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North-south asymmetry of the substorm intensity depending on the IMF B_Y-component

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The dependence of maximum variations of H-component negative bays at magnetic conjugate stations on a sign of the IMF B_Y-component during the substorms of small and moderate intensity with $|\Delta H|_{\max} < 750$ nT developed at $B_Z < 0$ and $|B_Z/B_Y| < 1$ has been studied. By data from Kotzebue ($\Phi = 64.5°$; $\Lambda = 249.7°$) and Macquarie Isl. ($\Phi = -64.5°$; $\Lambda = 247.8°$) observatories in the eastern hemisphere and Leirvogur ($\Phi = 65.3°$; $\Lambda = 68.2°$) and Syowa ($\Phi = -66.1°$; $\Lambda = 71.0°$) stations in the western hemisphere it is shown that at $B_Y < 0$ the absolute values of negative bays $|\Delta H|_{\max}$ are greater in the southern hemisphere and at $B_Y > 0$, on the contrary, in the northern hemisphere.

1. Introduction

It is well known that in the quasi-stationary conditions at the IMF $B_Y > 0$ the electric field in the northern polar ionosphere is similar to that in the southern polar ionosphere for $B_Y < 0$ (Heppner, 1972; Heppner and Maynard, 1987).

At the IMF B_Y different from zero between the northern and southern polar caps there is the potential difference, whose sign is defined by the B_Y sign (Leontyev and Lyatsky, 1974; Lu *et al.*, 1994). The potential difference becomes highly substantial at $B_Z/B_Y < 1$ (Lu *et al.*, 1994). In such a condition in both hemispheres the two-cell system of ionospheric convection with the asymmetric dawn and dusk vortices is observed. At $B_Y > 0$ in the northern hemisphere the dawn vortex is compressed and in the southern hemisphere the dusk vortex is compressed (Heppner and Maynard, 1987; Knipp *et al.*, 1991; Lu *et al.*, 1994). At $B_Y < 0$ the reverse picture is observed.

The potential difference between polar caps initiated by the IMF B_Y gives rise to the field-aligned current system between the hemispheres in the vicinity of day cusp (Leontyev and Lyatsky, 1974; Iijima *et al.*, 1978; Rich and Kamide, 1983; Ohtani *et al.*, 1995). In quasi-stationary conditions in the magnetosphere the field-aligned currents caused by B_Y flow on the open field lines where the resistance is considered to be large. The closed field lines are supposed to be equipotential. So on the night side a field-aligned current system does not depend on the IMF B_Y (Rich and Kamide, 1983). Currents from one hemisphere into another can be caused by ionospheric dynamo effects and seasonal differences in conductivity of the polar ionosphere in the northern and southern hemispheres (Forbes and Harel, 1989; Zakharov and Pudovkin, 1996). The influence of seasonal ionospheric conductivity variations on the field-aligned currents is also observed for non-stationary processes. Osaki *et al.* (1996) established that geomagnetic pulsation amplitudes in H- and D-components in the summer hemisphere were larger than in the winter one.

Murayama and Hakamada (1975) studied the effect of the IMF B_Y component on the electrojet intensity attracting AE-index values only for the northern hemisphere. They found the tendency of regular change of electrojet intensity depending on the sign of IMF B_Y. The authors showed that in the northern hemisphere at $B_Y > 0$ the westward electrojet was intensified and at $B_Y < 0$ it was weakened. The eastward electrojet slightly depends on the orientation of IMF B_Y. Murayama and Hakamada (1975) revealed the integral effect of dependence of electrojet intensity on the IMF B_Y. The behaviour of local current system during the substorm disturbance is not yet studied up to the present time.

On the simulation of current systems during the substorms it is usually supposed that the current branching off from the magnetotail equatorial plane into the ionosphere is divided into equal parts between the northern and southern hemispheres during the equinoxes. The distinctions can appear only due to the difference of the ionospheric conductivity in the night auroral zone (Harel *et al.*, 1981).

