Low-latitude geomagnetic disturbances caused by solar wind pressure impulses and storm-time periodic substorms during southward interplanetary magnetic field

C.-S. Huang and K. Yumoto

Abstract: The interplanetary magnetic field (IMF) may be continuously southward for many hours during magnetic storms. The geomagnetic field at middle and low latitudes often shows periodic ($\sim$ 3 hour) increases in association with the storm-time sawtooth-like oscillations of energetic plasma particle flux at geosynchronous orbit. Recent studies have demonstrated that the sawtooth oscillations represent flux injections of substorms. However, there is a significant controversy as to whether the periodic geomagnetic disturbances are caused by magnetospheric substorms or by solar wind pressure enhancements. In order to find a solution to this controversy, we perform a statistical study of the low-latitude geomagnetic response to solar wind pressure enhancements during southward IMF. Our result shows that the change of the geomagnetic field is proportional to the change of the square root of the solar wind pressure, and an empirical formula is derived. We may use this quantitative relationship to estimate the possible effect of the solar wind pressure on the geomagnetic field. This method is useful for identification and interpretation of magnetospheric-ionospheric disturbances related to storm-time periodic substorms during a prolonged interval of southward IMF. We apply the empirical formula to two storm cases in which periodic substorms occur. It is found that the periodic increases of the geomagnetic field are related to the substorm onsets but not to solar wind pressure variations.

Key words: Geomagnetic field, Periodic substorms, Sawtooth oscillations, Magnetic storms, Solar wind pressure..

1. Introduction

The solar wind dynamic pressure has important influence on the Earth's magnetosphere. When the dayside magnetosphere is compressed by an enhancement of the solar wind pressure, the magnetopause current is intensified, which results in an increase of the geomagnetic field in the dayside magnetosphere and on the ground. Observations of geomagnetic field variations measured by ground magnetometers during northward interplanetary magnetic field (IMF) were reported by [13, 14, 15, 16, 17]. Beside solar wind pressure enhancements, IMF southward turnings and magnetospheric substorms can also cause geomagnetic deviations at middle and low latitudes [19, 8, 18, 6].

The IMF can be continuously southward for many hours during magnetic storms. The magnetosphere becomes very dynamic, and a series of substorms can occur. The term, ”periodic substorms”, has been used to describe a specific type of substorms that last for many cycles, show well-defined waveforms, and have nearly constant periods. It is sugguested by [3, 4, 5] that magnetospheric substorms have an intrinsic cycle time of ~ 3 hours; this periodicity is determined by the magnetosphere, rather than by the solar wind. A prominent feature of energetic plasma particle flux variations during periodic substorms measured at geosynchronous orbit is the sawtooth-like shape with periodic repetitions of sudden flux increases followed by gradual flux decreases, so the storm-time periodic substorms are also termed sawtooth events [1, 2]. The sudden increases of the flux represent the plasma particle flux injections from the magnetotail to the inner magnetosphere at substorm onsets.

The low-latitude geomagnetic field often shows an increase on both the dayside and nightside after each onset during periodic substorms. It is shown by [6, 7] that the increases of the geomagnetic field are caused by three processes: magnetotail current disruption, magnetospheric dipolarization, and ionospheric electric field; all these processes are related to the onsets of substorms. On the other hand, it was argued by [9, 10] that the variations of the geomagnetic field were the signatures of solar wind pressure enhancements and that sawtooth oscillations were directly driven by series of solar wind pressure enhancements.

The solar wind always has some fluctuations, although the amplitude of the fluctuations may be large or small. In order to identify whether a specific variation in the geomagnetic field is caused by a variation in the solar wind pressure, we need a quantitative measure to determine how large the contribution of the solar wind pressure can be. This is important because it is related to the identification and interpretation of magnetospheric-ionospheric disturbances during storm-time substorms with continuous southward IMF. In this paper, we present the statistical result of low-latitude geomagnetic response to solar wind pressure enhancements during southward IMF and use the derived empirical formula to identify the generation mechanism of periodic geomagnetic disturbances during magnetic storms.

