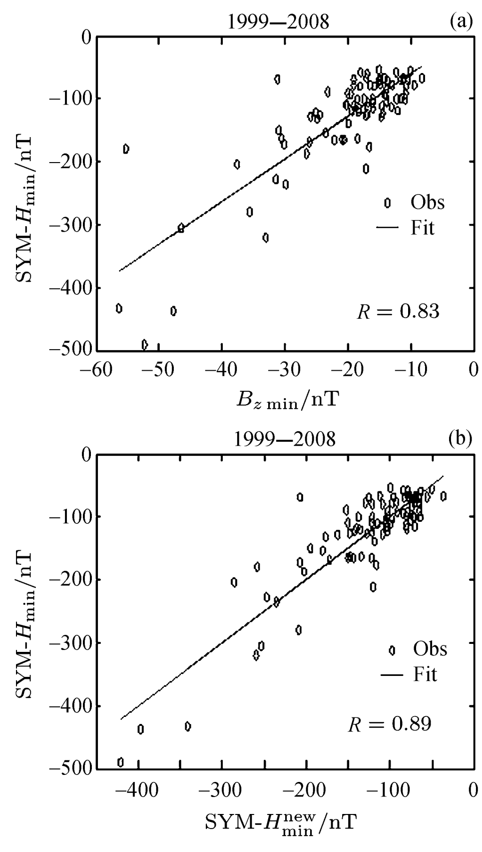

Fig. 3 Dependence of (a) SYM-$H_{\min}$ on $B_{z\min}$, (b) SYM-$H_{\min}$ on SYM-$H_{\min}^{\text{new}}$, for the 86 CME-IPS events during 1999−2008

Secondly, we use the SYM-$H_{\min}^{\rm new}$ obtained above to predict the $\Delta f_0F_{2\min}$. The empirical formula for the relationship between SYM-$H_{\min}$ and $\Delta f_0F_{2\min}$ under the conditions of $-200\,{\rm nT} \leqslant$ SYM-$H_{\min} \leqslant -50\,{\rm nT}$ is given as:

$$\Delta f_0F_{2\,\min}^{\rm new} = 0.2017 \times {\rm SYM}\text{-}H_{\min}^{\rm mew} - 30.3299, \quad (10)$$

which is also the fitting formula of solid line in Figure 2(b), and $\Delta f_0F_{2\,\min}^{\rm new}$ on the left-hand side is the prediction result of $\Delta f_0F_{2\min}$ from using SYM-$H_{\min}^{\rm new}$.

3.2 Method Testing and Error Analysis

In order to test the prediction method, we select 25 CME-IPS events in 1998 and 2009 and then pridict the SYM-$H_{\min}^{\rm new}$ and the $\Delta f_0F_{2\,\min}^{\rm new}$ from $B_{z\,\min}^{\rm new}$ of these 25 events. Next, we compare the SYM-$H_{\min}^{\rm new}$ and $\Delta f_0F_{2\,\min}^{\rm new}$ with the observations and make the error analysis. There are 19 cases left to predict $\Delta f_0F_{2\,\min}$ after removing the cases of SYM-$H_{\min} \leqslant -200\,{\rm nT}$. The case list of observations and predictions is given in Table 2. Figure 4 gives the histograms of errors between observations and predictions of (a) SYM-$H_{\min}$ and (b) $\Delta f_0F_{2\,\min}$. As Figure 4(a) shows, the biggest deviation between predictions and observations of SYM-$H_{\min}$ in the 25 cases is 66.25 nT, while the least deviation is 0.77 nT, the mean value of the deviation is −2.33 nT, and the standard deviation is 23.55 nT. Besides, about 80% errors are smaller than 20 nT. From Figure 4(b) we find that

Table 2 Prediction results and the observations of SYM-$H_{\min}$ and $\Delta f_0F_{2\min}$ for the 25 CME-IPS events in 1998 and 2009

