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DYNAMICS OF FIELD-ALIGNED CURRENTS IN TWO HEMISPHERES DURING A MAGNETOSPHERIC STORM FROM MAGNETOGRAM INVERSION TECHNIQUE DATA

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Abstract. We continue to study the physical processes occurring during the August 17, 2001 magnetospheric storm by analyzing the dynamics of the intensity of field-aligned currents (FACs) in Iijima—Potemra Region 1 in the polar ionospheres of two hemispheres, using the modernized magnetogram inversion technique. The results obtained on the dynamics of the FAC asymmetry of two types (dawn–dusk and interhemispheric), as well as the previously obtained regularities in the behavior of Hall currents and polar cap boundaries depending on the large azimuthal component of the interplanetary magnetic field (IMF), observed during the storm, and the seasonal behavior of the conductivity are consistent with the open magnetosphere model and with satellite observations of auroras in two hemispheres. We have shown that the weakening of the asymmetry of two types in the FAC distribution during substorms in the storm under study occurs almost completely in the winter hemisphere and is much weaker in the summer one. We associate this phenomenon with the predominance of the effect of long-term exposure to the azimuthal IMF component in the sunlit polar ionosphere of the summer hemisphere over the substorm symmetrization effect of the night magnetosphere. A symmetrization effect of the polar cap and FACs, created by the solar wind pressure pulse at the end of the storm, is observed. We propose a qualitative explanation of this effect.

Keywords: polar cap, field-aligned currents, magnetospheric storms and substorms, azimuthal component of the interplanetary magnetic field, dawn–dusk and interhemispheric asymmetries.

INTRODUCTION

An important line of research into substorm processes is the analysis of electric field and current dynamics in the high-latitude ionosphere, where during magnetospheric substorms and storms we can observe energetic electron precipitation and related intense auroras and enhancements of ionospheric conductivity in the E layer. Calculation and study of ionospheric electric fields and currents are the traditional task of the magnetogram inversion technique (MIT). MIT, according to data from the global network of ground magnetometers, provides time series of large-scale spatial distributions of convection systems, ionospheric and field-aligned currents, magnetic flux through the polar cap, and a number of other parameters characterizing magnetospheric-ionospheric processes under quiet and disturbed conditions [Mishin, 1990]. Because of the small number of stations in the Southern Hemisphere, such an analysis with MIT is usually performed using data only from Northern Hemisphere observatories. To study the substorm dynamics in the Southern Hemisphere, Mishin et al. [2011, 2019] have proposed a virtual model of the global electric circuit of the magnetosphere — ionosphere system in the two hemispheres. The model uses data on two events recorded only in the Northern Hemisphere, but during different seasons (winter and summer). The winter (northern) and summer (southern) ionospheres are connected in parallel to an external generator in the magnetosphere. Furthermore, it is assumed that between the ionospheres is an additional connection through the partial ring current [Mishin et al., 2011]. Due to the difference between conductivities in the summer and winter hemispheres, we can predict the presence of asymmetry in the distribution of FACs of two types at a time: dawn–dusk and interhemispheric, which is similar to that the open magnetosphere model and observations assume, but in terms of another factor — the azimuthal component of the interplanetary magnetic field (IMF). To overcome the difficulties in the virtual model caused by data from only one hemisphere, in [Lunyushkin et al., 2019] we have examined the dynamics of horizontal ionospheric Hall currents and polar cap (PC) boundaries simultaneously in two hemispheres, using updated MIT in the uniform ionospheric conductivity approximation. We have shown the convection systems in the two hemispheres are, in principle, similar and intensities of Hall currents are higher in the summer hemisphere, which is attributed to higher wave (driven by solar photons) conductivity. In that work, we focused on the dynamics of ionospheric convection and PC boundaries. In particular, we have established that their dynamics is consistent with the open magnetosphere model [Cowley, 1981; Cowley, Lockwood, 1992] depending on the strong IMF component B_y>20 nT observed during the long interval of the magnetic storm on August 17, 2001. As a follow-up to our previous work [Lunyushkin et al., 2019], this paper addresses the question about dynamics of large-scale field-aligned currents in two hemispheres during the magnetospheric storm occurring on August 17, 2001 at 11–24 UT. The question is crucial for physics of magnetospheric substorms. We also analyze the effect of the solar wind dynamic pressure enhancements and IMF component decrease, observed at the end of the storm, on FAC dynamics, which was outside the scope of our previous work.

