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High-altitude polar cap electric field responses to southward turnings of the interplanetary magnetic field

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Abstract. Interplanetary electric field coupling with the magnetosphere has been analyzed predominantly using data from the Wind magnetometer and the Polar electric field instrument. The coupling was investigated using the Polar Electric Field Instrument (EFI) to measure the electric field in the northern polar cap immediately following sharp southward turnings of the IMF as observed by Wind. Southward turnings were chosen which exhibited a sudden change of the IMF north-south component from $B_Z > 0$ to $B_Z < 0$ (GSM coordinates) after an hour or more of relatively stable conditions, and for which Polar was in the northern polar cap. These B_Z changes correspond to E_Y changes in the interplanetary electric field. For each of the 30 identified events, a time was estimated for the arrival of the IMF change at the magnetopause using the solar wind speed observed by the Wind Solar Wind Experiment (SWE), and Polar electric field data were examined to identify responses. For many of the selected events (about one third), abrupt changes of state in the magnetospheric electric field were evident with timing that matched the expected solar wind arrival time at Earth. For events for which additional data were available, we conducted in-depth examination of the individual events using IMP 8, Geotail, and GOES 9. In one such event, GOES 9 data showed a substorm growth phase and onset which also corresponded to features in the solar wind observed by Wind, Geotail, and IMP 8. In addition to the individual event studies, a superposed epoch analysis of all available events revealed a consistent rise in the mean polar cap electric field about 15 min following sharp IMF southward turnings.

1. Introduction

It is widely accepted that magnetospheric coupling with the solar wind proceeds via dayside reconnection at the magnetopause; however, the precise details of this coupling are not completely understood [e.g., *McPherron*, 1991]. One consequence of dayside reconnection is that the interplanetary electric field (IEF), given by $\mathbf{E} = -\mathbf{v} \times \mathbf{B}$ for solar wind velocity $\mathbf{v}$ and interplanetary magnetic field (IMF) $\mathbf{B}$, couples the solar wind and magnetosphere. Assuming field lines are equipotentials, the IEF imposed across open magnetospheric field lines should then be felt all the way down to the ionospheric base of the field lines. The efficiency and spatial response of this coupling of the IEF, as well as the manner in which it becomes distributed throughout the magnetosphere, are not known. In this study, we investigate the timing and manner in which the IEF is imposed on the polar cap. The research has involved surveying instances of sudden changes in the IEF and looking for signatures of responses in the polar cap as seen by an in situ electric field instrument to determine the timescale and efficiency of electric field coupling with the magnetosphere.

Prior work by *Lei et al.* [1981] investigated the relationship between the interplanetary electric field E_Y and the low-latitude magnetospheric convection electric field E_M. They calculated the IEF E_Y by assuming $E_Y = v_X B_Z$, where v_X is the solar wind speed directed earthward from the Sun and B_Z is the north-south component of the IMF. They also computed the magnetospheric convection field E_M from plasmapause positions detected by GEOS 1 and ISEE 1. The authors found a transfer coefficient $\Delta E_M / \Delta E_Y = 0.13$.

Much work has focused on the relationship between the IMF and the polar cap potential drop. *Reiff et al.*

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[1981] measured the polar cap potential drop using data from 32 passes over the polar cap by high-inclination, low-altitude satellites (AE-C, AE-D, S3-3) and found it to be well-correlated with the IMF. They found that the potential drop was well predicted by traditional merging theory, with the exception of a background 35 kV potential drop which appeared to be independent of solar wind parameters. They suggested that this background drop was likely due to some sort of viscous interaction at the magnetopause.

Wygant et al. [1983] also conducted a study correlating polar cap potential drops with the IMF using polar cap data from the S3-3 satellite. They found that polar cap potential values after several hours of northward IMF had declined from values which existed after only 1 hour of northward IMF. This observation led to the conclusion that the background potential drop (i.e., the portion not related to reconnection) could be limited to less than 20 kV. Further, they investigated correlations with solar wind dynamic pressure and concluded that the potential drop driven by dynamic pressure was limited to less than 1 kV. Additionally, S3-2 data were analyzed by *Doyle and Burke* [1983], who found an average of about 40 kV of polar cap potential to be residual or caused by processes other than reconnection. They could not confirm Wygant et al.'s result of the potential decreasing to a smaller residual of only 20 kV due to the lack of long-duration northward IMF in their database. They compared their data set to those of *Reiff et al.* [1981] and *Wygant et al.* [1983] and concluded that their results were largely consistent with each other as well as supportive of a model of energy transfer based on magnetic merging.

Reiff and Luhmann [1986] used polar cap potential data to derive two empirical formulae for the dependence of the asymptotic polar cap potential on IMF. They also found that after northward IMF lasting 3 hours or more, the residual polar cap potential was only about $6-13$ kV. More recent work by *Boyle and Reiff* [1997] used $\sim$ 58000 DMSP polar passes to derive empirical formulae for polar cap potential with IMF data or, in its absence, K_P data as input.

It should be noted that the work described above concerns steady state potentials in the polar cap and does not describe the polar region responses to IMF changes. *Lockwood and Cowley* [1992] showed that steady state convection patterns represent averages over timescales larger than a substorm timescale (1-2 hours) and are the exception rather than the rule for polar cap convection. They argued that polar cap responses to changing interplanetary conditions and resulting substorms are an integral part of the overall convection patterns, rather than a mere perturbation of a steady state. Some recent work has addressed the question of polar cap dynamics in nonsteady IMF. For example, *Cumnock et al.* [1992] investigated the polar cap response to a B_Y rotation in a particular event in 1988 and *Hairston and Heelis* [1995] analyzed a single 3-day period during which there were five IMF B_Z southward turnings. Hairston and Heelis used DMSP data to obtain polar cap convection patterns and determined that the response time of the polar ionosphere to the IMF reversals was $\sim$ 17 to 25 min. This lag was interpreted as an inertial response time of the ionosphere to IMF changes.

Work by *Ridley et al.* [1997] focused on the ionospheric response to southward IMF turnings for six events. Ridley *et al.* used the Assimilative Mapping of Ionospheric Electrodynamics (AMIE) technique to investigate polar cap convection patterns in response to IMF B_Z reversals. They determined that the ionospheric convection changes grew linearly with time and were linearly proportional to the change observed in the IMF B_Y or B_Z components. Further work by *Ridley et al.* [1998] used the same technique to investigate 65 events for a statistical study. They found that reconfiguration of the polar convection patterns started about 8.4 ± 8.2 min after the solar wind change reached the magnetopause and continued to reconfigure for about 13 min until it reached a steady state.

In this study, instead of looking at polar cap ionospheric convection patterns or cross-polar cap potentials, we examine the polar cap electric field at altitudes of 5-9 R_E before and after sharp IEF changes to investigate the efficiency of information coupling from the solar wind onto polar cap field lines. In particular, we look at events during which the IMF B_Z component changed from northward to southward (corresponding to IEF E_Y changing from negative to positive) after at least an hour of steady, northward IMF conditions. Whenever satellite positions permit, we examine both the IEF and local polar cap E_Y. Additionally, we conduct a superposed epoch analysis of the electric field measured by Polar in the spacecraft spin plane for all polar cap events.

