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Equivalent ionospheric currents above Antarctica during the austral summer

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Abstract: A regression analysis was carried out between the ground-based geomagnetic data from the southern polar regions (above -55° corrected geomagnetic latitude) and the interplanetary magnetic field (IMF) components in the geocentric solar-magnetospheric co-ordinate system and solar wind (SW) parameters. Hourly mean values of the geomagnetic field horizontal components H and D from 20 Antarctic observatories and automatic stations of 1978–80 and 1983–84 were examined. Regression coefficients were used as geomagnetic perturbation vectors which were rotated 90° clockwise to plot the equivalent current vector patterns in the "corrected geomagnetic latitude-magnetic local time" co-ordinates. The results which are described in the paper reflect geomagnetic phenomena associated with the IMF and SW parameters for the austral summer season only (November, December, January, February). It was found that, in general, global characteristics of the ionospheric convection patterns agree well for both hemispheres. Geomagnetic variations, which are generated by the interaction of the SW plasma and frozen-in IMF with Earth's magnetosphere, represent three types of equivalent current systems: a) two-vortex system with transpolar current from nightside to dayside, controlled by the "quasi-viscous" interaction and southward IMF; b) zonal current system, controlled by the azimuthal IMF; and c) two-vortex system with transpolar current from noon to midnight controlled by the northward IMF. The southern polar cap (above -75°), which was more densely packed with automatic magnetometers than the northern cap, permit us to investigate the fine structure of the high-latitude current systems in detail.

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Introduction

During the past two decades a number of excellent statistical analyses were performed to clarify the characteristics of magnetic perturbations, electric fields, ionospheric and magnetospheric currents at the high latitudes and their control by the interplanetary magnetic field (IMF) and solar wind (SW) parameters (Iwasaki 1971, Friis-Christensen *et al.* 1972, Sumaruk & Feldstein 1973, Berthelier *et al.* 1974, Friis-Christensen & Wilhjelm 1975, Maezawa 1976, Troshichev & Tsyganenko 1979, Afonina *et al.* 1980, Wolfe 1980, Mishin *et al.* 1981, Levitin *et al.* 1982, Troshichev 1982, Friis-Christensen *et al.* 1985, Feldstein & Levitin 1986 and others). During the 1980's, the same analyses were carried out with geomagnetic data from the southern polar cap (Sumaruk & Vorfolomeeva 1980, Mansurov *et al.* 1981, Papitashvili 1981, Papitashvili *et al.* 1983). There are 12 permanent magnetic observatories in Antarctica at corrected geomagnetic latitudes above -55° but only three of them are located in the southern polar cap (above -75°). It is obvious that a detailed analysis needs more points with observations in this region.

In spite of the great interest in the occurrence of substorms and the DP2 current system, and particularly their dependence on the north-south component (B_z) of the IMF (Nishida 1968), the so-called large-scale "quasi-steady" ionospheric plasma convection patterns are still an important subject of investigation to understand global features of magnetosphere-ionosphere coupling. Using the regression analysis technique the different types of geomagnetic variations have been distinguished in the northern polar regions which are associated with the southward ($B_z < 0$), northward ($B_z > 0$) and azimuthal (B_y) components of the IMF (Maezawa 1976, Levitin *et al.* 1982, Troshichev 1982). Also, it was found that the residual part of the variation field, which is free of the IMF's influence, correlates with the velocity (V) and density (n) of the solar wind plasma flow near the Earth's magnetosphere (Levitin *et al.*1982). The regression analysis technique permits us to relate the ground-based magnetic field hourly values quantitatively with the IMF and SW parameters on the same time-scale. The corresponding equation for each hour of UT might be written as follows:

$$H = K_{Bx} B_x + K_{By} B_y + K_{Bz} B_z + H_o \qquad (1)$$

where H is a total hourly value of the geomagnetic field (X, Y, Z) component on the Earth's surface and B_x, B_y and B_z are the IMF component hourly values measured near the Earth's magnetosphere in the geocentric solar-magnetospheric co-ordinate system. K_{Bx}, K_{By} and K_{Bz} are regression coefficients for the corresponding IMF components which are obtained

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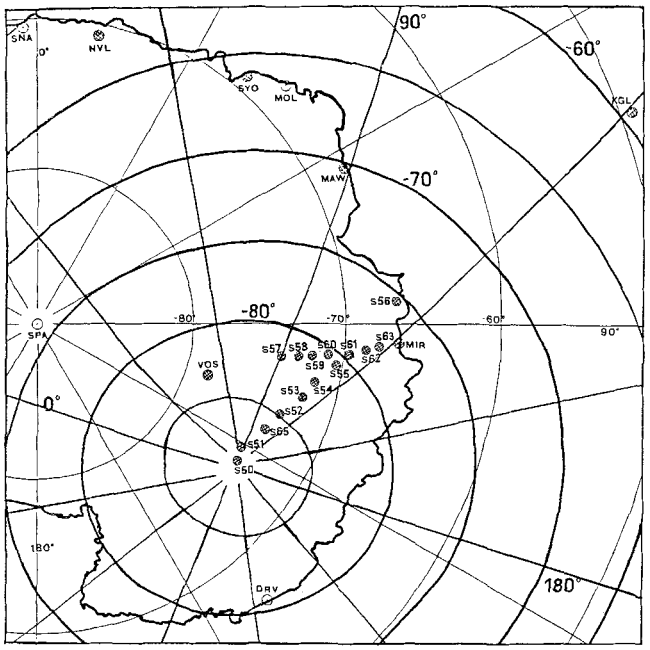


Fig. 1. Map of Eastern Antarctica with permanent magnetic observatories and automatic magnetometers which were used in the analysis (shaded).

