Reasons why some solar wind changes do not trigger substorms

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[1] Previous studies have shown that a northward turning of the interplanetary magnetic field (IMF) or a reduction in the magnitude of IMF B_y component can trigger a substorm. Also a solar wind dynamic pressure enhancement has been found to trigger a substorm under strongly southward IMF conditions. Solar wind changes directed opposite to those of, or not satisfying the conditions of, these known triggers may be considered as inherently nontriggers. In the present paper we have examined 12 events where more than one solar wind quantity change simultaneously and no substorm is triggered. We suggest that nontriggering by the solar wind changes studied in the present work can be explained by the following three reasons: (1) there is a lack of, or insufficient, substorm growth phase development prior to the potential triggering change; (2) the solar wind change is an inherently nontriggering change; (3) the nullifying effect occurs, where one quantity changes in the direction of a substorm trigger and simultaneously another quantity changes in the direction opposite to that of a trigger. The nontriggering types found in this study are consistent with the suggestion that variations of the solar wind that do not reduce the convection strength within the inner plasma sheet do not trigger substorms, which is opposite to what is expected from a triggering solar wind variation.

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1. Introduction

[2] The extent to which substorms are triggered externally by variations in the solar wind has long been an important issue [e.g., *Heppner*, 1955; *Schieldge and Siscoe*, 1970; *Kawasaki et al.*, 1971; *Burch*, 1972; *Tsurutani and Meng*, 1972; *Caan et al.*, 1975; *Kokubun et al.*, 1977; *Rostoker et al.*, 1983; *Dmitrieva and Sergeev*, 1983; *Sergeev et al.*, 1986; *Samson and Yeung*, 1986; *McPherron et al.*, 1986; *Troshichev et al.*, 1986; *Lyons et al.*, 1997; *Blanchard et al.*, 2000; *Bae et al.*, 2001; *Zhou and Tsurutani*, 2001; *Liou et al.*, 2003; *Hsu and McPherron*, 2002, 2003; *Lee et al.*, 2005; *Lyons et al.*, 2005a]. While the analyses of *Lyons et al.* [1997] and *Hsu and McPherron* [2002, 2003] have quantitatively demonstrated the association of external triggers with substorms, the issue has remained controversial among some substorm researchers. A major cause of the uncertainty is that significant inhomogeniety of the solar wind often occurs in both space and propagation angles [e.g., *Lyons et al.*, 1997; *Weimer et al.*, 2003]. This sometimes makes it difficult to determine the precise solar wind structure that actually interacts with the magnetosphere, in particular, when one relies on an observation from one solar wind monitoring spacecraft. Use of measurements from two or more spacecraft in the solar wind often helps to increase the reliability of knowing what solar wind structures actually impinge upon the magnetosphere.

[3] Not all solar wind changes that occur after a growth phase period of enhanced convection trigger substorms. Determining what types of solar wind changes do and do not trigger substorms is as important as determining the extent to which substorms are externally triggered. However, the topic of which changes do not trigger substorms and why has received considerably less attention than determining the extent to which substorms are triggered. Furthermore, substorm external triggering has primarily been evaluated solely on the basis of the variation of one component of the interplanetary magnetic field (IMF) or of the solar wind dynamic pressure $P_{\rm dyn}$. However, it is quite common that two or more of these variables of the solar wind change simultaneously, the effects of which should interact. We have recently found that such interplay of effects can play a key role in determining whether or not specific changes of the solar wind can be a trigger [*Lyons et al.*, 2005a, 2005b]. The main goals of this paper are to identify various changes of the solar wind that do not trigger substorms, to relate them to those that do trigger substorms, and to suggest possible reasons for the nontriggering. First, in the following section, we summarize the categories of solar wind variations that have previously been found to be a trigger. Then in section 3 we present specific events to

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identify various nontriggering situations. In section 4 we summarize our conclusions and give additional discussion.

2. Categories of External Triggers

[4] Before we proceed to discuss the nontriggers, it is useful to first summarize the specific types of solar wind variations that have been found to trigger a substorm:

[5] 1. Northward turning of the IMF B_z under steady IMF B_y and steady dynamic pressure conditions [e.g., *Caan et al.*, 1975; *Rostoker et al.*, 1983; *Samson and Yeung*, 1986; *McPherron et al.*, 1986; *Lyons et al.*, 1997; *Hsu and McPherron*, 2002, 2003]. Often, a trigger can be identified based on the requirement that B_z increases by at least 2 nT within 10 min and remains elevated for 10 min following 25 min of IMF $B_z \lesssim -2$ nT, which are essentially the criteria developed by *Lyons et al.* [1997] and applied by *Blanchard et al.* [2000] and *Hsu and McPherron* [2002, 2003].

[6] 2. IMF $|B_y|$ reduction under steady IMF B_z and steady dynamic pressure conditions following $\gtrsim$25 min of IMF $B_z \lesssim -2$ nT [e.g., *Blanchard et al.*, 2000; *Troshichev et al.*, 1986]. How much of a $|B_y|$ reduction is necessary to trigger a substorm has not been evaluated quantitatively.

[7] 3. Dynamic pressure enhancement under steady and strongly southward IMF conditions. As discussed further below, there has yet to be a realistic determination of the precise magnitude and length of the P_{dyn} increase required for triggering a substorm as a function of the preceding B_z and P_{dyn}.

[8] 4. Simultaneous occurrence of the basic triggers above: For example, simultaneous northward turning and dynamic pressure increase under strongly southward IMF conditions. Whether this would lead to a stronger substorm has not yet been evaluated.

[9] The triggering by northward turning of the IMF and reduction of the IMF $|B_y|$ is well-known in the community [e.g., *Blanchard et al.*, 2000; *Lyons et al.*, 1997; *Hsu and McPherron*, 2002, 2003, and references therein]. The P_{dyn} trigger has also been discussed by many researchers [e.g., *Heppner*, 1955; *Schieldge and Siscoe*, 1970; *Kawasaki et al.*, 1971; *Burch*, 1972; *Kokubun et al.*, 1977; *Zhou and Tsurutani*, 2001; *Liou et al.*, 2003].

[10] We note that there are some early reports [e.g., *Tsurutani and Meng*, 1972; *Iyemori*, 1980] indicating that southward IMF turnings might lead to substorms. However, recently, *Liou et al.* [2003] investigated 43 interplanetary shock events to check substorm triggering. From their study, we note that 16 out of 43 events were associated with southward turnings and none of them triggered a substorm. We will see below that all events presented here are also consistent with the southward turning not being a trigger. Therefore while the proper duration and strength of the southward IMF prior to the substorm onset is required for a growth phase development, evidence now indicates that it is unlikely that the southward turning is a substorm trigger.

[11] Using the Polar UV image data, *Zhou and Tsurutani* [2001] tested substorm triggering possibility by a P_{dyn} enhancement associated with interplanetary shocks and reported that substorm triggering was observed for $\sim$44% of the studied events. They reported that the triggers were under "strongly southward" IMF B_z for > 1.5 hours. However, we note that most of their events actually correspond to weakly southward IMF conditions ($B_z \sim 0$ to -4 nT) prior to the shock. In addition, *Liou et al.* [2003] pointed out that what *Zhou and Tsurutani* [2001] meant by substorm triggering was not precisely the nightside substorm onset auroral breakup. By examining a larger number of events, *Liou et al.* [2003] concluded that the probability of substorm triggering by a shock compression was very low for their studied events (for only four out of the 43 events studied was substorm triggering seen).

[12] However, *Lyons et al.* [2005a] and *Lee et al.* [2005] suggested that substorm triggering by the P_{dyn} enhancement is possible if the accompanied (preceding) IMF is strongly southward whereas, for northward and weakly southward IMF conditions, P_{dyn} enhancements result in only typical compressive disturbances without a substorm onset. What they meant by "strongly southward" is $B_z \lesssim -8$ nT. In fact, *Lyons et al.* [2005a] and *Lee et al.* [2005] reported several examples of substorm triggering by a P_{dyn} enhancement following $\gtrsim$1 hour period of IMF $B_z \lesssim -8$ nT, whereas, for most of the events studied by *Liou et al.* [2003], the accompanied IMF was not strongly southward, thus having led to low probability of triggering. Although there is yet a necessity for a more realistic determination of the precise magnitude and length of the P_{dyn} enhancement required for triggering as a function of the preceding IMF B_z and P_{dyn}, the above results indicate that prolonged and/or strong southward IMF is generally a favorable condition for a P_{dyn} enhancement to trigger a substorm. We note that the issue of the IMF preconditions for substorm triggering was also discussed much earlier by other researchers [e.g., *Burch*, 1972; *Kokubun et al.*, 1977].

3. What Types of Solar Wind variations Are Nontriggers?: Specific Examples

[13] Given the short summary of the known triggers in the previous section, we now proceed to identify types of nontriggers by examining specific events. In the following three subsections, we present 12 nontriggering (i.e., no substorm) interplanetary changes that occurred during three separate storm times. Several substorm events that occurred within the time interval of interest are also discussed for contrast.

[14] In the analysis below, whether or not there is a substorm onset is determined primarily based on four key substorm signatures: auroral breakup and expansion within the Harang reversal region, low-latitude nightside ground geomagnetic bays, geosynchronous magnetic field dipolarization on the nightside, and geosynchronous particle injections on the nightside. Formally, in order to categorize an event as a nontriggering event, we require that all the four signatures are absent. On the basis of this requirement, we identify 10 nontriggering events. For two additional events, useful auroral data are not available, but the other three signatures were unambiguously absent, so we categorize them as nontriggering events as well. There are three substorm events that occurred within the time interval of interest, and they all clearly exhibit the four key signatures with no ambiguity. There is one additional event for which categorization based on the four signatures is not unambiguous since three of the four signatures are either absent or vague, but the geosynchronous dipolarization is clearly

seen. To complement the analysis of this event, therefore, we have further used auroral zone magnetic data and have categorized it as triggered substorm.