However, these assumptions are not obvious. It is known that the magnetic field B'_Y-component at the magnetotail equator correlates with the IMF B_Y in sign and in value. It means that the E_Z-component of solar wind electric field

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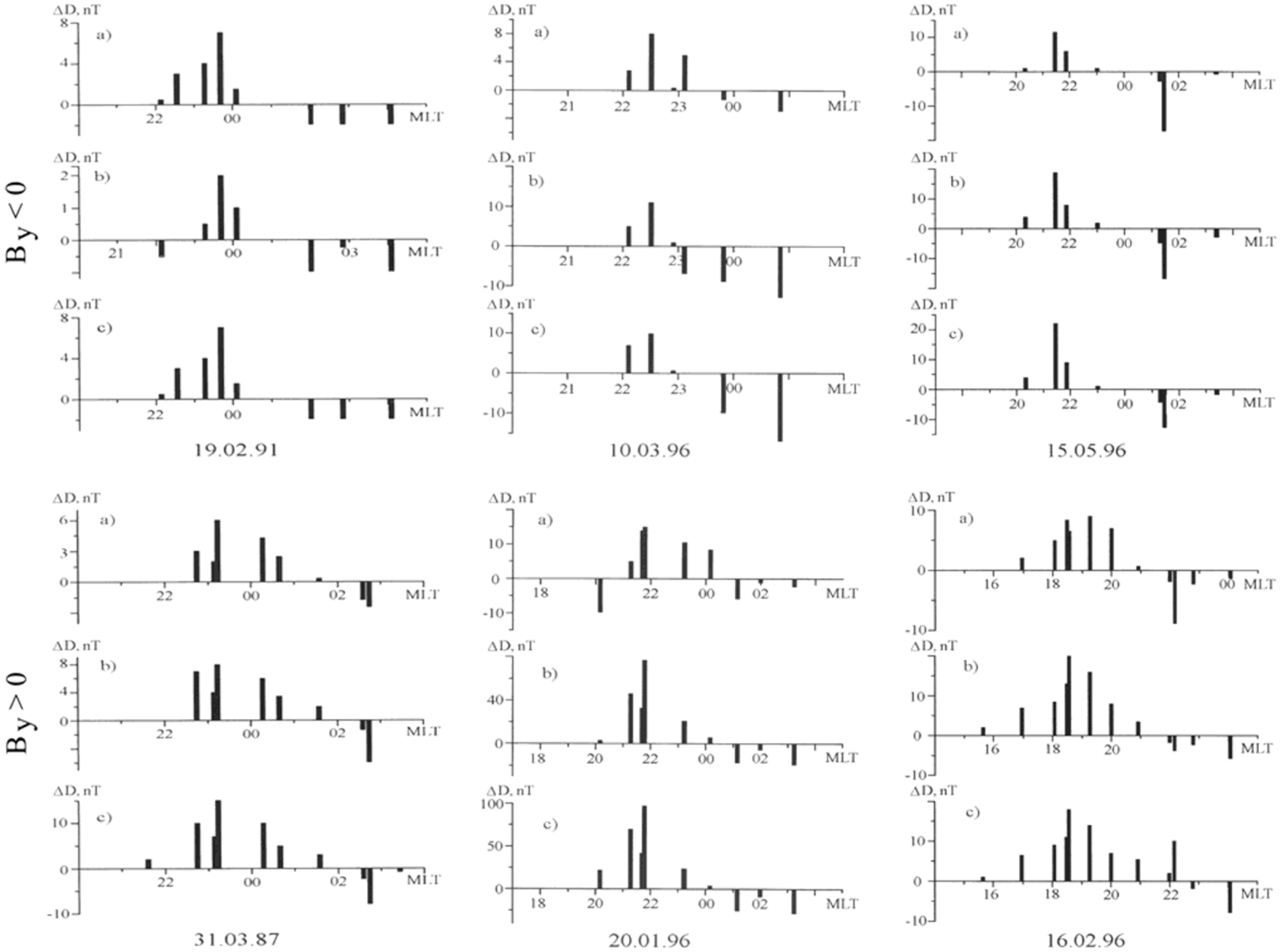