by the least squares method. The value H_o (which means X_o, Y_o, Z_o) is the free term of the equation which characterizes a "quiet" (IMF-independent) level for the given observatory. This is the main advantage of the regression technique against the real event analyses when the quiet levels have to be selected from magnetograms subjectively. It has been shown that the H_o variation may reflect a quasi-viscous interaction between the solar wind plasma flow and the Earth's magnetosphere (Levitin *et al.* 1982). Therefore, equation (1) might be written as follows:

$$H = K_{Bx} B_x + K_{By} B_y + K_{Bz} B_z + K_{V2} (V/100)^2$$
$$+ K_{nV2} (n(V/100)^2) + H_{oo} \qquad (2)$$

where V (velocity) and n (density) are the SW parameters, K_{V2} and K_{nV2} are the corresponding regression coefficients and H_{oo} is a residual part of the geomagnetic field which is free from IMF and SW influences. The H_{oo} variation around the daily mean value can be considered as an extension of the Sq-current system to high latitudes. Obviously it is possible to expand equation (2) if we suppose that any physical variation is still contained in the H_{oo} term.

The aim of this paper is to apply the above mentioned technique to the high-latitude geomagnetic data from the southern hemisphere. Previous works, which contain some Antarctic data, have used different techniques (Berthelier *et al.*1974), or have dealt with only a few geomagnetic observatories (Mansurov *et al.* 1981), or have been based on the incomplete IMF data set which was available at that time (Papitashvili *et al.* 1983).

Analysis of Antarctic geomagnetic data

Some chains of magnetometers in the northern hemisphere during the IMS (International Magnetospheric Study, 1976–79) provided a great opportunity to investigate the northern ionospheric convection patterns in detail (Kamide *et al.*1982). Otherwise, we have used geomagnetic data from the unique dense chain of automatic magnetometers in Antarctica (Fig.1), operated during 1975–84 (Papitashvili & Zaitzev 1986), to investigate the equivalent current patterns above Antarctica more accurately. The same approach has been used earlier for Greenland Magnetometer Chain Data (Friis-Christensen *et al.* 1985). In view of the fact that the Antarctic Magnetometer Chain provides the most detailed coverage for corrected geomagnetic latitudes above -75°, we pay special attention to the spatial and temporal structure of the equivalent ionospheric currents in the southern polar cap and near pole region.

Hourly mean values of the geomagnetic field horizontal components (H and D) of the observatories, listed in TableI, were transformed into X and Y components, which are directed to the north corrected geomagnetic pole and east respectively, and related to the hourly values of B_x, B_y and B_z components of the IMF and velocity and density of the SW (Couzens & King 1986) during the summer seasons in accordance with equations (1) and (2). Transformation formulas for each station are as follows:

$$X = H \cos (D_w - MSG)$$
$$Y = -H \sin (D_w - MSG) \qquad (3)$$

where H is the horizontal component intensity of the geomagnetic field directed along the local magnetic meridian, D_w is westward declination and MSG is the angle between corrected geomagnetic and geographic meridians for given observatory and listed in Table I.

Automatic magnetic variation stations (AMVS) S-60 and S-63 are mentioned in Table I to provide a full listing of the magnetometers; their data were not analyzed for the summer season. Also, we do not show new results of Vostok and AMVS S-57, S-58 and S-59 due to lack of space in the figures; data from these stations were analyzed earlier by Papitashvili *et al.* (1983).

We have chosen the main part of the analyzed data for 1978–79 austral summer (November, December, January and February); at that time the maximum number of automatic magnetometers worked well. Few stations have been analyzed for various austral summer seasons (S-55 for 1979–80, Syowa, S-65 and S-50 for 1983–84) because their data were not available for 1978–79. It is possible to use various seasons for the joint analysis; regression coefficients of (1) and (2) do not change significantly from year to year within the 11-year solar cycle (Papitashvili 1982). Also, we could not analyze some permanent Antarctic observatories; their magnetic data have been inaccessible via the World Data

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Table I. The list of magnetic observatories in Antarctica used in the analysis

Station	Code	Geographic		Corrected Geomagnetic		LMM (UT)	MSG angle	Summer season
		Latitude	Longitude	Latitude	Longitude			
Argentine Islands	AIA	65.2°S	295.7°E	49.2°S	9.0°E	4.2	5.1°	1978–79
Port-Aux-Francais	KGL	49.4	70.2	58.4	121.3	21.0	21.4	-"-
Novolazarevskaya	NVL	70.8	11.8	62.4	51.5	1.2	27.3	-"-
Syowa Station	SYO	69.0	39.6	66.1	70.8	23.9	35.5	1983–84
Mawson	MAW	67.6	62.9	70.2	89.3	22.6	39.1	1978–79
AMVS S-56	S56	66.8	86.2	75.6	112.6	21.0	37.6	-"-
Mirny	MIR	66.6	93.0	77.2	121.6	20.4	35.4	-"-
AMVS S-63	S63	67.9	93.8	78.2	118.4	20.5	38.3	—
AMVS S-62	S62	68.8	94.4	79.0	115.6	20.7	40.8	-"-
AMVS S-61	S61	69.5	95.5	79.7	113.8	20.8	42.7	-"-
AMVS S-60	S60	71.1	96.1	80.7	107.1	21.2	48.3	—
AMVS S-55	S55	70.4	97.8	80.9	112.5	20.8	45.2	1979–80
AMVS S-59	S59	72.2	96.6	81.3	101.6	21.5	52.9	1978–79
AMVS S-58	S58	73.0	97.0	81.6	96.7	21.8	57.2	-"-
AMVS S-57	S57	74.1	97.5	82.0	89.6	22.3	63.6	-"-
AMVS S-54	S54	71.6	101.8	82.5	110.4	20.8	48.9	-"-
Vostok	VOS	78.4	106.9	83.3	53.6	1.1	101.1	-"-
AMVS S-53	S53	72.2	105.4	83.7	110.8	20.7	50.1	-"-
AMVS S-52	S52	73.2	110.5	85.5	106.5	20.8	54.1	1979–80
AMVS S-65	S65	73.9	115.1	86.9	101.6	20.8	55.8	1983–84
AMVS S-51	S51	74.5	121.0	88.4	85.2	20.9	53.8	1978–79
AMVS S-50	S50	74.7	124.4	89.1	54.1	8.4	45.8	1983–84

Coordinates are given according to Papitashvili (1981), Abston *et al.*(1985) and Tsyganenko *et al.* (1986); the UTs of the various Local Magnetic Midnights (LMM) were calculated according to Belov (1984); "MSG" is the angle between corrected geomagnetic and geographic meridians for each station.