[15] Some previous studies have suggested that when a substorm is triggered by a northward IMF turning, onset triggering occurs 8–9 min on average after the trigger arrives at the magnetopause [*Lyons et al.*, 1997; *Blanchard et al.*, 2000; *Bae et al.*, 2001]. The response time seems to be shorter for a dynamic pressure trigger in the examples in the work of *Lee et al.* [2005] and *Lyons et al.* [2005a]. For the present analysis, while we generally refer to these previous reports regarding the response time to the arrival of solar wind changes, we have checked somewhat longer intervals around the time of solar wind impact.

3.1. Event of 11 May 2002

[16] Figure 1 shows the IMF and solar wind data from ACE (top four panels) and the H-component of the ground magnetic field at selected low-latitude stations around the Earth for 0900–1300 UT on 11 May 2002. This interval corresponds to the main phase of a storm with $Dst_{\min}$ = −110 nT. All solar wind data here and in the subsequent figures are presented as time-shifted to just in front of the nose of the magnetosphere at X = 15 R_E. Time-shifting can be done by several methods [e.g., see *Collier et al.*, 1998; *Ridley et al.*, 1998; *Ridley*, 2000; *Weimer et al.*, 2003], and we have chosen to use the Weimer mapping technique [*Weimer et al.*, 2003; *Weimer*, 2004] that takes into account the timing-varying orientation of the propagating IMF structures. In Figure 1 we have identified four interesting solar wind variations that are indicated by vertical lines in the top four panels and labeled N1, S1, N2, and N3. The times of the magnetospheric responses to each event can be determined by low-latitude H responses and are indicated by vertical lines in the rest of the panels. The compression and depression effects due to the magnetopause current changes in response to the dynamic pressure changes are clearly seen for the four events.

[17] Note the lack of precise agreement between the times of the Weimer mapped solar events and the corresponding ground H response times (differences ranging from ~2 to 15 min). This is due to inaccuracies in the Weimer mappings. The Weimer mapping technique is a significant improvement from simply doing a fixed time shift of IMF data to the Earth but is not perfect. The Weimer mapping technique has an inherent average uncertainty of about 4–5 min and also fails for large tilt angles of the phase front, i.e., tilt angle larger than 70 degrees and for shocks. It is important to note that because of the inaccuracies in the Weimer mappings, one needs to check other data whenever possible. The ground H data that we use here is useful for that purpose, and the H response safely determines the exact times when the solar wind pressure changes actually impacted the magnetosphere and approximately reflect that solar wind structure.

[18] The geosynchronous responses are presented in Figure 2 which shows the geosynchronous magnetic field data from two GOES spacecraft (top two panels) and the energetic proton and electron flux data at typical substorm energy levels, 50–75, 75–113, 113–170, 170–250, 250–400 keV for protons and 50–75, 75–105, 105–150, 150–225, 225–315 keV for electrons, respectively, from several Los Alamos National Laboratory (LANL) spacecraft for the same interval as in Figure 1. Also, the auroral responses are presented in Figure 3, which shows FUV auroral images for selected times as obtained from the WIC instrument onboard the IMAGE spacecraft. In each plot, noon is to the top and the dusk is to the left. For some images, the MLT locations of the geosynchronous spacecraft are indicated for reference.

[19] For the first event, N1, in Figure 1, which is seen at ~0958 UT in the Weimer mapping but actually impacted the magnetosphere at ~1012 UT, the dynamic pressure increased sharply by a factor of 2–3. Also the solar wind density, bulk speed, thermal speed, and the IMF magnitude all increased, implying that this is a fast forward shock. Simultaneous with the pressure enhancement, the IMF B_z became further southward and the IMF $|B_y|$ increased due to the shock compression [e.g., *Tsurutani et al.*, 1988]. The energetic particle flux response to these simultaneous changes in the dynamic pressure and IMF indicates only the compression-induced flux changes without any evidence for substorm injections, i.e., the fluxes increased near-simultaneously (to within the day to night MLT propagation timescale of a few minutes) at all available MLTs at ~1012 UT, did not show an enhanced near-midnight increase as is associated with current-wedge formation and did not show the energy dispersion signature away from the midnight region that is expected from a substorm-induced nightside injection (Note that the MLT values of each LANL spacecraft are indicated for this event near the first vertical line). Futhermore, the GOES magnetic field data does not indicate the substorm dipolarization due to this solar wind impact. As shown in Figure 3, the aurora response indicates no substorm onset brightening but only the broadly distributed compression-induced brightening primarily near dusk and from postmidnight through the dawnside.

[20] The accompanied IMF prior to this pressure enhancement remained moderately southward for many hrs, $B_z \sim -6.8$ nT at the minimum. The WIND data (not shown) indicates even less southward IMF B_z values for the same interval, although it should be noted that the WIND spacecraft was located far from the Sun-Earth line, $Y_{GSE} \sim 303$ R_E. It might be possible that the steady, moderately southward IMF drove the magnetosphere to a weak Steady Magnetospheric Convection state without storing much energy in the tail. However, the southward IMF prior to this event satisfied the growth phase criteria for a substorm to occur, and we believe that it is likely that the pressure enhancement and simultaneous IMF changes of N1 did not trigger a substorm for other reasons. We suggest two possible reasons for nontriggering in this case. The two reasons are distinguished by whether or not the IMF condition was sufficient for the pressure enhancement to be inherently a trigger. As discussed in section 2, although *Lee et al.* [2005] and *Lyons et al.* [2005a] found examples of substorms triggered by a pressure enhancement under strongly southward IMF conditions, the precise IMF B_z condition preceding the pressure increase required for triggering a substorm is not known at present. Thus it is possible that this was not a sufficient southward IMF for this pressure enhancement to be a trigger. However, the IMF changes, southward turning of B_z and $|B_y|$ increase, are not

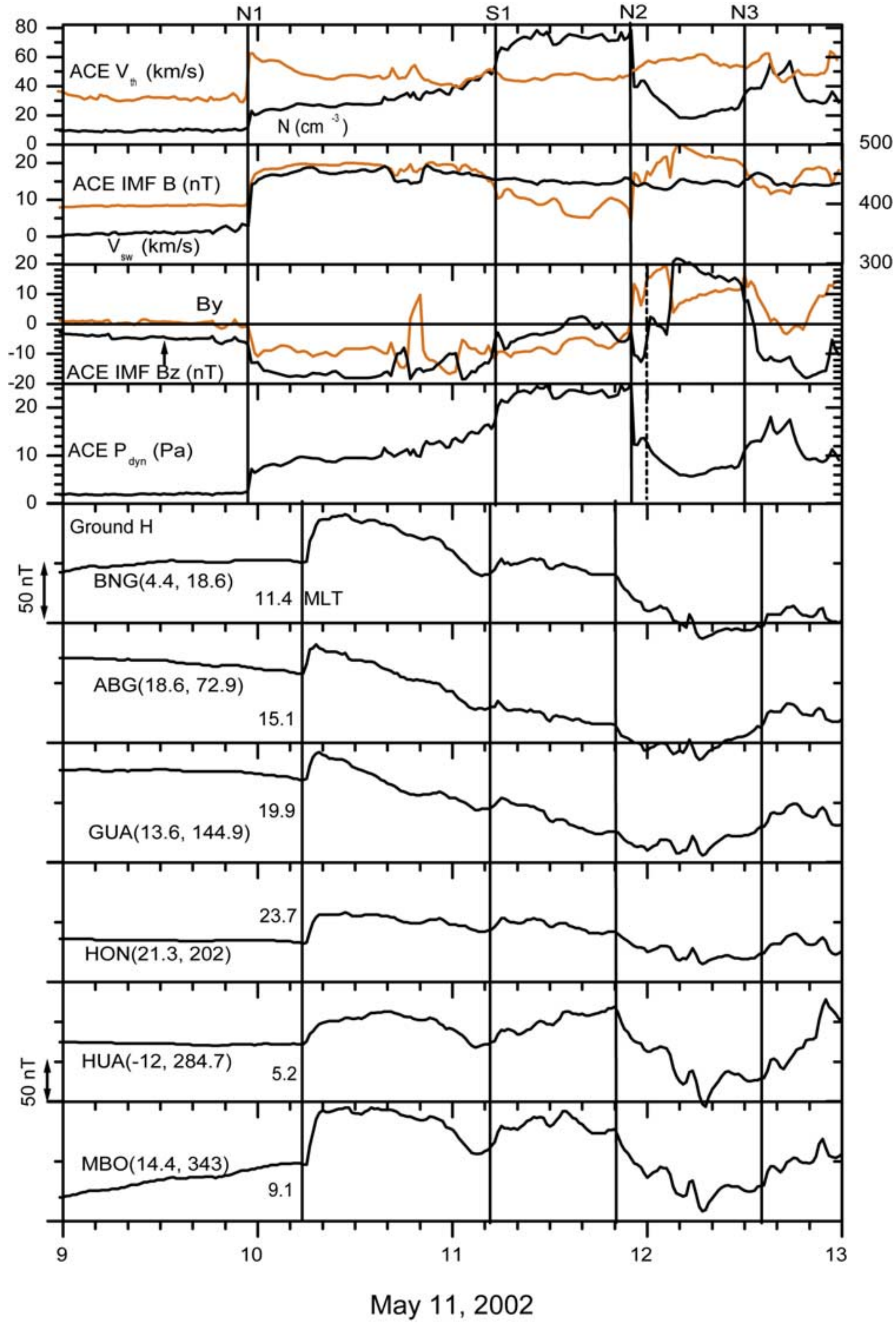

Figure 1. Data for the 11 May 2002 event. Top four panels show the ACE solar wind and IMF data, as presented as time-shifted by Weimer mapping technique to X = 15R_E [*Weimer et al.*, 2003]. The other panels show the ground H at six low-latitude to midlatitude stations around the Earth. The MLT values at ~1011 UT are shown for observations in individual panels.

triggers by themselves as they are opposite to the changes of triggers in section 2.

