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Field-aligned currents during IMF ~ 0

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Abstract. We report on field-aligned currents (FAC) obtained from precise magnetic field measurements made onboard the Ørsted and Magsat satellites when the interplanetary magnetic field (IMF) was near zero. We found that Region 1/Region 2 currents persist through southward IMF, IMF $\sim$ 0, and northward IMF; also the central area of both the northern and southern polar caps is always filled with FACs, even during slightly southward IMF. A statistical distribution of the latter currents resembles the dayside NBZ system with the downward/upward currents at post-noon/pre-noon hours, discovered earlier from Magsat observations. We hypothesize that the quasi-viscous interaction of the solar wind with the magnetospheric lobes may cause a sunward convection of the lobes' field lines through the bunch's core, effectively mapping the FACs of NBZ-type down to the near-pole area.

Introduction

The FAC distributions over high latitudes have been the subject of numerous studies since initial satellite observations in the 1960s. *Iijima and Potemra* [1976] found that the FAC direction is persistent in the dawn and dusk sectors of the auroral oval forming the R1/R2 pattern, whereas currents near noon at polar cusp latitudes are found to be strongly dependent on the IMF conditions. However, upon establishing the statistical R1/R2 pattern, most of the follow-on investigations focused on either the dayside or nightside, revealing the NBZ system related to the northward IMF [*Iijima et al.*, 1984] and B_y-controlled currents [e.g., *Taguchi et al.*, 1994; *Ohtani and Higuchi*, 2000].

Thus, though the R1/R2 pattern has become *de facto* standard in describing the high-latitude, large-scale FAC structure, we are unaware of any significant experimental, satellite-based study where these FAC systems are investigated in their entirety: from the spatial extent over the polar region to the time-dependent variability due to changing IMF conditions. In this study, we focus on FACs filling the central portion of both polar caps (above $\pm 80°$) for IMF $\sim$ 0, where we believe a new FAC system is revealed.

Method

We obtained experimental magnetic field disturbances over the polar regions by subtracting the DGRF-1980 or ØIF [*Olsen et al.*, 2000] models from 1-sec, 3-component samples, averaged from higher-rate measurements made onboard Magsat or Ørsted, respectively: $\Delta H_{x,y,z} = H^{obs}_{x,y,z} - H^{mod}_{x,y,z}$. These disturbances were then transformed into the corrected geomagnetic (CGM) coordinates defined by the same main geomagnetic field model, giving the satellites' location by the CGM latitude and magnetic local time (MLT) of the corresponding magnetic field line footprint.

Using Ampere's law and assuming vertical field line geometry, we may calculate the FAC density as the curl of the corresponding magnetic field disturbances $\mu_0 j_{||} = \partial H_y/\partial x - \partial H_x/\partial y$ where x (magnetic north) and y (east) are perpendicular to the magnetic field line. Here we are interested in average distributions of the current densities, therefore we collect all satellite passes for which the IMF falls within a certain range. To facilitate calculations, we then transform data in a Cartesian coordinate system with x in the direction of dawn and y – in the noon direction. The unit in this system corresponds to one degree of latitude, $\sim$ 111 km.

We divide the area under investigation in squares with sides of one unit and then take the average of all measurements of magnetic disturbances that fall within each cell fulfilling the given IMF condition. To calculate the curl, we fit the data for a 7×7 unit square to a function $H_{i,fit} = a_i + b_i(x - x_0) + c_i(y - y_0) + d_i(x - x_0)(y - y_0)$, which gives us the derivatives needed for the curl in the center of the fitted area: $\partial H_x/\partial y = c_x$ and $\partial H_y/\partial x = b_y$. The curl is calculated for every cell over the polar cap thereby smoothing the derived currents over the fitting window. If there are cells without data, we simply leave them out of the fitting procedure. We further smooth the obtained curl values by the same 7×7 boxcar average to reduce noise in observations.

