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A first comparison of POLAR magnetic field measurements and magnetohydrodynamic simulation results for field-aligned currents

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Abstract. This letter presents comparisons between POLAR magnetic field measurements and results from a global numerical simulation of the Earth's magnetosphere using WIND measurements of the solar wind parameters as input. The comparison shows that the simulation provides a good representation for the magnetic perturbation associated with an upward Region 1 field-aligned current (FAC) in the prenoon sector. This current system is caused by the interplanetary magnetic field (IMF) negative B_y component and also features downward current on open field lines at higher latitudes. The results also show effects caused by a gradual rotation of the IMF northward and a sudden return to its initial dawnward direction. The self-consistent simulation Birkeland current pattern at ionospheric altitudes is also presented, and its evolution caused by the IMF rotations is discussed.

Introduction and Method

The International Solar-Terrestrial Physics (ISTP) Program through its multiple spacecraft and ground-based data collection provides the opportunity to study the coupling processes between the solar wind and interplanetary magnetic field (IMF) and the Earth's magnetosphere. These studies are facilitated by making direct comparisons between collected data sets and the results of physical models of the magnetospheric system. In this study, we are particularly interested in making a comparison between POLAR magnetic field experiment (MFE) [*Russell et al.,* 1995] measurements and magnetohydrodynamic (MHD) simulation model results. A previous comparison of POLAR-MFE data to an empirical magnetic field model has been reported by *Zhou et al.,* [1997]; and the identification of FACs at the POLAR orbit has been made by *Russell et al.,* [1997].

For this study, we use the WIND spacecraft measured solar wind and IMF as input for a global numerical MHD simulation of the Earth's magnetosphere-ionosphere system. We then compare the simulation results to the POLAR-MFE measurements along the spacecraft orbit. The simulation results provide a good representation of the POLAR-MFE data. The simulations are used to interpret the MFE measurements in terms of the FACs which link the solar wind, the magnetosphere, and the ionosphere. We also address the evolution of the current systems caused by temporal changes of the IMF in the measured solar wind. The results provide new insight into the structure and evolution of the magnetospheric FAC system. The results demonstrate the presence of an upward evening Region 1 current sheet extending far into the morning sector; a feature caused by a negative IMF B_y which is not present in statistical models of the FAC systems. They also demonstrate the continuous smooth evolution of the evening-sense Region 1 current sheet into a morning Region 0 current as the IMF rotates northward. We discuss the implications of the results for the solar wind-magnetosphere coupling processes. Finally, we address the differences between the simulation fields and the MFE measurements and account for possible causes.

The numerical MHD simulation model has been described by *Fedder and Lyon* [1987, 1995], and *Fedder et al.* [1995a,b]. It models the solar wind and magnetosphere using an ideal MHD formalism. External boundary conditions are the super-magnetosonic solar wind, and internal boundary conditions are applied by a self-consistent ionospheric model. This study used the ionospheric model described in *Fedder et al.* [1995b] with the value of F-10.7 solar flux appropriate for May 19, 1996 which leads to a quite small ionospheric conductance, even in the summer northern hemisphere. We have also increased the angular resolution of the numerical simulation by a factor of two which quadruples the number of cells which map to the ionosphere.

The simulation was implemented using WIND measured solar wind and IMF parameters beginning at 1200 UT on May 19, 1996. The initial conditions were chosen from a previously completed simulation which had similar solar wind conditions to those observed by WIND before 1200 UT. Since a complete decomposition of the solar wind is not known, one must be assumed in order to propagate the solar wind from its measurement