Fig. 1. Examples of longitudinal distribution of field-aligned currents in SCW at IMF $B_Y < 0$ (19.02.91, 15.05.96, 10.03.96) and $B_Y > 0$ (31.03.87, 16.02.96, 20.01.96) for three time moments $-T_0 + 5$ min (a), $T_0 + 10$ min (b), $T_0 + 15$ min (c), where T_0 is the time of substorm onset.

penetrates into closed field lines and in non-stationary conditions (for example, on the substorm expansion phase) can cause the additional field-aligned current between the hemispheres (Velichko *et al.*, 2001).

Velichko *et al.* (2001) have shown that in the northern hemisphere at $|B_Z/B_Y| < 1$ and $B_Y < 0$ the band of currents flowing into the ionosphere in the substorm current wedge (SCW) is wider than the band of currents flowing away from it and at $B_Y > 0$ it is narrower. Figure 1 presents 6 examples reflecting this regularity: three events are at $B_Y < 0$ and three events when the azimuthal IMF component is positive. Longitudinal distributions of ΔD (Fig. 1) have been constructed by magnetic data from world station network located on the North-American Continent. The station list and their coordinates are given in Table 1.

The longitude Λ_W of the western edge of region of currents flowing away from the ionosphere is defined as the middle of interval between longitudes of the nearest stations which registered $\Delta D \leq 0$ and $\Delta D > 0$. The azimuthal extent $\Delta\Lambda_W$ of the region of field-aligned currents flowing away from the ionosphere is determined as a difference $\Delta\Lambda_W = \Lambda_W - \Lambda_C$, where Λ_C is a longitude of the boundary between regions of currents flowing in the ionosphere and flowing away from it. In analogous way the authors find the azimuthal extent Λ_E of the band of field-aligned currents flowing in the ionosphere in SCW $\Delta\Lambda_E = \Lambda_E - \Lambda_C$, where Λ_E is a longitude of the eastern boundary of inflowing current band. In those events when the eastern boundary of inflowing current region in the morning sector turned out to be beyond the longitudinal station chain, the size of $\Delta\Lambda_E$ is estimated in the following way: the longitudinal distance from the center of current loop Λ_C to the station with a maximum negative value ΔD is taken as $(1/2)\Delta\Lambda_E$. The asymmetry δ in longitudinal distribution of inflowing and outflowing currents is determined as $\delta = \Delta\Lambda_W - \Delta\Lambda_E$. An error in the measurement of δ is supposed to be equal to $\sigma_\delta = 2^{1/2}\sigma$, where $\sigma = (\Delta\Lambda_W - \Delta\Lambda_E)/2n$, n is the number of stations of longitudinal chain station used to construct the longitudinal distribution of ΔD in the interval from Λ_W to Λ_E. In other words, σ is equal to the half-width of mean interval between longitudinal chain stations. The multiplier $2^{1/2}$ in the expression for σ_δ takes into account a fact that σ_δ is the error of difference. To estimate the confidence of difference in the azimuthal extent of inflowing and outflowing currents a ratio $x = \delta/\sigma_\delta$ is used. It is assumed that this ratio is of the distribution close to the normal one. Then $x = 1.7$ corresponds to the confidence coefficient $P \approx 9$. Table 2 presents the azimuthal sizes for inflowing and outflowing field-aligned current regions, differences δ, errors σ_δ and parameter x for time moments $t_1 = T_0+5$ min, $t_2 = T_0+10$ min, $t_3 = T_0+15$ min.

Table 1. List of stations.