Centre System or have been of poor quality. Some stations were omitted in the figures for the entire polar region due to lack of space above -75° latitude but they were introduced in the figures for the polar cap.

The available original geomagnetic data sets for each observatory (X and Y hourly values, 120 points for each UT hour) were separated into two:($B_z < 0$) - according to south B_z (so called "disturbed conditions") and ($B_z > 0$) - according to north B_z (quiet geomagnetic conditions in the auroral latitudes). Then each subset ($B_z < 0$) and ($B_z > 0$) were separated into two again, according to positive ($B_y > 0, B_z > 0$ and $B_y > 0, B_z < 0$) and negative ($B_y < 0, B_z > 0$ and $B_y < 0, B_z < 0$) signs of B_y component. The ($B_z < 0$) and ($B_z > 0$) subsets were subjected to the regression analysis to obtain K_{Bz}, K_{V2} and K_{nV2} coefficients; other subsets were subjected to the analysis to obtain K_{By} coefficients only.

Regression coefficients K_{Bx}, obtained according to (1), were insignificant and the equivalent ionospheric current system for B_x was not notable. This result agrees well with the known result of the analyzes of northern geomagnetic data (Berthelier *et al.* 1974, Friis-Christensen & Wilhjelm 1975, Troshichev & Tsyganenko 1979, Levitin *et al.* 1982). Hence, B_x has not been used in our work in defining the equivalent ionospheric current pattern connected with the IMF.

Levitin *et al.* (1982) have derived the equivalent current system (nV^2) which connects with simultaneous deviations in the density and velocity of the SW plasma flow. Regression coefficient K_{nV2} reflects the magnetospheric response to SW pressure changes and the corresponding equivalent current system has two vortices like the "quasi-viscous" DP0 system connected with V^2 (Levitin *et al.* 1982, Troshichev 1982). We have tried to follow the same method in our analysis of the Antarctic geomagnetic data. Unfortunately, the coefficients K_{nV2} were very small for all observatories and no significant effect of the (nV^2) current system was found. In this way we have decided do not present the figures for (nV^2) here.

Following from the definition of the austral summer season (November, December, January, February) we have 120 hourly mean values for each UT-hour at each station. For lack of data from observatories and the IMF and SW observations we have had about 80–100 values only from one observatory for the season (better coverage for 1978–80 and worse coverage for 1983–84). Dividing the original set of data into four, we have had a minimum number of values of about 20–25 for some stations and UT-hours. Generally speaking, the number of values is enough for regression analysis, but we have smoothed (by three in one) the daily variation of regression coefficients to remove jumps from hour to hour. Nevertheless, as we shall see in the following, some stations still exhibit a peculiar behaviour.

Having regression coefficients of the X and Y geomagnetic field components from each station for the various IMF and

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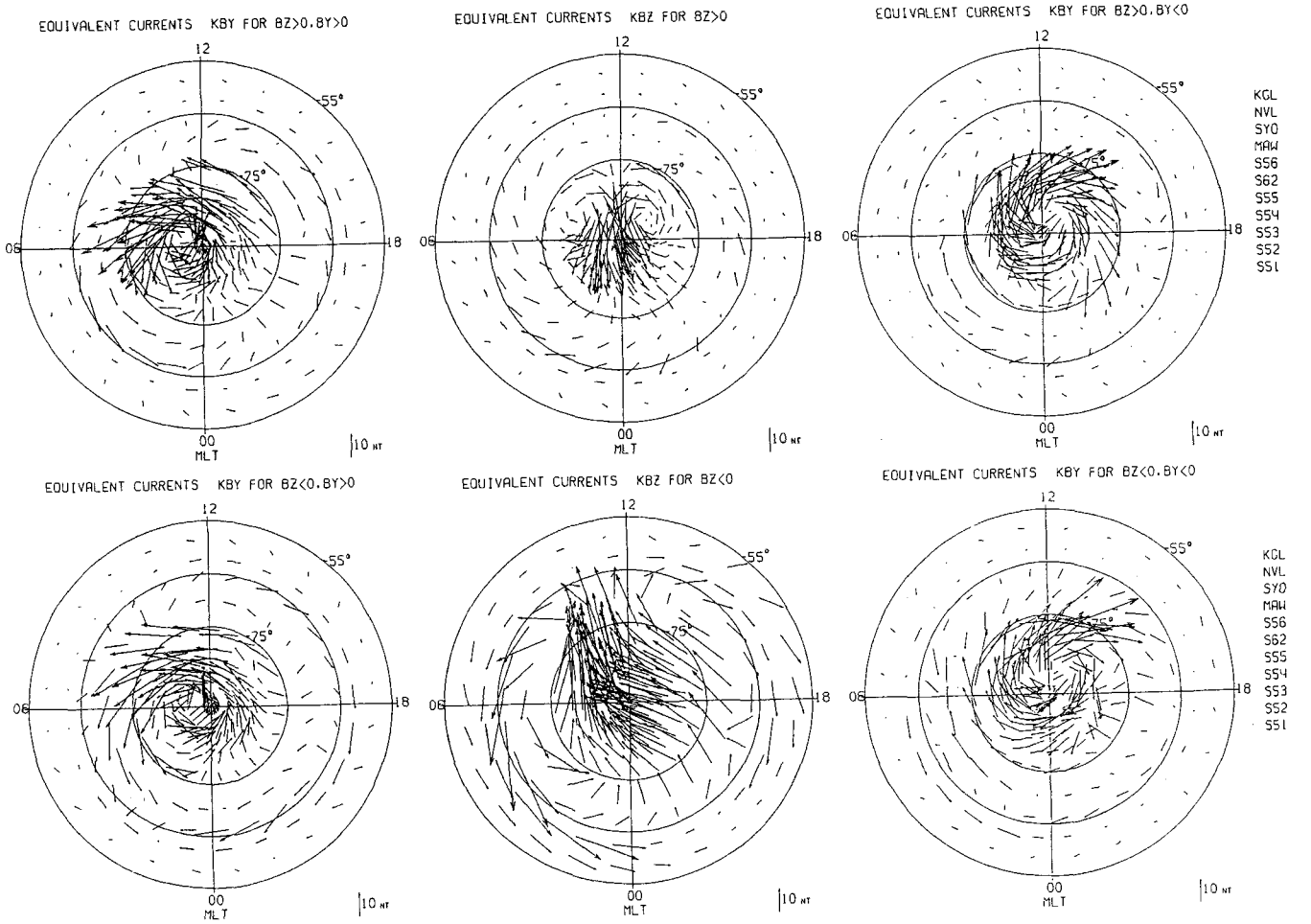