[21] Thus the first possibility for nontriggering is that all of the simultaneous changes were inherently nontriggers by themselves. The second possibility is that the southward IMF condition was sufficient and the pressure enhancement would by itself have been a trigger. However, since both the southward turning of IMF B_z and the IMF $|B_y|$ increase are inherently nontriggers, the triggering effect was nullified by the simultaneous nontriggering IMF changes. We will see more examples below which illustrate this possible nullifying effect.

[22] The idea of nullification is based on *Lyons et al.*'s [2005a] suggestion that the potential triggering effect by a

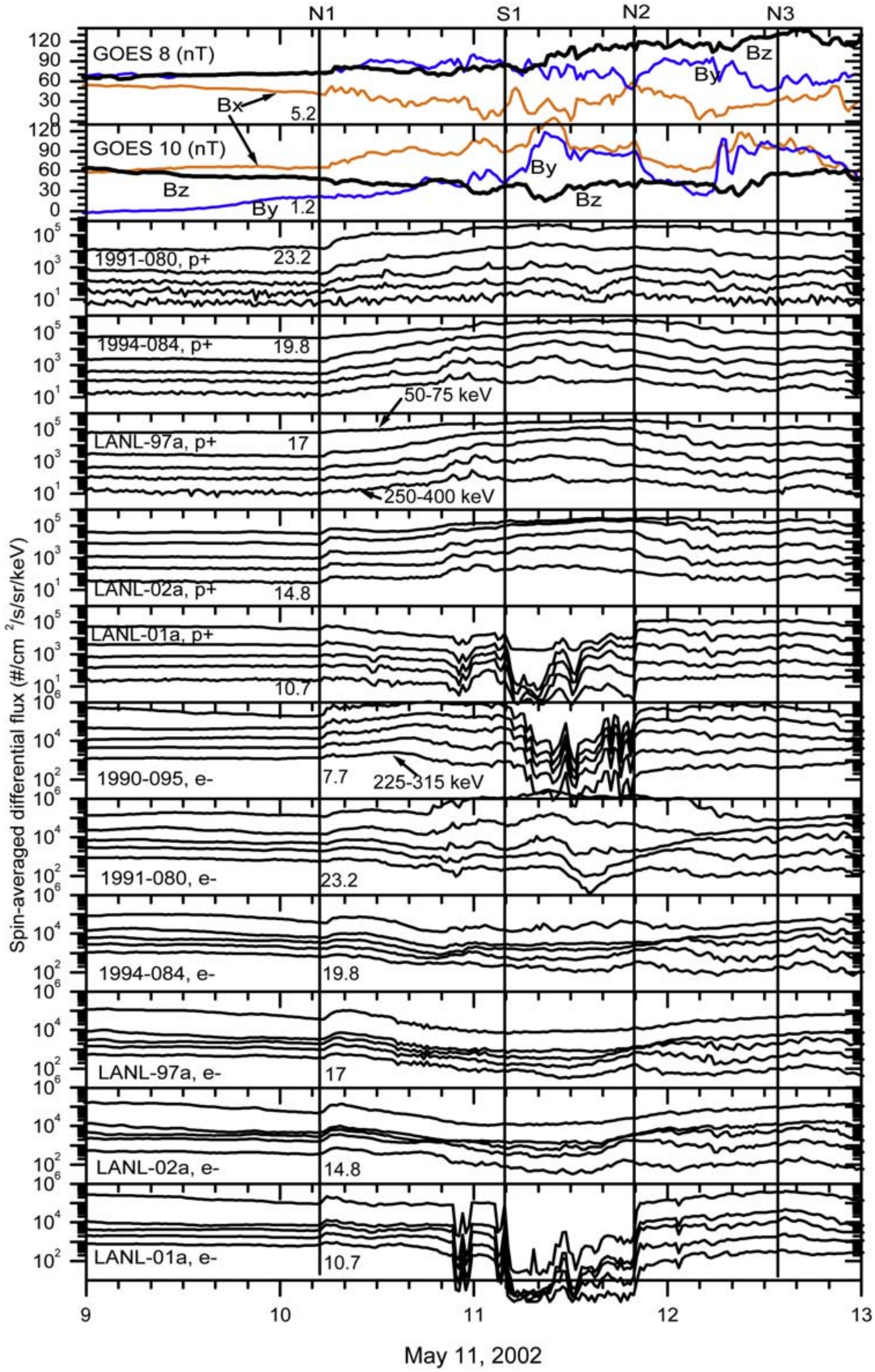

Figure 2. Top two panels show the geosynchronous magnetic field from GOES spacecraft for the 11 May 2002 event. The MLT values at ~1011 UT are shown for observations in individual panels. The other panels show the particle flux from LANL spacecraft in five energy channels, 50–75, 75–113, 113–170, 170–250, 250–400 keV for protons (as labeled p+), and 50–75, 75–105, 105–150, 150–225, 225–315 keV for electrons (as labeled e-).

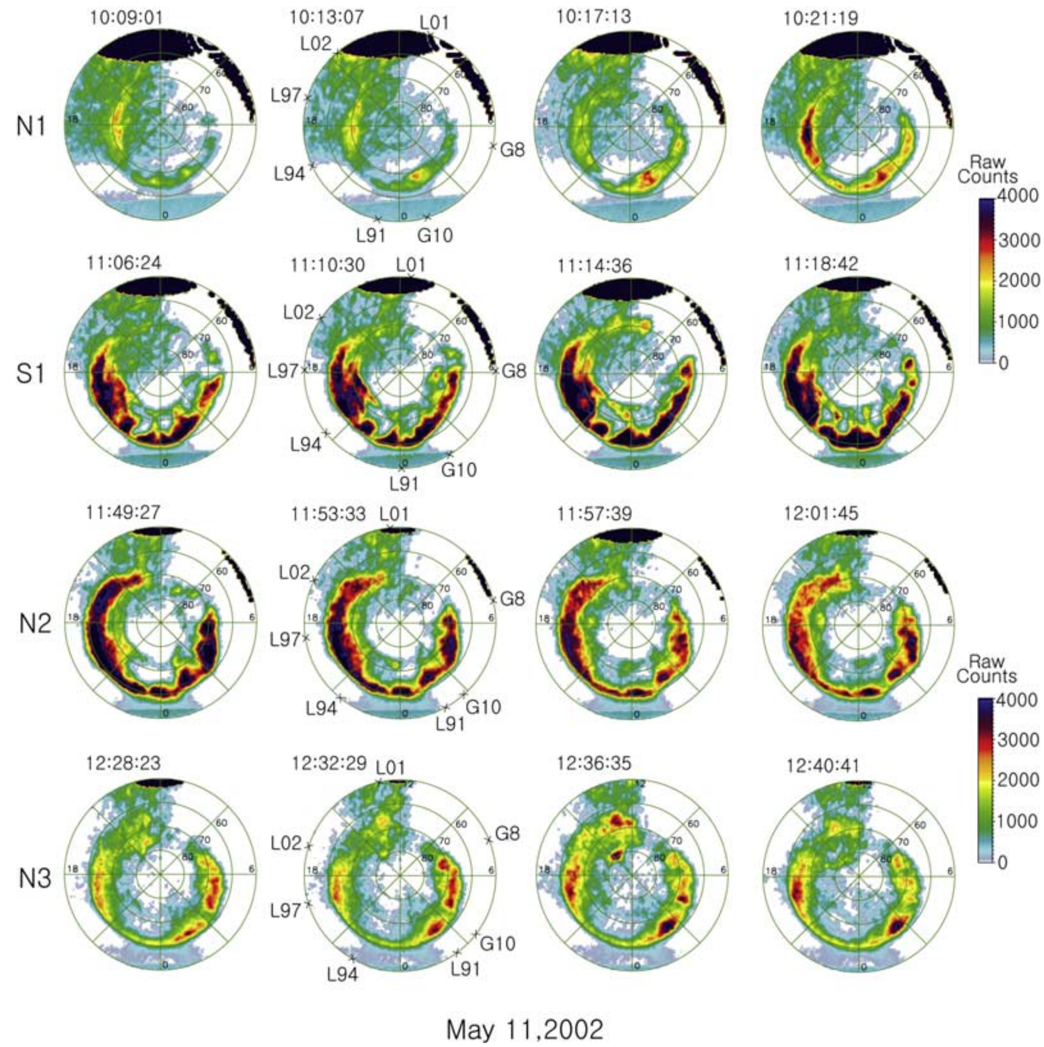

Figure 3. Auroral FUV images from the WIC instrument on board the IMAGE spacecraft for the events on 11 May 2002. In each plot, the noon is to the top, the dusk is to the left, etc. For some images, the MLT locations of GOES and LANL spacecraft are indicated for reference where G8, G10, L91, L94, L97, L01, and L02 mean GOES 8, GOES 10, 1991–080, 1994–084, LANL-97a, LALN-01a, and LANL-02a, respectively.

basic trigger can be cancelled out by a simultaneous change(s) in another quantity in the direction opposite to that of a trigger, leading to no substorm (referred to as a "null" event). The nullifying effect is expected between an IMF B_z northward turning and an IMF $|B_y|$ increase or between an IMF B_z southward turning and an IMF $|B_y|$ decrease. Also, a northward turning or IMF $|B_y|$ reduction, which would alone be sufficient to trigger a substorm, may be nullified by a simultaneous decrease of the dynamic pressure. In addition, the effect by a dynamic pressure enhancement under strongly 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 $|B_y|$. This last situation could be what happened to event N1.