N	Station	Geomag. long	Geomag. lat
middle latitudes			
1	Anchorage (AMU)	263.8°	61°
2	Sitka (SIT)	279.4°	60°
3	Victoria (VIC)	295.5°	54°
4	Newport (NEW)	302.7°	55°
5	Boulder (BOU)	319.1°	49.2°
6	Glenlea (GLN)	328.4°	60.4°
7	Fredricksburg (FRD)	357.6°	50°
8	Ottawa (OTT)	0.6°	56.7°
low latitudes			
9	Fresno (FRN)	303.2°	43.1°
10	Tucson (TUC)	314°	40°
11	Del Rio (DLR)	326°	39°
12	Bay St. Louis (BSL)	340°	41.5°
13	San Juan (SJG)	9.8°	30°
14	Saint Johns (STJ)	54.6°	31.2°

Table 2. Longitudinal extension and asymmetry of regions of currents flowing in the ionosphere and currents flowing away from the ionosphere in the SCW.

Date	$t - T_0$	$\Delta\Lambda_W$, deg	$\Delta\Lambda_E$, deg	$\delta = \Delta\Lambda_W - \Delta\Lambda_E$, deg	σ_δ, deg	$x = \delta/\sigma_\delta$
$B_Y < 0$						
19.02.91	5	44	69	−25	9	2.8
19.02.91	10	34	68	−34	8	4.3
19.02.91	15	43	68	−25	9	2.8
10.03.96	5	28	37	−9	6	1.5
10.03.96	10	17	56	−39	7	5.6
10.03.96	15	23	55	−32	10	3.2
15.05.96	5	46	64	−18	10	1.8
15.05.96	10	48	66	−18	10	1.8
15.05.96	15	48	66	−18	10	1.8
$B_Y > 0$						
31.03.87	5	55	29	26	7	3.7
31.03.87	10	54	25	29	7.3	3.9
31.03.87	15	63	22	41	7.3	5.8
20.01.96	5	60	45	15	8	1.9
20.01.96	10	60	45	15	8	1.9
20.01.96	15	63	45	18	8	2.3
16.02.96	5	68	43	25	4.6	3.8
16.02.96	10	86	70	16	9	1.8
16.02.96	15	102	50	52	9	5.8

It is seen from Fig. 1 and Table 2 that in all events during the substorm expansion phase there exist the regular difference in longitudinal distribution of inflowing and outflowing field-aligned currents in the SCW: at IMF $B_Y > 0$ the band of inflowing currents in the northern hemisphere is wider than the band of outflowing ones, and at $B_Y < 0$ it is narrower. In the process of development of the substorm expansion phase this regularity is invariable. The extension of currents during the substorm expansion phase is marked certainty only in the event of February 16, 1996 mainly due to the increase of $\Delta\Lambda_W$. Thus, the obtained results show that azimuthal IMF component causes the asymmetry in the lon-

