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Geomagnetic disturbances at high latitudes during very low solar wind density event

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Abstract. In this letter, we report geomagnetic observations over Greenland and Antarctica during May 11, 1999, when the solar wind almost disappeared. Greenland magnetometers show no magnetic activity in the nominal auroral zone but disturbances reached ~200 nT at higher latitudes; however, conjugate observations in Antarctica show much weaker activity ~40 nT. Analyzed data provide evidence that the cusp current system could be extended far to the dusk (dawn) in the northern (southern) polar region. This is consistent with the Ørsted satellite observations, where field-aligned currents were detected near cusp, over the northern geomagnetic pole, and in the nightside polar cap; however, almost no were detected over the southern polar cap. We conclude that the low-density solar wind quieted activity at auroral latitudes ("loading-unloading" processes); but the "directly-driven" convection observed over both polar caps was mainly unaffected by the significant inflation of the magnetosphere.

1. Introduction

During May 11, 1999, the NASA ACE spacecraft at 224 R_E upstream observed (not shown) that the solar wind plasma (SW) density dropped below 0.5 cm^{-3}, while the SW velocity was ~375 km/s and the interplanetary magnetic field (IMF) was weakly northward and away from the Sun. One can expect from pressure balance that the magnetosphere would be inflated under these conditions; this was confirmed by INTERBALL, which observed the magnetopause at 17.5 R_E near 1115 UT [*E. M. Dubinin*, private communication, 2000].

Though the bowshock is typically separated from the magnetopause by ~2 R_E in average, IMP 8 observed the bowshock at 43 R_E around 1115 UT, and then near 1730 UT WIND and Lunar Prospector observed the bowshock at 56 and 63 R_E, respectively. However, the latter occurred at the time of the lowest SW ram pressure recorded; this made the solar wind sub-alfvenic (e.g., V_A = 310 km/s for IMF B_T = 6.3 nT and n = 0.2 cm^{-3}) after ~1730 UT, when the bowshock determination could be incorrect or even impossible.

The ballistic propagation of the solar wind between ACE and the expected magnetopause at ~16 R_E would require 59 min for average SW velocity, though slowing-down the propagation of SW through the significantly extended magnetosheath may add another 5–6 min to this number. For example, GEOTAIL was aligned with the Earth but outside of the magnetosphere on the dusk side (GSM 0, 30, 0 R_E) at 1200 UT. For that time the simple ballistic propagation of IMF discontinuities between two spacecraft gives exactly 65 min.

Clauer and Friis-Christensen [1988] found that the cusp's ionospheric convection responds typically within ~3–6 min of an IMF discontinuity entering the subsolar magnetopause. These numbers are consistent with the expected Alfven wave travel time from the magnetopause to the ionosphere, though *Clauer and Banks* [1986] reported ~13-min as an upper limit for that delay. However, we might expect that directly-driven phenomena at high latitudes may manifest after a delay even larger than ~13 min because the field-aligned currents (FAC, i.e., Alfven waves) might require more time to propagate in the significantly inflated magnetosphere.

The Greenland West Coast magnetometer chain (http://www.dmi.dk/projects/chain/) crosses the magnetic local time (MLT) noon at ~1430 UT, and these magnetometers provide excellent data to study the interaction processes occurring at the subsolar magnetopause as they manifest themselves over the daytime polar ionosphere. Here we analyze these data in conjunction with geomagnetic observations in Antarctica and on-board the low-orbiting (650–865 km) Ørsted satellite.

2. Data and discussion

As Greenland remained at magnetic daytime (0830–2030 UT) on May 11, the IMF B_x and B_y components (measured by ACE) were stable and aligned along Parker's spiral (–4.5 and +4.5 nT, respectively). B_z was weakly northward (+1 nT) but varied with short southward excursions (–1 nT) at 0930 UT and 1425 UT; the latter excursion was accompanied by a weak SW shock recorded right after 1400 UT. The IMF again became northward after 2010 UT reaching +3 nT. The orientation of B_y during this day was consistent with the formation of a pair of DPY FAC sheets over the northern polar cusp, with the downward current at lower latitudes and the upward current at the poleward cusp boundary. Therefore, one can expect that the combined effect of both the IMF B_y and B_z components on the location of the FAC sheets should produce an observable response in the ionospheric DPY and DPZ cusp current systems as B_z experienced southward excursions.