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2. Observations

We first present the observations of geomagnetic changes in response to solar wind pressure enhancements during southward IMF in two cases. Figure 1a shows, from top to bottom, the IMF *Bz* component and solar wind pressure measured by the ACE satellite and the deviations of the geomagnetic field northward (*H*) component. The vertical dotted line indicates the solar wind pressure impulse and the sudden increase of the geomagnetic field. ACE was located at X_{GSM} = 250 R_E during the period of interest. We use the solar wind velocity and satellite position to calculate the propagation delay and then match the solar wind pressure impulse with the corresponding increase of the geomagnetic field. Accordingly, the ACE data are shifted by 53 min in Figure 1a. For all cases, including those used in the statistics, we use the same method to determine the solar wind propagation delay from the satellite position to the magnetosphere. The measurements of the geomagnetic field are made with the ground magnetometers of the Solar-Terrestrial Energy Program (STEP) 210 (degree) magnetic meridian chain around geographic longitudes 110-140^o [21]. We choose five magnetometers, spanning from magnetic latitude 36^o (in northern hemisphere) to -36^o (in southern hemisphere), for each event to calculate the geomagnetic response to the solar wind pressure impulse. It is obvious that the increase of the geomagnetic field is well correlated with the solar wind pressure impulse. The IMF *Bz* remains southward across the solar wind pressure impulse, but its magnitude has some changes. It is not certain whether the change in the magnitude of the IMF *Bz* has any significant effects on the geomagnetic field. We assume that the sudden increase of the geomagnetic field is attributed solely to the solar wind pressure enhancement.

Local time of the STEP magnetometers is about UT plus 9 hours. The case in Figure 1a occurred on the dayside. We present another case in Figure 1b that occurred on the nightside. The response of the nightside geomagnetic field to a solar wind pressure enhancement is similar to that on the dayside.

A quantitative relationship between the solar wind pressure enhancement and low-latitude geomagnetic response was studied previously. The following formula without distinguishing the IMF orientation was derived by [20]:

$$\Delta H = k(\sqrt{P_{sw2}} - \sqrt{P_{sw1}}), \tag{1}$$

where ΔH is the change of the geomagnetic field, *k* is a constant, and P_{sw1} and P_{sw2} are the solar wind pressure values before and after the pressure enhancement, respectively. The study of [20] included 13 cases. A coefficient of *k* = 18.4 from 14 cases during northward IMF was derived by [15]. In addition, *k* = 7.26 was used in the calculations of the corrected *Dst* index [11].

We are interested in the geomagnetic disturbances during southward IMF, and the events are selected through the following procedure. First, we search the STEP magnetometer data by vision to find the cases in which the low-latitude geomagnetic field shows a sudden increase, such as those shown in Figure 1. Second, we check the solar wind pressure and IMF data measured by the ACE and/or Wind satellites. The solar wind must have a sharp pressure impulse with a consistent propagation delay from the satellite position to the magnetosphere. The IMF *Bz* must be continuously negative for at least 1 hour prior to the solar wind pressure impulse and remain southward across the pressure impulse, in order to make sure that the magnetosphere is in a state that is controlled by southward IMF. We searched the geomagnetic data over seven years (1998-2005) and found 43 events that satisfy the above criteria.

The statistical result is shown in Figure 2. Figure 2a includes all events. The horizontal axis represents the change of the square root of the solar wind pressure across the impulse, and the vertical axis represents the increase of the geomagnetic field *H* component in response to the solar wind pressure impulse. As said above, five magnetometer stations are chosen, so there are five data points for each event. Figure 2 shows the result over a latitudinal range between 36^o and -36^o but not at a single latitude.