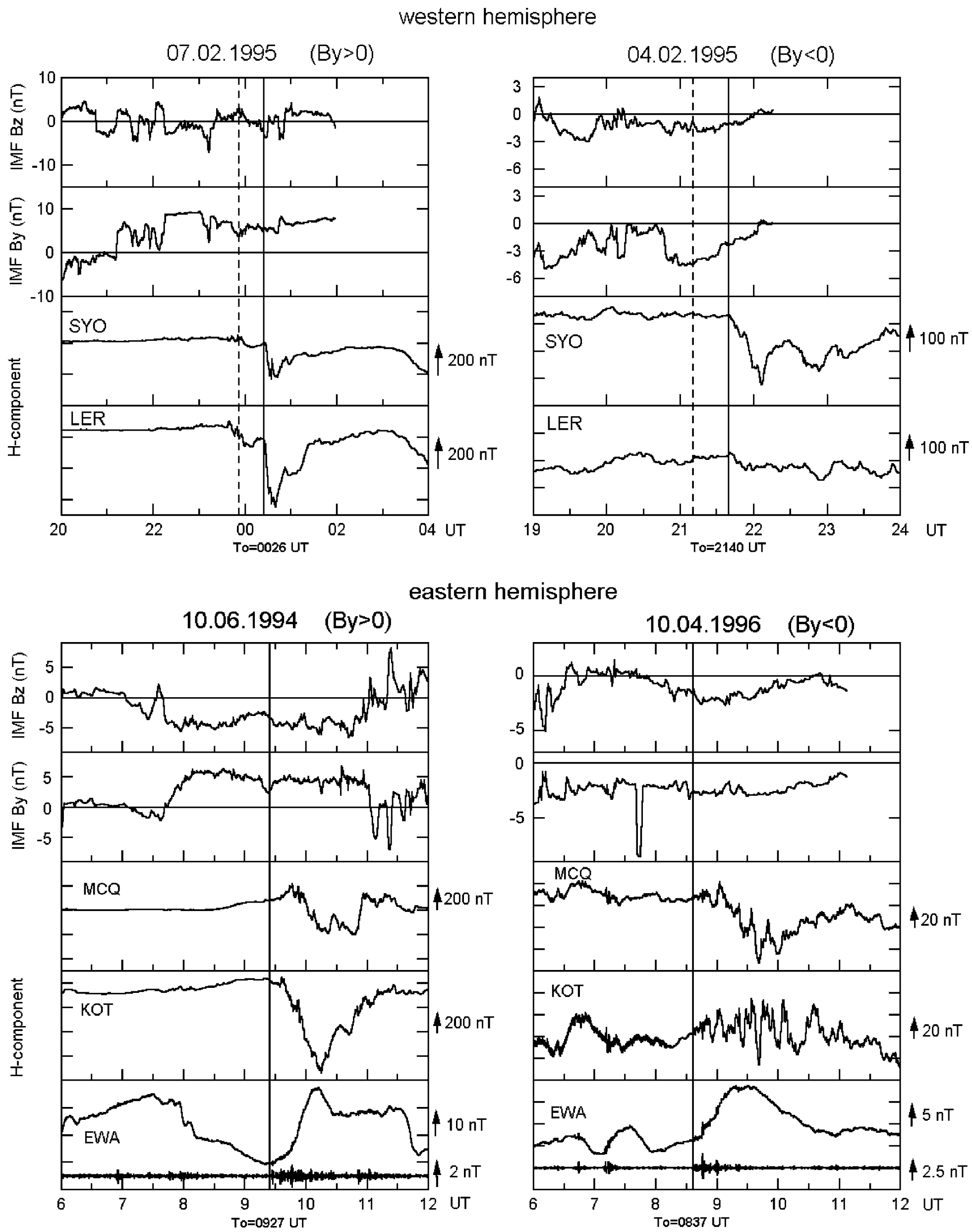

Fig. 2. Variations of the IMF and magnetic field H-component parameters in magnetic conjugate points of the Earth. The solid and dashed vertical lines indicate the substorm onset (T_o) and beginning of growth phase, respectively. Names of stations and their geomagnetic coordinates are following: Syowa (SYO; $\Phi = -66.1°$; $\Lambda = 71.0°$), Leirvogur (LER; $\Phi = 65.3°$; $\Lambda = 68.2°$), Macquarie Isl. (MCQ, $\Phi = -64.5°$; $\Lambda = 247.8°$), Kotzebue (KOT; $\Phi = 64.5°$; $\Lambda = 249.7°$) and Ewa Beach (EWA; $\Phi = 21.6°$; $\Lambda = 269.4°$).

gitudinal distribution of SCW field-aligned currents and testifies to the possibility to form potential differences in nonstationary conditions on the night side of the magnetosphere during substorm disturbances.