Fig. 2. "Corrected geomagnetic latitude - magnetic local time (MLT)" polar plots of the equivalent current patterns associated with the IMF for the entire southern polar region. Scale factor - amplitude of geomagnetic perturbation in proportion with the change by 1 nT of the corresponding IMF component.

SW conditions, we can plot the geomagnetic perturbation vectors as a geometric sum of these coefficients for each magnetic local time (MLT) hour. Equivalent current vectors might be obtained by simple clockwise rotation of magnetic vectors by 90°. Anticlockwise rotation by 90° produces the convection flow, on the assumption of uniform ionospheric conductivity during the summer season when entire polar cap is sunlit.

Equivalent Current Patterns

Figs 2 & 3 show the equivalent current patterns (corrected geomagnetic latitude - MLT polar plots) for the different signs of B_z and B_y. The scale factor on the figures corresponds to the change of the IMF components by 1 nT. Fig. 2 presents the entire southern polar region (above -55°) and Fig. 3 presents the southern polar cap only (above -75°). Fig. 3 contains two additional stations (MIR and S-50) which were omitted in Fig. 2 due to lack of space in the central part of figure. The upper panel shows the K_{BZ} equivalent current pattern for $B_z > 0$, and the K_{BY} (corresponding K_{By} coefficients) equivalent current patterns for $B_y > 0$ (left) and $B_y < 0$ (right sub-panels), also for $B_z > 0$. The lower panel shows the same equivalent current patterns for the $B_z < 0$ condition.

A very clear difference is seen between the patterns. The current system ($B_z < 0$)is characterized by two vortices which are centred at -73° and about 06 MLT in the morning and -68° and 15 MLT in the afternoon. At high latitudes wide transpolar currents flow along the 21–09 MLT meridian in the 00–06, 12–18 and 18–24 MLT quadrants and this current turns to the 23–11 MLT direction in the 06–12 quadrant. Exactly the same features were found in the northern polar region (Friis-Christensen & Wilhjelm 1975, Maezawa 1976, Troshichev & Tsyganenko 1979, Afonina *et al.*1980). The trans polar current, and both westward and eastward electrojets have approximately equal intensities and locations in both hemispheres. A westward electrojet flows in the morning and near-midnight sectors and has its

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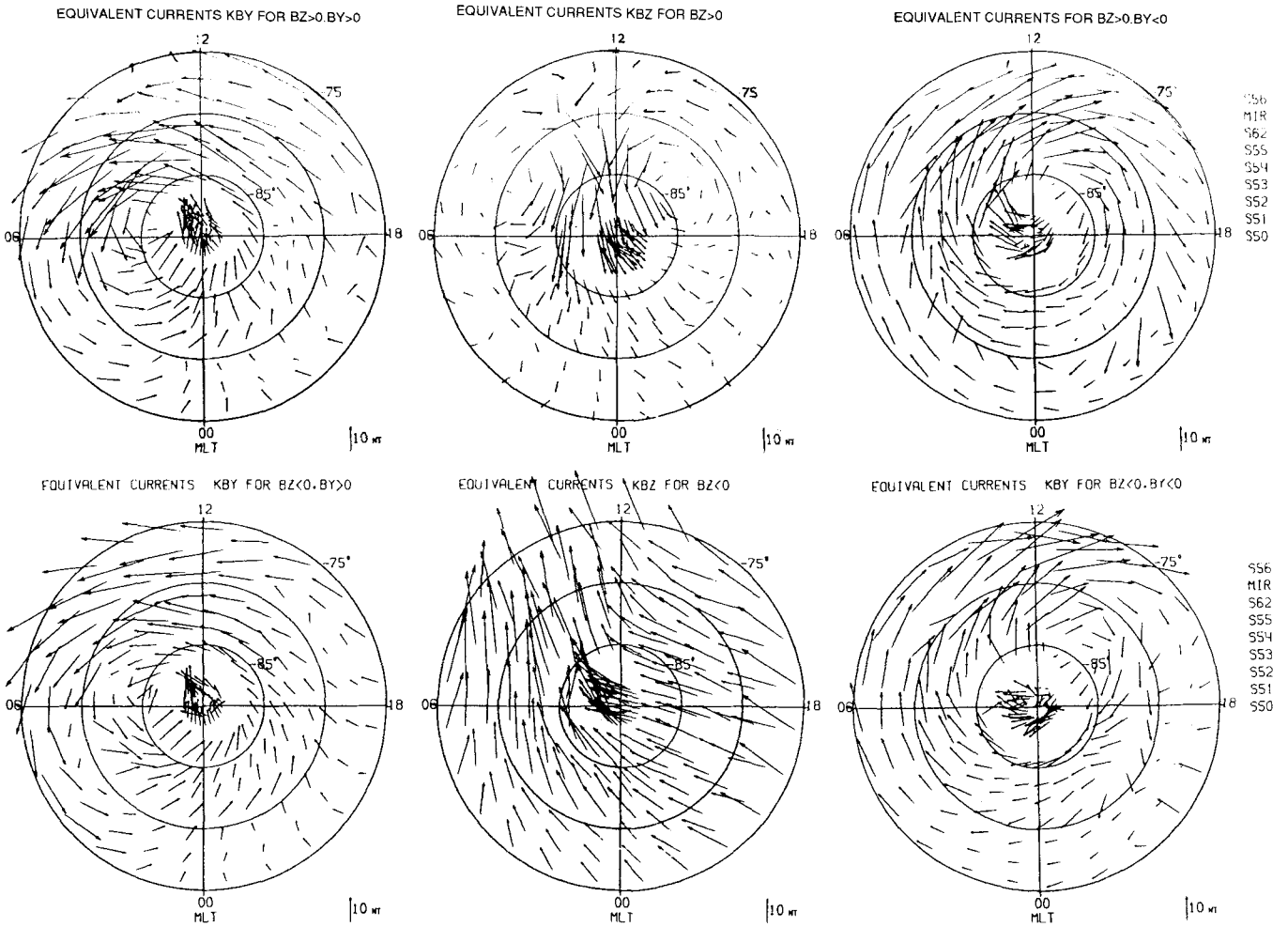


