Correlation of the Cosmic-Ray Cutoff Rigidity with Heliospheric and Geomagnetic-Activity Parameters at Different Phases of a Magnetic Storm in November 2004

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Abstract—The correlation of the variations in geomagnetic cutoff rigidity of cosmic rays ΔR with the interplanetary medium parameters and geomagnetic activity indices Dst and Kp was calculated for different phases of the superstorm on November 7−8, 2004. The strongest correlation was observed between the cutoff rigidity and Dst at all stages of storm development (correlation coefficients $k \approx 0.70-0.98$); some stable influence of the solar wind (SW) density N ($k \approx 0.50-0.80$) should also be noted. The dependence of the cutoff-rigidity variation on all of the dynamic parameters of the SW is observed in the main storm phase and is especially strong for the density N and pressure P. The correlation between ΔR and V is negative in all phases, while the correlation of ΔR with N and P is positive during the main phase and negative in the recovery phase. The cutoff-rigidity variations showed no sensitivity to the Bz component of the interplanetary magnetic field (IMF), the azimuthal component By, or the IMF absolute value B before the storm or in its main phase. A significant correlation or anticorrelation of ΔR with B and all the IMF components is observed only in the recovery period. The specific response of the geomagnetic cutoff rigidity to the heliospheric and magnetospheric parameters at different phases of the magnetic storm is apparently determined by the different relative contributions of the magnetospheric global current systems during these periods.

1. INTRODUCTION

The planetary distribution of the geomagnetic cutoff rigidity of cosmic rays (CRs), i.e., the lowest rigidity a particle must have in order to penetrate a given point of the magnetosphere, is determined by the spatial structure and intensity of the magnetospheric magnetic field slowing the particle. The properties of the geomagnetic screen vary over time depending on the dynamic interaction of the magnetic and electric fields of the solar wind (SW) with intramagnetospheric fields and currents. Especially significant variations in currents, plasma, and magnetic field of the magnetosphere occur during a geomagnetic storm (Leske et al., 2001). Knowledge of the variation in geomagnetic thresholds with respect to the SW and magnetospheric parameters during strong disturbances is becoming increasingly important for the safety of space vehicles and their crew, as well as for air travel (e.g., Iucci et al., 2005; Burov et al., 2005; Kress et al., 2015).

A number of studies revealed an intense relationship between variations in the geomagnetic cutoff rigidity and the geomagnetic activity. Tyssøy and Stadsnes (2014) found that the cutoff variations for the 2006 storm correlate rather closely with the Dst geomagnetic activity index. Ptitsyna et al. (2019) discovered a high correlation between the geomagnetic cutoff rigidity and Dst for seven storms of solar cycles 23 and 24; in this case, the correlation increases with decreasing Dst, i.e., with increasing storm intensity. Adriani et al. (2016) obtained a high correlation of the CR cutoff latitude with the geomagnetic Kp index and a smaller correlation with Dst. The strongest correlation with Dst is observed during the storm recovery phase. Tyasto et al. (2011) found that a decrease in geomagnetic thresholds for the storm of May 2005 clearly follows the course of Dst variation in the main phase, and the maximum drop in the cutoff rigidity is observed at the minimum Dst (the storm maximum). Conversely, it was found (Kress et al., 2010) that the greatest decrease in the cutoff rigidity during the storm of October 2003 was observed not during the maximum but 4 h before the onset of the storm.

A number of works studied the dependence of variations in CR cutoff rigidity on the SW and IMF parameters based on various experimental and theoretical approaches using both direct spacecraft observations of charged particles and numerical simulation. Based on measurement data from the SAMPEX

spacecraft, it was found that variations in the cutoff rigidity of high-latitude energetic particles were caused by variations in the IMF Bz component and SW speed V (Kanekal et al., 1998). Conversely, using the magnetohydrodynamic approach, Shimazu (2009) found that the particle penetration at a distance of four Earth radii Re during a magnetic storm is caused solely by an increase in the SW pressure P and does not depend on the sign or magnitude of the IMF Bz component. Similarly, Tyssøy and Stadsnes (2014) found that the cutoff latitude is affected mainly by the SW dynamic pressure (P). As a result of an experiment onboard the PAMELA spacecraft, Adriani et al. (2016) found that the cutoff latitudes (and cutoff rigidities) during the storm on December 14, 2006, had the highest correlation with the total magnetic field B, as well as with Bz and the SW speed V. Neither the dynamic pressure P nor the density N showed a significant correlation for the time scale of the entire storm. A high positive correlation of the cutoff latitudes with P was obtained only for the main storm phase. Ptitsyna et al. (2019) found that the SW speed V was the most geoeffective interplanetary parameter for four strong storms of cycle 24, while the correlation with Bz was weakly expressed.

Thus, the results of studies of the dependence of geomagnetic cutoff rigidity on interplanetary parameters and geomagnetic activity are rather inconsistent. At the same time, there is some indication that the correlation may vary for different storm phases. However, the control of cutoff-rigidity variation by the heliospheric and magnetospheric parameters at different phases of a magnetic storm has hardly been studied; we can mention only one detailed study, in which the corresponding correlation coefficients for different phases of the moderate storm of December 14, 2006, were found (Adriani et al., 2016). This area requires further research to clarify the degree of influence of various SW and IMF parameters at different stages of the evolution of magnetic storms, including very strong ones.

The period of late October–early November 2004 was marked by increased solar activity, flares, and eruptive emissions. This increased activity was associated with the passage of two sunspot groups across the solar disk: active regions 10691 and 10696 (Ermolaev et al., 2014). The number and strength of the flares were fairly low; nevertheless, the magnetic disturbance on November 7–13, 2004, was one of the strongest over the entire period of observations of the Dst index. This strong magnetic disturbance consisted of two storms, one after another, with a minimum of $Dst = -373$ nT for the first storm on November 7 and $Dst = -295$ nT for the second storm on November 10.

