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DISTURBED MAGNETOSPHERE ON NOVEMBER 7–8, 2004 AND VARIATIONS OF COSMIC RAY CUTOFF RIGIDITY: LATITUDE EFFECTS

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Abstract. We have studied the latitude behavior of cosmic ray cutoff rigidity and their sensitivity to B_z and B_y components of the interplanetary magnetic field and geomagnetic activity indices *Dst* and K_p for different phases of the November 7–8, 2004 strong magnetic storm. Cutoff rigidities have been calculated using two methods: the spectrographic global survey method in which the cutoff rigidity is determined from observational data, acquired by the neutron monitor network, and the method in which particle trajectories are calculated numerically in a model magnetic field of the magnetosphere. We have found that the sensitivity of observed cutoff rigidities to *Dst* changes with latitude (threshold rigidity of stations) is in antiphase with changes in the sensitivity to B_y. During the recovery phase of the storm, the D_{st} correlation with B_y is significantly greater than that with B_z, and the K_p correlation with B_z is greater than that with B_y. The B_y component is shown to be a predominant driver of the current systems that determine the *Dst* evolution during the recovery phase.

Keywords: cutoff rigidity, B_y, B_z, interplanetary magnetic field, geomagnetic activity indices, magnetic storm phases.

INTRODUCTION

The geomagnetic field allows or prevents the arrival of cosmic rays (CR) at a given point in the magnetosphere and atmosphere, depending on their energy. The lowest latitude to which energetic particles can penetrate is known as cutoff latitude. This latitude is a function of cutoff rigidity (momentum per charge). The geomagnetic cutoff rigidity *R* is a threshold rigidity below which the particle flux is zero due to geomagnetic screening. Latitude and longitude distribution of cutoff rigidity is determined by the spatial structure and intensity of the magnetospheric magnetic field, which changes the direction of CR propagation. Properties of the magnetic screen greatly vary with time depending on the dynamic interaction of solar wind magnetic and electric fields with intramagnetospheric fields and currents. Especially significant changes in magnetospheric currents, plasma, and magnetic field occur during geomagnetic storms [Leske et al., 2001].

Knowledge of distribution of CR cutoff rigidity variations ΔR during a magnetic storm is becoming increasingly important to monitor effects of bad space weather for space industry and high-latitude air transportation rapidly developing over the last 15 years [Iucci et al., 2005; Burov et al., 2005; Kress et al., 2015]. Longitude and latitude dependences of cutoff rigidity variations during quiet periods and during some magnetic storms have been analyzed in a number of papers [Dorman, 1963; Flueckiger et al., 1987; Antonova et al., 1990; Belov et al., 2005; Dvornikov et al., 2009; Danilova et al., 2019]. However, latitude dependences of the sensitivity of cutoff rigidities to different magnetospheric parameters have been beyond the scope of these studies.

In this paper, we examine the latitude dependence of ΔR and latitude effects in the ΔR correlation with variations of the interplanetary magnetic field (IMF) and geomagnetic activity for the November 7–8, 2004 storm The relationship between cutoff rigidity variations and magnetospheric parameters for the entire November 7–11, 2004 magnetospheric disturbance and separately for the first storm of this period on November 7–8 has been studied in our papers [Tyasto et al., 2013; Ptitsyna et al., 2019]. A novel aspect of this study is that we analyze precisely the latitude effects, in particular for each of the three storm phases: preliminary, main, and recovery phases of the November 7–8 storm.

METHODS AND DATA

Cutoff rigidity variations ΔR have been calculated using an “observational” method of spectrographic global survey that determines cutoff rigidities R_sgs from observations obtained at a network of neutron monitors (for more detail, see [Dvornikov et al., 2013]) and a “model” method that determines cutoff rigidities R_eff through numerical calculations of particle trajectories in a model magnetospheric magnetic field [Shea et al., 1965]. We have applied the magnetospheric model Ts01 [Tsyganenko et al., 2003] to strong magnetic disturbances, as described in detail in earlier works (e.g., [Tyasto et al., 2013]).

We defined ΔR_eff and ΔR_sgs as differences between geomagnetic thresholds calculated for each hour during the storm and those for the quiet period of November 6, 2004.

We have chosen the quiet period since during it the electromagnetic situation in the interplanetary space and geomagnetic conditions were quiet, and the spectrum of galactic CRs was the least modulated.