Fig. 3. As Fig. 2 polar plots for the southern polar cap only.

maximum intensity at about -66° at 03–07 MLT. Equatorward the intensity of the both electrojets decreases and falls to zero at -49.2° latitude (Argentine Islands, AIA, was subjected to regression analysis also, but the results are not presented here). In general, the southern polar region has slightly distorted K_{BZ} ($B_z < 0$) current system compared with the northern hemisphere.

The K_{BZ} ($B_z > 0$) current system also has two vortices with centres at 09 and 15 MLT and a transpolar current flowing from noon to midnight. The focus of the afternoon vortex is located at a higher latitude (-84°) than the focus of the pre-noon vortex (-80°). Closure currents of these vortices exist at auroral latitudes (between -60° and -70°). These features and the intensity of magnetic perturbations are exactly the same as for the corresponding KBZ system in the northern hemisphere (Maezawa 1976, Troshichev & Tsyganenko 1979, Afonina *et al.* 1980), but there is a difference with the $B_z > 0$ pattern reported by Friis-Christensen & Wilhjelm (1975, fig. 1). The authors of the last cited work have used a statistical (not regression) technique and their pattern might be influenced by B_y component of the IMF. The left and right panels in Fig. 2 and 3 show the K_{BY} equivalent current system for positive and negative B_y (DPY system, according to Friis-Christensen & Wilhjelm 1975). Upper and lower subpanels represent these patterns for $B_z > 0$ and $B_z < 0$. All K_{BY} polar plots are characterized by the single vortex, with a zonal current around the geomagnetic pole. According to the Svalgaard-Mansurov effect, the zonal current flows anticlockwise for $B_y > 0$ and towards the morning in the cusp region. The current has opposite direction for $B_y < 0$. Enhancement of the current intensity near noon represents the polar (cusp) electrojet. The focus of the $B_y > 0$ vortex is located near -84° and 07 MLT. A sunward current flows across the pole and the cusp electrojet has broad width and covers latitudes from -75° to -86° between 08-14 MLT, with maximum intensity at -80° to -83° for $B_z > 0$ and -78° to -81° for $B_z < 0$. Corresponding northern current patterns have the same features with a focus at +85° and 14 MLT and with the current across the pole according to Friis-Christensen & Wilhjelm (1975) and Troshichev & Tsyganenko (1979); the focus is located at the north geomagnetic pole according to Afonina *et al.* (1980).