2. Instrumentation

Several spacecraft, both inside and outside the magnetosphere, were used in this study. Three spacecraft used were at times in the solar wind: Wind, IMP 8, and Geotail. Wind provided magnetic field and solar wind data which were used to identify events. Geotail was also often in the solar wind and was used to confirm the signatures seen at Wind and to better determine the expected time for the discontinuities to reach Earth. IMP 8 was also used for these purposes, though data were not available for all events. Inside the magnetosphere were GOES 9 and Polar. GOES 9 is in a geosynchronous orbit and was used for magnetic field measurements, both to identify substorm timings and to obtain information about the inner magnetosphere dynamics and response.

The Polar spacecraft is in a highly elliptical orbit which reaches apogee at around 9 R_E over the north pole and perigee at 1.8 R_E over the south pole. The EFI instrument on Polar was used to obtain electric field data in the northern polar cap. The three-dimensional field measurements were taken by three pairs of booms: two wire boom pairs in the spin plane of the spacecraft and one rigid stacer pair on the spin axis. The sensors on the spin-plane booms are about 130 m apart, while the spin-axis sensors are only 13.8 m apart. This difference is because those in the spin plane can be held away from the spacecraft centrifugally, while the on-axis booms must be rigid and are therefore shorter [*Harvey et al.,* 1995]. Because the on-axis booms are closer to the spacecraft, they are more sensitive to the spacecraft potential and the plasma environment around the satellite. To avoid contamination difficulties with the shorter booms, only the spin-plane measurements are used in this study.

Clearly, to study the direct coupling of the IEF after a sudden change in the geocentric solar magnetospheric (GSM) Y component, the ideal data from the polar cap would include the GSM Y component of the magnetospheric electric field. Without using the spin-axis booms, obtaining a reliable third component of the electric field requires use of the local magnetic field measurements coupled with the assumption that there is no electric field parallel to the ambient magnetic field ($\mathbf{E} \cdot \mathbf{B} = 0$). This method is valid only when the magnetic field is greater than about 30° out of the spin plane of the spacecraft, ensuring that the spin axis magnetic field is substantial. Due to Polar's cartwheel orbit, typically having the spacecraft equatorial plane near the magnetic meridional plane, the magnetic field is seldom more than 30° out of the spin plane. For this study, one event was identified for which a third component of $\mathbf{E}$, and therefore geophysical coordinates for $\mathbf{E}$, could be obtained. For all other events, only the spacecraft spin-plane components were used. These coordinates are defined such that E_{X-Y} is a measure of the electric field in the spin plane of the spacecraft when the spin-plane booms are closest to the X-Y GSE plane, and E_Z is the spin-plane measurement when the booms are nearly perpendicular with the X-Y GSE plane. The spin-axis boom data are not used in this study.

3. Observations and Data Analysis

3.1. Event Selection

Sudden changes in the IMF B_Z from northward to southward (corresponding to IEF E_Y changes from negative to positive) which followed an hour or more of relatively stable IMF/IEF conditions were examined. These event identifications were made using data from June 1996 through April 1997 from the Wind MFI magnetometer. Selections were further narrowed by requiring that Polar be in the northern polar cap. The northern cap is preferable to the southern cap because Polar apogee is over the northern cap, so it spends a much longer time in the northern than the southern polar region, making it easier to separate temporal from spatial effects. Polar locations are shown in Figure 1. The

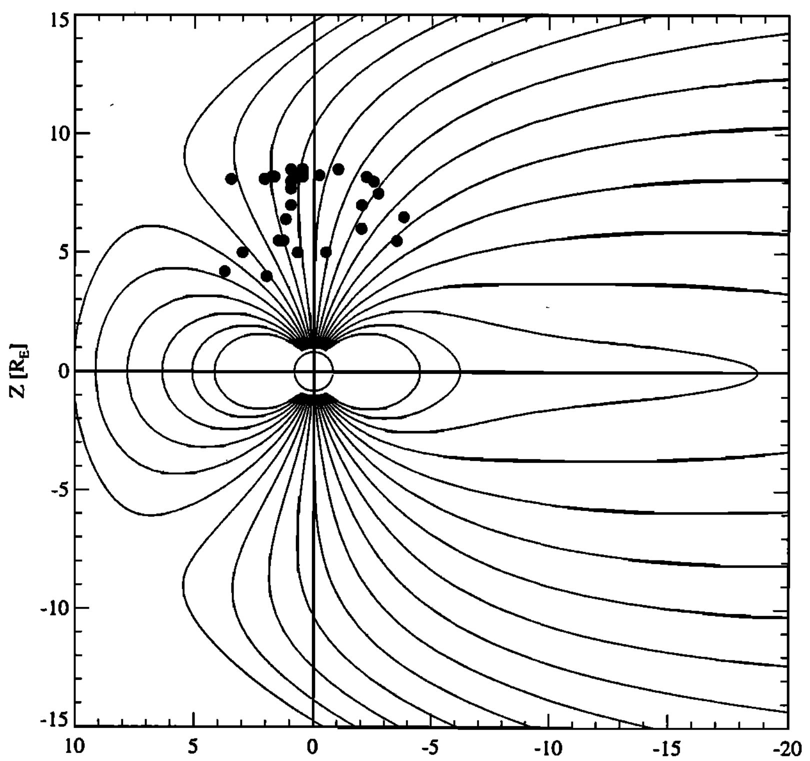

Figure 1. Map of the X-Z GSE plane showing the position of Polar for all events.

Table 1. Events Studied

Event	Date	Time,[a] UT	Location of Polar
1[b]	May 21, 1996	1840	cusp
2	June 05, 1996	1954	polar cap
3	June 10, 1996	1336	polar cap
4	June 17, 1996	0712	polar cap
5	June 24, 1996	1721	polar cap
6[b]	June 29, 1996	1313	cusp
7	July 06, 1996	0737	polar cap
8	July 11, 1996	1146	polar cap
9	Aug. 25, 1996	1721	polar cap
10	Aug. 31, 1996	1952	polar cap
11[b]	Oct. 18, 1996	0833	polar cap
12	Oct. 30, 1996	1357	polar cap
13	Oct. 31, 1996	0644	polar cap
14	Nov. 06, 1996	1504	polar cap
15	Nov. 14, 1996	0828	polar cap
16	Nov. 24, 1996	2059	polar cap
17[b]	Nov. 26, 1996	2230	polar cap
18	Jan. 26, 1997	1503	polar cap
19	Jan. 27, 1997	1605	polar cap
20	Jan. 28, 1997	0235	polar cap
21	Feb. 06, 1997	0213	polar cap
22	Feb. 09, 1997	1653	polar cap
23	Feb. 22, 1997	0930	polar cap
24	Feb. 24, 1997	0703	polar cap
25	Feb. 24, 1997	1005	polar cap
26	Feb. 26, 1997	1325	polar cap
27	Feb. 27, 1997	0921	polar cap
28	Feb. 28, 1997	0346	polar cap
29	March 24, 1997	0908	polar cap
30	April 01, 1997	1256	polar cap

[a]Time solar wind change reaches magnetopause.
[b]Not used in superposed epoch study.

model magnetic field shown is from the *Tsyganenko* [1989] model. The events chosen for this study are shown in Table 1.