Correlation coefficients *k* between cutoff rigidities and IMF parameters have been calculated for the following stations: Tokyo (35.75° N, 139.7° E), Almaty (43.20° N, 76.94° E), Rome (41.90° N, 12.52° E), Irkutsk (52.47° N, 104.03° E), Moscow (55.47° N, 37.32° E), and Hobart (42.90° S, 147.33° E) The stations were chosen so that under quiet conditions they covered the main region of threshold rigidities R_s affected by the geomagnetic field: Tokyo — 11.0 GV, Almaty — 6.18 GV, Rome — 6.10 GV, Irkutsk — 3.25 GV, Moscow — 2.12 GV, Hobart — 1.76 GV. Threshold rigidities of the stations R_s were calculated as mean for the quiet day of November 6, 2004.

The observed changes in threshold geomagnetic cutoff rigidities were computed using data from the neutron monitor database [http://www01.nmdb.eu/data/].

The correlation coefficients *k* and standard errors were obtained from the analysis of regression equations separately from samples of observations for each of three phases — preliminary, main, and recovery.

Data on IMF and geomagnetic activity parameters was taken from the website [https://omniweb.gsfc.nasa.gov/form/dx1.html].

According to features of the storm evolution [Yermolaev et al., 2014; Tsurutani et al., 2008], it can be divided into three phases: preliminary — the period before the storm from 03:00 to 19:00 UT on November 7, main — from 20:00 UT on November 7 to 06:00 UT on November 8, and recovery — from 07:00 to 24:00 UT on November 8.

RESULTS

Figure 1 exemplifies the latitude behavior of variations in the geomagnetic thresholds of ΔR_{sgs} and ΔR_{eff} depending on threshold rigidities of the stations R_s for several moments during the storm. It is obvious that during the preliminary phase, when *Dst*=7 nT R_{sgs} (panel *a*) does not vary with latitude (or with rigidity of the station). For the main and recovery phases, the latitude curve takes a typical shape with a maximum decrease in the cutoff rigidity at mid-latitude stations [Dorman, 1963; Flueckiger et al., 1987; Dvornikov et al., 2009]. The maximum during the main phase occurs when $R_s \approx 3$ GV, and during the recovery phase it shifts to $R_s \approx 6 \div 7$ GV, i.e. to lower latitudes.

We can see (*b*) that during the preliminary phase ΔR_{eff}, like ΔR_{sgs}, practically does not change with latitude. During the main and recovery phases, the latitude dependences of ΔR_{eff} differ from those of ΔR_{sgs} mainly in the fact that they do not show a typical curve with the maximum decrease in mid-latitude rigidities. During the main and recovery phases, ΔR_{eff} monotonically increases with increasing threshold rigidity of station, i.e. with decreasing latitude of the stations, with an implicit maximum at $R_s \approx 2$ GV. The greatest discrepancy between the $\Delta R_{sgs}(R_s)$ and $\Delta R_{eff}(R_s)$ curves occurs during the recovery phase. In the main phase, for $R_s \gtrsim 3$ GV the behavior of $\Delta R_{sgs}(R_s)$ is similar to that of $\Delta R_{eff}(R_s)$, but there is a significant difference in magnitude of ΔR. Comparison between panels *a*, *b* shows that during the main phase at the storm maximum (*Dst*=–373 nT), a maximum decrease in ΔR_{eff}=–1.5 GV, which is half again as much as ΔR_{sgs}=–0.96 GV. Such a great difference is not observed for the preliminary and recovery phases. Note that in both cases it is clear that a latitude rigidity decrease depending on latitude (or R_s) increases with increasing $|Dst|$.