Results

We utilized data from November 1979 through April 1980 (Magsat) and from April 1999 through June 2000 (Ørsted), selecting all polar passes satisfying the IMF "quiet" conditions $B_T = (B_y^2 + B_z^2)^{1/2} < 1.5$ nT. The Ørsted polar orbits were selected according to 1-min IMF observations made by NASA's ACE spacecraft and ballistically propagated from L1 to the nominal magnetopause at 12 R_E; then these data were averaged over $\sim$40-min time intervals centered at the satellite entries into the polar cap ($\pm 60°$); similar averaging is used in other studes of ionospheric electrodynamics [e.g., *Papitashvili et al.*, 1994, *Weimer*, 2001, and references therein]. For sorting Magsat data, we used IMF observations from IMP 8 and ISEE 3; the latter data were also propagated to the nominal magnetopause.

To be on sure ground regarding the validity of patterns under investigation, we further restricted our selection to the passes satisfying $|B_y| < 1$ nT and then scanned the IMF $|B_z| < 1.5$ nT interval by a 1-nT sliding window:

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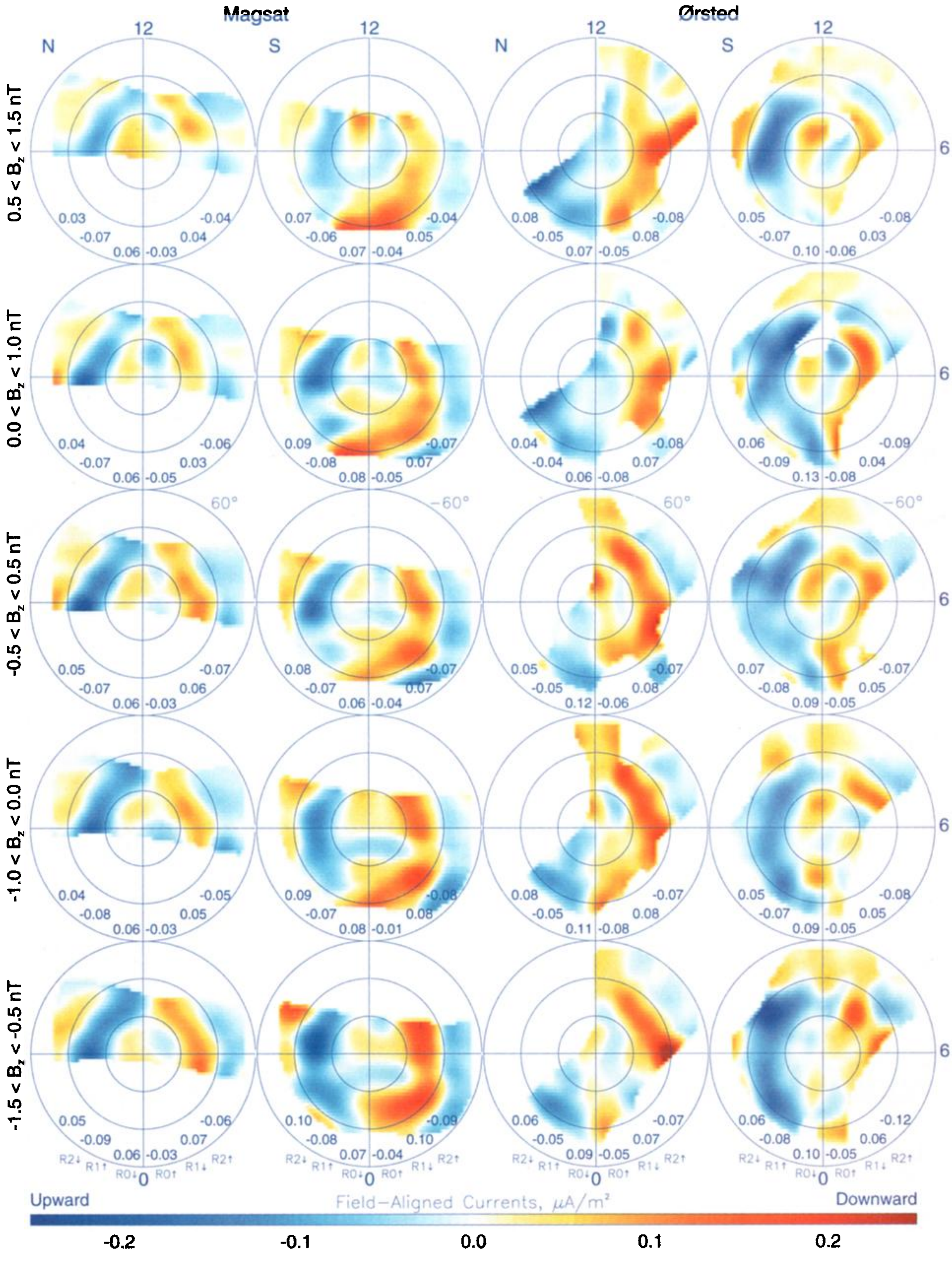

Figure 1. Experimental distributions of field-aligned currents for IMF ~ 0 (see text for details).