3.2. June 17, 1996, Event

For the June 17, 1996, event, three of the spacecraft were upstream in the solar wind, thus enabling the calculation of the orientation of the observed solar wind discontinuity. Using the positions of the spacecraft, the time each observed the discontinuity, and the solar wind speed as measured by Wind and verified by Geotail, this orientation was calculated, as shown in Figure 2. Once the orientation was known, a model magnetopause [*Petrinec and Russell,* 1995] was used to calculate the expected time of arrival for the sudden IEF E_Y change. The arrival time of the discontinuity at the magnetopause was estimated to be 0712 UT.

The Polar spacecraft was located in the polar cap, almost at apogee (see Figure 2), at the predicted arrival time of the discontinuity at Earth. At 0732 UT, Polar's spacecraft potential (Figure 3f) abruptly increased, indicating a large density enhancement. The Polar position in cartesian GSM coordinates is shown in the lower portion of the figure. At the same time, the E field (Figures 3d and 3e) underwent a sudden state change. Note that a reliable E_Y in GSM coordinates was unavailable for this event, so the electric field in spin-plane coordinates was used. The measured E field was observed to change from a widely varying and rapidly fluctuating character to relatively smooth, steady values in addition to a sudden change in the mean of the field. Also, the Polar Toroidal Imaging Mass-Angle Spectrograph (TIMAS) showed sudden particle enhancements coincident with the E field response (W. K. Peterson, private communication, 1997). The particles detected

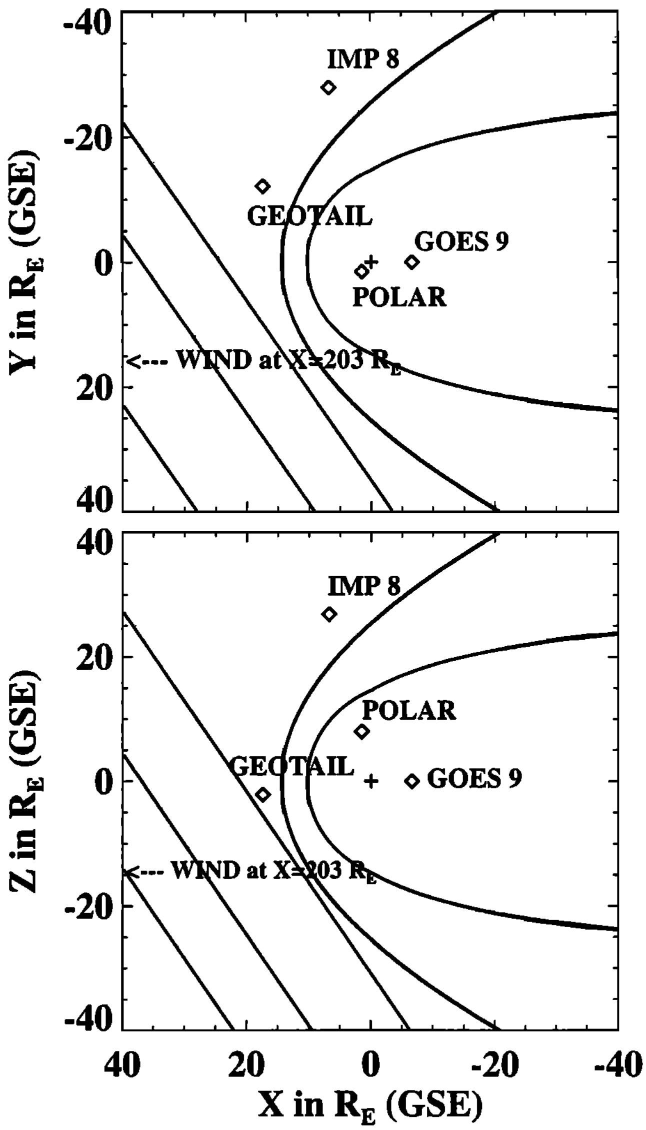

Figure 2. June 17, 1996: Map of the X-Y (equatorial) and X-Z (meridional) GSE plane with spacecraft positions. Positions shown for spacecraft outside the magnetosphere correspond to the time they saw the solar wind discontinuity. For spacecraft inside the magnetosphere, the position represents the time the earliest magnetospheric response was observed by that spacecraft. Slanted lines show the orientation of the solar wind discontinuity front.

