OBSERVATION OF FIELD-ALIGNED AND IONOSPHERIC CURRENTS DURING SPACE WEATHER MONTH, SEPTEMBER 1999

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ABSTRACT

September 1999 was a magnetically active month, with several geomagnetic storms occurring in sequence which influenced the current pattern of the high-latitude ionosphere. The DMI Greenland magnetometers recorded variations of the ionospheric Hall currents while Ørsted, a Danish low-altitude Earth-orbiting satellite, measured the magnetic effect of field-aligned currents (FAC). We discuss a particular dayside event which occurred a few hours after the peak of a moderate storm on Sept. 15, 1999. Ørsted proceeded polebound on a trajectory closely aligned with the Greenland west coast magnetometer chain, and the Sondrestrom Incoherent Scatter Radar was in operation scanning the ionosphere almost parallel to the Ørsted trajectory. Coincident solar wind (SW) and interplanetary magnetic field (IMF) data were obtained from the ACE spacecraft and ballistically propagated to a nominal subsolar bow shock location at 12 Re. A synoptic view of the data suggests that the dayside field-aligned and ionospheric current system responded quickly (within 5-10 min) to variations of the northward component of the IMF (IMF-Bz). Specifically, the latitude of the boundary between westward and eastward high-latitude Hall currents as well as the latitudes of the maxima of the eastward and westward currents followed closely IMF-Bz variations. © 2002 COSPAR. Published by Elsevier Science Ltd. All rights reserved.

INTRODUCTION

In September 1999, several geomagnetic storms occurred, including a moderate one in the late morning of September 15 (when Dst reached a minimum of -51 nT between 09 and 10 UT) and major one during the night, September 22/23, (when Dst reached a minimum of -173 nT between 23 and 24 UT on Sep. 22). In this paper we focus on the former one. During the hours following the deepest depression of the geomagnetic field (i.e., the maximum ring current intensity), space borne and ground-based measurements were conducted along the Greenland west coast. The data presented here cover the time interval, 11–17 UT, which is equivalent to 8.5–14.5 magnetic local time (MLT) at the Greenland west coast. We adopt the corrected geomagnetic (CGM) coordinate system (Gustafson et al., 1992), and this system is implied whenever we refer to magnetic latitude and magnetic local time.

We compare magnetic field observations collected by the Danish low-altitude Earth-orbiting Ørsted satellite (see http://www.dmi.dk/projects/oersted/) on a polebound pass along the Greenland west coast with ground-based magnetometer measurements from the coastal chain of the Danish Meteorological Institute (details are found at http://www.dmi.dk/projects/chain/) and measurements of the ionospheric plasma flow made with the Sondrestrom Incoherent Scatter Radar (http://irs.sri.com/). The Ørsted pass considered here is special insofar as it occurred around 11.5 MLT, i.e. just before local magnetic noon, with the satellite trajectory closely aligned with the Greenland west coast magnetometer chain and oriented...
almost perpendicular to the contours of constant magnetic latitude. The Sondrestrom radar performed antenna scans in a plane perpendicular to the local contour of constant magnetic latitude, i.e. almost parallel to the satellite trajectory. Solar wind (SW) and interplanetary magnetic field (IMF) data compiled from MAG and SWEPAM measurements made onboard the ACE spacecraft and provided by the ACE Science Center (ASC) yield information about the plasma conditions in the interplanetary medium.

In the next section we discuss the data in detail and show how observations from the various instruments fit together. We show that the plasma flow reversal measured with the incoherent scatter radar and the shear between eastward and westward ionospheric Hall currents sensed by the ground-based magnetometers coincide. The two boundaries between upward and downward field-aligned currents (FAC) seen by Orsted coincide with the maxima of the westward and eastward Hall currents, respectively. We further show that the eastward/westward Hall current boundary closely follows IMF-\(B_z\) with a few minutes delay (after taking account for the solar wind propagation from ACE to the subsolar magnetopause). This observation confirms the almost immediate effect of IMF-\(B_z\) variations on some features of the ionospheric current pattern.