The goal of our study was to trace the sensitivity of geomagnetic cutoff rigidity to the dynamics of the parameters of the interplanetary medium and magnetosphere during the evolution of the first of these storms. The present paper is a continuation of our studies (Tyasto et al., 2013; Ptitsyna et al., 2019), in

which the cutoff-rigidity variation during both storms of November 7–13, 2004, were examined. The new element of this study is that we analyzed the correlations of cutoff-rigidity variation in the GCR with interplanetary parameters and geomagnetic activity indices during each of the three phases of storm development: at the preliminary stage (before the storm), in the main phase, and in the storm recovery phase. The calculation and analysis of the correlations with the total IMF B and the Kp index of geomagnetic activity have been added as well.

2. RESEARCH METHODS AND DATA

We estimated the relationship of cutoff variations with variations in the parameters of IMF, SW, and geomagnetic activity for the storm of November 7–8, 2004, using the cutoff variations calculated for this storm earlier (Tyasto et al., 2013; Ptitsyna et al., 2019) with two different methods: spectrographic global survey (SGS) and the tracing of the trajectories of cosmic ray (CR) particles in a model magnetic field.

2.1. Methods

The SGS method is based on the consideration of the processes of change in the energy of charged particles in the regular electromagnetic fields of the heliosphere (Dvornikov et al., 2013). This method uses a complex of ground-based recording equipment (the world network of neutron monitors, ground-based and underground meson telescopes, etc.). The statistical error of the determination of cutoff rigidity with allowance for the statistical accuracy of measurements at the CR stations of the world network does not exceed 0.05 GV in absolute value. The cutoff variations obtained with this method (ΔR_{SGS}), following our previous study (Ptitsyna et al., 2019), will further be referred to as "observational."

To calculate geomagnetic thresholds via the tracing of the trajectories of CR particles, it is necessary to specify the magnetic field of the magnetosphere, which is usually described with a model (McCracken et al., 1962; Shea et al., 1965). The accuracy of the determination of the geomagnetic thresholds depends on the accuracy of the magnetospheric model used in the calculations. In our previous studies (Tyasto et al., 2013; Ptitsyna et al., 2019), we used the Ts01 magnetospheric model (Tsyganenko, 2002a, 2002b; Tsyganenko et al., 2003). In the Ts01 model, the main sources of the magnetic field of the magnetosphere are symmetrical and partial circular currents, the magnetotail current system, the Birkeland field-aligned currents of regions 1 and 2, and the magnetopause currents. The Dst variation, SW density and speed, and IMF components were used as input parameters determining the effect of interplanetary conditions on the magnetosphere. The cutoff variations obtained with this method (ΔR_{eff}),

following our previous study (Ptitsyna et al., 2019), will be further referred to as "model."

Tyasto et al. (2013) and Ptitsyna et al. (2019) determined ΔR_{eff} and ΔR_{SGS} as the differences between the cutoff-rigidity values calculated for each hour during the storm and the rigidities in the quiet period before the storm. The correlation coefficients k between ΔR_{eff} and ΔR_{SGS} and the studied parameters were calculated for the following stations: Tokyo (35.75° N, 139.72° 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). Stations at different latitudes were selected such that they covered a large band of cutoff rigidities R in quiet time: Tokyo—11.0 GV, Almaty—6.18 GV, Rome—6.1 GV, Irkutsk—3.25 GV, Moscow—2.12 GV, and Hobart—1.76 GV. In this case, the daily average cutoff-rigidity values on November 5, 2004, were taken as the "quiet" values ($Dst \approx 0$). The coefficients k and standard errors s were obtained from the analysis of regression equations separately from the observation samples for the periods of each of the three phases (preliminary, main and recovery), as well as on the scale of the entire storm.

2.2. Data

The data on the SW (density N, velocity V, and pressure P) and IMF (total field B, components Bz and By) parameters, as well as geomagnetic activity indices (Kp and Dst), are taken from the OMNI database at https://omniweb.gsfc.nasa.gov/form/dx1.html. Figure 1 shows these SW parameters and geomagnetic activity indices during the storm on November 7–8, 2004; the top panel illustrates the ΔR_{eff} and ΔR_{SGS} values for Moscow station. The cutoff-rigidity variations at other stations are qualitatively no different from the cutoff rigidity variations for Moscow (the corresponding curves are given in the paper by Tyasto et al. (2013)).

The magnetic storm on November 7–8, 2004, was preceded by three SSC bursts detected on November 7 at approximately 0300, 1100, and 1900 UT (Ermolaev et al., 2014; Tsurutani et al., 2008). These SSCs were caused by shock waves that "pumped up" the total magnetic field B from 4 nT to very high values (44 nT). This indicates that the corresponding interplanetary perturbation was very complex; it corresponded to the perturbed state of the geomagnetic field throughout the day of November 7 (Fig. 1), which does not allow an unambiguously correlation of the initial phase of the storm with the last SSC only. It is believed that the initial phase of the storm lasts until the appearance of the southern component of the IMF, after which the main phase begins, accompanied by a drop in Dst. On November 7, the negative IMF component appeared approximately at 2000 UT (Ermolaev et al., 2014). The Dst continued to fall until 0600 UT on November 8,

when the index reached its minimum value of −373 nT. The restoration of the parameters to the prestorm values then began. However, this process was interrupted by the onset of the second storm with the arrival of the next shock front in the morning of November 9, at a time when the Dst variation was still rather strong (~100 nT).

Given the above features, we divided the period of the magnetic storm of November 7–8 into three phases: the preliminary storm phase, i.e., the period before the storm from 0300 UT to 1900 UT on November 7; the main phase from 2000 UT on November 7 to 0600 UT on November 8; and the recovery phase from 0700 UT to 2400 UT on November 8.

3. RESULTS

Tables 1–3 show the correlation coefficients of ΔR_{eff} and ΔR_{SGS} with Dst, Kp, Bz, By, B, N, V, and P for different storm phases, as well as the mean value of the standard error s. The numerators and denominators in each cell of Tables 1–3 are the correlation coefficients of $\Delta R_{\text{SGS}}/\Delta R_{\text{eff}}$ with interplanetary parameters and geomagnetic indices. The last column shows the correlation coefficients K between the model ΔR_{eff} and the observational ΔR_{SGS} values. The last two rows show the k values averaged over all stations and the corresponding standard errors s, which are also averaged over all stations. The stations in the tables are arranged in order of decreasing thresholds in the quiet time from Tokyo station to Hobart station, i.e., from 11.02 GV to 1.75 GV.