[23] For event S1, seen at ~1112 UT in the Weimer mapping and which actually impacted at ~1109 UT, the IMF B_z, which had remained quite strongly southward following event N1, turned northward, and simultaneously the dynamic pressure increased by a factor of ~1.4. The WIND data (not shown) also indicates similar simultaneous changes. Both changes are expected to trigger a substorm according to the categories of triggers summarized in section 2. It is difficult to determine whether or not there was a substorm onset in the LANL particle data. The significant particle flux dropouts near noon as observed by LANL-01a and in the morning sector as observed by 1990–095 at and after ~1109 UT reflect the crossing of the magnetopause inside geosynchronous orbit due to the enhanced dynamic pressure. The IMAGE WIC auroral data does not indicate unambiguous evidence for an onset. However, the high-latitude ground magnetic field data as shown in Figure 4 seems to suggest the wedge current formation (courtesy referee 1). The negative X bays are seen in MCMU and DAWS near 1110 UT, and both poleward and equatorward propagating increases are seen in the Z component disturbances. The GOES 10 data in Figure 2 indicates that there seems to be a dipolarization of the

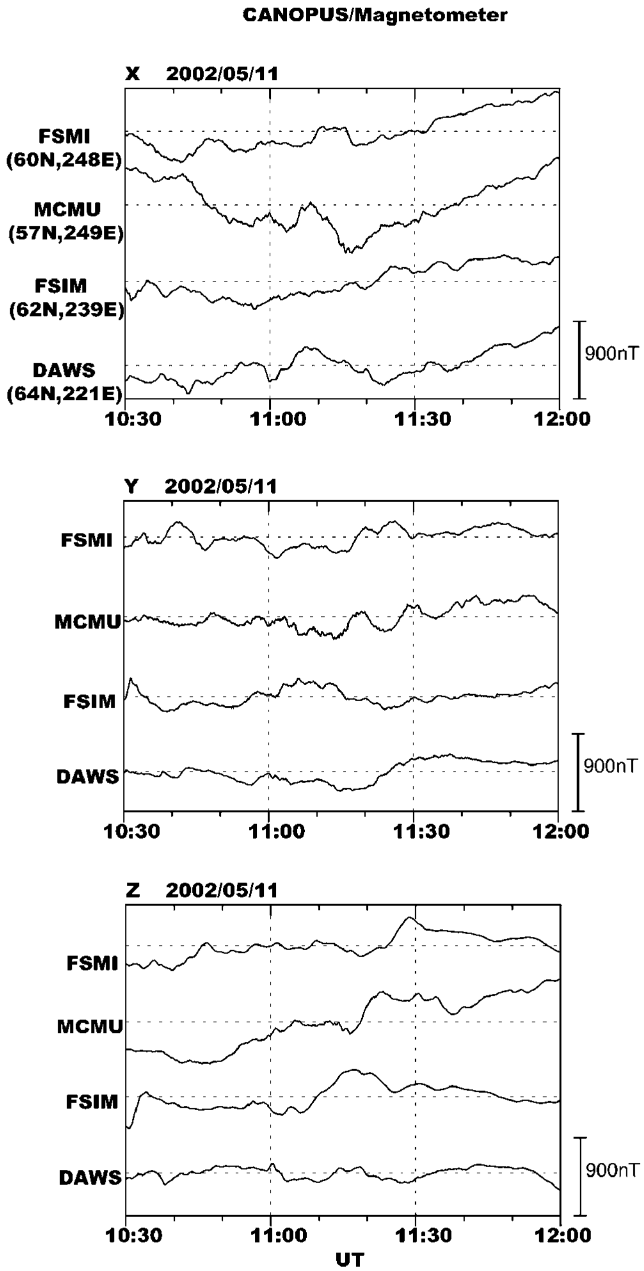

Figure 4. The ground magnetic field data from selected CANOPUS (CARISMA) magnetometer stations for the 11 May 2002 event. The geodetic coordinates of the stations are given in parenthesis below each station name at the top of the figure.

geosynchronous magnetic field at ~1125 UT associated with this onset. We note that there were two earlier, weaker dipolarizations at ~1045 and 1105 UT, which may be pseudobreakups, but whether or not they are associated with the short-lasting IMF changes at ~1045 and afterward is unclear.

[24] Event N2, seen at ~1155 UT in the Weimer mapping and which actually impacted at ~1150 UT, is initially characterized by a solar wind density decrease, a rather gradual increase of the solar wind thermal speed, an increase of the IMF magnitude, and a little change in the solar wind bulk speed. Whether or not this is a certain type of shock is unclear. What is of more interest here is that the event is characterized by three simultaneous changes: a dynamic pressure decrease, a further southward turning of the IMF B_z, and an IMF $|B_y|$ increase, as indicated by the solid vertical line. Because of the pressure decrease, the magnetopause retreated back as seen by sharp recoveries of the particle flux at LANL- 01a and 1990–095 at ~1150 UT. No substorm onset is found from the data presented in Figures 1 to 3, implying that the solar wind changes are nontriggers. The absence of a substorm could be due to the lack of a sufficiently long growth phase prior to the solar wind changes. The reduced polar cap size prior to the event seems to suggest that there may not have been a lot of magnetic energy to be released, or it may be due to the fact that all these changes are inherently nontriggers, as they are all opposite to those of the basic triggers in section 2. Then within ~5 min, the IMF B_z turned northward as indicated by short-dashed vertical line, which alone would be expected to trigger a substorm. However, simultaneous with this northward turning, the dynamic pressure decreased further and the IMF $|B_y|$ increased somewhat further. The WIC auroral images in Figure 3 (the images in the third row from the top) show decreasing auroral brightness as the dynamic pressure decreased, and no nightside onset brightening is seen. (There were some modest particle flux changes starting at ~1135 UT (prior to the event N2) just after midnight, as seen by 1991–080, at least in the two highest-energy channels. It seems unlikely that these flux changes imply a substorm associated with N2.) Clearly, these later simultaneous changes of the solar wind did not trigger a substorm. We suggest that the northward turning effect was nullified by the simultaneous changes, directed opposite to that of a trigger, of the dynamic pressure and IMF $|B_y|$. This is another example of the nullification effect discussed above.

[25] For event N3, which is seen near 1232 UT in the Weimer mapping, the dynamic pressure increased again but under northward IMF. Then the northward IMF turned southward rather gradually. While being located far from the Sun-Earth line, the WIND spacecraft observations indicate similar IMF changes but a much weaker pressure increase than what ACE observed. The ACE observation seems to be more consistent with the ground H data in Figure 1, which clearly shows that this pressure enhancement arrived at the magnetosphere at ~1235 UT. However, this solar wind impact did not trigger a substorm. The LANL particle fluxes mostly show only very small increases at 1235 UT in direct response to the pressure enhancement, and the WIC auroral images in Figure 3 show the increasing global brightening due to the increasing pressure but indicate no substorm onset brightening. This example confirms that triggering by a pressure enhancement under not strongly southward IMF conditions is unlikely, as discussed in section 2 and illustrates that the accompanied southward IMF turning does not change the result.

[26] A summary of the major nontriggering events presented in this section as well as those in the subsequent sections is given in Table 1. In this subsection we have presented three examples of nontriggering for simultaneous changes of the solar wind pressure and IMF. Nontriggering can be explained by the lack of the growth phase development prior to the solar wind changes (the

Table 1. Summary of Major Nontriggering Events Studied in the Present Paper

Event Date	Event ID	Preceding IMF $< B_z >$,[a] nT	Types of (Simultaneous) Solar Wind Variations	Likely Reasons for Nontriggering
05/11, 2002	N1	−5.7	P_{dyn} increase, south turning, $\|B_y\|$ increase	inherently nontriggers, lack of growth ph, or nullification
	N2	−4.2, then −11.2	south turning, P_{dyn} decrease, $\|B_y\|$ increase, then north turning, $\|B_y\|$ increase, further P_{dyn} decrease	lack of growth ph, or inherently nontriggers then nullification or still lack of growth ph
	N3	northward	P_{dyn} increase, south turning	lack of growth ph or inherently nontriggers
04/18, 2001	N1	−3.4	P_{dyn} increase, south turning	lack of growth ph or inherently nontriggers
	N2	−24.3	north turning, $\|B_y\|$ increase	nullification effect
	N3	−2.1	P_{dyn} increase, $\|B_y\|$ decrease, south turning	lack of growth ph or nullification effect
	N4	−10.2	short-lasting north turning, P_{dyn} decrease	inherently nontriggers
04/20, 2002	N1	northward	south turning, $\|B_y\|$ increase, P_{dyn} decrease	lack of growth ph and inherently nontriggers
	N2	−17.4	P_{dyn} increase, north turning, $\|B_y\|$ increase	nullification effect
	N3	−7.8	P_{dyn} increase, north turning, $\|B_y\|$ decrease: all, short-lasting	inherently nontriggers, or lack of growth ph
	N4	−7.2	P_{dyn} increase, north turning, $\|B_y\|$ decrease: all, short-lasting	inherently nontriggers, or lack of growth ph
	N5	−11.9	$\|B_y\|$ increase, P_{dyn} decrease	inherently nontriggers

[a]Averaged over ∼10 min prior to the identified solar wind variations.

first of N2), by the nullification effect (N1 and the second of N2), or by the fact that the changes are simply inherently nontriggers as they are opposite to those of (or not satisfying the conditions for) the known triggers in section 2 (N1, the first of N2, and N3).

3.2. Event of 18 April 2001

[27] The data for this event are presented in Figures 5 and 6 in similar format as for the previous event, and the available WIC auroral images are shown in Figure 7. The interval here corresponds to the main phase of a storm with $Dst_{min} = -114$ nT. In the top four panels of Figure 5, several interesting combinations of the solar wind variations are identified. As in the previous example, the low-latitude H data as presented in Figure 5 were useful for determining the impact times of the solar wind changes that involve a dynamic pressure change. For the event N2, which did not involve a pressure change, the precise impact timing could not be determined, though the event is discussed below. As before, note the up to ∼14 min disagreement between the event times from the Weimer mapped solar wind data and the actual impact times, which is again due to the typical inaccuracies of the Weimer mappings.