One can obtain such longitudinal distributions of inflowing and outflowing currents in the SCW summing the Birkeland's loop, which is symmetrical relative to the center, corresponding to $B_Y = 0$, with the current layer outflowing from the northern hemisphere ionosphere at $B_Y > 0$ and inflowing into it at $B_Y < 0$.

The aim of the present work is to show that in the certain conditions the substorms in the northern and southern hemispheres develop asymmetrically: a ratio of the amplitude of substorm disturbances in the northern hemisphere $|\Delta H|_{\max N}$ to that in the southern one $|\Delta H|_{\max S}$ depends on the IMF B_Y.

2. Criteria of Event Selection and Analysis of Substorms Observed at Two Conjugate Stations

The basis of experimental material is magnetograms from two pairs of auroral zone stations in the northern and southern hemispheres for the 1993 to 1996 period. For every pair of stations the magnetic conjugate condition is fulfilled.

The selection of events has been carried out by the geomagnetic field H-component registered at the observatory located in the southern hemisphere when during the transition from the magnetoquiet to disturbed conditions the isolated negative bays of moderate intensity have been observed. For every disturbance the bay onset moment identified as the substorm onset has been determined. The onset moment of the substorm expansion phase appearing at the ~250° geomagnetic meridian (Yumoto *et al.*, 1996) has been additionally

Table 3. List of events observed at $B_Y > 0$.

N	Date	Time, UT	B_Z	B_Y	B_Z/B_Y	$\|\Delta H\|_{\max N}$	$\|\Delta H\|_{\max S}$	A	$\|E_Z\|$
1	27.03.94	1221	−1.3	2.9	0.4	250	160	1.5	1.1
2	21.04.94	1116	−1.4	1.6	0.8	18	12	1.5	0.8
3	22.04.94	1124	−2.5	3.2	0.8	130	90	1.4	1.5
4	20.05.94	1329	−0.3	2.9	0.1	310	170	1.8	1.4
5	10.06.94	0926	−2.8	4.3	0.6	730	270	2.7	1.8
6	06.07.94	1109	−0.5	2.4	0.2	90	40	2.25	
7	17.07.94	0927	−2	3.6	0.5	410	170	2.4	2.7
8	21.07.94	1207	−4.5	5.2	0.7	210	30	7	2.4
9	22.07.94	1320	−0.1	0.6	0.2	75	30	2.5	0.2
10	15.08.94	1010	−2.1	3.6	0.6	520	170	3	1.9
11	07.02.95*	0027	−2	7.3	0.2	435	300	1.4	2.9
12	25.02.95	1207	−0.4	3.9	0.1	21	12	1.75	
13	02.09.95	1243	−1.6	2.7	0.6	45	21	2	0.8
14	12.09.95	1145	−1	2.4	0.4	170	30	5.7	1.1
15	22.11.95	1504	−2.2	3.6	0.6	180	130	1.4	1.2
16	24.04.94	1002	−1.8	2.1	0.8	115	60	1.9	0.8
17	19.07.94	0957	−1.4	2.1	0.6	270	140	1.9	1.1

Table 4. List of events observed at $B_Y < 0$.