3.1. Preliminary Storm Phase

Table 1 shows that the observed variations in cutoff rigidities ΔR_{SGS} before the storm demonstrate the highest correlation with the Dst index of geomagnetic activity. The correlation coefficients k exceed 0.70 for almost all CR stations, except for the station in Tokyo (0.50 ± 0.09), reaching a maximum of 0.80 ± 0.04 in Irkutsk. The correlations of the model ΔR_{eff} with Dst are somewhat smaller, which apparently indicates that the $Ts01$ model does not sufficiently describe the state of the magnetosphere in the prestorm period. The geomagnetic activity expressed by the Kp index had little effect on ΔR: $k \sim 0.40–0.50 \pm 0.08$ at all stations.

Of all of the dynamic SW parameters, the most geoeffective in the preliminary phase were the density (the mean $k = 0.65 \pm 0.06$) and, to a slightly lesser extent, pressure (Table 1). It should be noted that the correlation with density is the smallest for Tokyo station (0.45 ± 0.09), while the correlation coefficient $k \sim 0.70 \pm 0.06$ for Irkutsk, Moscow, and Rome stations, where the threshold rigidity values in the quiet time are much lower than for Tokyo. Neither the SW velocity nor the IMF parameters were in any way
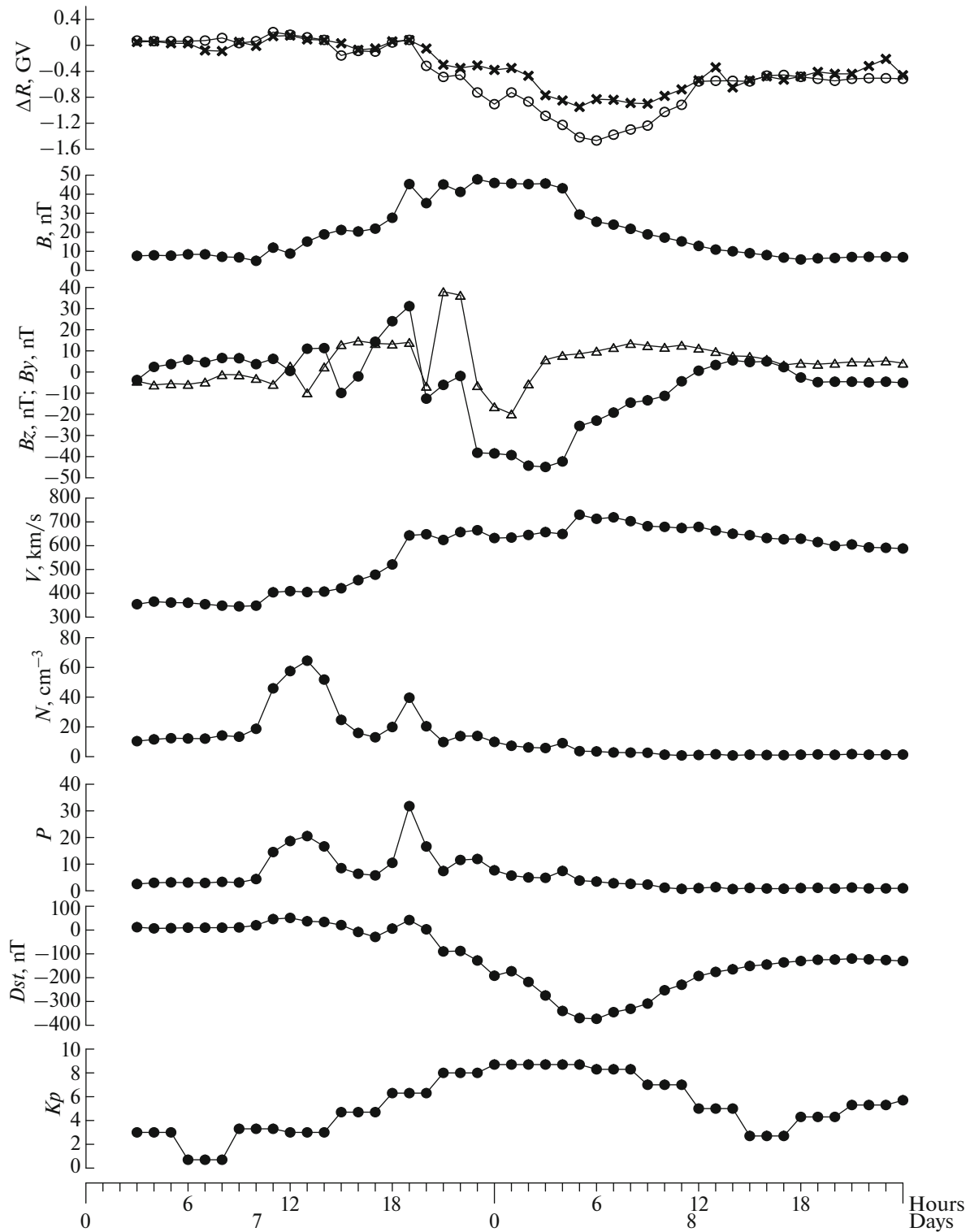
Fig. 1. Variations in the cutoff rigidities, SW and IMF parameters, and geomagnetic activity on November 7−8, 2004. ΔR_{eff} (open circles) and ΔR_{SGS} (crosses) for Moscow station; Bz is shown by the black circles, By is shown by the open triangles.

reflected in the ΔR_{SGS} values. The variations in the model rigidities ΔR_{eff} exhibit a similar, albeit slightly less pronounced, pattern of correlation with the SW parameters. The correlation between ΔR_{eff} and IMF has one difference: k for By is quite large (>0.60) for midlatitude stations, in contrast to ΔR_{SGS}.