OBSERVATIONS

We present in Figure 1 a synoptic view of the essentials of the data collected, laid over a map of Greenland. In addition to geographic latitude and longitude (dotted grid), contours of constant magnetic latitude are drawn (dashed lines). The solid, almost straight line extending from bottom to top traces the Orsted trajectory which has been mapped along magnetic field lines down to 110 km altitude (our nominal electrojet altitude). The diamonds (annotated 1347 through 1353) are UT markers. The horizontal component of the magnetic field measured onboard Orsted and reduced to magnetic variation vectors by subtracting the IGRF 2000 main field model, is plotted in 2.3-s spacing along the satellite trajectory. Occasional small gaps result from missing data. In order to give an idea of the magnetic field magnitude, the largest westward and eastward vectors are indicated (520 nT and 610 nT, respectively). The symbols for large-scale upward and downward FAC (\(\bigcirc\) and \(\bigotimes\), respectively) are annotated with the FAC density mapped down to 110 km altitude and integrated over the entire latitude range between zero magnetic perturbation and perturbation extrema (which indicate FAC reversal). In that sense, the FAC intensity from subauroral latitudes up to about 75.5° magnetic latitude amounts to 630 mA/m upward, between 75.5° and 80.5° to 1170 mA/m downward, and poleward of 80.5° to 540 mA/m upward.

The arrows indicate ionospheric Pedersen currents which are supposed to close the FAC. If the FAC were perfect sheet currents and confined to the zone between about 65° magnetic latitude and the magnetic pole, the Pedersen currents would have to match the FAC, that is, the Pedersen current should be about 630 mA/m equatorward of the current shear and 540 mA/m poleward of it. The corresponding Hall currents (but not the Pedersen currents) are inferred from the chain of ground-based magnetometers (located at the sites indicated by full circles and annotated with three-letter station codes), using a method proposed by Popov et al. (2001). It appears that the Hall current equals the Pedersen current assumed to flow between the poleward pair of down/up FAC, suggesting a Hall to Pedersen conductance ratio of about 1.0. The Hall current in the equatorward section is only 60% of the Pedersen current assumed to close the equatorward up/down FAC pair. We consider a Hall/Pedersen conductance ratio of 0.5 too small for the noon sunlit ionosphere. It is more likely that the infinite current sheet assumption is violated in this case.

The heavy line through STF (Sondrestrom) denotes the trace of the radar antenna scan plane at F region altitudes drawn as far as usable plasma flow vectors could be derived. The plasma flow reversal, seen at 77° magnetic latitude at the time of the Orsted pass, varies with time (not shown). It is worth noting that the flow reversal inferred from the radar measurements coincides over the entire time interval studied here with the boundary between eastward and westward Hall currents inferred from the magnetometer chain. This result lends credibility to the current pattern inferred from the Greenland west coast magnetometers.

A time sequence of the ionospheric Hall current over western Greenland is shown in Figure 2, along with time series of various plasma parameters in the interplanetary medium. The top panel displays the latitudinal distribution of the eastward and westward current as they develop in time. Note that this is not a snapshot taken over several magnetic longitude sectors, it is rather the temporal development of a north-south Hall current profile at a fixed location which proceeds from morning to afternoon as time progresses. Overlaid is the trajectory of Orsted with the magnetic field vectors and FAC distribution, copied
from Figure 1. The solid black line across the panel shows the IMF-\(B_z\) variation, and the dotted straight grey line marks its 0-nT level. The IMF-\(B_z\) trace has been copied from the lower part of Figure 2 into the top panel, retarded by 20 min in addition to the delay experienced between ACE location and 12 Re stand-off distance, and redrawn with an enlarged amplitude scale.