SOLAR WIND AND GEOMAGNETIC ACTIVITY PARAMETERS

The updated MIT and the behavior of solar wind parameters, geomagnetic activity indices, and the magnetic flux through PC during the August 17, 2001 magnetospheric storm have been described in [Lunyushkin et al., 2019]. We, therefore, plot variations of these parameters for 10:40–24:00 UT (Figure 1) without any detailed description. We can see that the geomagnetic storm features a strong IMF azimuthal component B_y≥20 nT. Lunyushkin et al. [2019] have shown that the B_y effect is in fact manifested in the mirror displacement relative to the noon meridian of the dayside throats of ionospheric convection in different hemispheres, which is theoretically expected in the open magnetosphere model [Cowley, 1981; Cowley, Lockwood, 1992], as well as in the displacement of the PC center of gravity in the dusk—dawn direction in the Northern Hemisphere and in the opposite direction in the Southern Hemisphere. These findings are consistent with the optical observations of auroras [Østgaard et al., 2018], made simultaneously by satellites in two hemispheres at 16:00–19:00 UT. Data on the dynamics of auroral oval and PC boundaries in two hemispheres has been obtained from field-aligned current distribution maps, which enable us to identify boundaries of their regions [Lunyushkin, Penskikh, 2019] and to monitor the substorm dynamics. In this paper, from FAC densities and boundaries of three Iijima—Potemra regions we have calculated total current intensities in each region for downward ("+") and upward ("–") FACs. As a result, we obtained time variations of current intensities in each of the three FAC regions for both hemispheres during the August 17, 2001 geomagnetic storm. Below, we restrict the analysis to the dynamics of region 1 FAC pair (Figure 2) in both hemispheres since it is precisely through the pair of these currents that the magnetospheric generator feeds the northern and southern polar ionospheres [Mishin et al., 2011]. The region 1 FAC intensity is approximately equal to the sum of region 2 and 0 FAC intensities (I_{R1}≈I_{R2}+I_{R0}) both in dawn and dusk sectors of the ionosphere [Kurikalova et al., 2018]. Proceed to the comparative analysis of FAC dynamics in region 1.