events No.	date	SYM-$H_{\min}$	SYM-$H_{\min}^{\rm new}$	SYM-$H_{\min}^{\rm new}$− SYM-$H_{\min}$	$\Delta f_0F_{2\,\min}$	$\Delta f_0F_{2\,\min}^{\rm new}$	$\Delta f_0F_{2\,\min}^{\rm new}$− $\Delta f_0F_{2\,\min}$
1	1998-01-07	−84	−84.77	−0.77	−47.43	−64.29	−16.86
2	1998-01-30	−60	−47.39	12.61	−39.89	−27.99	11.90
3	1998-02-18	−120	−128.73	−8.73	−56.30	−45.65	10.65
4	1998-03-10	−121	−104.39	16.61	−51.38	NaN	NaN
5	1998-03-21	−90	−97.68	−7.68	−50.03	−41.36	8.67
6	1998-04-24	−71	−68.06	2.94	−44.06	−52.83	−8.77
7	1998-05-04	−272	−282.81	−10.81	−87.37	NaN	NaN
8	1998-06-07	−55	−59.04	−4.04	−42.24	−39.27	2.97
9	1998-06-14	−51	−76.18	−25.18	−45.69	−34.98	10.71
10	1998-06-26	−120	−103.95	16.05	−51.30	−58.22	−6.92
11	1998-07-16	−76	−92.10	−16.10	−48.91	−47.27	1.64
12	1998-08-06	−169	−167.61	1.39	−64.14	−62.75	1.39
13	1998-08-20	−69	−83.88	−14.88	−47.25	−47.35	−0.10
14	1998-08-27	−174	−107.75	66.25	−52.06	−66.67	−14.61
15	1998-09-18	−61	−109.10	−48.10	−52.34	−31.88	20.46
16	1998-09-25	−217	−164.24	52.76	−63.46	NaN	NaN
17	1998-10-07	−70	−98.25	−28.25	−50.15	−52.11	−1.96
18	1998-10-19	−122	−124.65	−2.65	−55.47	−53.75	1.72
19	1998-11-08	−180	−171.34	8.66	−64.89	−53.41	11.48
20	1998-11-13	−124	−144.89	−20.89	−59.55	NaN	NaN
21	1998-12-11	−80	−83.11	−3.11	−47.09	−42.68	4.41
22	1998-12-25	−72	−86.23	−14.23	−47.72	−41.42	6.30
23	2009-07-22	−95	−108.34	−13.34	−52.18	NaN	NaN
24	2009-08-06	−53	−65.15	−12.15	−43.47	NaN	NaN
25	2009-10-23	−56	−60.68	−4.68	−42.57	−27.93	14.64

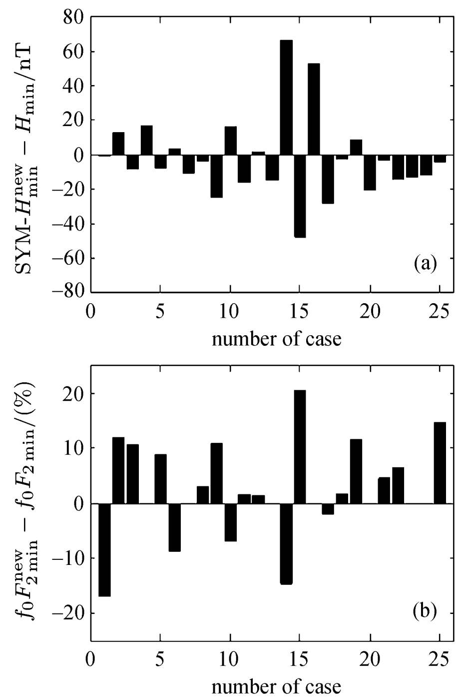

Fig. 4 Deviations between prediction and observation of (a) SYM-$H_{\rm min}$, (b) $\Delta f_0F_{2\,\rm min}$, for the 25 CME-IPS events in 1998 and 2009

the biggest deviation between predictions and observations of $\Delta f_0F_{2\rm min}$ in the 19 cases is 20.46%, the least deviation is 0.1%, the mean deviation is 3.04%, and the standard deviation is 9.82%.

For error analysis, we plot the B_z at 1 AU of the three biggest deviations between predictions and observations of SYM-$H_{\rm min}$, which are the cases of 27 August 1998, 18 September 1998 and 25 September 1998, as Figure 5(a) (b) and (c) shows, respectively. For the case of 27 August 1998, as Figure 5(a) shows, the $B_{z\,\rm min}$ is only −15.91 nT. But during the 06:00—08:00 UT on 27 August, the B_z varies nearly below −10 nT. The long duration southward B_z means greater energy injection from interplanetary to magnetosphere, which leads to the result that the prediction of SYM-$H_{\rm min}$ is smaller than the observation. The conditions on 18 September 1998, as Figure 5(b) shows, are opposite to the case of 27 August 1998 to a certain extent. Although the $B_{z\,\rm min}$ reaches −17.22 nT, the duration of southward B_z is not more than 2 hours, which results in a shortage of energy injection in the magnetosphere and the big deviation between the prediction and observation of $B_{z\,\rm min}$. The case of 25 September 1998 is similar to the case of 27 August 1998. From Figure 5(c) we can see that the $B_{z\,\rm min}$ is not very prominent. But a long duration southward B_z results in the big deviation.

Summing up, the prediction method is good at predicting SYM-$H_{\rm min}$ and $\Delta f_0F_{2\rm min}$. Moreover, the method based on the statistical results can be used in other subauroral and mid-latitude ionosonde stations. But please note that the method is not reliable when the station is in low-latitude because the behaviors of storm-time f_0F_2 are more complicated, and it is also suggested that the $B_{z\,\rm min}^{\rm new}$ matrix is not efficient enough to reflect the effect of long duration of B_z southward.

4 Conclusions and Discussion

The correlation between the peak value of (a) the solar wind parameters (B_z, E_y, $P_{\rm dyn}$) and the geomagnetic indices (SYM-H, ASY-H, Kp), (b) the coupling functions (Borovsky, Akasofu, Newell) and the geomagnetic indices, and (c) the solar wind parameters/coupling functions/geomagnetic indices and the ionospheric parameter ($\Delta f_0F_{2\rm min}$), are investigate using 86 CME-IPS events from 1999 to 2008. Based on the statistical results, we attempt to set up an empirical prediction method to predict SYM-$H_{\rm min}$ and $\Delta f_0F_{2\rm min}$ using modified $B_{z\,\rm min}$. Then we choose 25 CME-IPS events in 1998 and 2009 to check the prediction method and make error analysis. The main results may be summarized as follows.