Table 1. Correlation of the cutoff rigidity variations ($\Delta R_{SGS}/\Delta R_{eff}$) with the SW and geomagnetic field parameters in the preliminary storm phase

Station	Parameters								
	Dst	Kp	B	Bz	By	N	V	P	K
Tokyo	0.49/0.60	−0.01/0.10	−0.16/0.29	−0.33/0.63	−0.09/−0.09	0.45/0.41	−0.22/0.34	0.16/0.58	0.12
Almaty	0.77/0.64	0.13/−0.31	−0.07/−0.30	−0.19/0.15	−0.16/−0.66	0.69/0.46	−0.07/−0.23	0.42/0.26	0.41
Rome	0.78/0.67	0.14/−0.35	−0.06/−0.18	−0.19/0.37	−0.16/−0.60	0.69/0.61	−0.07/−0.13	0.43/0.43	0.40
Irkutsk	0.81/0.54	0.25/−0.44	0.08/−0.31	0.05/0.20	−0.18/−0.65	0.72/0.23	0.12/−0.23	0.58/0.19	0.26
Moscow	0.75/0.66	0.26/−0.39	0.12/−0.28	0.15/0.24	−0.18/−0.65	0.68/0.47	0.18/−0.18	0.59/0.32	0.51
Hobart	0.74/0.63	0.26/−0.17	0.16/0.04	0.21/0.50	−0.19/−0.37	0.64/0.42	0.22/0.11	0.60/0.49	0.52
Average	0.72/0.63	0.17/−0.26	0.01/−0.12	0.01/0.35	−0.16/−0.50	0.65/0.43	0.03/−0.05	0.46/0.38	0.37
s (±)	0.06/0.06	0.08/0.07	0.08/0.07	0.08/0.07	0.08/0.06	0.06/0.07	0.08/0.07	0.07/0.07	0.07

Table 2. Correlation of the cutoff rigidity variations ($\Delta R_{SGS}/\Delta R_{eff}$) with the SW and geomagnetic field parameters during the main storm phase

Station	Parameters								
	Dst	Kp	B	Bz	By	N	V	P	K
Tokyo	0.53/0.98	−0.66/−0.78	−0.05/0.25	0.40/0.66	0.26/0.21	0.51/0.84	−0.11/−0.52	0.52/0.82	0.55
Almaty	0.92/0.99	−0.75/−0.69	0.31/0.40	0.42/0.50	0.03/0.07	0.79/0.84	−0.53/−0.56	0.77/0.82	0.89
Rome	0.93/0.99	−0.75/−0.66	0.31/0.41	0.43/0.51	0.03/0.09	0.80/0.80	−0.54/−0.62	0.77/0.77	0.91
Irkutsk	0.98/0.99	−0.67/−0.69	0.44/0.40	0.36/0.53	−0.01/0.09	0.80/0.84	−0.66/−0.61	0.76/0.81	0.96
Moscow	0.97/0.99	−0.66/−0.65	0.43/0.48	0.36/0.48	−0.13/0.02	0.80/0.81	−0.67/−0.70	0.76/0.77	0.94
Hobart	0.95/0.96	−0.73/−0.76	0.33/0.25	0.40/0.69	−0.15/0.27	0.84/0.85	−0.60/−0.50	0.81/0.84	0.89
Average	0.88/0.98	−0.70/−0.70	0.30/0.37	0.39/0.56	−0.01/0.13	0.78/0.83	−0.52/−0.59	0.73/0.80	0.86
s (±)	0.09/0.07	0.18/0.28	0.24/0.36	0.24/0.32	0.25/0.39	0.16/0.22	0.21/0.31	0.17/0.23	0.17

Table 3. Correlation of the cutoff rigidity variations ($\Delta R_{SGS}/\Delta R_{eff}$) with the SW and geomagnetic field parameters in the storm recovery phase

Station	Parameters								
	Dst	Kp	B	Bz	By	N	V	P	K
Tokyo	0.05/0.98	−0.36/−0.88	−0.05/−0.97	0.50/0.82	0.03/−0.83	−0.34/−0.79	0.11/−0.82	−0.25/−0.88	0.17
Almaty	0.68/0.98	−0.68/−0.82	−0.65/−0.96	0.75/0.79	−0.53/−0.84	−0.63/−0.79	−0.53/−0.84	−0.66/−0.88	0.72
Rome	0.71/0.98	−0.68/−0.85	−0.68/−0.97	0.74/0.80	−0.56/−0.83	−0.64/−0.77	−0.57/−0.84	−0.67/−0.86	0.72
Irkutsk	0.86/0.98	−0.66/−0.85	−0.83/−0.98	0.65/0.82	−0.72/−0.82	−0.62/−0.77	−0.77/−0.84	−0.71/−0.86	0.85
Moscow	0.89/0.97	−0.63/−0.85	−0.86/−0.96	0.58/0.83	−0.76/−0.81	−0.55/−0.77	−0.83/−0.81	−0.67/−0.86	0.87
Hobart	0.88/0.98	−0.64/−0.87	−0.87/−0.97	0.57/0.82	−0.75/−0.86	−0.51/−0.77	−0.82/−0.83	−0.64/−0.85	0.85
Average	0.80/0.98	−0.61/−0.86	−0.66/−0.97	0.63/0.81	−0.55/−0.83	−0.55/−0.78	−0.71/−0.83	−0.60/−0.87	0.67
s (±)	0.11/0.05	0.14/0.14	0.1/0.06	0.13/0.15	0.14/0.15	0.15/0.17	0.13/0.15	0.13/0.14	0.17

3.2. Main Storm Phase

Table 2 shows that the correlation of ΔR_{SGS} with geomagnetic activity and the dynamic parameters of SW increased during the main storm phase. The correlation between ΔR_{SGS} and the *Dst* index is highest in this phase. The coefficients k were in the range of 0.91–0.98 at all stations except Tokyo (0.53 ± 0.14).

The correlation between *Dst* and ΔR_{eff} at all stations was even higher (0.98–0.99). The correlation of ΔR with the geomagnetic activity expressed by the *Kp* index was significantly lower (the average over all stations is $k = 0.70 \pm 0.2$). It should be noted that the correlation coefficient for *Dst* has a maximum at Moscow and Irkutsk stations, for which the threshold rigidity

values in the quiet time are $\approx 2–3$ GV, while the maximum for Kp is observed at Almaty and Rome stations, where the cutoff rigidity in the quiet time is ≈ 6 GV.