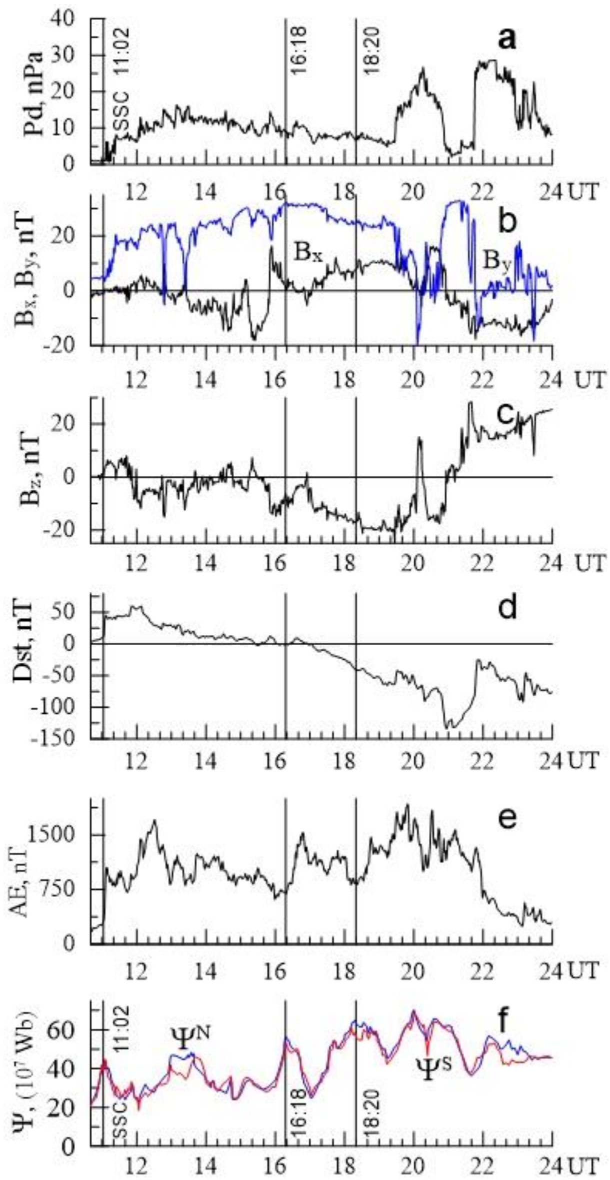

Figure 1. Variations in SW pressure P_d (*a*); IMF components B_x, B_y, B_z (*b*, *c*); ring current (*d*) and auroral activity *AE* indices (*e*); magnetic flux (*f*) through PC of the Northern (Ψ_N, blue line) and Southern (Ψ_S, red line) hemispheres during the August 17, 2001 magnetic storm. Vertical lines indicate onsets of the substorm expansion phase

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Comparing intensities of downward (I_{R1+}) and upward ($I_{R1–}$) FACs in region 1 (Figure 2) shows the inequality I_{R1+}>$I_{R1–}$, which corresponds to the dawnward PC expansion observed that time [Lunyushkin et al., 2019], as predicted by the open magnetosphere model for the Northern Hemisphere. In the dawn sector, the FAC intensity ratio between the Northern (N) and Southern (S) hemispheres is as high as ≥2, whereas in the dusk sector the ratio is slightly greater than 1, except for several short intervals between substorm activations. As evidenced by the comparison between FAC intensity variations in the dawn and dusk sectors (with respective region 1 downward and upward FACs located there), in