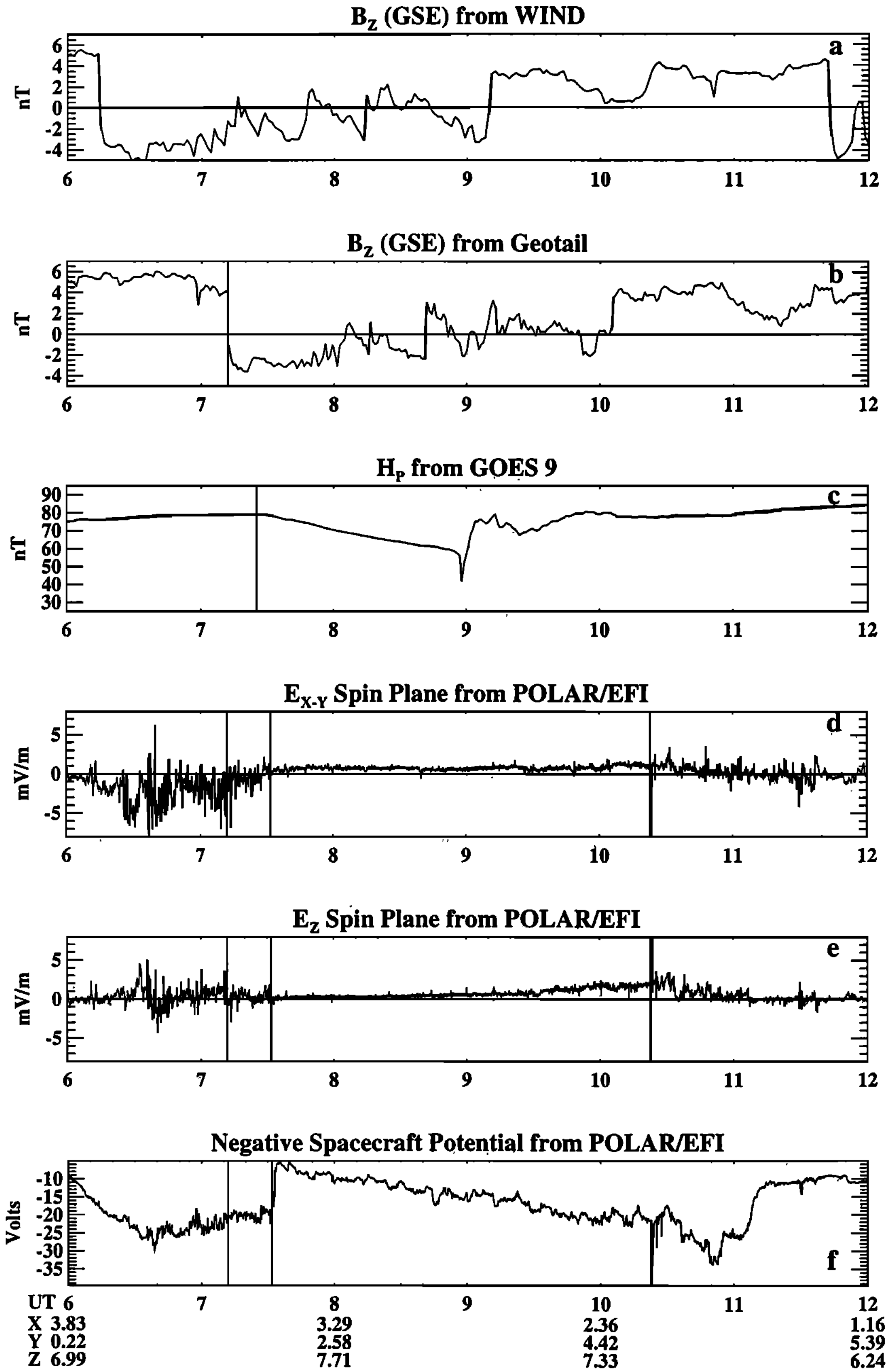

Figure 3. Solar wind discontinuity seen by Wind and Geotail, and the responses seen in the polar electric field and spacecraft potential as well as in the GOES 9 magnetometer for June 17, 1996.

by TIMAS had a composition suggestive of solar wind origin.

At 0725 UT, GOES 9, which was located near local midnight in geosynchronous orbit, observed Hp (Figure 3c), the magnetic field component parallel to the Earth's spin axis, to start decreasing. This decrease indicated field line stretching in the tail, and was the start of the substorm growth phase [e.g., *Baker et al.*, 1996; *Singer and Wolf*, 1992]. Note that the growth phase began just before Polar detected a density enhancement and E field change. The growth phase continued for about an hour and a half, and then substorm onset occurred at 0856 UT, as indicated by the dipolarization of the magnetic field observed by GOES 9. Further, the E field state change seen by Polar reversed after 2 hours and 51 min, which was the same duration that the interplanetary B_Z was predominantly southward.

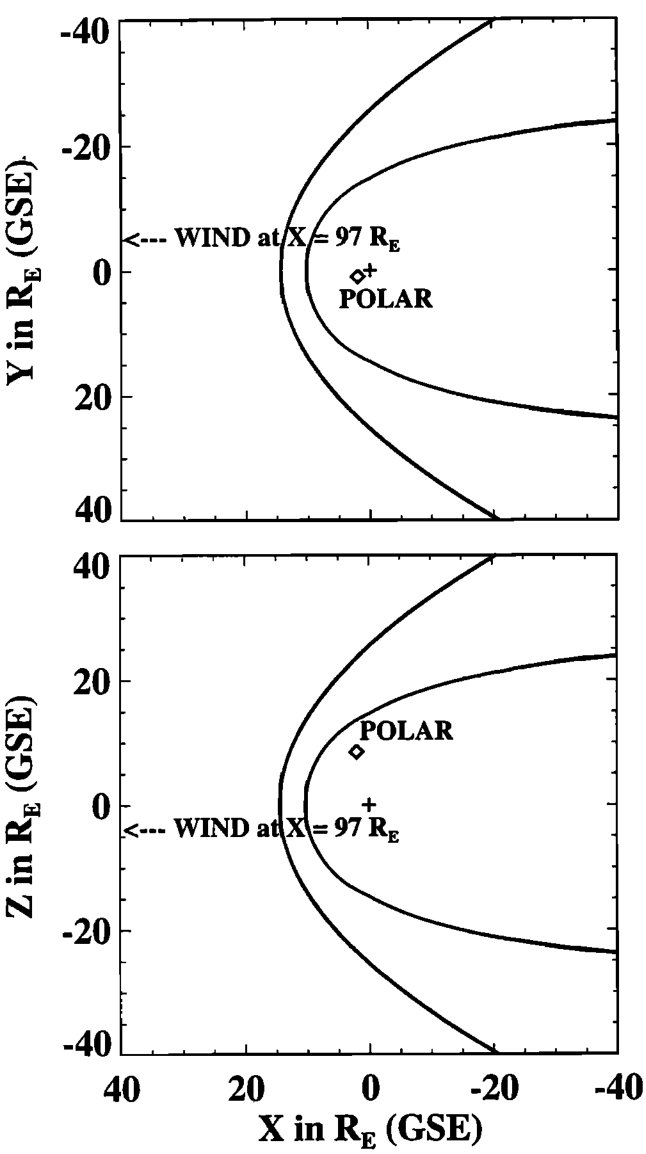

Figure 4. Equatorial and meridional plane maps for August 31, 1996.

3.3. August 31, 1996, Event

While substantial information may be obtained from the spin-plane electric field measurements, a small change in one E field component of interest may be obscured by larger changes, or simply larger fields, in another component. For this reason, it is very useful to examine the field in geophysical coordinates whenever possible. For the event on August 31, 1996, the magnetospheric magnetic field was more than 30° out of the spin plane of the Polar spacecraft, thus allowing the calculation of the full, three-dimensional field in GSM coordinates. For this event, the general spacecraft positions are shown in Figure 4. Figure 5 presents the Wind and Polar data, along with GSM positions for Polar during the event interval. (Note that the data plotted from Wind are shown at the times at which they were observed by Wind and have not been propagated to the magnetopause in this figure.) The southward IMF turning observed by Wind (Figure 5a) was calculated to arrive at the magnetopause at 1952 UT. About 14 min after this arrival, E_Y as measured by Polar in the polar cap was seen to increase suddenly by about 2 mV/m, as shown in Figure 5c. At about the same time, the spacecraft potential decreased toward zero and, in general, the field fluctuation level diminished.

3.4. Cusp Events

Cases of the sort described above occurred when Polar was apparently rather far from the dayside magnetopause and cusp. Two events, however, were studied in detail in which Polar was nearing the cusp region.

3.4.1. May 21, 1996. On May 21, 1996, Wind and Geotail data were available for solar wind measurements. Using these data, the arrival time of the solar wind southward turning at the magnetopause was estimated to be 1840 UT. Polar was on the dayside of the magnetosphere, moving toward apogee in the polar cap (see Figure 6). The apparently related changes in the E field and the spacecraft potential were seen at 1855 UT (see Figure 7). This event produced a response in the electric field seen at Polar which was in some ways the converse of that in the June 17, 1996, event. In the May 21 case, the electric field at Polar was seen to change from a smoother, steadier field to a noisier, more widely varying field. As observed in the June 17, 1996, case, the disturbance in the electric field lasted about as long as the IMF B_Z was southward (in this case, around 40 min). This is consistent with the idea that the magnetospheric disturbance was caused by the solar wind change, since the IMF also reversed after 40 min. The spacecraft potential changed as well at about 1855 UT, but the change was much less dramatic than on June 17. The main effect was that the spacecraft potential became noisier after the time of the IEF arrival.

