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STUDYING AURORAL ACTIVITY USING THE *SME* INDEX AT THE MAGNETIC STORM MAIN PHASE DURING CIR AND ICME EVENTS

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Abstract. In this paper, we examine the relationship of the *SME* index with magnetic storm characteristics and interplanetary medium parameters during the main phase of magnetic storms caused by CIR and ICME events. Over the period 1990–2017, 107 magnetic storms driven by (64) CIR and (43) ICME events have been selected. In contrast to *AE* and K_p, a stronger correlation is shown to exist between the average *SME* index (SME_{aver}) and interplanetary medium parameters during the magnetic storm main phase. Close correlation coefficients between SME_{aver} and the SW electric field (southward IMF B_z) have been obtained for CIR and ICME events. SME_{aver} has been found to increase with the rate of magnetic storm development and $|Dst_{min}|$. For CIR and ICME events, no difference has been revealed between SME_{aver} and $|Dst_{min}|$ in linear regression equations.

Keywords: magnetic storm, *SME* index, *Dst* index, solar wind, electric field.

INTRODUCTION

It is known that amplification of magnetospheric-ionospheric currents during magnetic storms leads to an increase in the geomagnetic activity indices *Dst*, *AE*, K_p. The geomagnetic indices, calculated from ground-based observations, describe the dynamics and intensity of magnetic disturbances during magnetic storms. The low-latitude *Dst* index [Sugiura, 1964; Burton et al., 1975] is used to estimate the magnetic storm intensity. The high-latitude *AE* index characterizes the intensity of the auroral current and is an indicator of substorm activity [Davis, Sugiura, 1966]. Auroral activity is also assessed by the planetary (mid-latitude) K_p index [Bartels, 1949; Khorosheva, 2007]. Correlation analysis of geomagnetic activity and interplanetary medium parameters during magnetic storms has shown that the southward interplanetary magnetic field component B_z, whose efficiency is associated with the effect of the SW electric field $E_{sw}=V\times B_z$, is the main driver of geomagnetic disturbances [Burton et al., 1975; Gonzalez et al., 1994; Kane, 2005, 2010]. The relationship between *AE*, K_p, and *Dst* indices during magnetic storms has been extensively discussed in [Gonzalez et al., 1994; Grafe et al., 1997; Grafe, Feldstein, 2000; Kane, 2010] (see also references therein).

However, the results of recent statistical and morphological studies suggest that the development of magnetic storms and substorms differs depending on the type of the solar wind (SW) [Gonzalez et al., 1999; Borovsky, Denton, 2006; Yermolaev et al., 2010; Dremukhina et al., 2018a]. The following SW types are distinguished: interplanetary coronal mass ejections (ICME) including magnetic clouds (MC) and pistons (ejecta), regions of interaction between fast and slow streams (CIR), and compression regions before ICME (sheath). Each SW type has a specific set of SW and IMF parameters.

Analysis of the relationship between SW parameters for different types of streams and the geomagnetic activity indices (*AE*, K_p, and *Dst*) has revealed [Plotnikov, Barkova, 2007; Yermolaev et al., 2010; Guo et al., 2011; Nikolaeva et al., 2011; Yermolaev et al., 2012; Cramer et al., 2013; Dremukhina et al., 2018a] that during storm main phases the geomagnetic indices increase with increasing SW electric field E_{sw}, but for MC events there is a nonlinear dependence of the indices on E_{sw}. Boroyev et al. [2020] have carried out a comparative analysis of the *AE* and K_p indices during CIR and ICME events. It has been found that for CIR events, in contrast to ICME (MC + ejecta), *AE* increases with E_{sw}. The K_p index correlates with E_{sw} only for ICME. The authors of [Borovsky, Denton, 2006; Plotnikov, Barkova, 2007; Yermolaev et al., 2010] attribute the observed variations in the auroral indices to SW stream type. Differences between SW types are manifested in the behavior of the ring current, auroral precipitation, Earth's plasma sheet, magnetospheric convection, and saturation of the polar cap potential [Borovsky, Denton, 2006]. In [Boroyev, Vasiliev, 2018; Boroyev et al., 2020], the authors believe that variations in the *AE* and K_p indices are influenced by the position of the auroral current relative to the stations at which the indices are calculated. A significant decrease in IMF B_z leads to an expansion of the auroral oval [Akasofu, Chapman, 1974] and to the drift of ionospheric currents to lower latitudes. Boroyev et al. [2020] assume that it is the SW type that determines the drift of currents relative to the stations at which *AE* and

K_p are calculated. For example, during ICME events, unlike CIR events, large values of the southward IMF B_z are observed. As a result, we can see higher correlation coefficients between E_{swaver} and K_{paver} than between E_{swaver} and AE_{aver} during the main phases of ICME-induced magnetic storms.