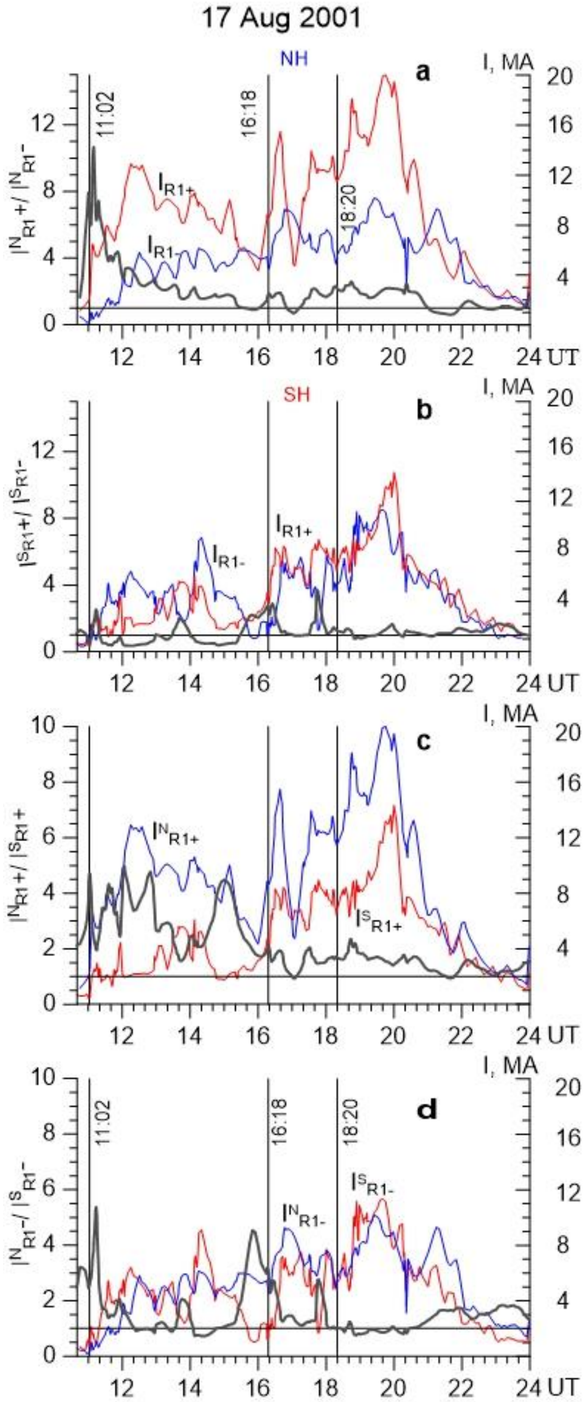

Figure 2. Variations in region 1 FAC intensities during the storm in two hemispheres: downward (I_{R1+}, dawn, red line) and upward (I_{R1-}, dusk, blue line) FAC in the Northern (*a*) and Southern (*b*) hemispheres and their ratios (black line); comparison between FAC intensities (*c*, *d*) I_{R1+} and I_{R1-} in the Northern (blue curve) and Southern (red curve) hemispheres and their ratios (black line)

the N hemisphere the dawn–dusk inequality/asymmetry in the region 1 FAC intensities is much greater than in the S hemisphere (panels *a*, *b*, Figure 2). In the Southern Hemisphere, the inequality sign at 11:00–15:30 UT reversed ($I_{R1+} < I_{R1-}$), which corresponds to the effect of the IMF component $B_y \geq +20$ nT manifesting itself in the PC boundary expansion and in corresponding amplification of FAC on the dusk side. The subsequent substorms (with the expansion phase onsets at 16:18 and 18:20 UT) led to a complete and long-term disappearance of the dawn–dusk asymmetry in the S hemisphere, and only to a short-term (around 19:00 UT) weakening of this asymmetry in the N hemisphere. Then, immediately after 19 UT, the effect of hydrodynamic shock was observed: a sharp increase in P_d with simultaneous weakening of all IMF components caused a symmetric compression of the dayside magnetosphere and PC expansion in both hemispheres with a corresponding increase in magnetic fluxes in them and a simultaneous rapid growth in the *AE* indices (Figure 1) and region 1 FAC intensity (Figure 2), which was stopped by a short strengthening of northern IMF at around 20:10 UT. The noted hydrodynamic shock did not cause the disappearance of the dawn–dusk FAC asymmetry in the Northern Hemisphere, but caused it in the Southern Hemisphere.

A significant consequence of this shock was a complete symmetrization of PC, manifested in the coincidence of their configurations in both hemispheres (Figure 3). The second P_d pulse (21:30 UT) observed after its first pulse was even stronger, but caused no FAC and *AE* amplification.

DISCUSSION

To interpret the above dynamics of the interhemispheric asymmetry in FAC development, we give additional data on the dynamics of terminators in both hemispheres and related polar cap and auroral zone illumination. As follows from [Lunyushkin et al., 2019], the PC illumination was virtually complete in the Northern Hemisphere and was absent in the Southern Hemisphere. Checking the position of the terminator from