[28] First, for event N1, which is a fast forward shock seen at ∼0059 UT in the Weimer mappings, the dynamic pressure increased sharply by a factor of ∼8–9. The accompanied IMF remained weakly southward, $B_z \sim -3$ to −4 nT until it became further southward simultaneous with the pressure enhancement. The IMF B_y made only a brief negative excursion at the same time. The strongly southward IMF B_z then turned northward quite significantly ∼9 min after N1, and near-simultaneously the IMF $|B_y|$ increased but less significantly (as labeled S1). WIND observed a similar shock-associated pressure increase but the IMF variations (data not shown) differ from what ACE observed. We note that the WIND location was far from the Sun-Earth line, Y ∼ −264 R_E, and thus what ACE observed is more likely what actually impacted the magnetosphere. The impact time of this pressure enhancement on the magnetosphere is clear from the ground H data and was ∼14 min prior to that inferred from the Weimer mapping. The WIC auroral images shown in the first row (as labeled N1) in Figure 7 indicate the compression-induced brightening starting at ∼0047:51 UT. This compression effect is also clear in the particle flux data in Figure 6. This compressive response was then followed by a substorm onset brightening which is clearly seen at 0053:39 UT, as shown in the second row (as labeled S1) in Figure 7. The substorm-induced injection features are also clear in the LANL particle flux data, and the substorm dipolarization is seen in the GOES 8 magnetic field data, as shown in Figure 6. In summary, two types of solar wind and IMF variations, N1 and S1, are identified, and the corresponding magnetospheric response is that the pure compression effect is first seen followed by the substorm onset. Our interpretation is that for N1 both the pressure increase under the weakly southward IMF preceding the shock and the simultaneous southward turning are inherently nontriggers, leading to the pure compression effect only. The following substorm onset was likely triggered by the later large northward turning of S1 that was seen in the Weimer mappings ∼9 min after N1. This implies that the simultaneous increase of the IMF $|B_y|$ of S1 was not sufficient to nullify the triggering effect of the large northward turning, unlike the nullification example above (see more discussion below).

[29] For event S2(?) at ∼0336 UT in the Weimer mapping, the IMF $|B_y|$ decreased and simultaneously B_z turned further southward. There was no pressure change, which makes it difficult to determine the precise impact timing of the IMF changes. There was a substorm expansion starting at ∼0309 UT (courtesy referee 1), as indicated by an arrow and dashed vertical lines in Figure 5 and 6. From the available solar wind data, we see no indication for a possible trigger for this substorm. There is evidence for a later intensification: an increase of the ground H at HUA at ∼0345 UT is seen in Figure 5. Also, a nightside dispersionless electron enhancement is seen at LANL-01a at ∼0335 UT, and dispersed flux increases are seen at 1994–084 in both species. It may be that the $|B_y|$ decrease, which was larger than the simultaneous further southward

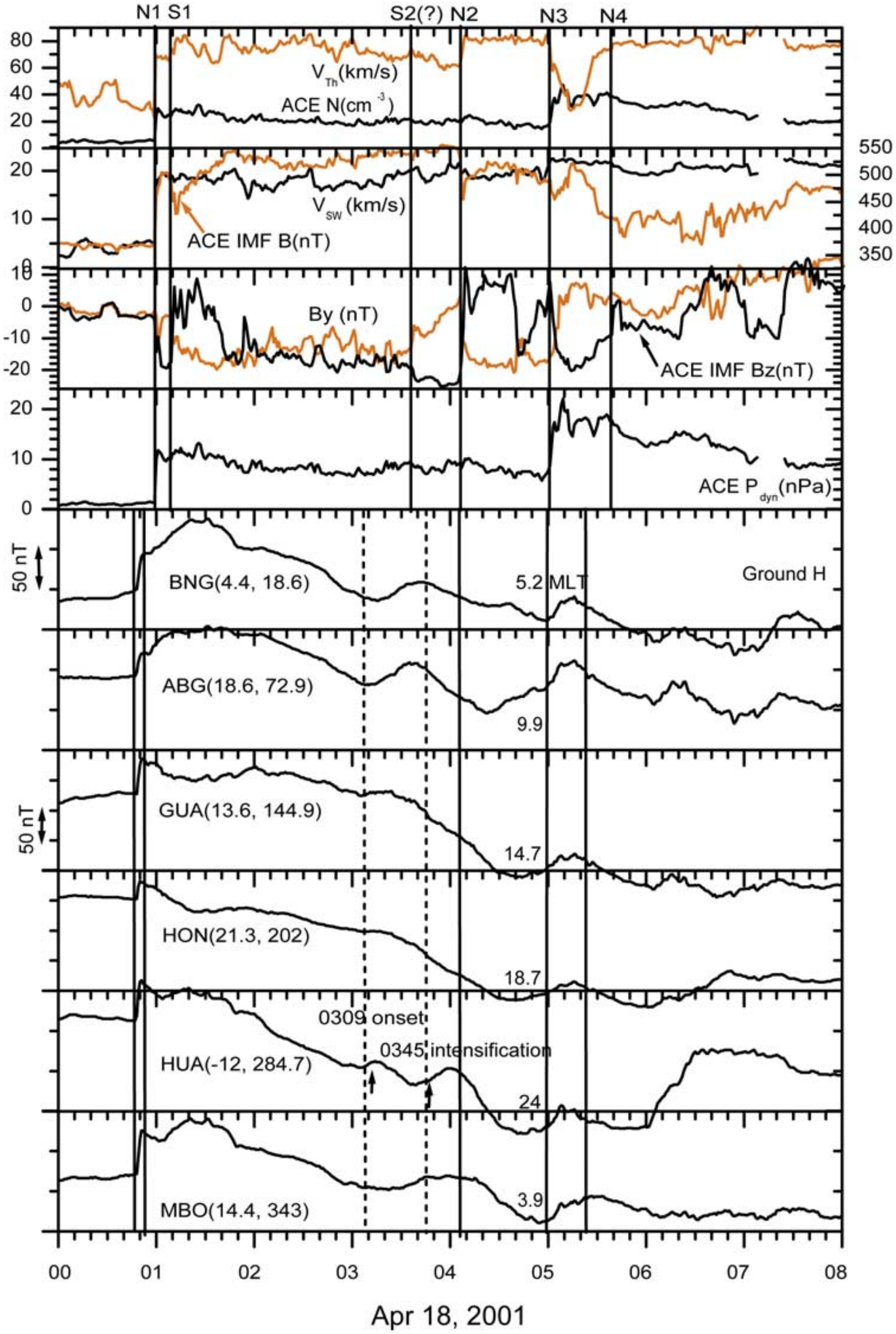

Figure 5. Data for the 18 April 2001 event in the similar format as in Figure 1. The two dashed lines indicate a substorm onset and a following further intensification (see text for discussion).

IMF B_z turning, is responsible for the later intensification, but we have no proof for this.

[30] For N2, which occurred at ~0406 UT in the Weimer mapping, the IMF B_z turned northward but simultaneously the IMF $|B_y|$ increased significantly. Similar but less strong IMF changes are seen in the WIND observations (data not shown). Since no change in the dynamic pressure was involved, it is difficult to determine a precise impact time of these IMF changes, but it should be sometime in the vicinity of 0405 UT as indicated by the vertical line and clearly before 0500 UT when a new disturbance arrived. For this expected period, no evidence for a substorm onset is seen from the WIC aurora images (the bottom row in Figure 7) and the LANL particle fluxes in Figure 6. The top panel in Figure 6 shows the elevation angle of the geosynchronous magnetic field as measured by two GOES

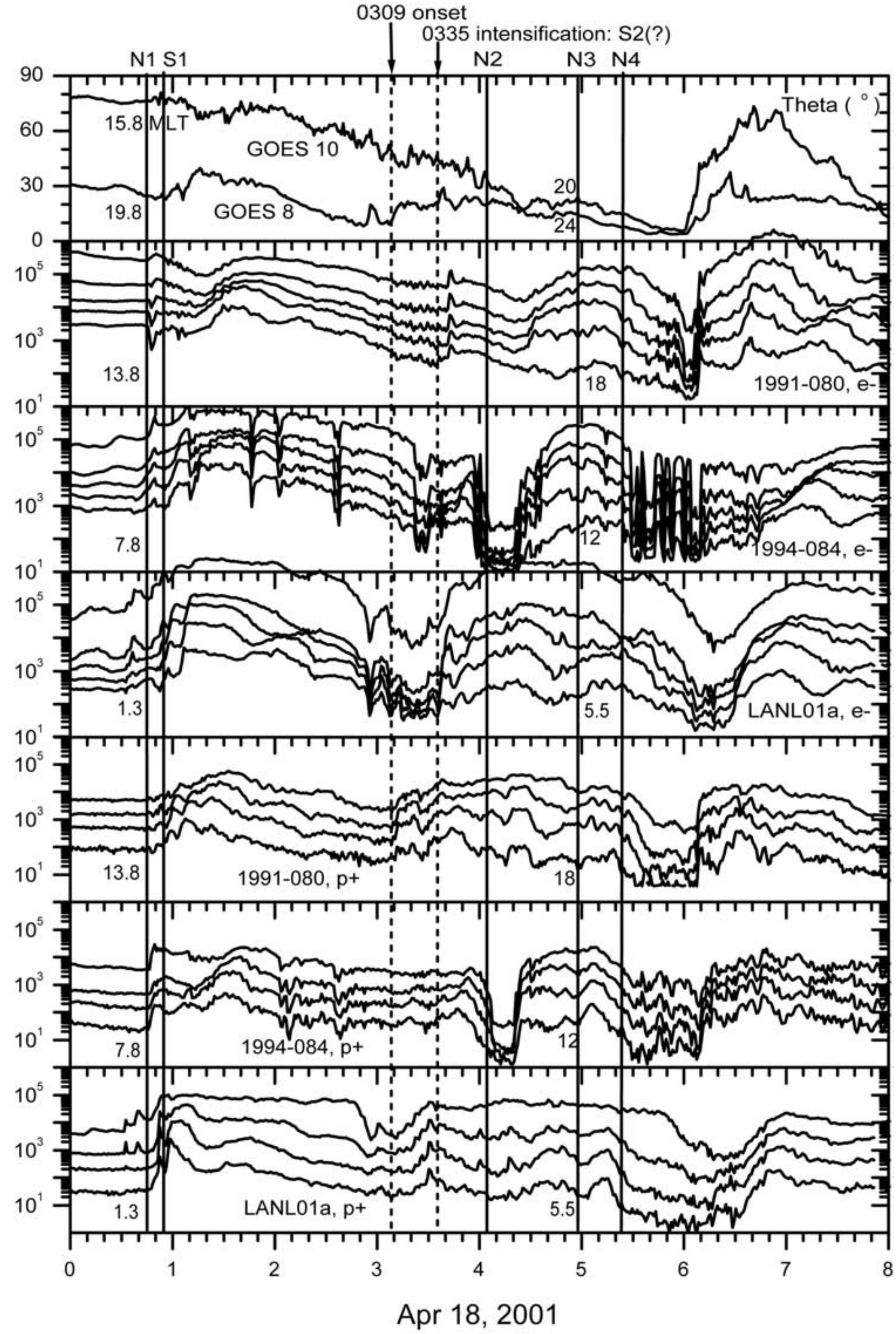

Figure 6. The geosynchronous data for the 18 April 2001 event in the similar format as in Figure 2. The two dashed lines indicate the substorm onset and the following further intensification identified in Figure 5 (see text for discussion).