N	Date	Time, UT	B_Z	B_Y	B_Z/B_Y	$\|\Delta H\|_{\max N}$	$\|\Delta H\|_{\max S}$	A	$\|E_Z\|$
1	15.12.93	1228	−1.7	−11.6	0.14	440	480	0.91	
2	16.12.93	0933	−3.96	−11.5	0.34	220	430	0.51	6.3
3	15.01.94	1229	−1.2	−3.8	0.31	280	380	0.73	2.4
4	16.01.94	1104	−1.2	−4.9	0.24	300	525	0.57	3.1
5	18.02.94	0939	−1.2	−1.3	0.9	120	140	0.85	0.5
6	20.02.94	1045	−1	−1.7	0.6	175	220	0.8	0.9
7	20.03.94	1055	−0.17	−4.15	0.04	230	275	0.8	1.9
8	08.01.95*	0107	−0.85	−2.26	0.37	148	192	0.7	1.4
9	18.01.95*	2210	−0.14	−3.8	0.04	167	241	0.7	1.9
10	04.02.95*	2131	−1.85	−4.26	0.44	65	271	0.24	2.4
11	06.02.95*	0020	−0.81	−2.22	0.36	128	272	0.47	0.8
12	16.03.95	1230	−1.1	−3.4	0.32	220	250	0.9	1.6
13	26.06.95*	0242	−1.9	−10.6	0.2	494	708	0.7	5.4
14	27.07.95*	0130	−3.4	−4.6	0.74	370	450	0.8	1.7
15	30.09.95	1055	−1.7	−3	0.56	80	95	0.84	0.9
16	22.11.95	1109	−0.7	−4.4	0.17	70	75	0.9	1.5
17	05.03.96*	0148	−1.1	−3.2	0.34	25	250	0.1	1.4
18	06.03.96	0954	−1.9	−3.5	0.54	120	195	0.6	1.4
19	10.04.96	0837	−1.6	−2.3	0.7	30	60	0.5	1.1
20	13.04.96	1313	−1	−2	0.5	125	75	1.7	0.8

revised in time of the beginning of Pi2 irregular geomagnetic pulsations.

The level of geomagnetic activity before the substorm for the 1993–1994 seasons is controlled by current values of K_P-, AU-, AL-, AE-indices but for the 1995–1996 seasons—only by values of K_P-index. In most cases, the mean level of geomagnetic disturbance does not exceed $K_P \leq 2$.

By 1-min data aboard the IMP-8 and Wind satellites the mean values 30 min before T_O values of the IMF B_Y- and B_Z-components, solar wind speed V_X and the electric field

$E_Z = -V_X \times B_Y$ have been calculated. The lists of events, magnetic bay amplitudes $|\Delta H|_{\max N}$, $|\Delta H|_{\max S}$, their ratio $A = |\Delta H|_{\max N}/|\Delta H|_{\max S}$ and B_Z-, B_Y-, E_Z-components are given in Tables 3 and 4. The cases observed at stations of the western hemisphere are marked by an asterisk.

Figure 2 presents an example of 4 events illustrating the revealed regularities of the asymmetric distribution of substorm intensity in the geomagnetic field: for the western hemisphere at $B_Y > 0$ on February 7, 1995 and at $B_Y < 0$ on February 4, 1995; for the eastern hemisphere at $B_Y > 0$ on June 10, 1994 and at $B_Y < 0$ on April 10, 1996.

From Fig. 2 it is seen that for substorms on February 7, 1995 and June 10, 1994 which develop at $B_Y > 0$ the negative bay amplitude in the H-component is larger in the northern than southern hemisphere. At $B_Y < 0$ in events of February 4, 1995 and April 10, 1996 the intensity of westward electrojet is larger in the southern hemisphere.

3. Discussion

From Fig. 2 and Tables 3 and 4 it is seen that the IMF B_Y-component causes the regular asymmetry in the substorm intensity in the northern and southern hemispheres. At $B_Y > 0$ the amplitude $|\Delta H|_{\max}$ of variations of geomagnetic field H-component is larger in the northern hemisphere, and at $B_Y < 0$ it is larger in the southern hemisphere. Since this regularity exists during all seasons, it cannot be explained only by seasonal variations of the ionosphere conductivity.

The IMF B_Y-component could cause the deformation of closed field lines and the disruption of magnetic conjugation of points where there were magnetic observatories. The stations could be at different distances from the substorm center and had the different amplitudes. However, because the location of the substorm center relative to one station was accidental then at equal signs of B_Y the second observatory might be with equal probability nearer as well as farther than the first observatory relative to the center of the substorm expansion phase and a ratio of amplitudes might be larger as well as less than 1. Only in the April 13, 1996 event the above regularity was not found.