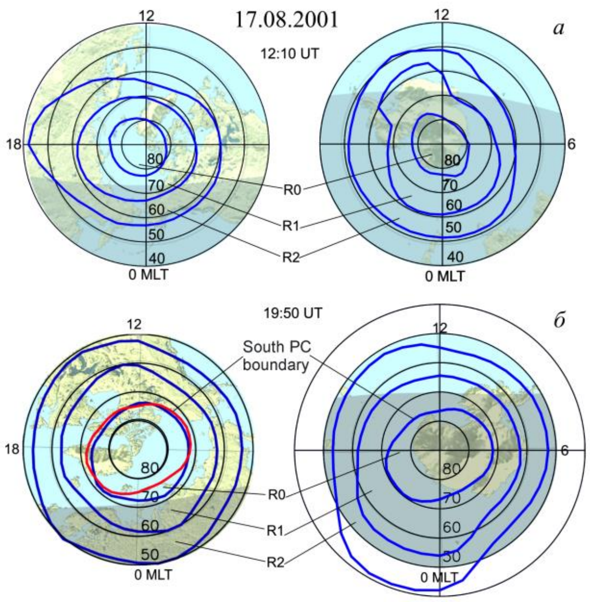

Figure 3. Position of the terminator (shadow boundary) and boundaries of FAC regions (thick blue lines) in the Northern (left) and Southern (right) hemispheres at 12:10 UT (*a*) and 19:50 UT (*b*). The outer contour of blue lines traces the boundary of FAC region R2; the middle contour shows the boundary between FAC regions R1 and R2; in the center is the polar cap (the northern boundary of FAC region R1). Coordi-

nates: geomagnetic latitude – magnetic local time (MLT) data posted on the website [http://supermag.jhuapl.edu] has shown the same picture: southern PC throughout 12–20 UT was in an unlit (shaded) region, and northern PC was in a sunlit region (Figure 3). FAC regions 1 and 2 surrounding PC were therefore much more illuminated in the summer (Northern) hemisphere than in the winter (Southern) one.

Accordingly, the main contribution to the region 1 total FAC intensity in the summer hemisphere is made by daytime FAC region 1, closed by ionospheric Pedersen currents in the region of higher wave conductivity. Thus, the high wave conductivity of the auroral ionosphere in the summer hemisphere yielded, in general, higher FAC intensities as compared to FAC in the winter hemisphere (as well as ionospheric Pedersen and Hall currents [Lunyushkin et al., 2019]). While in this paper we apply MIT in the uniform ionospheric conductivity approximation, this finding is quite reasonable as conditioned by the presence of implicit wave conductivity in equivalent currents generating a field of ground geomagnetic variations, which is initial for MIT. The wave conductivity effect described above and its explanation are consistent with the results from [Laundal et al., 2016]. The ambiguous behavior of I_{R1+}/I_{R1-} in both hemispheres is associated with the presence of the strong azimuthal component B_y, which causes FAC amplification in the dawn sector of the winter hemisphere and in the dusk sector of the summer hemisphere. The wave conductivity in the Southern Hemisphere being much lower than in the Northern Hemisphere in the event we analyze, at first glance no significant dawn–dusk asymmetry due to the IMF B_y effect takes place in the Southern Hemisphere. A careful analysis, however, shows the presence of asymmetry of $I_{\mathrm{R1+}} \leq 0.5\, I_{\mathrm{R1-}}$ in the Southern Hemisphere in the interval 11:20–15:40 UT (Figure 2, *b*), except for three short intervals between substorm disturbances (at around 14, 16, and 18 UT) when there was an opposite asymmetry. We can therefore say that the development of substorms leads to the disappearance of the dawn–dusk asymmetry (eliminates the IMF B_y effect) in the FAC distribution in the Southern Hemisphere. The same is true of the interhemispheric asymmetry, i.e. $I^N_{\mathrm{R1-}} / I^S_{\mathrm{R1-}}$ variations in the dusk sector (Figure 2, *d*). Thus, the IMF B_y effect (FAC amplification in the dusk sector) compensates for the attenuation of these currents in the Southern Hemisphere because of low illumination. In the dawn sector of the Northern Hemisphere there is no complete symmetrization since both factors (B_y and high illumination) provide here a large amplification of FAC, and the symmetrization in the magnetotail during the substorm expansion phase is mainly manifested on the night side (Figure 2, *c*). A short-term symmetrization in the dawn sector between FACs in the two hemispheres ($I^N_{\mathrm{R1+}} / I^S_{\mathrm{R1+}} \rightarrow 1$) results from the strong substorm expansion phase around 17:00 UT.