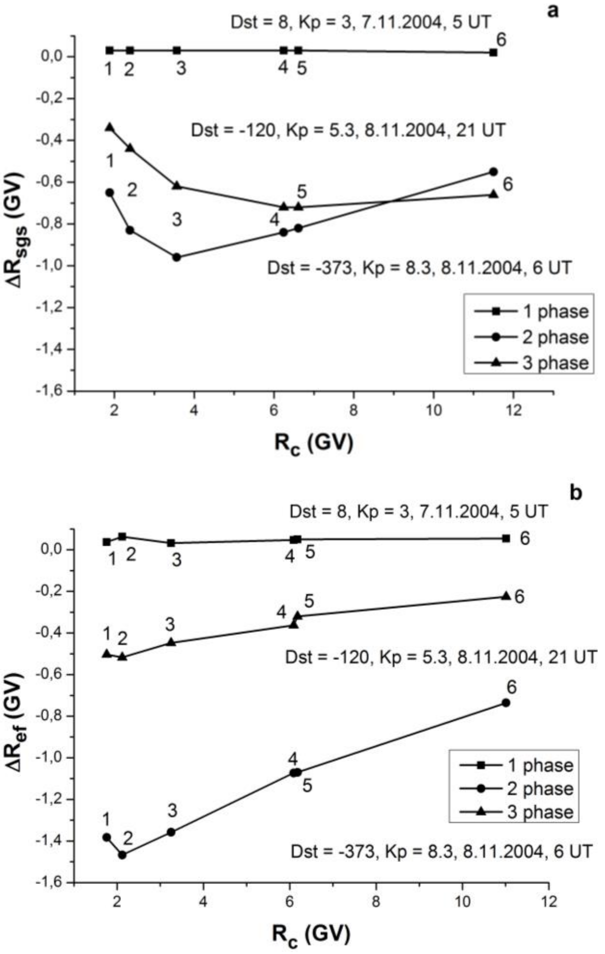

Figure 1. ΔR_{sgs} (*a*) and ΔR_{eff} (*b*) as a function of the threshold rigidity of station R_s for different storm phases: 1 phase — preliminary, 2 phase — main, 3 phase — recovery. Stations are given in the order of decreasing latitude: 1 — Hobart, 2 — Moscow, 3 — Irkutsk, 4 — Rome, 5 — Almaty, 6 — Tokyo

In view of these results, we conduct further research for observed values of ΔRsgs, and focus only on the storm main and recovery phases. We calculate the correlation coefficients *k* between ΔRsgs and IMF and geomagnetic activity parameters for the main and recovery phases at the six stations selected for the study, and trace these relationships in terms of the threshold rigidity of the stations. The coefficients *k* and the standard error of regression σ are listed in Table.

Figure 2 depicts the coefficients *k* between ΔR_{sgs} and *Dst*, K_p, B_y, and B_z depending on the station for the main and recovery phases. They show interesting features. Correlation between ΔR_{sgs} and *Dst* increases, and that between ΔR_{sgs} and B_y decreases with decreasing threshold rigidity of station. Thus, the latitude dependence of *k* for the relationship between ΔR_{sgs} and *Dst* mirrors the

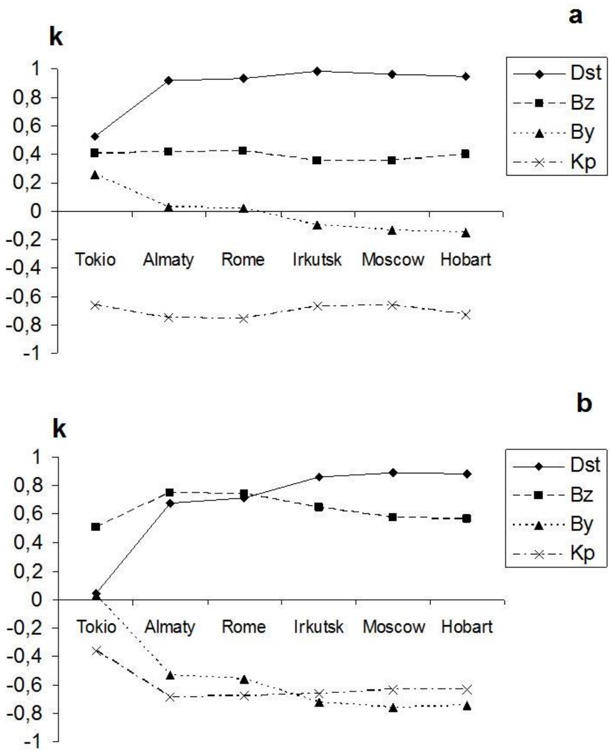

Figure 2. Latitude dependence of correlation coefficients *k* between ΔR_{sgs} and IMF and geomagnetic activity parameters for the storm main phase (*a*) and recovery phase (*b*). The stations are in the order of increasing latitude

latitude curve of *k* for the relationship between ΔR_{sgs} and B_y. The latitude dependence of *k* for the relationship with K_{p} mirrors the latitude curve of *k* for the relationship with B_z. This pattern is most pronounced for the recovery phase (panel *b*). For this period, the latitude curve of *k* for the relationship between ΔR_{sgs} and *Dst* practically coincides with the latitude curve of |*k*| for the relationship with B_y. Similarly, the latitude curve of *k* for the relationship with K_{p} practically coincides with the latitude curve of |*k*| for B_y. Furthermore, during the recovery phase *k* between ΔR_{sgs} and *Dst* increases with increasing latitude of station, whereas changes in the correlation between ΔR_{sgs} and K_{p} are more complex. During the main phase, the relationship of the correlation of ΔR_{sgs} and K_{p} with the threshold rigidity of station is a poorly resolved wave that is in antiphase with a similar wave for *k* between ΔR_{sgs} and B_z.