The regular asymmetry of longitudinal distribution of field-aligned current amplitude in the SCW is shown by Velichko *et al.* (2001). At $B_Y > 0$ in the northern hemisphere the band of field-aligned currents outflowing from the ionosphere is broader than for the inflowing currents, and at $B_Y < 0$ it is on the contrary. At $B_Y > 0$ ($B_Y < 0$) the asymmetric SCW can be presented like the superposition of the symmetric Birkeland loop and a band of field-aligned currents $J_{\parallel}$ outflowing (inflowing) from the northern hemisphere ionosphere. The field-aligned currents caused by the IMF B_Y flowing along the open field lines of the magnetotail have the identical direction (Leontyev and Lyatsky, 1974). Apparently, on the substorm expansion phase, when the field-aligned resistance in field tubes passing through the SCW becomes finite, then between the auroral ionospheres of the northern and southern hemispheres the finite potential difference appears and the field-aligned currents flow from the northern to southern hemisphere at $B_Y > 0$ and in the inverse direction at $B_Y < 0$. The current outflowing from the ionosphere causes the additional electron precipitation, the increase of ionosphere conductivity and the rise of the geomagnetic variation amplitude.

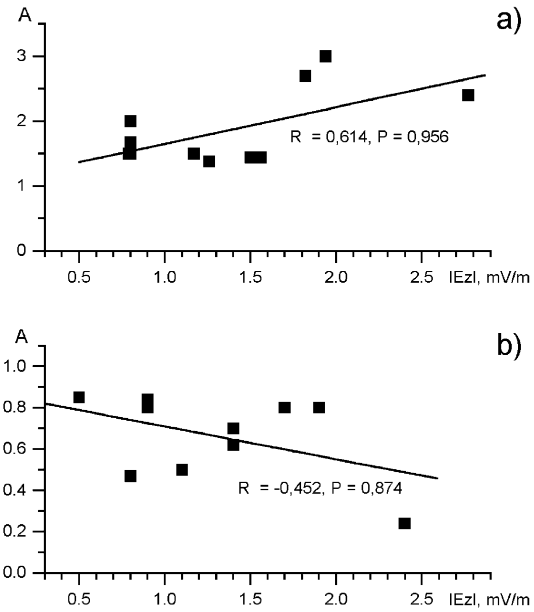

Fig. 3. The dependence of a ratio of the geomagnetic bay amplitudes A on $|E_Z|$ at restrictions: $0,35 < |B_Z/B_Y| < 1$, $|E_Z|$ 3 mV/m, a) $B_Y > 0$; b) $B_Y < 0$. R is the correlation coefficient, P is the probability of the linear relation between A and $|E_Z|$.

Based on a sampling of events (Tables 3 and 4) we have failed to establish the correlation dependences for a ratio of bay amplitudes in the northern and southern hemispheres on B_Y, B_Z, B_Z/B_Y parameters. Most likely, physical processes in the magnetosphere are not simple linear functions of these parameters. However, if we narrow down the variation limits of parameters then the dependence of the ratio A on $|E_Z|$ will be manifested. At $B_Y > 0$ the value A decreases with the rise of $|E_Z|$ and at $B_Y < 0$ it increases (Fig. 3).

4. Conclusion

We used magnetic data of two conjugate stations to estimate the influence of the IMF B_Y on the character of substorm expansion phase development. The intensity of substorm disturbances in two hemispheres has been determined and differences of negative bay amplitude in the magnetic field H-component have been compared with values of the IMF B_Y. Our finding that by measurements of the H-component in the magnetic conjugate points during weak and moderate substorms in the conditions $B_Z/B_Y < 1$ in all seasons the ratio $A = |\Delta H|_{\max N}/|\Delta H|_{\max S} > 1$ at $B_Y > 0$ and it <1 at $B_Y < 0$.

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