$0.5 < B_z < 1.5$ nT, $0 < B_z < 1$ nT, $-0.5 < B_z < 0.5$ nT, $-1 < B_z < 0$ nT, and $-1.5 < B_z < -0.5$ nT. Figure 1 shows the FACs experimental distributions over both the northern and southern polar regions, plotted in the CGM Latitude–MLT coordinates. Figures at the bottom of each dial plot show average current densities (in $\mu A/m^2$) calculated over the areas on the plots where the R1/R2 and R0 currents are detected. Because our FAC maps cover the polar region only partially, these numbers could be inadequate in some dial plots; however, they might be helpful for the reader in better quantifying colors on the dials. Unfortunately, the partial mapping did not allow calculations of the R1/R2 and R0 total currents over the corresponding areas.

To increase the data statistics, we repeated the scan by an IMF 1.5-nT sliding window (i.e., $0 < B_z < 1.5$ nT, $-0.75 < B_z < 0.75$ nT, and $-1.5 < B_z < 0$ nT), but found that the resulting distributions are the same as shown in Figure 1. Note that all these results we obtained analyzing dependencies of the FAC distributions on the IMF B_y/B_z "clock angle", where we followed the traditional approach not constraining the IMF B_x at all; these ionospheric maps of FACs will be published soon elsewhere.

The most obvious observation from the presented plots is that the R1/R2 systems exist even for IMF ≥ 0, being a dominant structure between ±60° and ±80° latitudes. This indicates that for the selected range of IMF these currents are likely controlled by the "quasi-viscous" processes, occurring at the flanks of the Earth's magnetosphere. The average densities for R1↑ (R2↓) currents are ~0.07 (0.06) μA/m^2, for R1↓ (R2↑) currents ~0.06 (0.07) μA/m^2. Both satellites complement each other providing almost global distributions of R1/R2 currents over the entire polar region.

The top rows of the dial plots show that the NBZ current system is clearly observed in both the northern and southern polar caps, being located at and above ±80°. However, a surprising observation is that the central and bottom rows of the dial plots also show that the entire near-pole area (above ±80°) is always filled with wide-spread FACs, in most cases nearly symmetrically placed with respect to the noon-midnight meridian. The most striking in this picture is that the observed direction of these near-pole currents (in 17 out of total 20 distributions) is the same as for the NBZ system. (The reversed currents are observed only in the single dial plot at the right bottom corner of Figure 1; two of the Ørsted's northern plots for IMF > 0 lack data in the afternoon quadrant.) The average density for R0↓ currents is ~0.08 μA/m^2, for R0↑ ~0.05 μA/m^2. These current density numbers are comparable with the current density of the corresponding pair of R1 currents. Noting that the currents in the central portion of the polar caps persist through the entire scan of IMF $-1.5 < B_z < 1.5$ nT, we think that *Iijima and Potemra* [1976] called exactly these currents "Region 0", coining the term. Thus, below we will refer to this new NBZ-type system as R0 currents.

Because of the orbit inclination and the offsets between the geographic and CGM poles, Magsat was unable to cover the entire polar region; however, its data show that the R0 currents are spread over the near-pole area and clearly separated from the R1/R2 system even for $B_z < 0$. Ørsted completed the full 180° orbit drift in Spring 2001, but even in the data used in this study one can see clearly existence of R0 currents, separated from the R1/R2 system.