Figure 1 shows stack-plotted H-component magnetograms from the Greenland West Coast stations (left panel), as well as the data filtered with a cutoff period of 60-min (right panel). (Geomagnetic variations over Antarctica plotted at the bottom of the figure are discussed below.) The magnetograms show almost no magnetic activity in the nominal auroral zone, though at higher latitudes disturbances reached ~200 nT. After 1200 UT the three northernmost stations show increases in H indicating the existence of a very high-latitude eastward cusp electrojet as the chain approaches local magnetic noon. Note that stations below 80° CGM latitude show negative variations indicating probably a combined effect of the dayside Sq current system extended into the polar region and the closure currents from the cusp electrojet.

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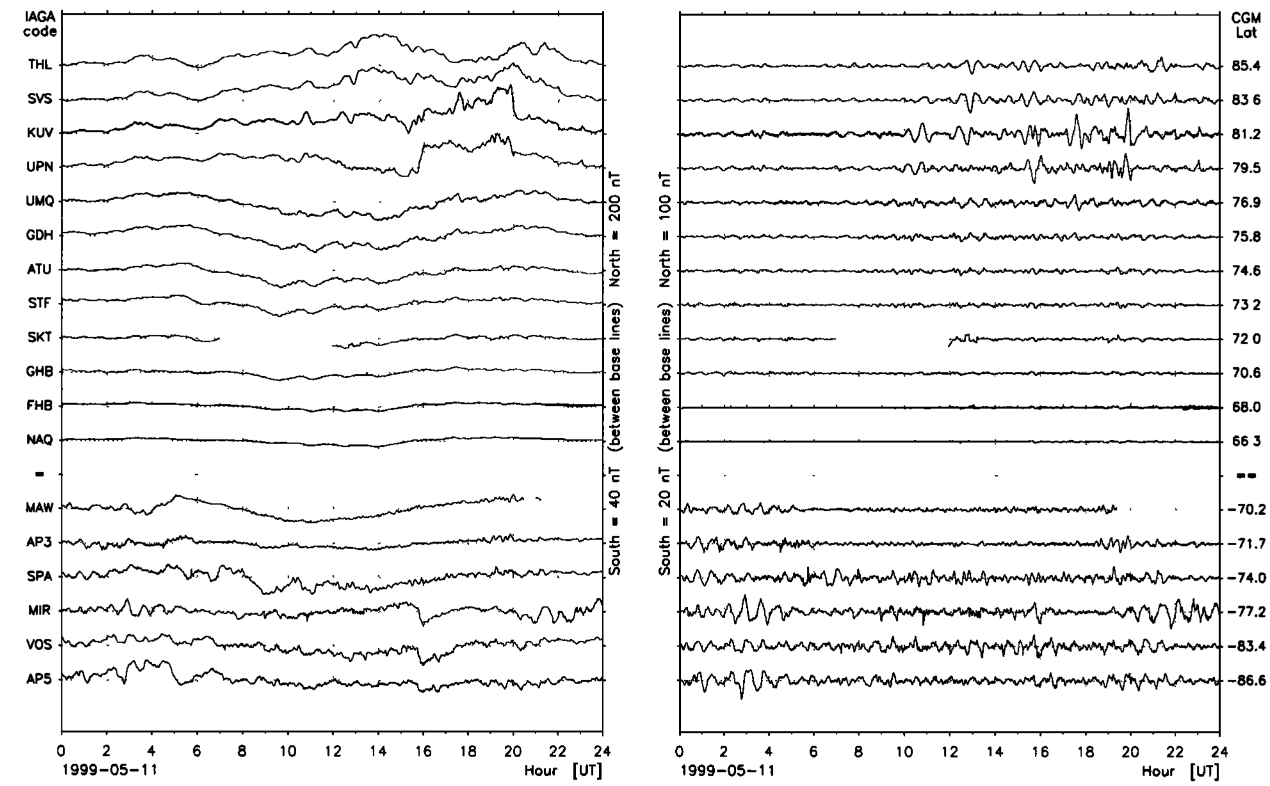

Figure 1. The original (left) and high-pass filtered (right) geomagnetic variations in H-component at the Greenland West Coast (top) and some Antarctic (bottom) stations. Note different scales used to plot Greenlandic and Antarctic data.

As shown in the right panel, the quasi-periodic, short-lived geomagnetic field oscillations with periods ~20–30 min are mainly confined to the latitudes above 75° and over the afternoon sector, maximizing at UPN and KUV where the two most pronounced bursts occurred near 1540 UT and 2000 UT. These bursts are associated with the weak SW shock and the corresponding southward excursion of B_z recorded by ACE at ~1425 UT as it propagated to the magnetosphere. A gradual time shift is seen going from the lower to higher latitudes (e.g., follow the characteristic dip near 1300 UT); this indicates poleward phase propagation of observed oscillations, typical for the closed magnetic field lines.