There was a rather significant correlation of ΔR_{SGS} with the dynamic SW parameters (density and pressure) during the main phase. The coefficients k were highest for the correlation with the density N, reaching ~0.80 for all stations except Tokyo, where k, however, was also relatively high (0.50 ± 0.14). The correlation with the dynamic pressure P reached 0.81 ± 0.13 at Hobart station and dropped to 0.50 ± 0.14 for Tokyo. The correlation between ΔR and the velocity V on average showed $k = -0.52 \pm 0.21$ at that stage.

The correlation of ΔR with the total interplanetary magnetic field B and its Bz component during the main storm phase was insignificant ($k \leq 0.40$). There was virtually no correlation with By. In addition, there were high errors in the determination of k.

The correlation of ΔR_{eff} with all of the studied parameters looks similar, although with slightly higher k values and large errors. Thus, for the main phase, the $Ts01$ model most likely overestimates the contribution of Bz to the variation in the geomagnetic thresholds.

Figure 1 shows that the total IMF B and its components at the very beginning of the main phase are in a perturbed state. To detect the possible contribution of these disturbances to the cutoff variations, in addition to the calculation of k during the entire main storm phase (Table 2), we performed the same calculations for the period from 2200 UT (the correlation results are not shown in the article). In this case, the calculation of rigidity correlations with Bz and By does not lead to any noticeable changes in k. The correlation relations linking the ΔR variations with the dynamic parameters of SW also change insignificantly. However, the correlation between ΔR_{SGS} and the total field B shows an increase in the correlation coefficient: averaged over all stations, $k = 0.54 \pm 0.17$; for midlatitude stations Moscow and Irkutsk, $k > 0.70 \pm 0.2$. The coefficients $k \approx 0.70 \pm 0.27$ are also obtained for the correlations between B and ΔR_{eff}.

3.3. Storm Recovery Phase

Table 3 shows that the correlations between ΔR and geomagnetic indices slightly decrease in the recovery phase; nevertheless, the correlation with Dst remains the highest as compared to other parameters. Note that the correlation coefficient between ΔR_{SGS} and Dst reaches its maximum (0.89 ± 0.11) at Hobart station, for which the cutoff rigidities in the quiet time are ≈ 1.75 GV. The correlation between ΔR_{SGS} and Kp is $k = 0.61 \pm 0.14$ on average with a maximum at Rome and Almaty stations, the threshold rigidity of which is ≈ 6 GV. The correlation of ΔR_{eff} with Kp reaches a maximum of 0.88 ± 0.14 at Tokyo station.

It can be seen that the Bz and By components of the IMF, especially its total value B, make a significant contribution to the variations in the cutoff rigidities in the storm recovery phase (Table 3), unlike other phases. There is a negative correlation of ΔR with B and By and a positive correlation with Bz. The correlation coefficient k between ΔR_{SGS} and B varied from 0.65 ± 0.13 at Rome and Almaty stations (cutoff rigidity of ≈ 6 GV) to 0.87 ± 0.06 at Moscow and Hobart stations (cutoff rigidity of ≈ 2 GV). Thus, there is a tendency of a slight increase in the correlation between ΔR_{SGS} and B with a decrease in the geomagnetic thresholds of the stations. As for ΔR_{eff}, its correlation with B is very high, $k = 0.96–0.98 \pm 0.06$ for all stations including Tokyo.

The correlation of ΔR with the dynamic parameters of the SW showed that all of them have a rather strong effect on cutoff rigidity; however, the strongest relationship is observed for P and V. The maximum absolute value of the correlation coefficient between ΔR_{SGS} and V is achieved for Moscow (-0.83 ± 0.12), and the minimum is achieved for Tokyo (0.11 ± 0.14). The correlation with P is maximal in Irkutsk (-0.71 ± 0.13) and minimal in Tokyo (-0.25 ± 0.14). The correlation coefficients of ΔR_{eff} with V and P lie in the range from -0.81 to -0.87 for all stations.

It should be emphasized that the correlation of ΔR with all SW and IMF parameters (N, V, P, B, and By) in the recovery phase is negative, except for Bz. I.e., the decay of current systems in the storm recovery phase causes a response in the cutoff variations that is in antiphase with the behavior of nearly all parameters of both the SW and the magnetic field.

3.4. Geoeffective Parameters

In this section, we analyzed the global behavior of the parameters that affect the variations of geomagnetic thresholds most significantly, regardless of latitudinal effects. Figure 2 shows the parameters for which the correlation coefficients averaged over all stations $|k| \geq 0.50$ for both kinds of ΔR (observational and model) or at least one of them. Figure 2 illustrates the most significant correlations between ΔR and the parameters of the IMF, SW, and geomagnetic activity during (a) the preliminary, (b) main, (c) recovery phases, and (d) on the scale of the entire storm. In addition, the last column K depicts the correlation coefficient between ΔR_{SGS} and ΔR_{eff}. These figures show the evolution of the cutoff-rigidity response to variations in the most geoeffective parameters of the SW, IMF, and geomagnetic activity during the development of a magnetic storm. Note that the coefficient for By before rounding $k = -0.503$, i.e., it exceeds 0.5 in absolute value.

Figure 2 shows that ΔR has the strongest relationship with Dst, and it can be traced throughout the storm in all its phases, reaching a maximum during the main phase (average $k = 0.88 \pm 0.09$ for ΔR_{SGS} and 0.98 ± 0.07 for ΔR_{eff}). The k values during the recovery

phase are only slightly inferior to the magnitude of the k values in the main phase. The influence of Kp on ΔR is somewhat less and begins only in the main phase: $k = -0.70 \pm 0.18/-0.70 \pm 0.28$ for $\Delta R_{SGS}/\Delta R_{eff}$ in the main phase and $k = -0.61/-0.86 \pm 0.14$ in the recovery phase.