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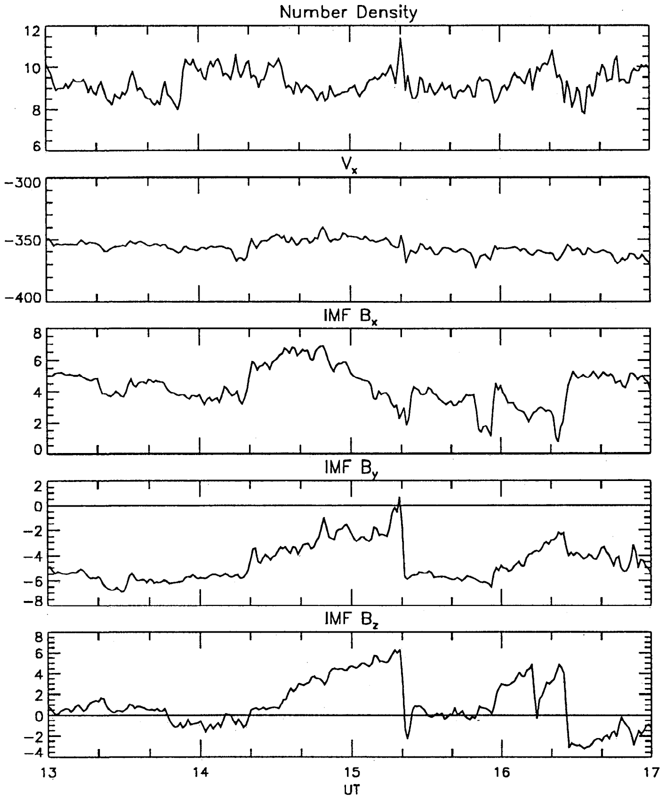

Figure 1. WIND measurements for the solar wind data for May 19, 1996 in GSM coordinates from 1300 UT to 1700 UT during the POLAR-MFE measurements. The solar wind number density and x component of velocity shown in the upper panels were nearly constant at 10 cm^{-3} and 355 km s^{-1} respectively. The lower three panels show the components of the IMF in nT. The plots are lagged by 25 minutes to allow for solar wind propagation from the WIND position to the simulation upstream boundary.

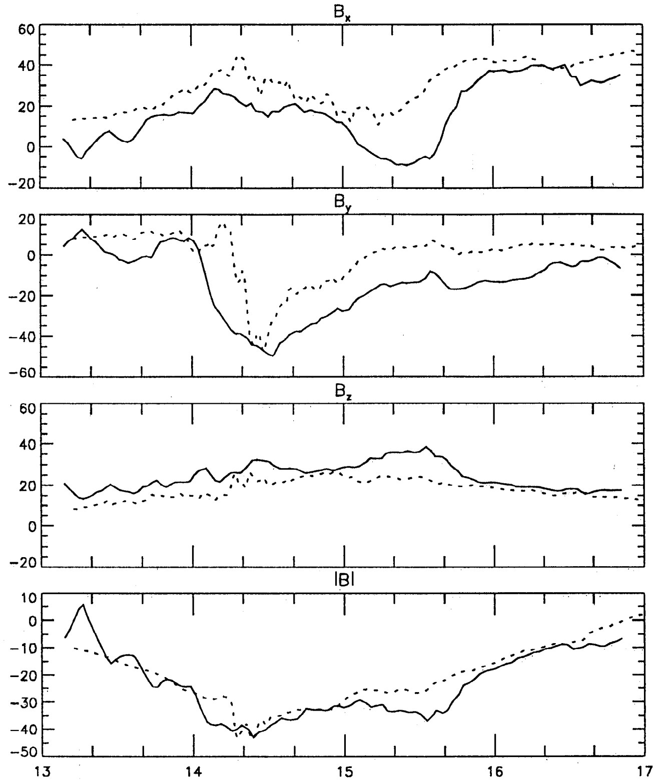

Figure 2. The comparison of the MFE magnetic measurements and the simulation magnetic field along the POLAR spacecraft trajectory. The curves shown in the top three panels are the residual between the MFE field components and the IGRF magnetic model and the residual between the simulation field components and the model dipole field as dashed and solid lines, respectively. The lower panel compares the simulation and measured residuals of the magnetic field magnitude.

point, ≈ 100 R_E upstream, to the upstream simulation boundary at $x = 25$ R_E in solar magnetospheric (SM) coordinates. For this simulation the measured solar wind and the IMF time series shown in Figure 1 were simply lagged by 25 minutes. The solar wind vector quantities were transformed into the simulation SM coordinates with only the IMF B_y and B_z SM components retained to keep from introducing a divergent magnetic field into the simulation mesh. It is satisfying that the simple method chosen worked so well.