The results presented in Figure 2 allow us to assume that during the storm under study the *Dst* behavior was largely controlled by the IMF B_y component, whereas K_{p} by the B_z component. To test this assumption, we conducted a correlation analysis between the IMF parameters and the geomagnetic activity indices for different storm phases; the results of the analysis are shown in Figure 3.

Scatterplots for the main phase (*a*–*d*) indicate that the correlation between the geomagnetic activity indices (*Dst* and K_{p}) and IMF components (B_y, B_z) is relatively low. Note that while there is a sufficiently significant correlation (*b*) between *Dst* and B_z (0.46), points in the scatterplots for *Dst* (*a*, *b*) are randomly located. Only the scatterplots (*d*) show a significant dependence of K_{p} on B_z (−0.60). During the recovery phase, the relationship between K_{p} and B_z becomes more significant. We can see that during the recovery phase (*e*–*h*) the correlation coefficients both between K_{p} and B_z (0.87) and between *Dst* and B_y (0.81) are high. It is seen that the correlation between *Dst* and B_z (0.75) and between K_{p} and B_y (0.62) is slightly lower.

DISCUSSION

For the main and recovery phases of the storm considered, the latitude curve of $\Delta R_{\mathrm{sgs}}(R_{\mathrm{s}})$ takes a classical form with a maximum decrease in the cutoff rigidity at mid-latitude stations. The decrease in rigidities during the main phase is maximum at $R_{\mathrm{s}}\approx3$ GV, which generally agrees with the commonly observed picture. During the recovery phase, the maximum shifts to $R_{\mathrm{s}}\approx6\div7$ GV, i.e. to lower latitudes. This value of R_{s}, at which the rigidity decrease is maximum, is close to $R_{\mathrm{s}}\approx7\div8$ GV, obtained for the very severe storm in November 2003 [Belov et al., 2005]. The latitude dependences of model $\Delta R_{\mathrm{eff}}(R_{\mathrm{s}})$ differ from those of observed $\Delta R_{\mathrm{sgs}}(R_{\mathrm{s}})$ in magnitude. Moreover, they do not represent a characteristic curve with a maximum cutoff rigidity at mid-latitude stations. Belov et al. [2005] when studying the storm in November 2003 have found that for $R_{\mathrm{s}}<6$ GV the latitude dependences obtained using the Ts01 model differ greatly from those obtained using neutron monitor data. We can conclude that the Ts01 model that was designed specifically for disturbed conditions of the magnetosphere cannot fully reflect the spatial configuration of the disturbed magnetosphere during superstorms and in particular during the storm under study.

This conclusion is consistent with the results received in the paper [Kudela, Bucik, 2005], which has compared the cutoff rigidities calculated by a trajectory method using different magnetospheric models during several storms, including the November 7–8, 2004 storm,

Correlation coefficients between ΔR_{sgs} and *Dst*, K_p, B_y, B_z depending on the observation station for the main and recovery phases

	Main phase/recovery phase							
	Dst	σ	B_z	σ	B_y	σ	K_{p}	σ
Tokyo	0.53/0.05	0.14/0.14	0.40/0.50	0.15/0.12	0.26/0.03	0.16/0.14	−0.66/−0.36	0.13/0.13
Almaty	0.92/0.68	0.10/0.12	0.42/0.75	0.22/0.11	0.03/−0.53	0.24/0.14	−0.75/−0.68	0.16/0.12
Rome	0.93/0.71	0.09/0.12	0.43/0.74	0.23/0.12	0.03/−0.56	0.25/0.15	−0.75/−0.68	0.17/0.13
Irkutsk	0.97/0.86	0.08/0.12	0.36/0.65	0.31/0.18	−0.10/−0.72	0.33/0.17	−0.67/−0.66	0.25/0.18
Moscow	0.97/0.89	0.08/0.09	0.36/0.58	0.28/0.17	−0.13/−0.76	0.30/0.13	−0.66/−0.63	0.23/0.16
Hobart	0.95/0.88	0.07/0.06	0.40/0.57	0.21/0.10	−0.15/−0.75	0.22/0.09	−0.73/−0.64	0.16/0.10