3.4.2. June 29, 1996. On June 29, 1996, solar wind data were again available from Wind and Geotail. The estimated arrival time of the southward turning

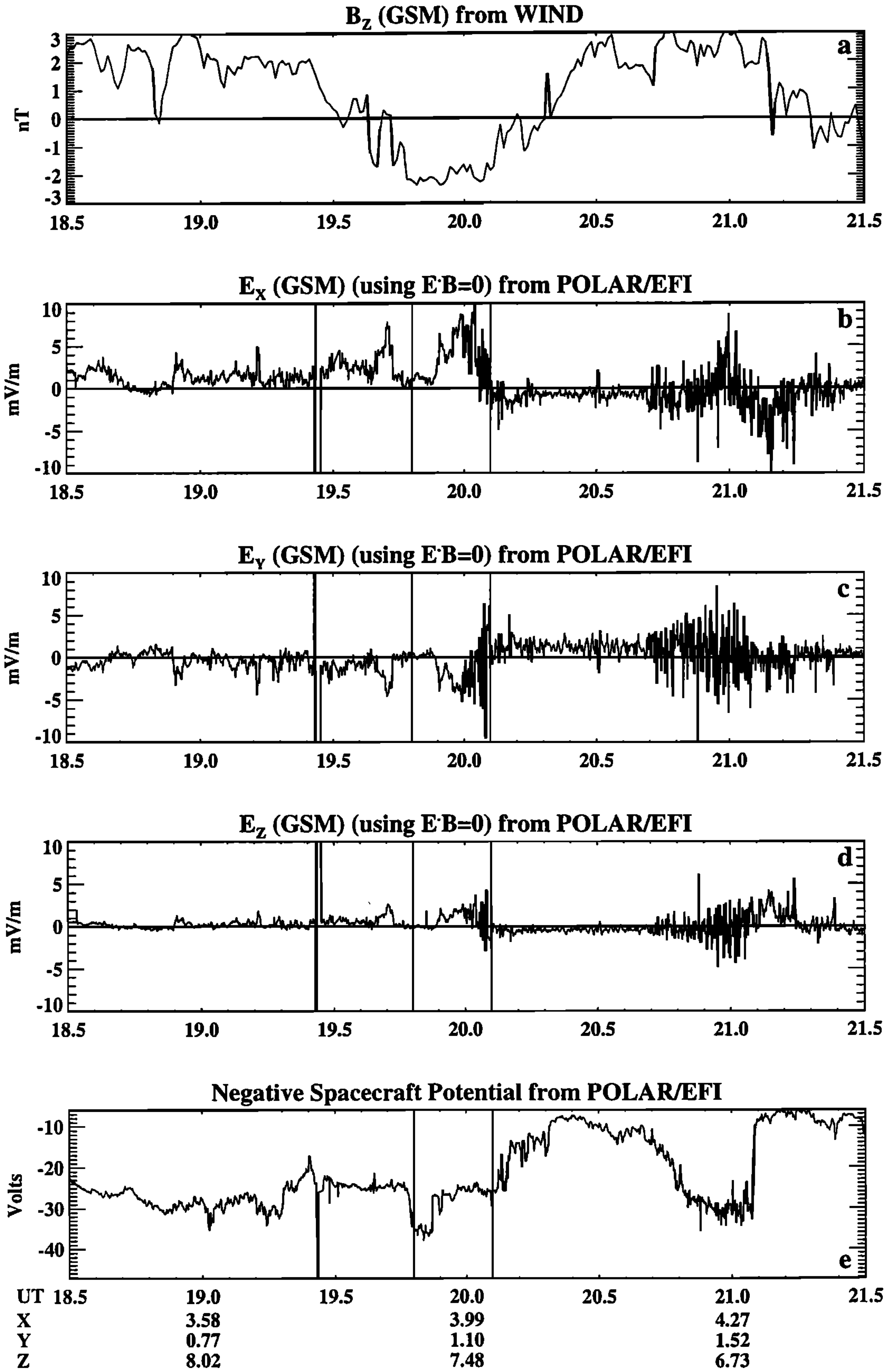

Figure 5. Solar wind measurements and responses seen by Polar for August 31, 1996, in GSM coordinates.

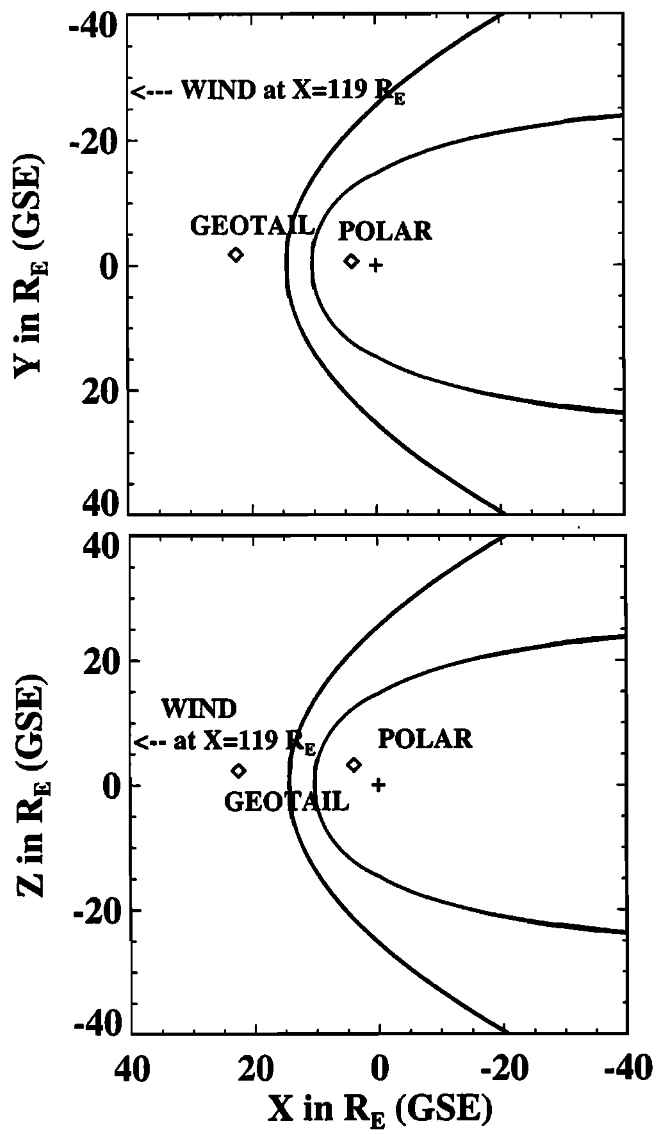

Figure 6. Spacecraft locations for May 21, 1996, event.

of the magnetic field at the magnetopause was 1313 UT. Polar was in a position very similar to the May 21, 1996 event. The spacecraft was on the dayside of the magnetosphere and moving northward, nearing the polar cusp (see Figure 8). The responses in the EFI data were also very similar to those observed on May 21 (see Figure 9). The electric field was seen to change from smooth and steady to noisy and disturbed, while the spacecraft potential became noisier at 1317 UT. The magnetospheric electric field as measured by Polar for this event reversed after about an hour and a half, while the IMF B_Z remained southward, which may indicate that the spacecraft left the cusp region.