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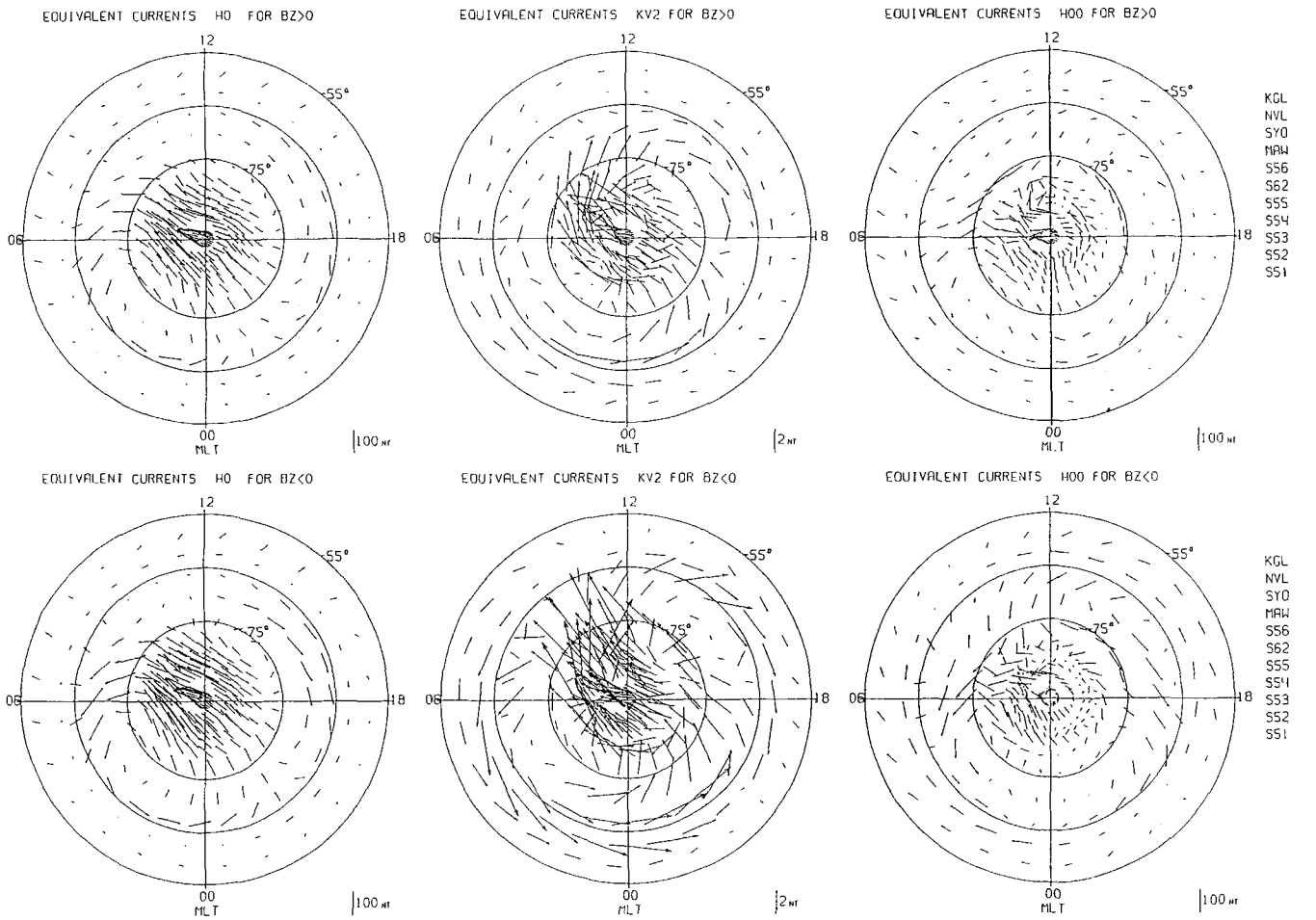


Fig. 4. Polar plots of the equivalent current patterns associated with the SW velocity and free terms of regression equations for the entire southern polar region. Scale factor for K_V^2 - amplitude of geomagnetic perturbation in proportion with the change for 100 km/h units of velocity. Scale factor for free terms - deviation around daily mean values.

The K_{BY} ($B_y < 0$) current pattern has a single vortex with a focus at -85° and 14 MLT. Current flows across the pole from dusk to dawn and the cusp electrojet is narrower (from -77° to -83°) for $B_z > 0$ than for $B_z < 0$ (from -75° to -83°). Cusp currents are more intense at noon and slightly more intense for $B_z < 0$. As it was for $B_y > 0$, the cusp electrojet covers 08-14 MLT. It is interesting to note that sunward currents across the pole have been obtained for positive B_y in the southern polar cap and for negative B_y in the northern polar cap, and, *vice versa*, dusk-dawn currents across the pole have been obtained for negative B_y in the southern hemisphere and for positive B_y in the northern hemisphere, respectively (see Friis-Christensen & Wilhjelm 1975).

Equivalent ionospheric currents for both signs of B_y exist in the entire polar cap, not only in the cusp region. Closure currents exist in the afternoon and evening sectors for $B_y > 0$ in spite of the sign of B_z and appear in the pre-noon and morning sector for $B_y < 0$ and $B_z < 0$ only. Such a feature was not found in the northern hemisphere (Friis-Christensen & Wilhjelm 1975). Figs 4 & 5 show the equivalent current patterns for H_0, K_V^2 and H_{00} (see corresponding terms and coefficients in equations (1) and (2)) for the entire polar region and polar cap respectively. The H_0 current pattern (in deviation from daily mean value) is IMF-independent (DP0, according to Troshichev 1982) and reflects the "quasi-viscous" interaction between the SW plasma flow and the Earth's magnetosphere (Levitin *et al.* 1982). This is a two-vortex system with uniform transpolar current along the 21-09 MLT meridian and weak closure currents at auroral latitudes. As in the northern hemisphere (Friis-Christensen & Wilhjelm 1975, Troshichev & Tsyganenko 1979, Afonina *et al.*1980), the morning vortex has anticlockwise rotation and is centred at -74°and 03 MLT. the afternoon vortex has clockwise rotation and is centred at -76°and 15 MLT. There is no difference in intensity of both vortices; the $H_0(B_z > 0)$ current system is about 20% less intense than the $H_0(B_z < 0)$ system.

The IMF-independent data sets for negative and positive B_z were subjected to regression analysis according to equation (2) to obtain the Kv^2 and K_nV^2 current systems. As was