The effect of strong P_{d} pulse impact, mentioned at the end of the previous section, occurred simultaneously with a decrease in the IMF azimuthal component and with an increase in geomagnetic activity and FAC amplification, and their symmetrization. Further increase in FAC and development of the substorm expansion phase were interrupted by a sharp northward IMF pulse. To explain this phenomenon of symmetrization, we suggest the following scenario: a sharp increase in pressure in the presence of the southward IMF component and minimization of non-radial IMF components produce a symmetrical hydrodynamic shock, which compresses the magnetosphere symmetrically both on the day side and on flanks of the magnetosphere. Increasing pressure in the magnetotail also causes compression of the neutral layer, reconnection, and onset of the substorm expansion phase. Reconnection in the magnetotail reduces there the asymmetry in magnetic and plasma pressure distribution [Østgaard et al., 2018]. As a result, we can see that PC configurations in two hemispheres are equal (Figure 3, *b*, left), and not only their areas, as it was before the P_{d} pulse. An even stronger pulse (~22:00 UT) observed after the first P_{d} pulse (19:20 UT) caused no geomagnetic activity enhancement, and was accompanied by FAC attenuation and a decrease in geomagnetic activity as a whole, and by the end of the storm. We attribute this to the predominance of northward IMF during that period (see Figure 1). If B_y had continued to prevail during the second pulse, it would have caused a burst of activity again (Parkhomov et al., 2005].

Let us now compare our findings with the virtual global model. The conclusions that the FAC magnitude in the summer hemisphere is higher than in the winter one are consistent as they follow from Ohm's law for the electric circuit with paralleled loadings-ionospheres. Note, however, that the global virtual model of electric circuit of the magnetosphere and two ionospheres [Mishin et al., 2011, 2019] deals with FAC intensities in mesoscale cells on the night side. Direct comparison of our results with this model is, therefore, not quite correct because above we have considered intensities in the entire FAC regions, including their day side. Hence we can talk about comparison in the summer hemisphere, where FAC is amplified in the dawn sector, which is consistent with the predictions of the virtual model. In this event, nonetheless, this amplification might have been caused only by the positive IMF component B_y. That is why these results, although consistent with the findings of this model, cannot confirm them. It is necessary to analyze events with oppositely directed azimuthal field or without it ($B_y \leq 0$), as well as to delve into the dynamics of intensities in mesoscale cells of FAC on the night side, taking into account the FAC system rotation during a substorm observed in [Mishin et al., 2019].

RESULTS

1. We have shown that region 1 FAC intensities in the summer hemisphere exceed those in the winter hemisphere, which corresponds to the significant difference between their illumination and hence between their conductivities in two polar ionospheres.

2. The sign of inequality between FAC intensities in the dawn and dusk sectors changes when passing from the Northern Hemisphere to the Southern one, according to the known effect of the IMF azimuthal component.

3. Development of substorms reduces the FAC dawn–dusk asymmetry, which almost completely disappears in the winter hemisphere.

4. We attribute the weak effect of symmetrization in the summer hemisphere to the strong effect of IMF B_y in well-lit daytime sectors of FAC regions whose contribution to FAC intensity dominates over the contribution of the nighttime regions prone to the symmetrization effect.

5. The sharp rise in geomagnetic activity, FAC intensity, and the weakening of their asymmetry, as well as coincidence between PC configurations in both hemispheres around 20:00 UT are likely to result from the symmetric compression of the magnetosphere by the strong solar wind pressure pulse.

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