spacecraft, and it can be seen that the nightside magnetic dipolarization that is expected from a substorm did not occur for this event. There was a substorm expansion about an hour earlier, starting at ~0309 UT, as discussed above. However, the quite strongly southward IMF, $B_z \sim -24$ nT for about half an hour, preceding the IMF changes of N2 well exceeds the growth phase criterion. The northward turning would then by itself be a trigger, but triggering did not occur because of the opposing effect of the large IMF B_y change, namely, the nullification effect.

[31] It is worthwhile to stress here again that for the substorm event S1 and possibly S2, the triggering change in

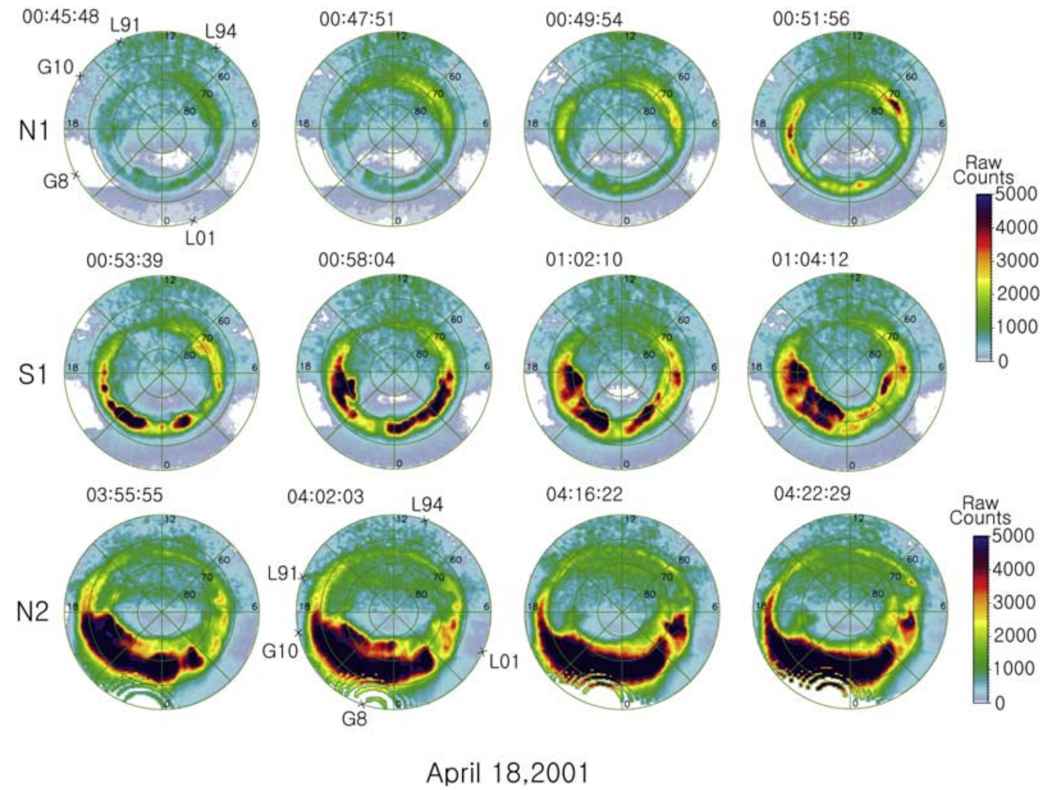

Figure 7. Auroral FUV images from the WIC instrument onboard the IMAGE spacecraft for the events on 18 April, 2002. In each plot, the noon is to the top, the dusk is to the left, etc.

one of the IMF components was larger than the nontriggering change in the other component so that the nullifying effect could probably not be achieved. In contrast, for N2 above and for other earlier events on 11 May 2002, the nullification effect seems to have taken place. These examples all together suggest that the nullification effect requires that the nullifying change must be sufficiently large to cancel out the potential triggering effect.

[32] For event N3, which occurred at ~0503 UT in the Weimer mapping, the IMF $|B_y|$ decreased and the dynamic pressure increased simultaneously. However, note that the IMF B_z turned very strongly southward nearly simultaneously and was preceded by a B_z state of near zero for ~10 min. The overall trend of variations is confirmed by the WIND observations (data not shown), but there is some significant difference in the preceding IMF B_z state between ACE and WIND observations. We rely on ACE observations because WIND was far from the Sun-Earth line. No evidence for substorm triggering by these changes is found from the LANL particle fluxes, the nightside geosynchronous magnetic field, or the low-latitude H (the IMAGE WIC data coverage became poor around this time). Only the compression effect due to N3 exists, which clearly identifies the time of impact at ~0458 UT. One possible reason for nontriggering in this event is that the condition of prior IMF $B_z \sim 0$ for ~10 min preceded by a strongly southward B_z for ~10 min was not sufficient for a well-developed growth phase. Another possibility is that the growth phase development was actually achieved for N3, and the southward turning of IMF B_z has nullified the potential triggering effect by the IMF $|B_y|$ reduction and pressure increase. There was also a northward turning near 0450 UT, prior to N3, which was preceded by a ~10 min period of strongly southward IMF. This earlier northward turning did not trigger a substorm, which is expected since the period of southward IMF prior to the northward turning was too short to satisfy the substorm growth phase criteria.

[33] For N4, which occurred at ~0539 UT in the Weimer mapping, a sharp northward turning occurred but only lasted ~5 min. Also, the simultaneous, rather gradual, decrease of the dynamic pressure led to primarily adiabatic decreases of the LANL particle flux at ~0525 UT and later. No evidence for substorm triggering is seen from the nightside geosynchronous magnetic field, the particle fluxes, or the ground H. (The electron flux fluctuations near noon seen by 1994–084 are due to magnetopause crossings.) The short-lasting northward turning does not satisfy the duration requirement for substorm triggering in section 2, and the gradually decreasing pressure is inherently a nontrigger.

[34] A summary of the major nontriggering events presented in this section is given in Table 1. We see types of nontriggers similar to those found in the previous section. Namely, we again have examples (N1, and N4) of nontriggering due to the (simultaneous) changes opposite to those of, or not satisfying the conditions of, the known triggers in section 2. These are therefore inherently nontriggers. We also have examples (the northward turning prior to N3, and possibly N3) of nontriggering due to the lack of well-defined growth phase development. Also the

nullification effect seems to be a possible reason for N2 and for N3.

3.3. Event of 20 April 2002

[35] This event has several interesting combinations of dynamic pressure and IMF variations as presented in Figure 8. This interval corresponds to the main phase of a storm with $Dst_{\min} = -149$ nT. As in the previous examples, the H data at selected low-latitude stations are checked and shown in Figure 8, the geosynchronous data are presented in Figure 9 and the WIC auroral images are presented in Figure 10.

[36] First, for event N1, which occurred at ~0048 UT in the Weimer mapping, simultaneous changes occurred in three variables of the solar wind. The dynamic pressure decreased (being preceded by a brief rise), the IMF $|B_y|$ increased, and the IMF B_z turned southward. These together did not trigger a substorm. Nontriggering is not surprising because each of these changes is inherently a nontrigger in that all of these changes are opposite to those of triggers in section 2 and also because the IMF had been solidly northward for about an hour prior to the solar wind changes so that a substorm growth phase was not possible. The pressure decrease effect is clear in the particle flux changes at 0048 UT, which show near-simultaneous flux decreases at most available MLTs and in most energy channels. The same effect is also clear in the H responses as shown in Figure 8.

[37] The IMF B_z remained quite strongly southward ($B_z \sim -18$ nT over 30 min) until the start of the event N2 where it turned northward and at the same time (~0124 UT in the Weimer mapping) both the dynamic pressure and the IMF $|B_y|$ increased (It is interesting to note that the Akasofu epsilon parameter remains nearly constant for the interplanetary changes of N2). The WIND observations (data not shown) indicate variations consistent with the ACE observations, despite that the spacecraft was located far from the Sun-Earth line, Y ~ 217 R_E. They arrived at the magnetosphere at ~0128 UT as seen in the H response, but we see no evidence for the substorm onset from the LANL particle flux, which show only the compression-induced flux changes. The WIC aurora images (not shown here, but presented by *Lyons et al.* [2005a]) indicate only weak global brightening without an onset brightening. As suggested by *Lyons et al.* [2005a], the triggering effect by the northward turning and pressure increase was likely nullified by the large (~10 nT) simultaneous increase of the IMF $|B_y|$.