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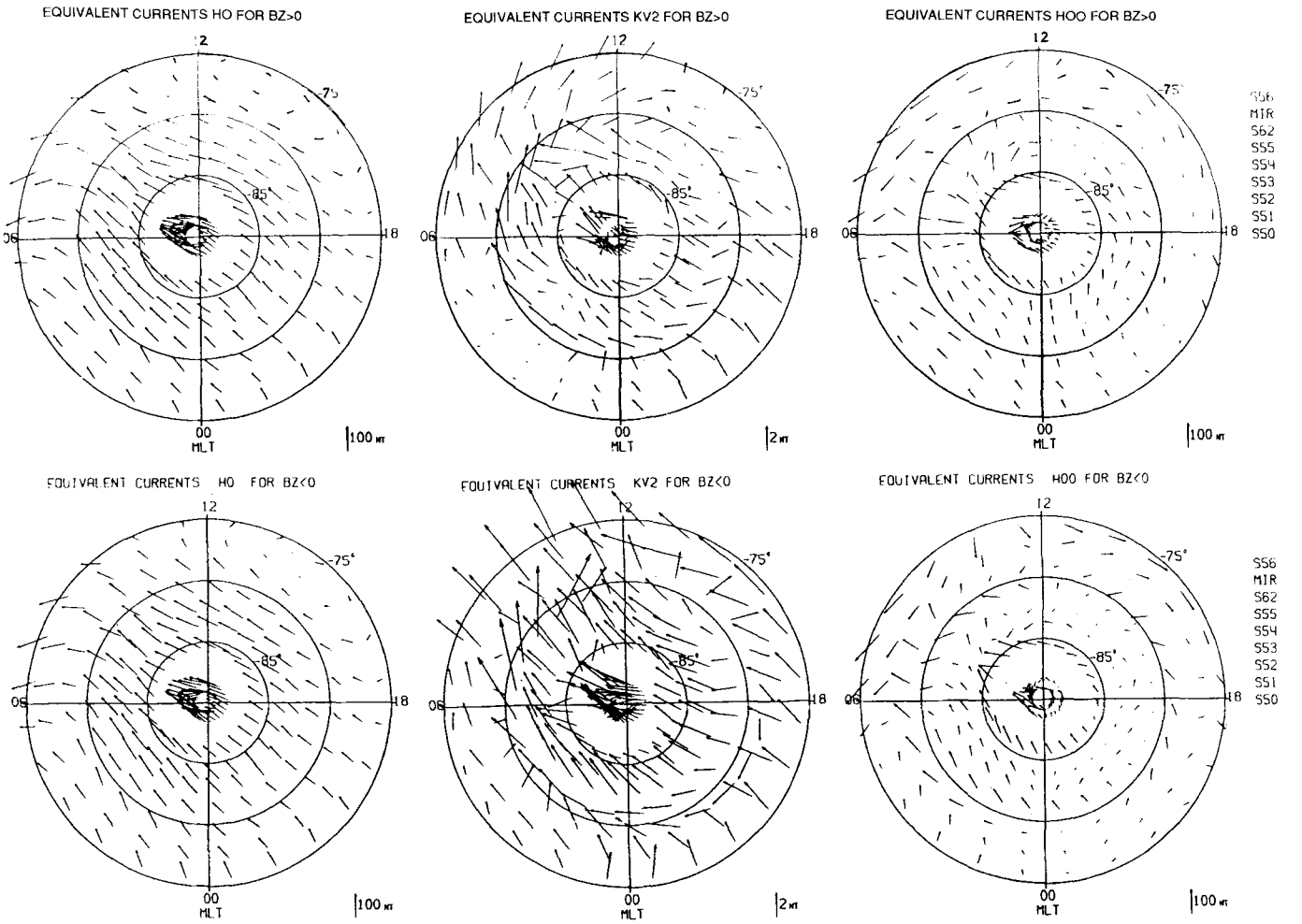


Fig. 5. As Fig. 4 polar plots for the southern polar cap only.

mentioned above, the $K_n V^2$ system was not noticeable as a regular pattern and it is not presented here. The K_V^2 system has two vortices which are centred at -75° and 03 MLT for $B_z > 0$ and -72° and 15 MLT for $B_z < 0$. Peculiar directions of the current vectors at some stations and hours are caused by the relative shortage of the SW data (Couzens & King 1986) and the weakness of the system in general (scale factor corresponds to the 100 km/h unit of the SW velocity).

The IMF and SW independent equivalent current pattern are presented in the right panel of Figs 4 & 5. With great difficulties we can recognize here two vortices between -55° and -76° in the 00-06 and 12-18 MLT quadrants with foci at -70° and -72° respectively for both signs of B_z. The intensity of the current in the vortices for $B_z > 0$ is half that for $B_z < 0$. A regular feature at auroral latitudes in both patterns is the direction of the current vectors being generally from dusk to dawn in the noon and midnight sectors. It is possible to consider this direction as an extension of the Sq current system to the pole region, but it is not so obvious. Inside the polar cap we can recognize, between -75° and -86°, regular sunward transpolar current in the night quadrants (more regular for $B_z > 0$) which turns to the morning and has very small local vectors at -84° in the afternoon. Two stations in the near-pole region follow this bend, too. Uniformity in the direction of the vectors for different stations shows that it is not an artefact; probably, the polar cap contains another kind of current source than at lower latitudes. This source might be derived only when we exclude the IMF and SW sources from the ground-based geomagnetic data.

Discussion

It has been demonstrated (Mishin *et al.* 1981, Levitin *et al.* 1982, Troshichev 1982, Friis-Christensen *et al.* 1985, Feldstein & Levitin 1986) that, by using the geomagnetic field variations at the Earth's surface, it is possible to investigate the spatial and temporal structure of the equivalent ionospheric current systems connected with the various IMF and SW parameters. In this way the regression analysis technique provides the possibility to obtain an "elementary" system, or, with knowledge of the height integrated conductivity of the high-latitude ionosphere, "elementary" cells of potential which

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correspond to definite IMF or SW parameters. The equivalent currents represent Hall currents in the E-region ionosphere, and, as these currents flow in the opposite direction to the plasma flow, the plots provide useful insight into the nature of plasma convection in the Antarctic polar cap ionosphere. Representation of the ionospheric convection patterns by the sum of "elementary" cells coincides with the three types of magnetospheric convection cells proposed by Potemra *et al.* (1984), Burch *et al.* (1985) and Reiff & Burch (1985), namely the merging cells (corresponding to $B_z < 0$ in this paper), the viscous cells ($B_z = B_y = 0$, i.e. H_0 or K_V^2) and lobe cells (controlled by B_y and $B_z > 0$). These authors and Lytsky *et al.* (1985) suppose that the central part of the polar cap should be free from the "quasi-viscous" convection flow because this part of cap connects, via geomagnetic field lines, with the central part of the tail lobes which do not suffer friction with the SW plasma.