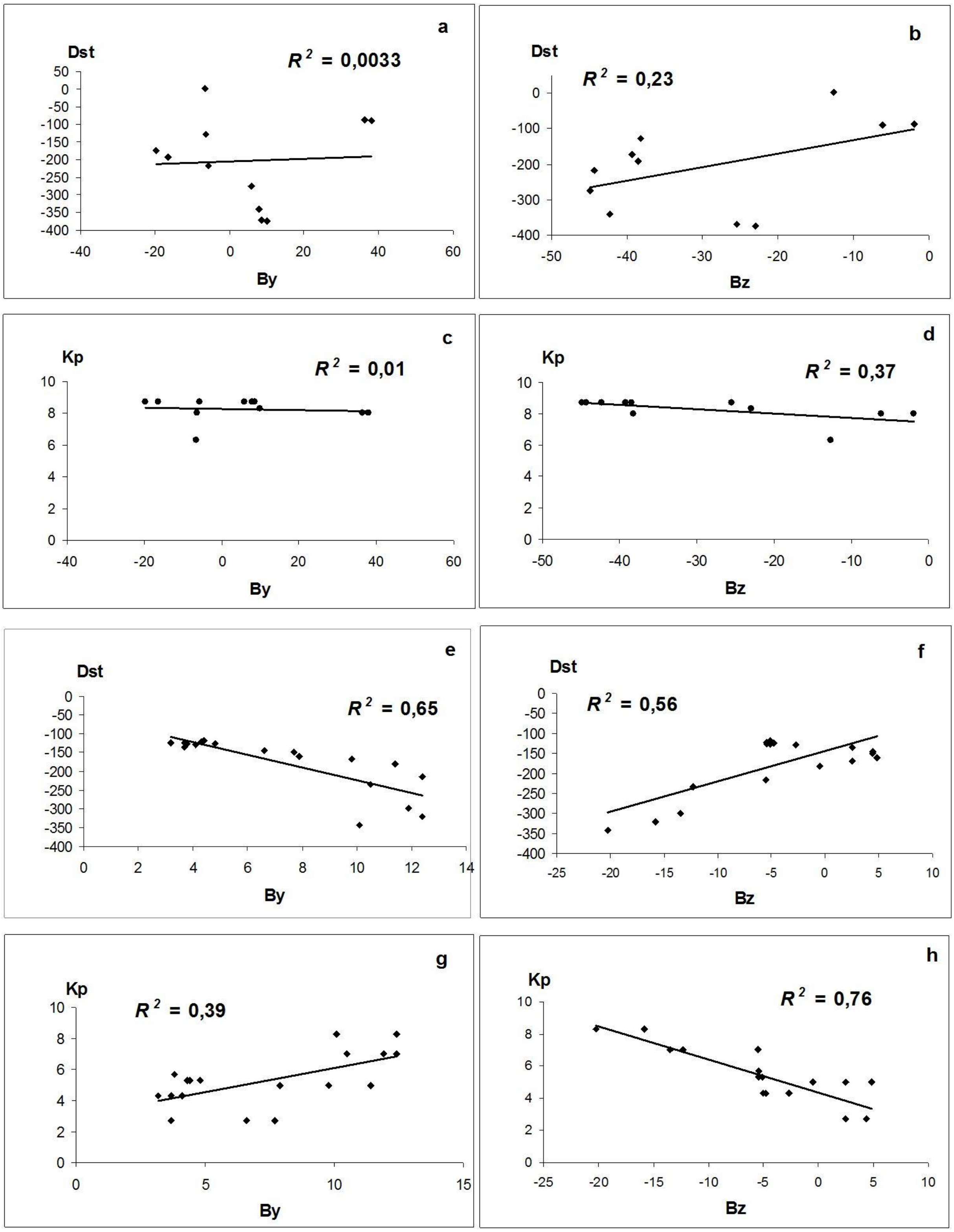

Figure 3. Scatterplots for the storm main (*a–d*) and recovery phases (*f–h*). Linear trend is shown by a straight line; R^2 is the approximation reliability

with observations made by neutron monitors and the spacecraft CORONAS-F. The authors state that for intense storms the results for middle latitudes obtained using the Ts01 model can significantly differ from observations.