We have performed the least square fitting of the data, which are given by the dashed lines in Figure 2. In Figure 2a for all events, the data fitting can be expressed by the following formula

$$\Delta H = 21.67 \times (\sqrt{P_{sw2}} - \sqrt{P_{sw1}}) - 2.74, \tag{2}$$

where ΔH is measured with nT, and P_{sw} is measured with nPa. The solid line in Figure 2a is plotted from Eq. (2), so it overlaps the dashed line (data fitting). Note that our result is derived exclusively from southward IMF, which is different from [15] for northward IMF.

There is an offset of -2.74 nT on the right-hand side of Eq. (2). Several potential processes may cause the offset. First, the statistics includes 43 events, and the limited number of events may be unable to guarantee an accurate empirical formula. Second, we neglected possible effects of the change in the magnitude of the IMF *Bz* when we calculated the net increase of the geomagnetic field, which may bring some uncertainty to the result. Third, the offset means that the increase of the geomagnetic field will be zero if the increase of the square root of the solar wind pressure is 0.126 (nPa)$^{-1/2}$; this amount may represent the minimum solar wind pressure increase required to cause observable changes in the geomagnetic field. We will further study this issue in the future.

Figures 2b and 2c show the events that are detected when the magnetometers are on the dayside and on the nightside, respectively. The dashed line represents the least square fitting for each category, and the solid line is from Eq. (2). The data fitting line in Figure 2c for the nightside events is very close to the solid line. However, the data fitting line in Figure 2b for the dayside events does not coincide very well with Eq. (2) because of the data scatter in fewer cases.

The statistical result, Eq. (2), can be used as an estimate of the possible contribution of the solar wind pressure to the generation of geomagnetic disturbances. We examine such a case that occurred on 18 April 2002 during a prolonged interval of continuous southward IMF. Figures 3a and 3b present the shifted IMF *Bz* and solar wind pressure data measured by the ACE satellite. The IMF is continuously southward for the whole day. The solar wind pressure shows an enhancement at 0030 UT and a second, smaller one around 0300 UT. The solar wind pressure becomes small ($\sim$ 1 nPa) after 0500 UT. Figures 3c and 3d display the energetic electron flux measured by the LANL 1991-080 and 1990-095 geosynchronous satellites.

The sawtooth like variations of the electron fluxes have been analyzed in detail by [4, 2] and identified as the signature of periodic substorms with a period of $\sim$ 3 hours. The vertical dotted lines indicate the sudden increases in the electron fluxes at the substorm onsets.

Figure 3e shows the geomagnetic deviations measured by the STEP magnetometers. Only the measurements from five magnetometers are plotted over a latitudinal range between 36^o and -36^o magnetic latitudes. There are more magnetometers within this range and beyond this range, and all magnetometer measurements have similar characteristics. The most interesting feature in Figure 3e is that the geomagnetic field shows an increase after each onset of the periodic substorms. The only exception is a decrease after 0530 UT and then an increase after 0600 UT. Note that the periodic increases of the geomagnetic field occur over an interval of 24 hours. Half of the geomagnetic increases occur on the dayside, and half on the nightside.

We examine whether the periodic increases of the geomagnetic field can be caused by corresponding variations in the solar wind pressure. Eq. (2) provides a method to estimate the effect of the solar wind pressure. However, it is difficult to determine the background solar wind pressure. In stead, we take P_{sw1} = 0 and P_{sw2} = P_{sw}, so Eq. (2) is reduced to

$$\Delta H = 21.67 \times \sqrt{P_{sw}} - 2.74, \quad (3)$$

where P_{sw} is the total solar wind pressure. It is obvious that Eq. (3) overestimates the contribution of the solar wind pressure. We plot in Figure 3f the possible effect of the solar wind pressure predicted by Eq. (3) with the measured pressure as input.