Comparing such an approach with our results, we can conclude, however, that the ionospheric manifestation of the viscous cells (H_0 or K_V^2) appeared in the entire southern polar cap (Figs 4 & 5, left and middle panels), while the lobe cells (B_y) are extended to the auroral latitudes (Figs 2 & 3, left and right panels). This conclusion has been made earlier in the works by Troshichev & Tsyganenko (1979), Afonina *et al.* (1980) and Levitin *et al.* (1982), but the number of observatories, used in the northern polar cap, were only 4 or 5.

We have used a dense chain of 15 stations in the southern polar cap and four magnetometers were located above -85°, i.e. above the latitude of Thule in the northern hemisphere. What is new in our work is that the results of these four stations are in agreement with the other eleven regarding the expansion of the viscous cells above the entire southern polar cap, including the near-pole region.

The intensity of magnetic perturbations in the polar cap is approximately the same for H_0 and an average B_y about 3 nT. This means that, during strong positive or negative B_y, the lobe cell appears in the polar cap as a single vortex and is superposed on the transpolar flow of the viscous cells. Negative B_z (merging cells) superimposes additional transpolar flow on these patterns. Positive B_z generates the two-vortex current system, with opposite direction of transpolar current from noon to midnight. These vortices are not limited by the polar cap; they expand into auroral latitudes.

Thus, all our "elementary" cells of convection, in general, agree well with proposed schemes of Potemra *et al.* (1984) and Reiff & Burch (1985) individually. We can find an analogue in the schemes for each "elementary" equivalent current system, but the sum of these systems will be considerably different in shape from the theoretical patterns. Our "elementary" cells do not displace each other and form the four-vortex system, but superimpose on each other and keep the two-vortex system (Feldstein & Levitin 1986, fig. 12 and 13).

The merging cells ($B_z < 0$, Figs 2 & 3, middle lower panel) are practically as intense as the B_y-lobe cells (left and right panels). The transpolar current of $B_z < 0$ system have a noticeable bend which was interpreted by Maezawa (1976) as the result of the superposition of the ionospheric Hall current, directed along 00-12 MLT meridian, and equivalent currents of the 3-dimensional current system associated with the westward electrojet. This interpretation was confirmed, supposedly, when computer codes to calculate the potential, electric and magnetic fields and currents with nonuniform ionospheric conductivity were developed (Levitin *et al.* 1982, Feldstein *et al.* 1984, Friis-Christensen *et al.* 1985). In these works, the total ionospheric transpolar current is purely sunward.

We might expect that the transpolar current for $B_z > 0$ (Figs 2 & 3, middle upper panel) should be directed straight from noon to midnight, due to the absence of the westward electrojet in this case. But it is clear from the figures that the transpolar current bends here also, and, as a result, the two vortices are placed not so symmetrically as might be expected. The general dawn-dusk asymmetry of the magnetosphere might cause this.

Our results for the B_y-component are in agreement with Sondrestrom radar observations (de la Beaujardiere *et al.* 1985). There is clear evidence in the data for the east-west Hall currents in the polar cusp region whose magnetic signature on the ground is the Svalgaard-Mansurov effect of the DPY disturbance. Localization of the currents in the noon sector permits us to consider a cusp electrojet as a manifestation of the "curtain-type" pair of field-aligned currents which sandwiches the ionospheric currents and is controlled by the B_y component of the IMF. There is no manifestation of the pre-noon or afternoon field-aligned currents in this region as was proposed by Saunders (1989, fig. 9).

Westward cusp currents for $B_y > 0$ exist at all local times in the polar cap and auroral zone during the evening hours for both signs of B_z. A sharp reversal is observed in the morning hours at -70° which causes sunward currents at midnight for $B_z < 0$ and pre-midnight for $B_z > 0$. These features coincide with the scheme of Potemra *et al.* (1984) for positive B_z and B_y better than with the scheme of Reiff & Burch (1985).

The negative B_y current system is characterized by the strong eastward cusp current in the noon sector which is felt at all local times in the polar cap. There are no sunward currents in the midnight sector, the current ring is more regular and expands to -70°. Sharp reversals are observed in the morning and evening hours, with more intense closure currents for $B_z < 0$. It is clear that the convection pattern for $B_y < 0$ is not the mirror image of that for $B_y > 0$. This is contrary to the models proposed by Potemra *et al.* (1984) and Reiff & Burch (1985), but agrees with the experimental model of Friis-Christensen *et al.* (1985). Closure currents appear at auroral latitudes for both signs of B_y (see NVL, SYO, MAW), i.e. these currents may contribute some part of the geomagnetic activity into the AU and AL indices.

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Conclusions

The results described in this paper indicate that high-latitude equivalent current systems of the summer season are very similar in both hemispheres. Statistical patterns are confirmed also by the event studies during stable conditions in interplanetary space (Papitashvili *et al.* 1989, Troshichev *et al.* 1988). The fine structure of the polar cap part of the systems in the southern hemisphere permits us to conclude that viscous convection cells cover the near pole region and superimposed on the merging and lobe cells. But if we remove the influence of the IMF and SW parameters from the ground-based geomagnetic data, some peculiar features are still observed in the near-pole region. This result causes us to suggest either that, in the centre of the polar cap, there might exist some extra 3-dimensional current system which reflects the quasi-viscous interaction between the SW plasma flow and the magnetospheric tail lobes (Papitashvili 1987), or that the generation of the ionospheric current systems by the IMF and SW is non-linear. In accordance with Papitashvili *et al.* (1981), we have derived here the linear part of the interaction. Some features of the high-latitude ionospheric current systems become clear now, but some new phenomena require investigation.

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