The bottom portion of Figure 1 shows conjugate magnetic perturbations over Antarctica, which are in very good agreement with Greenlandic observations. The geomagnetic activity was weak at auroral stations South Pole (SPA, –74.0°, MLT noon at 1535 UT), AGO P3 (AP3, –71.8°, 1401 UT), Mawson (MAW, –70.2°, 1040 UT), and Davis (DVS, –74.5°, 1000 UT). However, at higher latitude stations Mirny (MIR, –77.2°, 0835 UT), Casey (CSY, –80.8°, 0630 UT), Dumont d'Urville (DRV, –80.6°, 0055 UT), Scott Base (SBA, –80.0°, 1855 UT), Vostok (VOS –83.4°, 1300 UT), and AGO P5 (AP5, –86.7°, 1450 UT) variations reached 30–50 nT. For example, one can see that Antarctic stations also show ~20-min pulsations in the local magnetic afternoon sector; early UT hours are filled with even longer period ~40-min pulsations. Though the periods observed in both polar caps are beyond the typical Pc5 range, the analysis shows that the most intense, short-lived oscillations in H are approximately in phase at VOS and SVS (KUV) from 1200 to 2200 UT, though similar oscillations in D-component lack coherency. We speculate that at daytime the magnetic field lines at the equatorward edge of the cusp could be closed and then the pulsations with observed ~20–30 min periods could be the fundamental mode pulsations of the inflated magnetosphere.

Taking into account the 75-min estimate of the delay time, we believe that the brief southward excursion of the ACE's B_z at 1425 UT caused the cusp current to move sharply southward at 1540 UT; this is seen in Greenlandic magnetograms as an increase (~180 nT) in H at UPN and KUV, located at ~1330 MLT. The latter variation remained positive at these two stations until 2000 UT, indicating the existence of the eastward electrojet (controlled by $B_y > 0$) through the entire afternoon sector. The decrease in H at these stations at ~2000 UT was likely caused by the decrease in B_y, accompanied by the increasing B_z and the significant drop in the SW velocity at ~1845 UT, when the quasi-viscous interaction of SW with the magnetosphere almost ceased to exist. Similar enhancement in the X-component (~100 nT) at 1540 UT and the decrease around 2000 UT is also seen at all of the northernmost stations of the IMAGE network (not shown) from Bear Island (71.3°) to Ny Ålesund (76.1°). During that time, IMAGE was at 1830 MLT, still sensing the eastward electrojet extended much farther duskward and to the lower geomagnetic latitudes; the electrojet intensity decreased at 2000 UT when the chain was almost near magnetic midnight.

The Canadian and Alaskan magnetic observatories located over the morning MLT sector show clearly that the eastward current developed at 1540 UT over Kaktovik (Alaska, 71.1°, 0320 MLT) and Resolute Bay (Canada, 83.5°, 0830 MLT). At the same time, Yellowknife (69.6°, 0710 MLT) and Iqaluit (72.7°, 1130 MLT) sensed a westward-directed current; Kaktovik actually shows a "sign-changing bay" where the eastward electrojet is embedded in a broader westward current.

Figure 2 shows dynamics of "east-west" equivalent ionospheric currents reconstructed from the magnetometer obser-

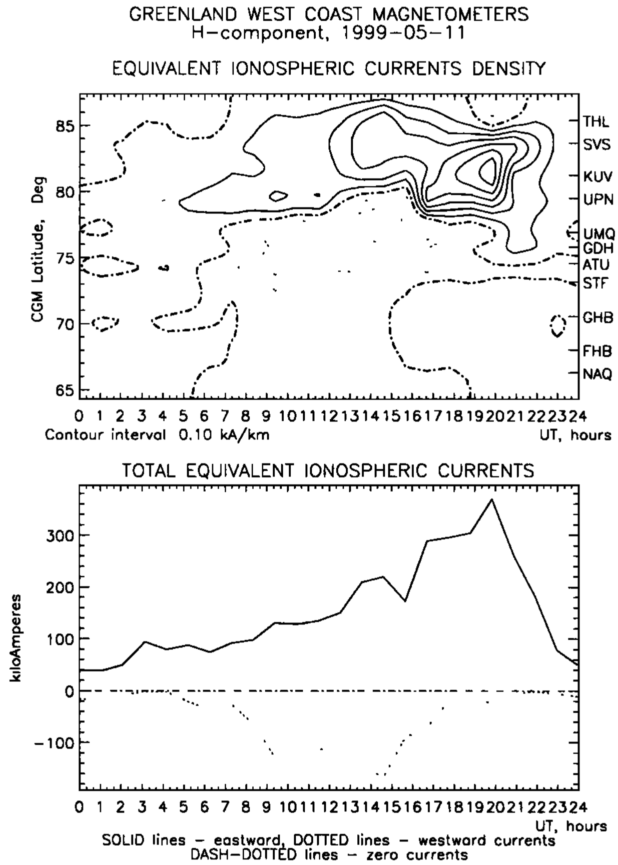

Figure 2. Equivalent ionospheric currents reconstructed from the Greenland West Coast magnetometer data.