We are now able to identify which increases of the geomagnetic field are related to the solar wind pressure and which are not. At 0030 UT, an increase of the geomagnetic field is measured by the magnetometers (Figure 3e) and predicted by the empirical formula (Figure 3f), so this increase may be the geomagnetic response to the solar wind pressure enhancement. At 0240 UT, the predicted geomagnetic increase is smaller than the measured value, implying that the contribution from substorms is important for this one. After 0500 UT, the possible geomagnetic disturbances caused by the solar wind pressure are very small. However, the measured geomagnetic field shows large periodic increases in coincidence with the substorm onsets. The comparison between the measurements and prediction indicates that the periodic increases of the geomagnetic field are related to the substorms but not to the solar wind pressure.

Another example of the difference between the solar wind pressure and substorm effects is shown in Figure 4. This case occurred on 6 November 2000. Figure 4 shows the IMF *Bz*, solar wind pressure, energetic electron flux measured by the LANL 1994-084 and 1989-046 geosynchronous satellites, geomagnetic field deviations measured by the STEP magnetometers, and the possible effect of the solar wind pressure predicted by the empirical formula. There are some fluctuations in the IMF *Bz*. The solar wind pressure shows three enhancements of 2.2 nPa at 0949 UT, 20 nPa at 1757 UT, and 12 nPa at 1838 UT, respectively, as indicated by the vertical dashed lines. The solar wind pressure is relatively stable at other times.

Figure 4c and 4d show the energetic electron flux at geosynchronous orbit. The sudden increase of the flux, as indicated by the vertical dotted lines, is a typical signature of magnetospheric substorm onsets [4, 5, 12]. The solar wind pressure does not have any noticeable variations at the times of the substorm onsets. The geomagnetic field in Figure 4e shows an increase after each substorm onset, as well as after each solar wind pressure impulse. However, the increases of the geomagnetic field after the substorm onsets with stable solar wind pressure are comparable to, or even larger than those caused by the significant enhancements of the solar wind pressure at 1757 and 1838 UT.

As discussed above, Eq. (2) provides an estimate of the solar wind pressure effect on the geomagnetic field, which is depicted in Figure 4f. The geomagnetic field has a gradual decrease from 1000 to 2200 UT, which is related to the storm-time drift. What we are interested is the sudden increases of the geomagnetic field after the substorm onsets or after the solar wind pressure impulses. The measured increases of the geomagnetic field at 1757 and 1838 UT coincide reasonably with the value predicted by Eq. (2), indicating that they are caused by the solar wind pressure impulses. The increase of the geomagnetic field at 0949 UT is also consistent with the effect of the solar wind pressure. However, the increases of the geomagnetic field at 1051, 1300, and 1554 UT are obviously related to the substorm onsets, as indicated by the vertical dotted lines, and the contribution from the solar wind pressure is negligible at these times.

3. Discussion and Conclusions

As mentioned in Introduction, there is a controversy as to what causes storm-time geomagnetic disturbances during continuous southward IMF. It was argued by [10] that all geomagnetic field variations were caused by solar wind pressure enhancements and that the sawtooth oscillations were driven directly by the solar wind pressure but not related to magnetospheric substorms. However, the different effects of the solar wind pressure and magnetospheric substorms were not appropriately separated in the study of [10]. In contrast, the characteristics of the magnetospheric substorms and relevant ionospheric disturbances are carefully examined by [7, 2], and the authors conclude that the sawtooth oscillations are indeed caused by periodic substorms. Our statistics deals with the effects of the solar wind pressure on the low-latitude geomagnetic field during southward IMF. The result shows that the increases of the geomagnetic field are caused by the periodic substorms but not by solar wind pressure enhancements.

The changes of the low-latitude geomagnetic field caused by solar wind pressure enhancements during southward IMF can be estimated by Eq. (2). If multiple processes, such as solar wind pressure enhancements and magnetospheric substorms, occur nearly simultaneously, we may use Eq. (2) to find which process is responsible for the generation of low-latitude geomagnetic disturbances. This method is particularly useful in identification and interpretation of the magnetospheric and ionospheric disturbances related to storm-time periodic substorms with continuous southward IMF.