Results

The primary result of this study is shown in Figure 2. It shows the residual between the POLAR-MFE measured field and the Internal Geomagnetic Reference Field (IGRF) and the residual between the simulation field and the simulation dipole along the spacecraft orbit as dashed and solid lines,respectively. The IGRF and the dipole are the base magnetic field models without any external disturbing currents for the Earth and the simulation, respectively. The agreement between the curves is remarkable. The field magnitude residuals in the lower panel clearly show the field depression associated with the cusp just after 1400 UT. The curves for all of the components also follow each other faithfully with the differences between the residuals generally being about 10 nT. In the cases of the B_x and B_z components, this residual is small compared to the >100 nT magnitude of the field components themselves. In contrast, the B_y component field is larger than the model field and indicates the passage of the POLAR orbit through the FAC system. The field deflections indicate passage through a narrow upward current followed by an adjacent broader downward current. The narrow upward current is broader than the measured current sheet owing to the limited numerical resolution (it is resolved in 3 cells). More important physically is the matching magnitude of the field deflections indicating that the sheet current magnitude in the simulation and in the measurement are the same.

In order to aid the discussion of the results, Figure 3 shows snapshots of the simulation FAC in the north polar ionosphere during the pass. The series of snapshots show the evolution of the currents caused by the changing IMF beginning before POLAR entered the FAC region and ending after POLAR leaves. The first three snapshots show a relatively steady current system appropriate for IMF B_y negative. The second three show

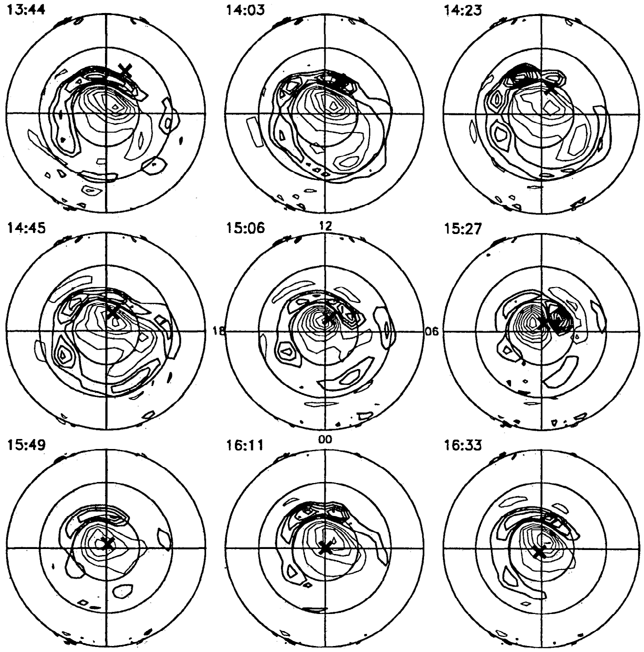

Figure 3. Plots of the simulation ionospheric field-aligned current density at geomagnetic latitudes from 60° to the pole at ≈ 20 minute intervals during the POLAR measurements. The contour intervals are 0.2 μamp m^{-2} and the black and gray contours show upward and downward current, respectively. The approximate field line projection of POLAR is shown by the × in each image.

the gradual evolution of the currents as the IMF steadily rotates to strongly northward; and the last three show the recovery of the currents for dawnward IMF after it snaps back to its initial direction as seen at ≈ 1520 UT in Figure 1. The POLAR trajectory enters the FAC system from lower latitudes at 1030 magnetic local time (MLT) and passes almost directly over the geomagnetic pole. Its footprint is indicated by the × in each contour plot. The POLAR orbit goes from (2.0, 0.8, 4.5) at 1400 UT to (0.3, 0.1, 7.5) R$_E$ at 1600 UT in SM coordinates.

Discussion

The broad agreement shown between the simulation magnetic field and the measured magnetic field shown in Figure 2 and the morphology and evolution shown in the simulation FACs seen in Figure 3 have important implications for solar wind-magnetosphere coupling. Because of the high degree of agreement between the simulation and the measurement, we can use the simulation to guide our interpretation of the POLAR-MFE measurements. It is important that the reader recognize that the magnetosphere was in a very ordinary state during the measurements. The solar wind density and velocity are nominal and the IMF had a predominantly negative y component of about 5 nT. Moreover, the magnetospheric cross-polar potential is between 50 and 100 kV except when the IMF turns strongly northward leading to a smaller value.