4. Superposed Epoch Analysis

Electric field traces, as shown in Figures 3, 5, 7, and 9, are often noisy and have many abrupt changes which complicate the identification of significant features. In many cases it is difficult to determine which changes evident in the data are due to geophysical disturbances and which might be due to instrumental effects or noise. Therefore, a superposition was conducted of all events with the expectation that random changes would tend to average away, highlighting only consistent IMF-driven responses.

Polar cap electric field data were aligned according to the solar wind arrival time at the magnetopause so that time zero coincided with the arrival of the solar wind change. Additionally, because only the change in the electric field was of interest, the signal mean before the arrival of the solar wind change was subtracted from each signal, so E field measurements had a zero mean before the solar wind change. Finally, because there is no directional information in the spin-plane components alone, changes in the mean of the electric field were defined as positive (e.g., if the measured spin plane electric field decreased after the solar wind change, the entire signal for that event was multiplied by -1). The two events interpreted as entries into the polar cusp (May 21 and June 29, 1996) and two additional events with large data gaps were removed, leaving 26 events in the superposed epoch study.

As shown in Figure 10, the superposed epoch results reveal a clear change in the mean polar cap electric field. Time zero is defined as the arrival time of the solar wind change at the magnetopause, and times are plotted in hours. The data show that a change in the mean of ~ 0.5 mV/m occurred consistently by about 15 min after the solar wind changes reached the magnetosphere and after 30 min the change was nearly 1 mV/m. Since there is no directional information, it is uncertain which component underwent the largest change, but the superposition clearly demonstrates that a change in the mean occurred. Figure 10c shows all of the individual traces used in the study plotted together. From Figure 10, it is evident that the change in the EFI signals shown in the superposition was the characteristic response for most events, and thus no single event overwhelmed the superposition.

In addition to the analysis of all 26 events, events were separated according to the location of the Polar satellite. Each subset was superposed as well to look for differences in timing or response features in different regions of the polar cap. There were no evident differences between dawn and dusk locations or between nightside and dayside.

5. Discussion

In the events studied, clear responses to the solar wind changes were seen in Polar EFI data. For June 17, 1996, Polar was in the dayside polar cap region and saw clear changes in the ambient electric field: both the onset and termination coincided well with corresponding solar wind changes. The density increase inferred from the spacecraft potential was consistent with recon-

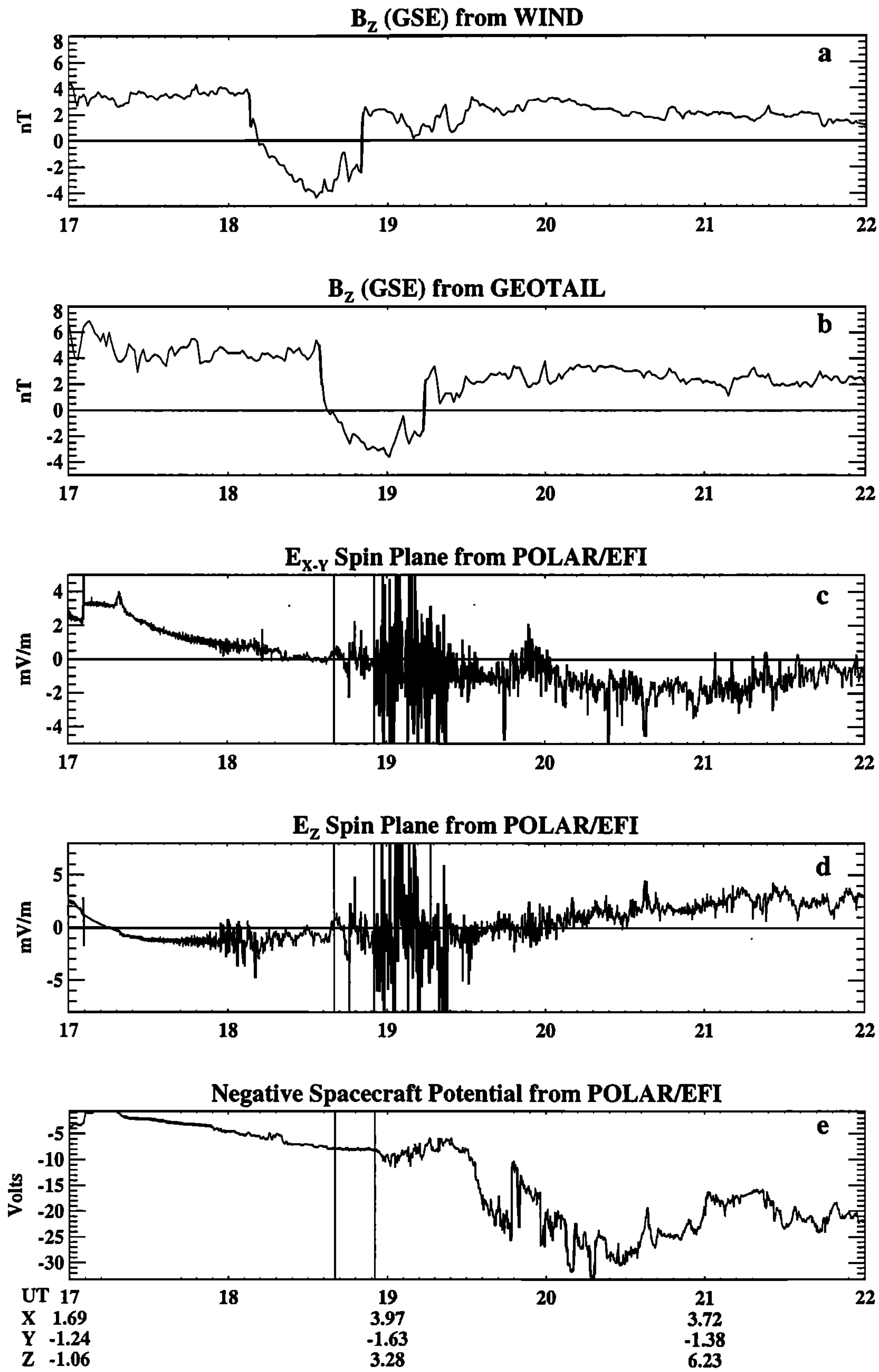

Figure 7. Solar wind measurements and responses seen by Polar for May 21, 1996, event.