![Figure 1](image-url)  
*Fig. 1. Map of Greenland with Ørsted trajectory, horizontal magnetic field variation vectors from Ørsted, and Sondrestrom radar scan trace. See text for details.*

The lower part of Figure 2 shows the IMF (in GSM coordinates), and SW density and bulk velocity, propagated to 12 Re upstream of the Earth. 12 Re is taken as the approximate stand-off distance of the bow shock. IMF-\(B_z\) is negative and \(B_y\) positive throughout the interval, and both are rather stable. \(B_x\) is mostly (but not always) negative and varies more than \(B_z\) and \(B_y\), thereby covering the range, -13 to +4 nT. The plasma bulk velocity varies little and shows only a weak gradual decrease over time while the plasma density is more variable but generally low throughout the time interval considered (less than 3 H\(^+\) cm\(^{-3}\)).

We mentioned that a plasma flow reversal was observed by the Sondrestrom incoherent scatter radar at 77° magnetic latitude where the boundary between eastward and westward Hall current, estimated from the ground-based magnetometer chain, was found. We note that the peak intensity of the westward Hall current at the time of the Ørsted pass coincides with the upward/downward current shear observed by Ørsted at about 75.5° magnetic latitude, and the peak intensity of the eastward Hall current coincides
with the downward/upward current shear at about $80.5^\circ$ magnetic latitude. This would be expected if
the Pedersen/Hall conductance ratio changes little over small spatial scales, because the FAC need to be
closed by Pedersen currents, and the maximum Pedersen current intensity should occur at the shear between
upward and downward FAC. Consequently the maximum Hall current should appear at the same latitude.

The most interesting feature is the close correlation between the variation of the (retarded) IMF$-B_z$
component and the boundary between westward and eastward Hall currents. This indicates that the latitude
of the ionospheric current system in the cusp and adjacent morning and afternoon regions (which are
probably connected to the HLBL) follows closely IMF variations with only minimal time delay. One can
attribute some 10–15 minutes of the 20 min retardation between IMF (propagated to the magnetospheric bow shock) and ionospheric current pattern to the propagation of the IMF variation through the bow shock and magnetosphere, down to ionospheric altitudes. This leaves 5–10 min for the response of the daytime ionospheric current system to IMF–$B_z$ forcing. Given the excellent coincidence between the magnetic latitudes of FAC boundaries and and electrojet shears during the Ørsted pass we have good reason to assume that the latitude where the FAC boundaries are found follows IMF–$B_z$ variations the same way the ionospheric Hall current shear does.

**DISCUSSION AND CONCLUSION**

We have compared solar wind and interplanetary magnetic field observations with measurements from the low-altitude Earth-orbiting Ørsted satellite, the Greenland ground-based magnetometer chain, and the Sondrestrom incoherent scatter radar. The latitudinal distribution of FAC (inferred from the Ørsted satellite), ionospheric Hall currents (derived from Greenland west coast magnetometers), and ionospheric plasma flow (obtained from the Sondrestrom Incoherent Scatter Radar) show excellent agreement. The higher latitudes (poleward of the FAC transition at 75.5° magnetic latitude) carry more intense FAC and Hall currents than the lower latitudes (which cover the typical auroral oval).

The FAC sequence observed between 66° and 85° magnetic latitude is consistent with the statistical pattern obtained by Iijima and Potemra (1976) for the dayside magnetosphere shortly before magnetic noon. Our FAC intensities exceed the intensity range reported in their paper, but the magnetic disturbance level during our event (AL quicklook index $\approx -1200$ nT) was also much higher than during the weakly disturbed cases they had selected. The currents we observe have been termed Region 2 (R2), Region 1 (R1) and Region 0 (R0) FAC (proceeding from low to high latitudes). Our FAC pattern can also be explained by the Cowley et al. (1991) model which shows that an upward–downward–upward FAC sequence can be expected in the northern hemisphere under positive IMF–$B_y$ conditions, simply through a partial overlap of $R1$ and $R2$ currents without the need to invoke a separate $R0$ current system.