All of the dynamic SW parameters are geoeffective during the main and recovery phases, and the SW density N shows a significant relationship with ΔR in all three storm phases. The influence of N ($\Delta R_{SGS}/\Delta R_{eff}$: $0.76 \pm 0.16/0.83 \pm 0.22$) and P ($0.73 \pm 0.17/0.80 \pm 0.23$) is dominant in the main phase (Fig. 2b), while V ($-0.71 \pm 0.13/-0.83 \pm 0.15$) is dominant during the recovery phase (Fig. 2c).

At the same time, Fig. 2 shows that the IMF has nearly no effect on the geomagnetic thresholds, either in the preliminary or main storm phase. Only during the recovery phase is there a significant relationship of ΔR with both the total field B and its components. The response of ΔR to the component variations is oppositely directed. There is a direct correlation of ΔR with Bz and anticorrelation with By.

Note that the correlation of the studied parameters with the model variations in cutoff rigidity is almost always higher during the main and recovery phases than the correlation with the observed variations. In the preliminary phase, the situation is the opposite. This is consistent with the fact that the $Ts01$ model was developed to describe the magnetosphere under the conditions of a strong disturbance, which was not yet achieved before the storm onset. The correlation between ΔR_{SGS} and ΔR_{eff} is 0.70 ± 0.17 in the recovery phase, 0.86 ± 0.17 in the main phase, and only 0.37 ± 0.07 in the preliminary phase.

It can be concluded that, if we consider all three stages of storm development, the Dst index of geomagnetic activity affects the variations of geomagnetic thresholds most significantly, while the SW density N is also affected. Two dynamic SW parameters, N and P, were geoeffective during the main phase; V was also geoeffective, although to a lesser extent, but not the magnetic field. The situation on the scale of the entire storm is somewhat different. In this case, the complex dynamics of the cutoff-rigidity response to the studied parameters, including the correlation or anticorrelation of the same factors at different phases, leads to the significance of both geomagnetic indices, as well as Bz and dynamic parameters. In this case, ΔR_{SGS} and ΔR_{eff} were most significantly influenced by Dst and V ($k > 0.80$).

4. RESULTS AND DISCUSSION

Our results (Tables 1–3, Fig. 2) indicate that the dependence of variations in the CR cutoff rigidities on the parameters of the interplanetary medium and geomagnetic activity varies significantly at different stages
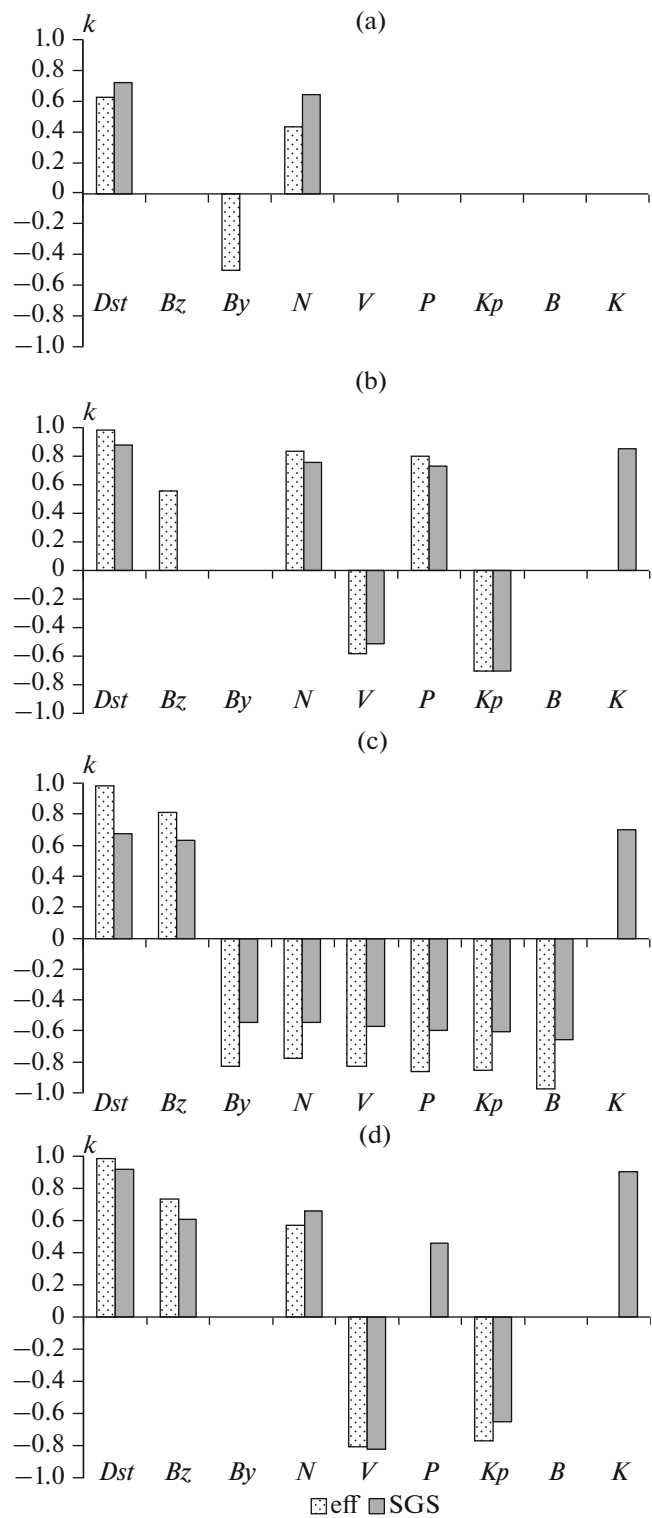

Fig. 2. Correlation of the cutoff rigidity variations (observational and model) with the parameters of the IMF, SW, and geomagnetic field, as well as the correlation coefficient K between ΔR_{SGS} and ΔR_{eff}. The correlation coefficients $|k| \geq 0.50$ are shown for the (a) preliminary phase, (b) main phase, (c) recovery phase, and (d) the entire storm.

of the magnetic storm on November 7–8, 2004. The closest relationship throughout the storm is found between ΔR and Dst. The sensitivity of ΔR to Kp is somewhat lower and is nearly absent in the preliminary storm stage. Different storm phases show opposite trends in the dependence of these correlations on the threshold rigidities of the stations in the quiet time. The difference in the sensitivity of the cutoff rigidity to Dst and Kp can be explained by the fact that these indices reflect the behavior of different current systems. Dst is determined by the variations of the terrestrial magnetic field at low-latitude stations and reflects the effect of the equatorial ring current. Kp is determined by midlatitude stations. However, during a strong magnetic disturbance, when the auroral oval moves to the south, these midlatitude stations begin to detect the effects of high-latitude currents.