vations at the Greenland West Coast stations during May 11. The current densities are obtained from applying the Biot-Savart law and solving the inverse problem by fitting magnetic disturbances in the H and Z components between THL and NAQ to the field of 100 narrow current strips at 115-km altitude (http://www.dmi.dk/projects/chain/). As seen, eastward currents (caused by the standard ionospheric convection system for $|B_y| >> |B_z|$ in the northern hemisphere) are confined to very high latitudes showing clear evidence of the current enhancement near magnetic noon (1430 UT) at ~83°. Then, after ~1540 UT, this eastward current sharply moves equatorward over KUV and UPN, being seen over entire Northern Greenland (not shown) and extending over the entire dusk sector from magnetic noon to pre-midnight.

Analysis of Antarctic magnetograms shows that only AP5, VOS, and MIR sensed a decrease of ~20 nT in their H components (opposite to an increase in H at UPN and KUV) exactly at 1540 UT. At that time, AP5 and VOS were near 1300 MLT and 1440 MLT, respectively. Being magnetically conjugate to the northernmost Greenland stations, AP5 and VOS detected the westward cusp electrojet, developed over Antarctica in accordance with the Svalgaard–Mansurov effect for $B_Y > 0$. Though MIR was located farther at magnetic dusk (1900 MLT), it might have sensed the DPY closure currents for $B_Y > 0$ flowing through the afternoon sector over almost ceased "quasi-viscous" ionospheric current system. However, we note that at the same time SBA was at 0920 MLT showing the IPCL-like ~6-min pulsations (on top of continuing 20–30 min oscillations) that persisted for the next few hours, while SPA (at 1200 MLT), AP3 (1340 MLT), MAW (1700 MLT), and partially DVS (1540 MLT) sensed the extended eastward "quasi-viscous" electrojet at lower latitudes. Therefore, the overall picture of the broad DPY current system is consistent for both the northern and southern polar regions, where the cusp currents are likely shifted asymmetrically to the dusk and dawn, respectively. The opposite (to the cusp) MLT sector shows the DPY eastward (westward) electrojets at higher latitudes in the northern (southern) polar cap and the westward (eastward) R1/R2-related ionospheric currents in the morning (evening) hours at lower latitudes.

The Ørsted satellite geomagnetic field observations were available only for the first part of May 11. Ørsted entered the northern (southern) polar regions (as its field-line footprint crossed ±60° CGM latitude) near magnetic noon (midnight) and exited at ~0300 MLT (1500 MLT); the orbit drifted (as the Earth rotated) over the half-day toward dusk (dawn) in the northern (southern) hemispheres. All eight available passes show FACs over the dawn and daytime sectors in the northern hemisphere; however, only two southern passes detected very weak upward currents (not shown) above −80° at 0450 UT (~1600 MLT) and at 0630 UT (~1330 MLT). Figure 3 shows one of the latest available passes over the northern polar cap where the magnetic disturbance vectors are plotted over the FAC patterns obtained from the IZMEM model [*Papitashvili et al.*, 1994] for 40-min IMF averages centered at the time when the satellite entered the polar region. (The disturbance vectors are obtained by subtracting the IGRF-