Our result suggesting that the IMF B_y component plays an important role in the latitude distribution of ΔR and in the interaction between geomagnetic activity and IMF components during the storm of interest, especially during its recovery phase, merits more detailed consideration. The relationship between the geomagnetic activity indices and interplanetary medium parameters has been examined in many papers, in particular for magnetic storms [Dungey, 1961; Burton et al., 1975; Russell, 2000; Newel et al., 2007; Borovsky, 2014; Borovsky, Birn, 2014; and references therein]. It has been found that one of the geoeffective IMF parameters is its southward component $B_z<0$ whose increase triggers the reconnection of the solar wind magnetic field and the magnetospheric field. However, in [Daglis et al., 1999; Gosling et al., 1985; Crooker, 2000; Park et al., 2006; Rawat et al., 2007] it has been established that the B_y component under certain conditions in the magnetosphere can also have a significant effect on the reconnection. In particular, Rawat et al. [2007] have found that the IMF B_y component plays an essential role in developing an intense storm in the presence of the southward component B_z. The IMF configuration at which $B_y>0$, $B_z<0$ is also the most geoeffective. For the storm of interest, $B_z<0$ was observed almost throughout the main and recovery phases from 21:00 UT on November 7, but $B_y>0$ for a long time (over 18 hrs) was recorded only during the recovery phase.

The fact that the latitude dependences of ΔR_{sgs} on the geomagnetic indices *Dst* and K_p are in antiphase may be attributed to the fact that these zonal indices are determined in different ways and reflect the behavior of different current systems. *Dst* is determined from geomagnetic field variations at low-latitude stations (18°–35°) and reflects the effect of the equatorial ring current. Furthermore, *Dst* is also contributed by the partial ring current [Liemohn et al., 2001], transverse tail currents [Dubyagin et al., 2014; Ohtani et al., 2001; Turner et al., 2000], and currents at the magnetopause [Burton et al., 1975; Siscoe et al., 2005]. *Dst* does not describe the dynamics of particles from radiation belts [Reeves et al., 2003], whereas K_p is closely related to it [Borovsky, Shprits, 2017]. K_p is determined from subauroral stations (44°–62°). Because of the dependence of this index on the width of the zone of auroral currents (e.g., [Feldshtein, Starkov, 1962]), K_p can serve as a measure of magnetospheric convection [Thomsen, 2004]. During a strong magnetic disturbance when the auroral oval shifts to the south, the stations included in the K_p network begin to record effects of magnetospheric currents flowing at high latitudes. These currents are controlled by the vertical component B_z [Potemra, 1987]. Thus, we can assume that during the recovery phase of the November 7–8, 2004 storm ΔR_{sgs} variations were governed both by the ring current decay and by high-latitude current systems, the influence of the latter was more significant.

CONCLUSIONS

We have examined latitude features of variations in model and observed geomagnetic thresholds during three phases of the November 7–8, 2004 storm: preliminary, main, and recovery. We have obtained the following results.

1. During the main and recovery phases, the latitude curve of $\Delta R_{sgs}(R_s)$ takes a classical form with a maximum decrease in the cutoff rigidity at mid-latitude stations ($R_s \approx 3$ GV). During the recovery phase, the maximum is achieved at $R_s \approx 6 \div 7$ GV, i.e. at lower latitudes. The latitude distribution of model ΔR_{eff} differs substantially from the distribution of observed ΔR_{sgs}, especially for middle and low latitudes.
2. Our results suggest that for the November 7–8, 2004 magnetic storm the magnetospheric model Ts01 poorly reflects the spatial configuration of the disturbed magnetosphere, depending on storm phases.
3. During the storm main and recovery phases, the latitude dependence of ΔR_{sgs} on *Dst* is in antiphase with the latitude dependence of ΔR_{sgs} on B_y; the latitude dependence of ΔR_{sgs} on K_p varies in antiphase with the latitude dependence of ΔR_{sgs} on B_z. These latitude effects are most pronounced during the recovery phase.
4. During the recovery phase, the correlation of *Dst* with B_y is higher than with B_z, whereas the correlation of K_p with B_y is lower than with B_z.

Our results suggest that during the November 7–8, 2004 magnetic storm, the main contribution to the development of current systems, which determine the evolution of *Dst* during the recovery phase, is made by B_y, rather than B_z. The K_p index, on the contrary, largely depends on B_z. The relationship of variations in the cutoff rigidity ΔR_{sgs} with *Dst* and K_p and their relationship with the IMF B_y and B_z components depend on the relative contribution of different current systems. Our results allow us to conclude that during the storm, especially during its recovery phase, observed ΔR_{sgs} reflected effects of both the ring current and high-latitude current systems, the contribution of the latter being more significant.

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