[38] The substorm event (labeled S1 + P1) then occurred at ~0145 UT in association with a modest dynamic pressure increase and some weak, delayed, northward turning under the strongly southward IMF condition, $B_z \sim -12$ nT. While being located far from the Sun-Earth line, WIND observed a similar dynamic pressure increase under the strongly southward IMF condition but not a northward turning (data not shown). However, note that the IMF $|B_y|$ did not change much in both spacecraft observations. These dynamic pressure and IMF B_z changes triggered a substorm. The substorm features are clear in the particle flux, in the geosynchronous magnetic field elevation angle, and in the WIC aurora images (not shown here, but presented by *Lyons et al.* [2005a]). The auroral response consisted of the dayside compression-induced brightening and the nightside onset brightening as reported by *Lyons et al.* [2005a]. Substorm triggering by the dynamic pressure increase and northward turning was possible in this case since the IMF $|B_y|$ was nearly constant, unlike for N2.

[39] Event N3, which occurred at ~0225 UT in the Weimer mapping, may be a slow forward shock as it shows increases in the solar wind density and thermal speed but a decrease of the IMF magnitude, though the bulk speed did not change much. What is of more interest here from the viewpoint of substorm triggering is that it is characterized by an increase of the dynamic pressure, an IMF northward turning, and an IMF $|B_y|$ reduction, but all were short-lasting, i.e., <10 min. The accompanied IMF B_z was ~−8.6 nT on average for ~45 min prior to the event N3. The compressive effect by the pressure enhancement is seen in the particle flux, the ground H, and the WIC aurora images at ~0227 UT and later (top row images in Figure 10). However, no evidence for the substorm effect is seen. This simply suggests that, given the strength of the southward IMF, such short-lasting IMF turnings and pressure enhancement could not trigger a substorm.

[40] The nontriggering seen in event N4, which occurred at ~0244 UT in the Weimer mapping, is similar. In this case, the dynamic pressure increased but soon decreased in ~15 min. Also the IMF B_z was ~ −7 nT on average and turned northward but soon returned southward again within ~10 min. The IMF $_{By}$ rapidly switched its direction twice within ~10 min, the first switch resulting in an increase in magnitude. These simultaneous, short-lasting, changes impacted the magnetosphere at ~0248 UT and did not trigger a substorm but resulted in only the compression effect due to the pressure enhancement as seen in both the particle flux data in Figure 9 and the WIC aurora data in Figure 10.

[41] Note that the dynamic pressure enhancement for S1 was also short-lasting as for N3 and N4 but triggered a substorm. However, also note that the accompanied IMF B_z was more negative for S1. Furthermore, the differences in the H increases between S1, N3, and N4 are far less significant (except for large increases on the nightside for S1 due to the substorm wedge current) than are the differences in the pressure enhancements in the ACE observations. These imply that three pressure increases that actually impacted the magnetosphere were of similar magnitude, but only the one that was under the most strongly southward IMF condition, namely S1, triggered a substorm. This suggests that the southward IMF condition is indeed critical in determining triggering by a pressure enhancement. Consistent with this, the GOES observations in Figure 9 indicate that the geosynchronous magnetic field for N3 and N4 was not as stretched prior to the solar wind impact as for S1, which implies that growth phase conditions were stronger for S1.

[42] Event N5, which occurred at ~0302 UT in the Weimer mapping, may be a slow reverse shock, but the solar wind bulk speed did not change much. For this event, the dynamic pressure decreased substantially and the IMF $|B_y|$ increased simultaneously. Only a minor change is seen in the IMF B_z. These changes arrived at the magnetosphere at ~0305 UT. No evidence of substorm triggering by these changes is seen. However, the pressure effects are clear in

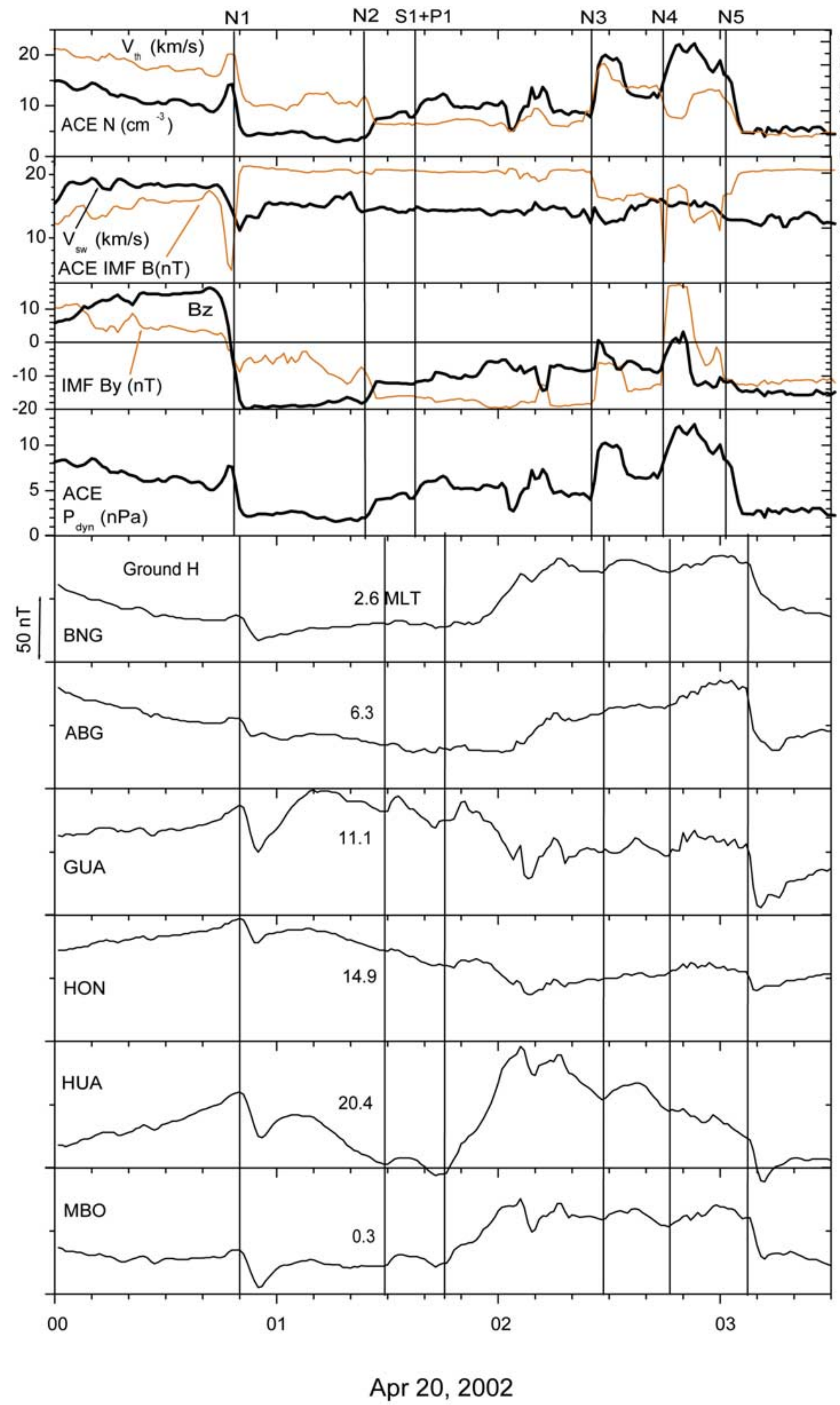

Figure 8. Data for the 20 April 2002 event in the same format as in Figure 4.

the particle flux data, the H data, and the WIC aurora data: Note that the particle flux and H decreased and the auroral brightness weakened as the dynamic pressure decreased. Both pressure decrease and IMF $|B_y|$ increase are changes opposite to those of triggers in section 2, so it is reasonable to regard these opposite changes as inherent nontriggers.

[43] The major nontriggering events presented in this section are summarized in Table 1. As for the events in