The FAC patterns, in Figure 3, responsible for the good agreement seen in Figure 2 are different from the average statistical patterns of NBZ, Region 1, and Region 2 currents [*Iijima*, 1984; *Iijima and Potemra*, 1978; *Iijima and Potemra*, 1976; and *Erlandson et al.*, 1988]. The evening upward Region 1 current sheet is seen to extend well into the morning sector in Figure 3, much farther than reported by *Erlandson et al.* The morning downward Region 1 sheet is seen only nightward of the 0600 MLT meridian. The dayside downward current is well poleward of the Region 1 sheet. We would emphasize again, this is a very normal state for the solar wind-magnetosphere coupling and the simulation FAC systems. Situated between the dayside morning currents in Figure 3 is the well known Svalgard-Mansurov ionospheric Hall current channel and the so-called convection throat. Prenoon, the convection is primarily a zonal flow, sunward and duskward. The channel is the ionospheric signature of the dayside merging process and the FAC patterns seen in Figure 3.

In the top row of current plots, the ionospheric footprint of the merging region lies at about 80° geomagnetic latitude (GML) and 0900 MLT between the end of the Region 1 upward sheet and the downward current at higher latitudes. The dayside open-closed field topological boundary is imbedded in the poleward region of the upward current sheet at about 80° GML. We note that POLAR electron data show magnetosheath energy (60-80 eV) and density (20-32 cm^{-3}) typical of the cusp at ≈ 1415 – 1430 UT (private communication *J. Scudder*, 1997). The dayside morning downward current lies on open field lines. As the IMF rotates northward in the second row of plots, the morning upward current sheet evolves poleward and nightward until by 1528 UT the merging gap is situated on the 0600 MLT meridian at about 87° GML. Evidently, the evening Region 1 current sheet extended across noon into the morning sector and evolved continuously and smoothly into an upward morning NBZ current in direct response to changes in the magnetic merging geometry as the IMF rotates strongly northward. The 1528 UT current plot also shows the creation of a new downward morning Region 1 current sheet which has its origin in a reconnection driven low-latitude boundary layer [*Song and Russell*, 1992; *Fedder and Lyon*, 1995]. This evolution, which is in agreement with the POLAR-MFE measurements, does not easily fit into the accepted classification scheme of Region 1, Region 0, NBZ, and cusp/cleft/mantle currents as distinct systems. The simulations show that the difference between dayside Region 1, Region 0, NBZ, and cusp/cleft/mantle current systems is the merging geometry. The dynamo (source) for the currents is the bow shock; the load is the dayside Pedersen conductance. The major physical difference in the current systems is the magnetic geometry created by the merging process.

A clear difference between the simulation results and the MFE measurements is the latitudinal width of the upward FAC. The sheet thickness is under-resolved but represents the best achievable with our current computer resources. In the region where the POLAR orbit crosses the FAC sheets, the numerical mesh is approximately cartesian, and the extension of the upward sheet well into morning is not a numerical artifact. Throughout the morning sector the FAC sheet and the numerical mesh are misaligned; as a result the sheet-like character and its longitudinal extension are most robust.

At least two other factors can cause errors in the simulation results: the time lag between WIND and the upstream simulation boundary, and the transformation of the IMF vector to the upstream boundary of the simulation mesh. The sudden rotation in the IMF from strong northward to dawnward seen in Figure 1 at 1520 UT provides a marker for the time lag. Its effect on the magnetosphere is seen simultaneously by POLAR-MFE and in the simulation results as the field deflections which begin at 1530 UT. The imposed 25 minute time delay between the WIND measurements and the upstream simulation boundary is accurate. The apparent offset between the B_x and B_z residuals in the simulation result and the MFE measurement which is seen in Figure 2 can be the result of the simple transformation of the measured IMF to the simulation upstream boundary. This offset can be caused by a too-positive IMF B_z component. To test this, a different decomposition of the WIND magnetic field data was used for input to the simulation. For this case, only the IMF component perpendicular to the solar wind velocity vector was transformed to the upstream simulation boundary. The results from the new upstream conditions reduced the offsets between the measurement and the simulation; however, it was unable to completely correct the large excursions in the simulation results between 1510 and 1550 UT. The new results also degraded the comparison between the B_y residuals. Owing to the possibility of real spatial gradients in the IMF, it is difficult to draw stronger conclusions concerning possible simulation errors with this data set. Additional studies will be undertaken in the immediate future using solar wind data measured immediately upstream of the bow shock.

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