The dependences of ΔR on the SW and IMF parameters at different stages of the storm vary even more strongly. At the preliminary stage, this dependence is expressed extremely weakly, and the relation of ΔR with both the IMF and most of the dynamic SW parameters is not significant; there is a noticeable correlation with only one parameter, the SW density. In the main storm phase, the dependence of the cutoff-rigidity variation on all of the dynamic SW parameters, especially on the density N and pressure P, increases. However, in the main storm stage, there is no connection with the parameters of the magnetic field, including the Bz component. Only at the storm recovery phase is there a strong connection of ΔR with all parameters of both the SW and IMF. This may have been facilitated by the fact that Bz had a southern direction for most of the storm recovery phase, and the velocity V had rather high values of ~700–600 km/s.

During the storm, global current systems (ring current around the Earth, magnetopause currents, magnetotail currents, and high-latitude currents) develop and evolve over time as a response to the changes in the SW and IMF dynamics. The formation, intensification, and further decay of these current systems occurs not simultaneously but at different time scales; this leads to complex dynamics of the magnetosphere, which, in turn, determines the complex dynamics of the cutoff rigidities during the evolution of a magnetic storm. Therefore, depending on the dynamics of the current systems at different stages of the storm, a different scenario is apparently realized for the control of the cutoff variations by the parameters of the interplanetary medium and geomagnetic activity. For example, an increase in SW pressure leads to an increase in currents across the magnetotail and magnetopause currents, which have the opposite effect on cutoff rigidities. The ratio of global currents may vary for different storms and different stages of the development of one storm. For example, Fluekiger et al. (1990), examining the cutoff variations during the storm of December 17, 1971, found that the contribution of the magnetopause currents to the observed Dst value (20 nT) was 80 nT

during the initial phase, while the contribution from the ring current was −60 nT.

It is believed that the main role in the development of magnetospheric disturbances is played by two factors: the IMF southern component Bz, the growth in which causes the reconnection of the SW magnetic field and the magnetospheric field, and the SW dynamic pressure P, which is responsible for magnetospheric compression (Dungey, 1961; Akasofu, 1981; Russell, 2000). Both of these factors weaken the geomagnetic screen and facilitate the penetration by the SW plasma into the magnetosphere and the Earth's atmosphere. From this viewpoint, our result is quite surprising: the correlation of ΔR, both with the IMF Bz component and with the SW velocity V, is nearly absent before the storm, and the correlation of ΔR with the density N exceeds the correlation with the dynamic pressure P. That being said, N exhibits a rather high correlation with ΔR in all storm phases.

In studies of magnetic storms, the SW density N was long considered only as a component of pressure. However, Fenrich and Luhman (1998), as well as Crooker (2000), expressed the view that density is an independent parameter acting on its own. This view is based on the recent understanding that the response of the magnetosphere to the variations in the SW density is a response to the variations in the density of the plasma layer; the time scale for this process is much longer (~5 h) than for the response to Bz (<1 h) (Smith et al., 1999, and references therein). An increase in density leads to an increase in pressure only if the IMF southern component is present at the same time (Fenrich and Luhman, 1998). The statistical processing of satellite data (Khabarova and Rudenchik, 2003; Khabarova, 2007) showed that the SW density N before the storm onset is an important independent parameter; it determines the time of the onset of the magnetic storm, which expands the possibilities for the prediction of the disturbances in the Earth's magnetic field. An increase in N, together with a southward turn of Bz, leads to the occurrence of magnetic storms (Khabarova and Rudenchik, 2003; Khabarova, 2007). In our case, this is the scenario that was realized: a surge in N to 54 cm^{-3} and a southward turn of the Bz component occurred (Fig. 1) in the period of 1900–2000 UT, which caused a very strong storm. It is characteristic that the correlation between ΔR and the amplitude of Bz is not observed either in the preliminary or in the main storm phase. Moreover, there is no connection of ΔR with either By or the total field B in the main phase. At the same time, the correlation of the cutoff variations with the dynamic pressure during the main storm phase on November 7–8, 2004, was significant. This result may be correlated with the conclusions of Kalegaev et al. (2015), who showed, using the model of the magnetospheric magnetic field, that the storm development is controlled by both the interplanetary magnetic field and the SW pressure, although the contribution of these parameters may

vary from storm to storm. For example, according to the results of Kalegaev et al. (2015), the main role in the development of the magnetic storm on January 21−22, 2005, was played by a powerful impulse of SW pressure, in contrast to the storm of December 14−15, 2006, which was initiated by a change in the orientation of the interplanetary magnetic field. As a result, the Dst variation of the geomagnetic field during the 2005 storm was determined mainly by the development of the ring current, while it was determined for the 2006 storm by the contributions of the ring current and magnetotail currents, which are comparable in magnitude (Kalegaev et al., 2015).