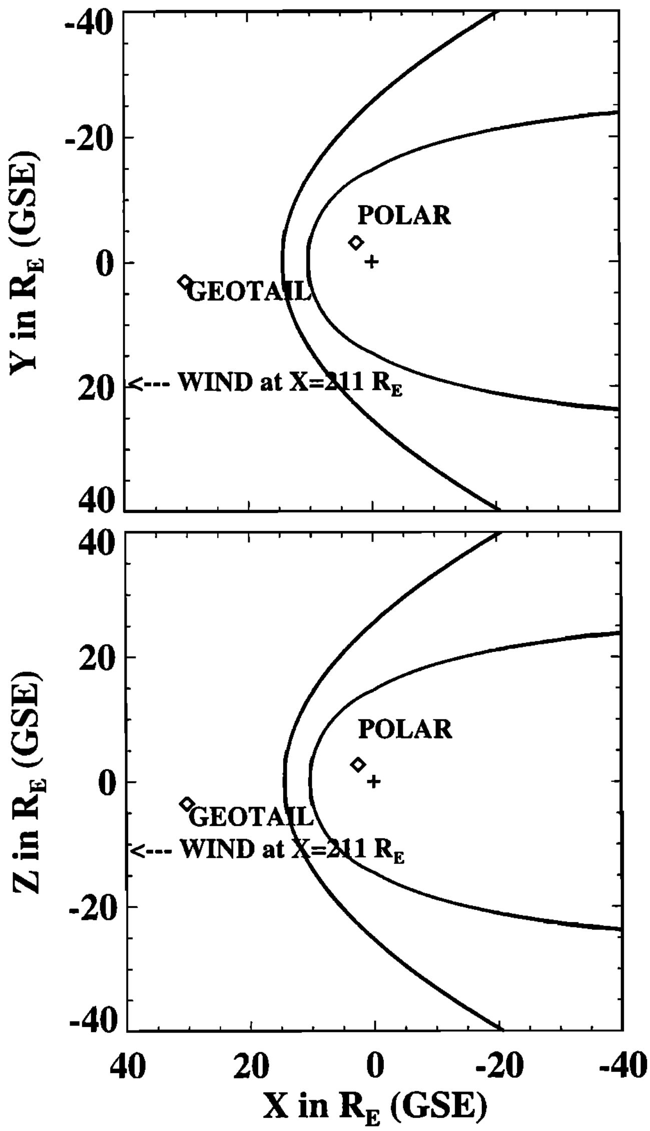

Figure 8. Spacecraft locations for June 29, 1996, event.

necting flux tubes passing over Polar during tailward convection, suggesting that the spacecraft was near the cusp and so could observe newly reconnected fieldlines. Additionally, TIMAS data showed an injection of ions with composition suggestive of solar wind origin, supporting the idea of an encounter with a reconnected flux tube (W. K. Peterson, private communication, 1997). This sudden increase in plasma density was most likely the cause of the change in the variance of the electric field signal, since the noise level in the electric field measurement normally decreases in higher-density regions. However, the change in the mean of the electric field was likely due to actual changes in the ambient field that were driven by the IMF southward turning. GOES 9 data showed clear substorm signatures in the period following the southward turning. The substorm growth phase signature at GOES 9 was observed before the response seen by Polar, suggesting that the electrodynamic coupling for the low-latitude magnetosphere was evidenced faster than the reconnecting field could convect over the polar cap. Prior work that has been done on information propagation throughout the magnetosphere [e.g., *Wilken et al.*, 1982; *Coroniti*, 1985] suggests that wave propagation from the dayside magnetopause to the nightside magnetosphere near geosynchronous orbit probably travels as a fast mode compression wave. The fact that information about the IMF change reached GOES 9 before it reached Polar suggests that the signal propagation method into the polar cap region is a slower mode of transport, perhaps at Alfven speeds. As noted above, both the E field state change observed by Polar and the solar wind IMF change observed by Wind reversed after nearly 3 hours, further supporting the view that the electric field changes at Polar were related to the solar wind variations.

Two events were studied during which Polar appeared to have entered the cusp. On May 21, 1996, changes were observed in the electric field which coincided first with IMF southward, and then with northward turnings. The field signatures indicate that Polar entered the cusp region following a southward IMF turning and then exited after the field returned northward. This suggests that as Polar was nearing the cusp region the cusp boundary may have moved southward and enveloped the spacecraft as a result of increased reconnection due to the southward IMF turning. Given its position, Polar could have simply crossed boundaries which it would have crossed anyway during stable IMF, but the timing for the initial electric field changes and subsequent return makes this seem less likely. The June 29, 1996, event is less clear, though Polar did see a sudden electric field change when the solar wind discontinuity was expected to arrive at Earth. The electric field returned to its previous state after $\sim$ 90 min with no clear solar wind-associated driver. This was likely a result of leaving the cusp region due to the natural motion of the spacecraft.

Both cusp events noted above showed the magnetosphere responding rapidly to changes in the imposed solar wind magnetic and electric fields. In each case, dayside reconnection was seen to enhance on a short timescale, and the cusp appears to engulf the Polar spacecraft. These events are similar to an event studied previously by *Pulkkinen et al.* [1997].

The superposed epoch results indicate a consistent response in the polar cap electric field data. This 26-event superpositon study showed that the mean electric field began to change, on average, $\sim$ 10 min after a southward turning reached the magnetopause. After 15 min, the change was typically around 0.5 mV/m, and it reached a maximum of $\sim$ 1 mV/m after 30 min of southward IMF.

One particularly interesting result of the present study is the fact that the time delay from the southward IMF turning at the magnetopause to the response signature measured at Polar did not, to the resolution of our data set, vary over the polar cap. This implies that