(1) Between the peak value of the solar wind parameters and the geomagnetic indices chosen in this paper, $B_{z\,\rm min}$ and SYM-$H_{\rm min}$ have the strongest correlation with the correlation coefficient $R = 0.83$. For the group of the coupling functions and the geomagnetic indices, $A_{\rm max}$ and SYM-$H_{\rm min}$ have the strongest correlation with the correlation coefficient $R = 0.81$.

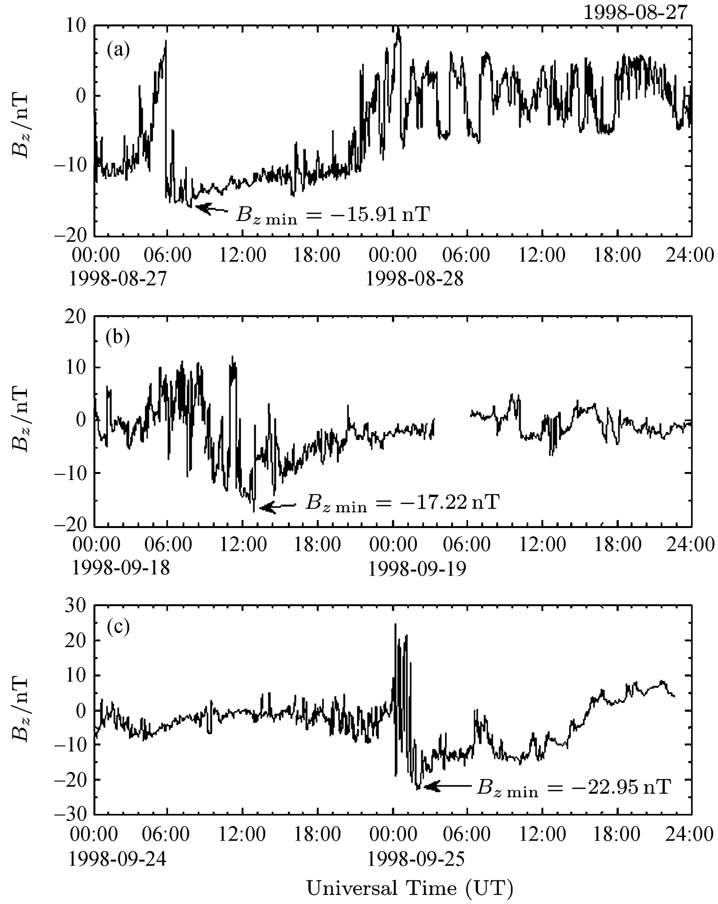

Fig. 5 Interplanetary magnetic field B_z at 1 AU in the case of (a) 27 August 1998, (b) 18 September 1998 and (c) 25 September 1998

For the group of the solar wind parameters/coupling functions/geomagnetic indices and the ionospheric parameter, the biggest coefficient is 0.51 between $\Delta f_0F_{2\mathrm{min}}$ and Kp_{max}. It is noted that although the coefficient R between SYM-H_{min} and $\Delta f_0F_{2\mathrm{min}}$ is 0.46 of all the events, it reaches 0.59 for the geomagnetic storms of $-200\,\mathrm{nT} \leqslant$ SYM-$H_{\mathrm{min}} \leqslant -50\,\mathrm{nT}$.

(2) Based on the statistical results above, we set up an empirical method to predict SYM-H_{max} and $\Delta f_0F_{2\mathrm{min}}$ during the disturbances using modified $B_{z\,\mathrm{min}}$. Firstly we input the modified $B_{z\,\mathrm{min}}$ and output SYM-H_{min}, secondly we use the SYM-H_{min} derived above to predict $\Delta f_0F_{2\mathrm{min}}$.

(3) The results after checking the method are given as follows. The biggest deviation between predictions and observations of SYM-H_{min} in the 25 cases is 66.25 nT, the least deviation is 0.77 nT, the mean deviation is −2.33 nT, and the standard deviation is 23.55 nT. Besides, the deviations of nearly 80% events are smaller than 20 nT, the biggest deviation between predictions and observations of $\Delta f_0F_{2\mathrm{min}}$ in the 19 cases is 20.46%, the least deviation is 0.1%, the mean deviation is 3.04%, and the standard deviation is 9.82%.

Hence, the prediction method is able to predict SYM-H_{min} and $\Delta f_0F_{2\mathrm{min}}$ using modified $B_{z\,\mathrm{min}}$, and it can be used in other subauroral and mid-latitude ionosonde stations. But it is also suggested that $B_{z\,\mathrm{min}}^{\mathrm{new}}$ are not very efficient in reflecting the effect of long duration of southward B_z. In addition, how to improve the accuracy of prediction, especially that of the $\Delta f_0F_{2\mathrm{min}}$, is a subject worthy of further study.

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