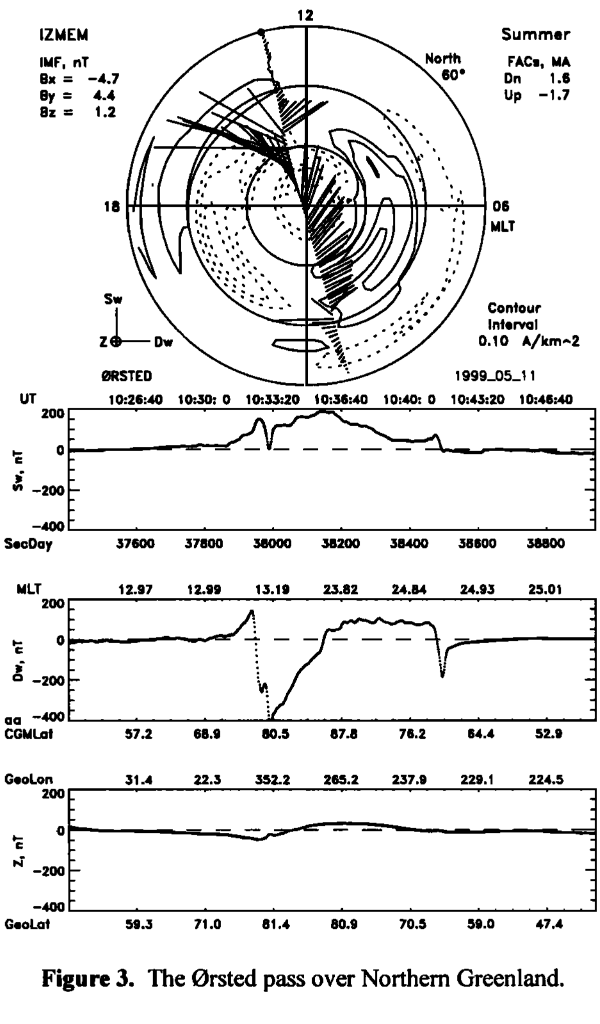

Figure 3. The Ørsted pass over Northern Greenland.

2000 model from the high-precision satellite observations.) During the pass Ørsted did not detect any significant R2/R1 FACs between 60°–70° along the ~1300 MLT meridian. Then, as the satellite entered the cusp, west-east magnetic disturbance vectors of significant magnitude (up to 400 nT) indicate the presence of a downward FAC sheet at 77°–78°, paired with upward currents at higher latitudes. This pair of FACs is consistent with ground-based observations showing the development of the eastward cusp electrojet at these latitudes from 1000 to 1200 UT. As the satellite moved poleward, a large-scale upward FAC system was detected over the pole; we interpret these observations as a strong evidence of the vast Region 0 current system. Passing then down to 80° along 0100 MLT, Ørsted detected large magnetic disturbances consistent with a transition from the upward R0 to downward R1 currents. The satellite observed another transition from the downward R1 to upward R2 currents at lower latitudes (~72°) in the post-midnight sector. This nightside portion of the pass is in good agreement with the IZMEM model. Though the model failed to clearly show the existence of the cusp currents, the model's prenoon downward (but less intense) currents can be extended over noon from the R1 system's edge at ~1130 MLT to match the satellite observations. Note that all available northern passes show similar FAC configurations with a weaker equatorward sheet of the cusp currents than its higher-latitude counterpart. This configuration is confirmed by the AMIE study [*Knipp et al.*, 2000]. Therefore, a major finding from the Ørsted observations is evidence of the strong system of upward R0 currents.

4. Conclusions

The large-scale ionospheric convection over both the northern and southern polar regions appears to be typical for the prevailing IMF orientation during this long-duration event of an unusually tenuous solar wind. Magnetometers at the Greenland West Coast showed almost no magnetic activity in the nominal auroral zone; however, disturbances at higher latitudes were large. Conjugate magnetic observations in Antarctica are in agreement with Greenlandic observations, though they were ~5 times weaker due to much lower ionospheric conductivity over the dark winter polar cap. There was significant ULF activity at cusp latitudes, mainly during postnoon hours; the pulsation periods are of the order of 20–30 min with a magnitude ~20 nT. Eastward cusp currents (from the ionospheric convection system for $|B_y| >> |B_z|$) in the northern hemisphere were confined to very high latitudes.

The Ørsted observations reveal the downward FAC system near noon at 77°–80° as the satellite orbit moved towards magnetic postnoon hours from 0300 UT to 1230 UT. Strong upward FACs were detected poleward of the cusp (R0) growing from 0400 UT to 1000 UT as the IMF B_y component was increasing. The observed R1/R2 system at dawn appears typical (at least over the northern polar cap). However, in this study we were not able to obtain clear evidence that the typical R1/R2 system existed at dusk during the event under investigation. Moreover, extension of the eastward (westward) cusp electrojet in the northern (southern) polar cap deep into the magnetic afternoon (morning) sector suggests that the entire, global R1/R2 system was significantly skewed (or rotated) toward dusk (dawn) [e.g., *Ohtani et al.*, 2000]. Though ground observations are consistent with the cusp current system extended far to the dusk/dawn sectors in the corresponding hemispheres, we were not able to obtain firm evidence that the R1/R2 ceased completely; it could be simply pushed far to the pre-midnight sector. The Ørsted observations also suggest seasonal (i.e., hemispheric) asymmetry in the high-latitude field-aligned current systems.

Thus, we conclude that the unusually low-density solar wind quieted phenomena at auroral latitudes (i.e., "loading-unloading" processes); however, the "directly-driven" convection processes over both polar caps remained intense despite the significant inflation of the magnetosphere.

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