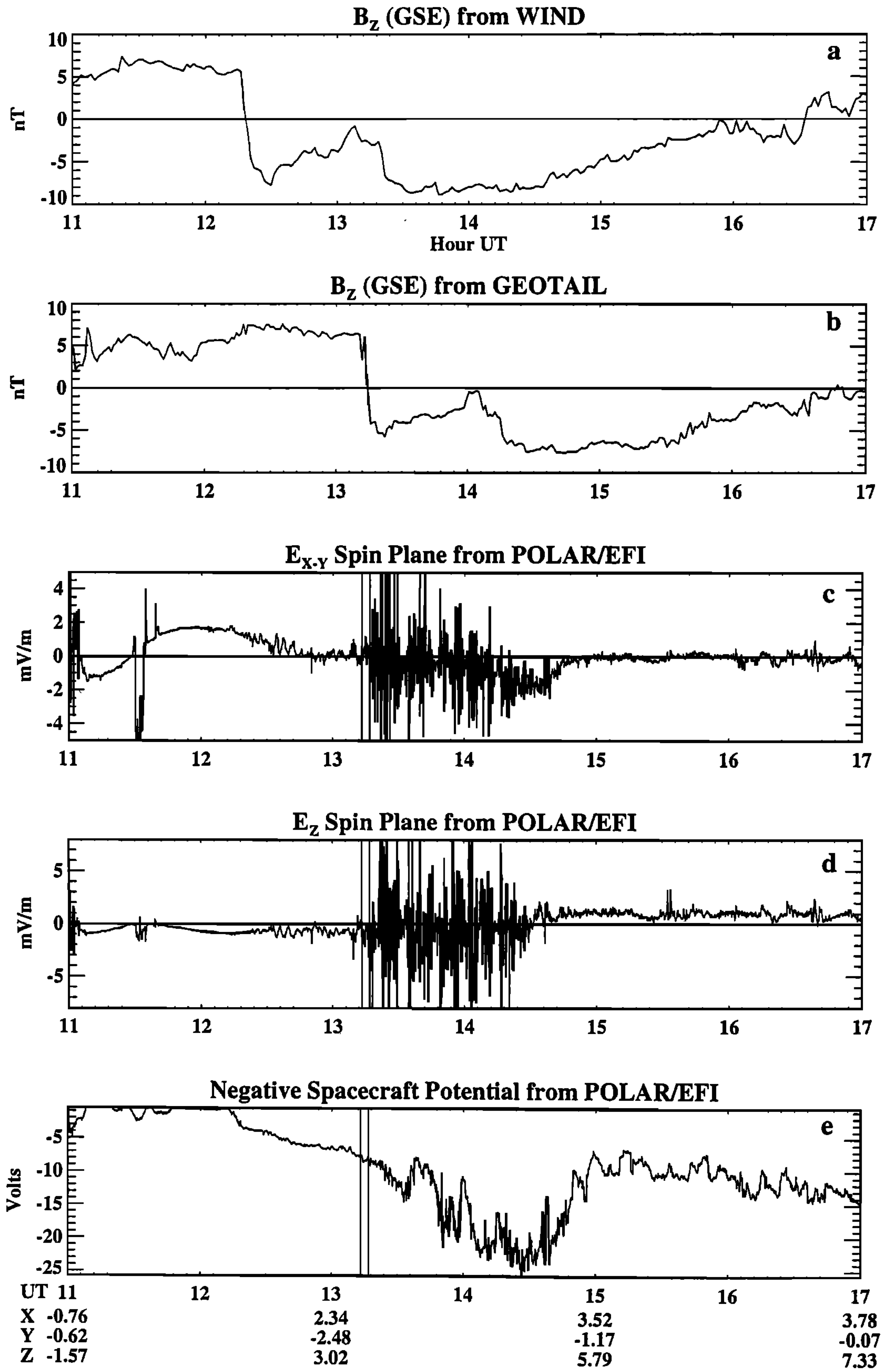

Figure 9. Solar wind measurements and responses seen by Polar for June 29, 1996 event.

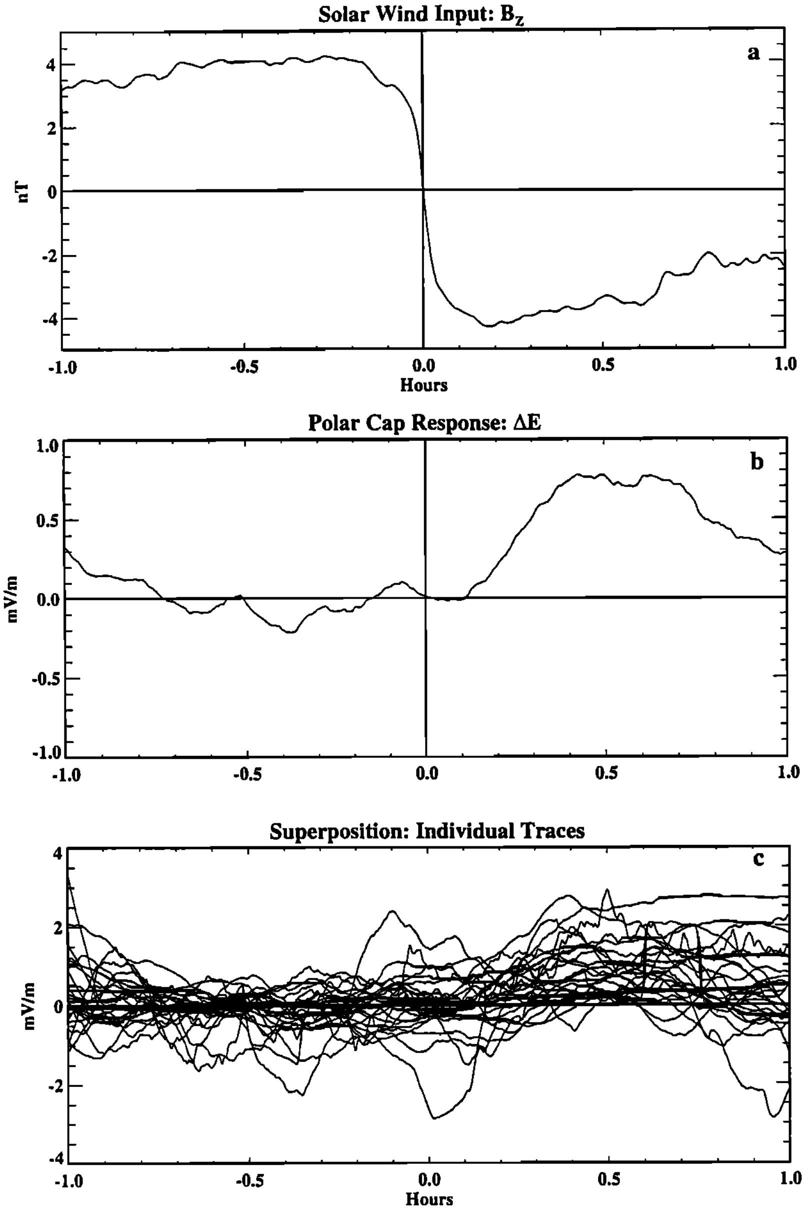

Figure 10. Superposed epoch analysis for the solar wind input and magnetospheric field response.

the potential drop is imposed relatively rapidly over the portion of the polar cap surveyed by Polar. If the electric field were being imposed along field lines directly linked to the solar wind, one would expect a long delay for reaching the nightside polar cap. This might take on the order of several hours, the time it takes a field line to traverse the cap. Since we do not observe a substantial delay, one must conclude that the potential is applied rapidly over a substantial portion of the polar cap. This result is consistent with work by *Ridley et al.* [1998], who found that the reconfiguration of the polar cap ionospheric convection patterns began in all regions of the polar cap nearly simultaneously, over a period of less than one minute. They concluded that the electric field applied across the cusp must control the entire dayside convection pattern, consistent with the description by *Lockwood et al.* [1990]. Additionally, the timescales derived in this study are slightly longer than the timescales reported by *Ridley et al.* [1998]. This seems to suggest that once the electric field is imposed via the cusp, it affects the polar ionosphere, and then the signal reaches the Polar spacecraft (at 5-9 R_E) via an Alfven wave from the ionosphere. This is consistent with the aforementioned ionospheric convection studies and would explain the lack of a substantial delay seen by Polar for signals in the nightside cap relative to signals in the dayside cap.

Thus, the present work is generally quite supportive of the picture in which the interplanetary magnetic field interconnects with the geomagnetic field to drive subsequent magnetospheric dynamics [e.g., *Baker et al.*, 1996, and references therein]. However, it would still be highly desirable to have more cases in which we can derive the absolute strength of the electric field that couples into the polar cap and tail lobes from the interplanetary medium. With such quantitative information, we would finally be able to address the longstanding question of the "efficiency" of electric field coupling between the solar wind and the magnetosphere. We are hopeful that continuing ISTP measurements will eventually provide a suitable database to extend the present study and address this key coupling question.

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