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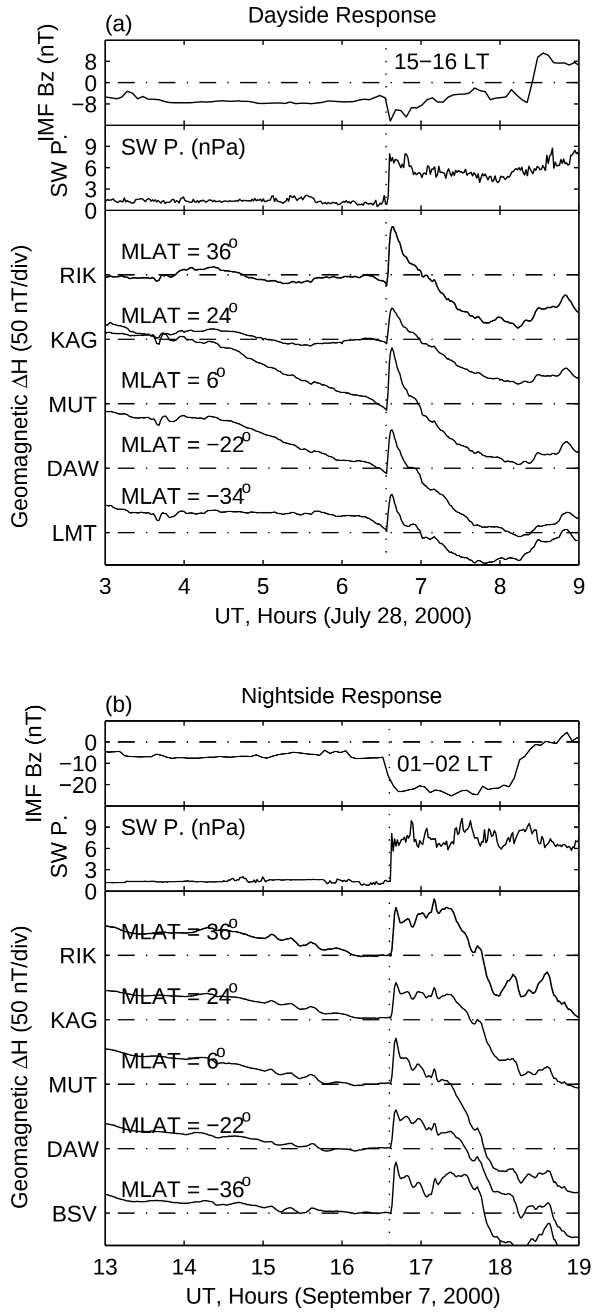

Fig. 1. Sudden increases of the geomagnetic field northward (*H*) component at low latitudes in response to a solar wind pressure impulse during southward interplanetary magnetic field (IMF). Shown from top to bottom are the IMF *Bz* component, solar wind pressure, and geomagnetic *H* deviations. The event in Figure 1a occurred during daytime on 28 July 2000. The event in Figure 1b occurred at night on 7 September 2000. The magnetometer stations are Rikubetsu (RIK), Kagoshima (KAG), Muntinlupa (MUT), Darwin (DAW), Learmonth (LMT), and Birdsville (BSV). Magnetic latitude (MLAT) for each station is given in the figure.