We paid special attention to the study of the relation between ΔR and the total interplanetary magnetic field B, since Adriani et al. (2016) recently found a high correlation of geomagnetic thresholds with this parameter based on direct measurements of geomagnetic thresholds at the PAMELA spacecraft. A relationship was found earlier between B and geomagnetic activity, in particular, with the Ap index (Bieber et al., 1993). Statistical studies (Kane, 2005) revealed that the B values are high (30% higher than the average values) when Bz is high. Note that the opposite may not be true: there are many cases in which Bz is close to zero or even positive, while B is high due to the contribution of the IMF Bx and By components (Kane, 2005). In a recent study by Rathore et al. (2013) based on a statistical analysis of storms of the 23th solar cycle, it was pointed out that the intensity of the storms predominantly correlates with the total field B as compared to Bz. Adriani et al. (2016) found a high correlation between ΔR and B in the main and recovery phases, as well as on the scale of the entire storm of December 14, 2006. At the same time, a high correlation between ΔR and B was observed both in the case of strong correlation with Bz and By, and in its absence. The results obtained in our study indicate that the correlation between ΔR and B on the scale of the entire storm of November 7−8, 2004, as well as on the scale of the entire main phase, was small. However, 2 h after the start of the main phase, the correlation between ΔR and B starts to increase, reaching high values in the recovery phase: $k = 0.86$ and 0.87 (± 0.1) between ΔR_{SGS} and B for Moscow and Hobart, respectively, while k between ΔR_{eff} and B reaches $\approx 0.96−0.98$ (± 0.06) for all stations. Note that such high k values are observed only in the recovery phase, when the correlation of ΔR with both Bz and By components was also high (Table 3). Thus, the comparison of our results with those of Adriani et al. (2016) indicates the possibility of a significant contribution of the total magnetic field B to the dynamics of the cutoff variations during storm development and the specificity of this contribution for different storms.

One should note the systematic differences in the obtained correlation coefficients for Tokyo station from the values of other stations; these differences go beyond the margin of error. Tokyo station is a low-latitude station and is often used in CR studies as a typical representative of a station with high geomagnetic cutoff rigidity R (high particle energies) for quiet time as opposed to stations with lower R (e.g., Tiwari et al., 2004; Mishra and Agarwal, 2011). The CR characteristics for Tokyo often differ significantly from the cosmic ray characteristics for stations with lower cutoff rigidity. In particular, Tyasto et al. (2013) found that, the maximum decrease in cutoff rigidity ΔR_{eff} during the storm of November 8, 2004 was 6.9% in Tokyo as compared with 67.9% in Moscow and 78.6% in Hobart; for ΔR_{SGS}, the decrease was 5% at Tokyo station as compared with 42% in Moscow and 38.2% in Hobart. Thus, the cutoff rigidities R at Tokyo station during the studied storm are much less sensitive to magnetospheric disturbances than at midlatitude stations. Accordingly, the correlation coefficients that we calculated for ΔR and different SW and IMF parameters in Tokyo, as a rule, are much lower. The differences in the k values obtained for Tokyo from the k values of other stations reflect a nonuniform, nonlinear global distribution of ΔR over the Earth's surface during large geomagnetic storms, as demonstrated by the example of superstorms in October and November 2003 (Kress et al., 2010; Danilova et al., 2018).

Our analysis showed that the time variations of model and observational geomagnetic thresholds obtained with two different methods are generally consistent with each other. However, the difference in the sensitivity of ΔR_{SGS} and ΔR_{eff} to the parameters of the interplanetary medium for individual stations and for different phases of the storm may vary significantly. The response of model and observation thresholds may differ, because the $Ts01$ model, which was used to calculate ΔR_{eff}, does not fully take into account some current systems that, as it turned out recently, can be of great significance in the description of very strong storms. In particular, Levitin et al. (2014) noted that the DP system of currents developing in high-latitude regions of the magnetosphere can be of significant importance for the development of giant geomagnetic storms. In addition, the $Ts01$ model describes the perturbed magnetic field of the inner and near-Earth magnetosphere in the region $R \le 15R_e$. Therefore, the $Ts01$ model does not accurately represent the far tail field. At the same time, the observational ΔR_{SGS} were determined with ground-based detection data of charged particles, which are affected by all regions of the magnetosphere.

5. CONCLUSIONS

This paper analyzes the correlations of cutoff-rigidity variation with the parameters of SW, IMF, and geomagnetic activity at all stages of the development of the magnetic storm on November 7−8, 2004: before

the storm, in its main phase, and in the recovery phase. The following results were obtained.

1. Dependence of ΔR on geomagnetic activity. The closest relationship throughout the storm is found between ΔR and Dst, which reaches the maximum during the main phase (for $\Delta R_{SGS}/\Delta R_{eff}$, $k = 0.88/0.98$). The sensitivity of ΔR to Kp is slightly less than that to Dst and is nearly absent in the preliminary phase. The opposite trends are observed in the dependence of these correlations on the threshold rigidities of stations in the quiet time. In the main phase, the correlation coefficient between ΔR and Dst is maximal at stations with lower thresholds, and the correlation coefficient between ΔR and Kp is maximal at stations with higher thresholds. In the recovery phase, k between ΔR and Dst is maximal at stations with higher thresholds, and k between ΔR and Kp is maximal at stations with lower thresholds.

2. Dependence of ΔR on the IMF. The dependence of ΔR on Bz and By is nearly absent during the preliminary and main storm phases. The correlation with B begins to increase 2 h after the onset of the main phase. In the recovery period, there is a strong correlation and anticorrelation of ΔR with B and all its components.

3. Dependence of ΔR on the dynamic SW parameters. There is a strong dependence of the cutoff variations on the density N and pressure P during the main storm phase. A significant dependence of ΔR on all three dynamic parameters of the SW is observed for the recovery phase. The correlation between ΔR and V is negative in all phases, while the correlation with N and P is positive during the main phase and negative in the recovery phase.

Thus, we can conclude that the Dst index was the most influential parameter for the variations of geomagnetic thresholds at all stages of the storm on November 7−8, 2004; a stable influence of N can also be noted. The most significant factors during the main phase were both geomagnetic indices and all three dynamic SW parameters (N, P, and V). At the same time, the cutoff variations showed no sensitivity to the IMF Bz component, either before the storm or in the main phase. The effect of Bz, like that of By and B, was significant only in the recovery phase and at the stage of decay of all current systems.

The sensitivity of ΔR to the SW, IMF, and geomagnetic activity parameters at different stages of a magnetic storm differs, because global current systems (ring current around the Earth, magnetopause currents, magnetotail currents, and high-latitude currents) develop during the storm in response to the variations in the SW and IMF parameters and evolve over time. The formation, intensification, and subsequent decay of these current systems occur not simultaneously but at different time scales. This leads to a different relative contribution of current systems to cutoff variations during the evolution of the geomagnetic disturbance, which determines the specific response of the cutoff rigidities to the heliospheric and magnetospheric parameters in different storm phases.

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