Discussion

The weak and patchy FACs in close vicinity to the geomagnetic poles have been reported in many studies. However, even *Iijima and Potemra* [1976] were not sure where their R0 system should be placed: although their schematic pattern (in Figure 5) for $|AL| < 100$ nT shows R0 right below 80°, the actual Triad data (in Figure 3) for the same AL show the detected FACs below and above this latitude. *Watanabe et al.* [1998, Figure 3] showed the NBZ-type FAC system spread above 80° for IMF $B_T \sim 0$, but concluded that the FAC systems "in the magnetospheric ground state ($Kp = 0$, IMF $|B_y| \leq 1.5$ nT and -0.5 nT $\leq B_z \leq 1.5$ nT) consist of global region 1/region 2 currents and a dayside region 0 current." In another example, *Kustov et al.* [2000] obtained the upward (downward) R0 currents over the 0800–1100 (1300–1600) MLT sectors just above 80°, noting however that these currents are not expected to be detected in the near-pole region. Taking into account that their radar observations barely reach 85°, the latter conclusion is not fully justified.

For the first time, the new, NBZ-type R0 current system during southward IMF was obtained by *Papitashvili* [1987] in analyzing ground-based autonomous magnetometer data from the vicinity of southern CGM pole [*Papitashvili et al.*, 1990]. In explaining these currents, the author utilized a theoretical approach proposed by *Lyatsky et al.* [1985], where a bunch of field lines, forming both the northern and southern magnetospheric lobes, is considered as a separate domain in the "non-ideally closed" magnetosphere (as it is expected for the absolute absence of IMF). The latter means that some lobes' field lines may be open (or closed at near-infinity) due to the patchy reconnection of the IMF ~ 0 components with the geomagnetic field.

Lyatsky et al. [1985] hypothesized that this bunch of lobes field lines is risen high enough (in the Z_{GSM}-axis direction) over the near-pole region (before aligning with the solar wind streamlines) and the "quasi-viscous" interaction processes may cause the field-lines' sunward convection through the bunch's core. This convection over the poles is controlled by a degree of near-perpendicularity of the rising bunch to the solar wind flow, effectively producing an NBZ-type FAC system in the near-pole area, "quasi-independent" on the IMF strength and direction.

Thus, we suggest here that the Axford-Hines "quasi-viscous" interaction may produce four ionospheric convection vortices in the polar region: the anti-sunward convection at the polar cap boundary (with the return flows at lower latitudes) caused by viscous processes on the magnetospheric flanks and the sunward convection (with the return flows at the polar cap boundary) caused by the same viscous processes but applied to the lobes bunch of field lines. As the IMF "clock angle" increases in either direction (southward or northward), the lobes' "viscous" interaction with the solar wind is being dwarfed or reversed by the corresponding B_z-related reconnection process. The IMF B_y component complicates this picture skewing the ionospheric convection pattern towards dusk or dawn.

We believe that this complication was a reason why the near-pole FACs and the corresponding ionospheric sunward convection of "viscous" origin have not been detected in many previous studies of satellite or ground-based data; note also that there is almost no magnetic observatories above ±85°. Recently *Weimer* [2001] developed an IMF-dependent model of field-aligned currents derived from DE 2 data. Not to our surprise, we found that the R0 system under discussion is clearly seen in his dial plots for the southward IMF, though unfortunately this model does not deal with IMF ~ 0. It is interesting to note also that the NBZ-type, R0 currents can be seen for IMF = 0 in the FACs mapping to the ionosphere from MHD modeling [e.g., *Ogino*, 1986; Figure 5] and from the semi-empirical LiMIE model [*Papitashvili et al.*, 1994; http://www.sprl.umich.edu/mist/].

Conclusion

We believe that the NBZ-type, R0 system under investigation has been observed by others on many occasions, but then related to the cusp currents following the scheme introduced by *Reiff and Burch* [1985]. However, even in the latter scheme the upward/downward "lobe-cell"-related FACs are placed in the center of the polar cap for weakly northward IMF (see Figure 8 in the cited paper). Some researchers believe that the R0 system is always present in the polar magnetosphere irrespective of the IMF [e.g., *Kustov et al.*, 2000, and references therein]. Our results provide the solid experimental evidence that both the northern and southern near-pole regions are filled by the FACs (even when IMF turns southward) and the significant R1/R2 currents persist through southward IMF, IMF ~ 0, and northward IMF. We conclude that more studies are needed to substantiate these new findings.

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