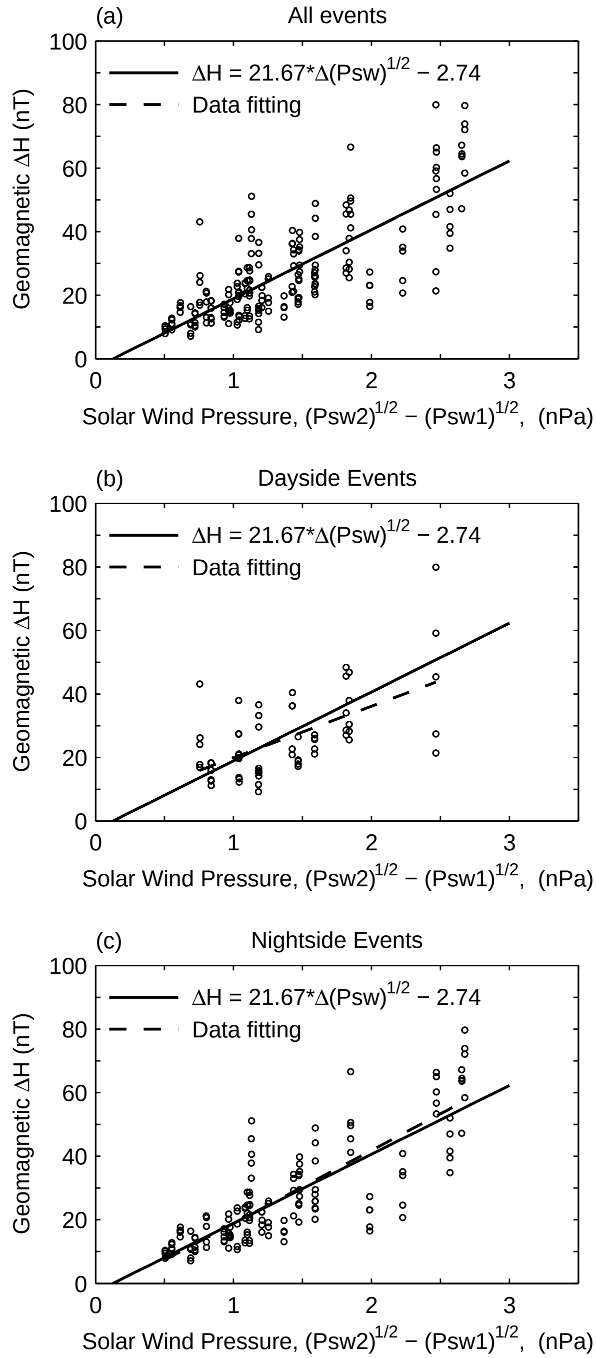

Fig. 2. Statistical results of the sudden increases of the low-latitude geomagnetic field *H* component caused by solar wind pressure impulses during southward IMF for (a) all events, (b) dayside events, and (c) nightside events, respectively. The dashed line represents the least square fitting of the data. The solid line represents Eq. (2).