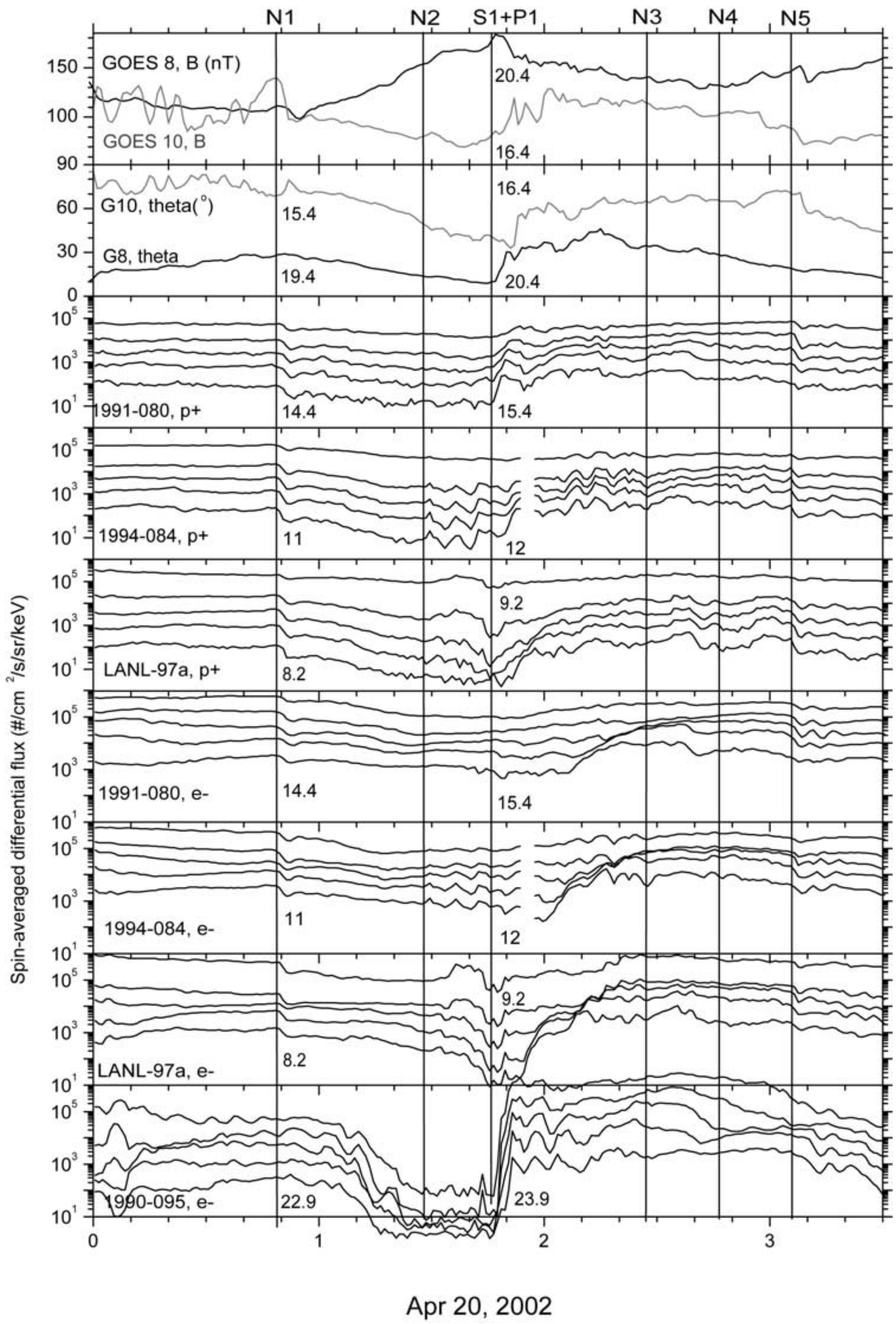

Figure 9. The geosynchronous data for the 20 April 2002 event in the similar format as in Figure 2.

the previous sections, we again have examples (N1, N3, N4, and N5) indicating that (simultaneous) changes opposite to those of (or not satisfying the conditions of) the known triggers in section 2 did not trigger a substorm. These are considered as inherently nontriggers. In particular, we have two examples (N3 and N4) indicating that the lack of sufficient duration and/or strength of the southward IMF, or equivalently weaker growth phase development, seems to be the most likely reason for nontriggering by a short-lasting pressure increase. Also the nullification effect was seen for N2.

4. Conclusions and Discussion

[44] We have identified 12 major events where interplanetary changes did not trigger a substorm. All the interplanetary events are characterized by simultaneous changes of two or three of the solar wind and IMF variables. We have

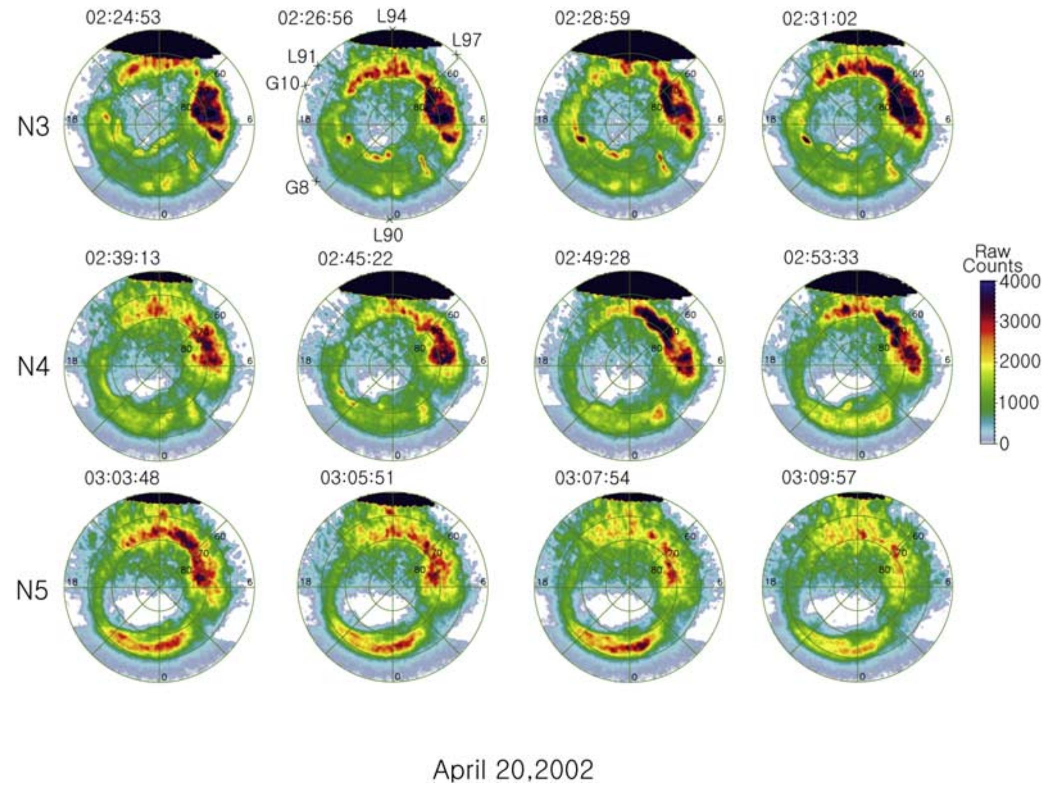

Figure 10. Auroral FUV images from the WIC instrument on board the IMAGE spacecraft for the events on 20 April 2002. In each plot, the noon is to the top, the dusk is to the left, etc.

suggested that nontriggering in our studied events can be explained by one or more of the following three reasons. First, interplanetary events having simultaneous changes of two or three of the following types do not trigger a substorm: (1) southward turning of the IMF B_z, (2) increase of the IMF $|B_y|$, (3) dynamic pressure decrease, (4) dynamic pressure increase under not strongly southward (i.e., northward or weakly southward) IMF conditions. Note that these changes are either opposite to or do not satisfy the conditions of those of the conventional triggers. We refer to them as inherently nontriggers. Second, no substorm triggering is expected when there is not sufficient energy input into the tail for well-defined growth phase development prior to the interplanetary change. Third, the nullification effect leading to no substorm can take place between opposite changes of two or three solar wind variables (such as a northward turning and a simultaneous dynamic pressure decrease or a dynamic pressure increase and a simultaneous southward turning).

[45] Regarding the nullification effect, it is worthwhile to point out the following. For some events (e.g., S1 of 18 April 2001) where there were opposite changes of two variables, the nullification effect did not take place and a substorm was triggered. For those cases, the triggering change in one of the IMF components was larger than the nontriggering change in the other component so that the nullifying effect could probably not be achieved. These examples imply that the nullification effect can takes place when the opposing changes by a solar wind variable(s) are sufficiently large to cancel out the potential triggering effect by the changes in other variable of the solar wind.

[46] Also we have compared three events of relatively short-lasting pressure increases which were of similar magnitude (S1 + P1, N3, N4 of 20 April 2002), but only the one that was under the most strongly southward IMF condition, namely S1, triggered a substorm. This comparison seems to suggest that the southward IMF condition is a critical factor in determining triggering by a pressure enhancement.

[47] The events studied here are characterized by simultaneous changes of two or more solar wind variables. We stress that our study is not biased by this selection since it is in fact quite common that two or more variables in the solar wind change simultaneously. Furthermore, it is important to appreciate the interplay effects between simultaneous changes. Consideration of the interplay effects accounts for why some IMF northward turnings and dynamic pressure increases do not trigger a substorm, and we have presented several events showing the nullification effect.

[48] The present work is a first report toward identifying main nontriggering solar wind changes, a topic which has not been substantially studied in the past. While there can be other types or situations of solar wind variations as nontriggers, we suggest that those found in this study are the main types of nontriggers or nontriggering situations. It would certainly be desirable in the future to test the statistical significance of these types of nontriggers based on a larger number of events than considered here.

[49] Also, the events studied here correspond to storm times. This selection was made because pressure enhancements are far less likely to trigger a substorm during nonstorm times than during storm times because of the strongly southward IMF during storm times. However, the IMF B_z northward turning is a common trigger during both storm and nonstorm times. Therefore storm times provide more variety of combinations of solar wind variations to consider which could lead to triggering or nontriggering. It will, however, still be useful to extend the present work to include more events from both storm times and nonstorm times to check the generality of our results.

[50] One promising suggestion that is related to the present work is that by *Lyons et al.* [2005a] that both triggering and nontriggering by solar wind variations can be understood based on the idea of convection reduction within the inner plasma sheet [*Lyons et al.*, 1997]. They used the plasma sheet continuity equation to suggest that only solar wind changes that can lead to a convection reduction trigger a substorm. Therefore the simultaneous changes of two or more solar wind variables that leave the inner plasma sheet convection unchanged or increased will not trigger a substorm. While we do not preclude other possibilities, the types of nontriggers presented in our paper are consistent with this idea. However, to validate this idea firmly, a further test in a more quantitative way than in the present work is desired. For example, in a future study it would be worthwhile to examine the convection change by solar wind variations of the types studied in this paper using more direct convection-monitoring data such as radar measurements of ionospheric convection or spacecraft measurements in the plasma sheet. Such a study would allow one to more quantitatively and firmly determine whether or not the convection change caused by the types of solar wind variables studied in the present work is consistent with triggering and nontriggering of substorms.

[51] The statistical significance of the external triggering is an important question. At least two aspects need to be appreciated for a reliable answer to the question: Understanding both the conventional triggers and the nontriggers, including the important interplay effect, and determining precisely the solar wind structure that actually impinges on the magnetosphere. The main goal of the present paper has been to report various nontriggering events to help with the first aspect. Regarding the second aspect, the impact of solar wind variations that include a dynamic pressure change can be verified by looking at low-latitude to midlatitude H responses. For pure IMF changes, however, one has to generally rely almost entirely on the solar wind data itself, though observations of dayside convection within the ionosphere have proved to be useful. Also, use of more than one interplanetary spacecraft and the Weimer mappings can often help.

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