Our observations are consistent with the Heelis (1984) plasma flow pattern for negative IMF–$B_z$ and positive IMF–$B_y$, determined from satellite data, and the equivalent current system determined from ground-based measurements by Friis-Christensen et al. (1985). In our specific case, we face a magnetospheric configuration in which the dayside electric current pattern, manifested through the high-latitude Hall currents, closely traces IMF–$B_z$ variations with 5–10 minutes delay. Specifically, the boundary between eastward and westward current as well as the latitude of the current maxima (which coincide with the boundary between upward and downward FAC at the time of the Ørsted pass), both follow IMF–$B_z$ variations. Over the time interval considered here, 8.5–14.5 MLT, the sequence of ionospheric Hall current orientations, westward at the equatorward side of the flow reversal and eastward at the poleward side, does not change. Consequently, the sequence, upward–downward–upward FAC, should not change either. This implies that the Iijima and Potemra (1976) noon sector model, if applicable, is more extended in MLT than the average pattern presented in their paper.

Whether we assume an Iijima and Potemra (1976) FAC system with three independent upward–downward–upward ($R2$–$R1$–$R0$) current sheets or a continuous extension and overlap in MLT of a Cowley et al. (1991) $R2$–$R1$ system is not critical for our argumentation. Important is that three major FAC sheets are found close to magnetic noon. The significance of our paper lies in the fact that we have, for a single event, confirmed that ionospheric Hall current and FAC distribution in the noon sector match quantitatively poleward of the convection reversal (not quite as well on the equatorward side). Specifically, we have shown that the ionospheric electrojet pattern closely traces IMF–$B_z$ variations over several hours in both, Universal Time (UT) and magnetic local time. The temporal stability of the Hall current pattern, only modulated by IMF–$B_z$ variations, leads us to suggest that the observed coincidence between FAC distribution and Hall currents may hold for the entire interval considered here.

Let us assume that we have observed an $R2$–$R1$–$R0$ FAC system. The $R0$ current is usually considered to connect to cusp and mantle, at least in the noon sector. Stauning et al. (2001) analysed some 40 Ørsted satellite observations of $R1/R0$ FAC transitions near local magnetic noon under positive IMF–$B_y$ and varying IMF–$B_z$ conditions. They found their results to be consistent with the Newell et al. (1989) IMF
dependence of the equatorward boundary of the cusp. Simultaneous measurements from the Ørsted charged particle detector (CPD) revealed that the $R1/R0$ FAC transition coincided with the poleward boundary of high-energy trapped particle fluxes. This led them to conclude that the observed $R1$ currents flow on closed and the $R0$ currents on open field lines.

In our case presented here, Ørsted CPD measurements are more difficult to interpret because of the presence of an intense background of solar protons. But the CPD data seem to support the view that the trapped particle flux decreases to polar cap intensity somewhere between 75° and 77° magnetic latitude. We would thus expect to find the boundary between closed and open field lines in the same latitude range. The interval of largely downward current, 75.5°-80.5°, may possibly consist of two sub-intervals, an $R1$ sheet from 75.5° to 77.5° characterized by a substantial and monotonic magnetic field change, and a more turbulent FAC pattern between 77.5° and 80.5° which coincides with the cusp (indicated in Figure 2 by a grey-colored pair of FAC symbols, in contrast to the black FAC symbols). This picture is consistent with the average location of the cusp equatorward boundary as reported by Newell et al. (1989). If we take the poleward limit of the trapped particle regime, namely 77°, we find good agreement between poleward boundary of trapped particles, convection reversal and poleward boundary of the $R1$ FAC (the two latter at 77.5°). We would then place the $R2$ and $R1$ FAC on closed and the cusp and $R0$ FAC on open field lines.

The close resemblance between IMF-$B_z$ magnitude and electro jet latitude over the entire time interval studied here suggests that an IMF-$B_z$ dependence of the FAC system does not only apply in a statistical sense (i.e., to an average over many single-point measurements as obtained from low-altitude spacecraft) but also to individual cases of IMF-$B_z$ variations as they occur with progressing time, at least during negative IMF-$B_z$. If we accept this view then our results further suggest that such tracking can be sustained over several hours in magnetic local time and not only in a narrow longitude sector around the cusp. The conditions under which a generalization of this statement holds may yet to be investigated. In particular non-uniform conductivity distributions and filamentary FAC patterns may render our suggestion invalid.

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