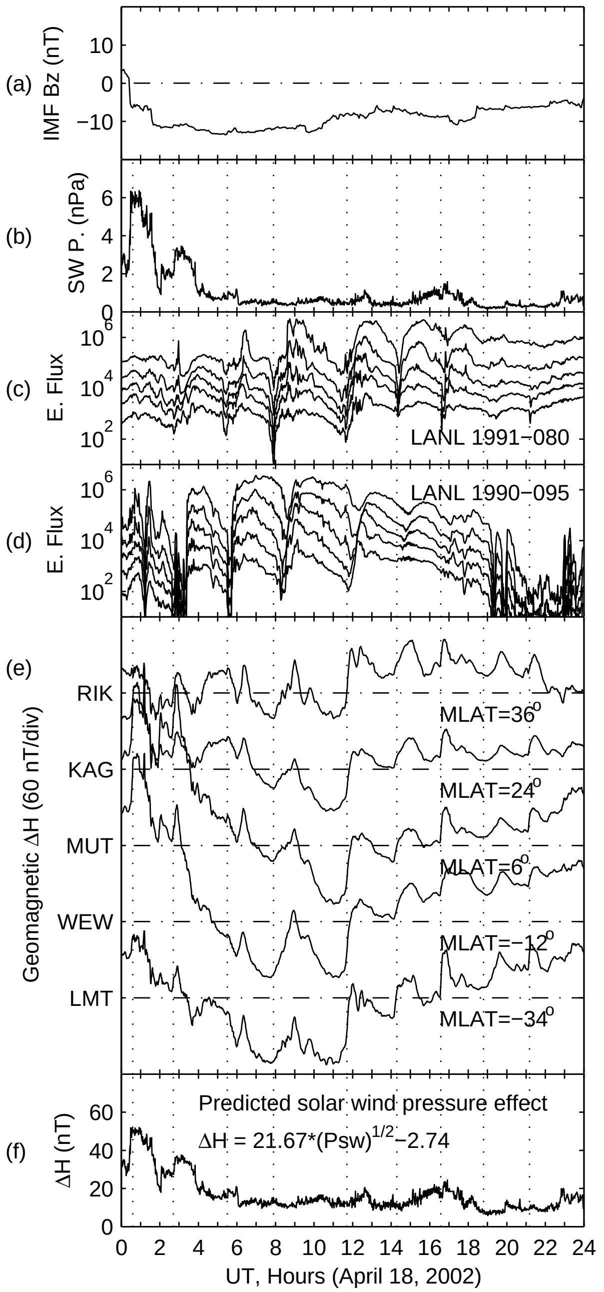

Fig. 3. Effects of storm-time periodic substorms on the geomagnetic field during southward IMF on 18 April 2002. From top to bottom are (a) IMF *Bz*, (b) solar wind pressure, (c)-(d) energetic electron fluxes at geosynchronous orbit, (e) measured low-latitude geomagnetic *H* deviations, and (f) possible geomagnetic *H* deviations caused by the solar wind pressure. The vertical dotted lines indicate substorm onsets.

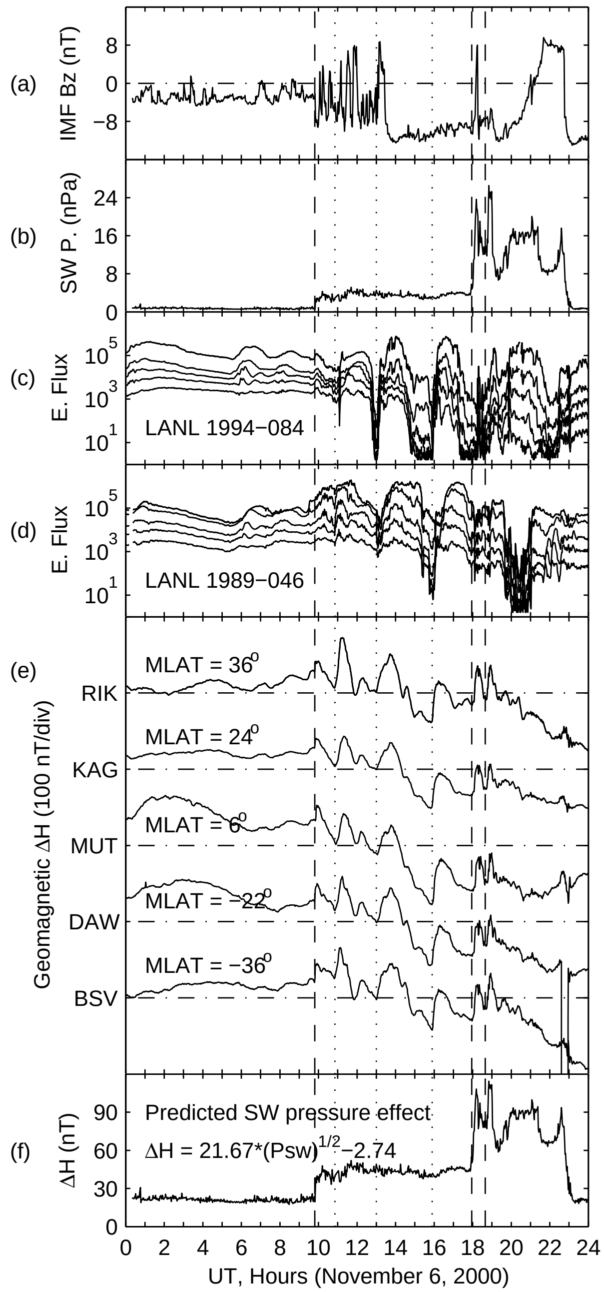

Fig. 4. Same as Figure 3 but for 6 November 2000.