To take into account the spatial features of the influence of the equatorial drift of the auroral electrojet on *AE* and K_p during magnetic storms, we examine the SuperMAG *SME* index. The SuperMAG indices *SME*, *SMU*, and *SML* are geomagnetic activity indices [Newell, Gjerloev, 2012]. Calculation formulas, say, for *AE* and *SME*, are similar. The *AE* index is calculated from the *H* component at twelve high-latitude magnetovariational stations located in a narrow band of geomagnetic latitudes 65°–70°. The *SME* index is calculated using data from more than 100 geomagnetic stations [Newell, Gjerloev, 2011], covering the range of geomagnetic latitudes from 40° to 80°. The *SME* index, unlike *AE*, allows for a more accurate assessment of the auroral electrojet intensity. Besides, during magnetic disturbances the shift of the auroral electrojet in latitude does not affect the *SME* index. Unlike *SME*, *AE* values are underestimated due to the shift of the auroral electrojet to low latitudes for magnetic storms with $Dst<–60$ nT [Khorosheva, 2007]. Using the SuperMAG database, Newell et al. [2013] have examined annual, seasonal, and diurnal variations in the rate of occurrence of substorm disturbances in 1984–2005. Du et al. [2018] have analyzed semiannual and annual variations in *SML*/*SMU*, taking into account SW parameters.

The purpose of this work is to continue the cycle of studies of auroral activity during magnetic storms induced by SW of different types, namely, to examine the correlations of the *SME* index with magnetic storm characteristics and interplanetary medium parameters during main phases of magnetic storms induced by SW of different types.

EXPERIMENTAL DATA

To assess geomagnetic activity, we have used the *SME* and *Dst* indices. Their values were taken on the websites [https://supermag. jhuapl.edu, http://wdc.kugi.kyoto-u.ac.jp/dstae/index.html]. For the period 1990–2017, we have selected 107 magnetic storms with $Dst_{min}\leq–50$ nT, induced by CIR (64) and ICME (43) events. We do not deal with other SW types here. A magnetic storm is considered driven by SW of a given type if the main phase and the minimum *Dst* index were observed under the impact of SW of this type. A classification method for different SW types is described in detail in [Yermolaev et al., 2009; Yermolaev et al., 2010]. The website [ftp.iki.rssi.ru/pub/omni/catalog] contains a catalog of SW types. Of the ICME events before which a sheath was detected we have selected only those magnetic storms for which the main phase and minimum *Dst* were observed during ICME (ICME body). It is known (e.g., [Yermolaev et al., 2021]) that the efficiency in magnetic storm generation by sheath is 50 % higher than that by ICME. Therefore, we analyze events occurring after a magnetically quiet period, which allow us to more accurately determine whether the magnetosphere interacts with ICME or sheath during magnetic storm main phases.

For each event, as in [Boroyev, Vasiliev, 2018], we calculate mean *SME* values during the magnetic storm main phase and the rate of magnetic storm development as the time derivative of *Dst* $|\Delta Dst|/\Delta T$ [Ermolaev et al., 2015]. The duration of the main phase ΔT is defined as the time interval from the moment of a sharp decrease in *Dst* (Dst_0) to the moment of detection of Dst_{min}. $|\Delta Dst|$ is calculated by the formula

$$|\Delta Dst|=|Dst_{min}–Dst_0|.$$

To take into account the SW and IMF parameters, we use hourly average data [http://www.omniweb.com] to find mean values of the SW azimuthal electric field $E_{swaver}=\Sigma E_{sw}/\Delta T$ and IMF B_z $B_{zaver}=\Sigma B_z/\Delta T$ during the magnetic storm main phase, where ΣE_{sw} and ΣB_z are the total values of the dawn–dusk electric field and southward B_z for the time interval corresponding to the magnetic storm main phase. The average values of the interplanetary medium parameters and the geomagnetic activity indices allow us in general to assess the development of the magnetic storm main phase.

We have used a linear approximation as the simplest way to establish the relationship of the *SME* index with the magnetic storm and interplanetary medium parameters. In this work, linear approximations and Pearson correlation coefficients are calculated with a probability $P=0.99$ and a significance level $p=0.01$.

RESULTS

Figure 1, *a*, *c* illustrates a correlation between average *SMESME*$_{aver}$ and the rate of magnetic storm development $|\Delta Dst|/\Delta T$ during CIR and ICME events. The relationship between SME_{aver} and $|Dst_{min}|$ is displayed in Figure 1, *b*, *d*. Table lists correlation coefficients between SME_{aver} and magnetic storm $|\Delta Dst|/\Delta T$, $|Dst_{min}|$ and interplanetary medium parameters, as well as linear regression equations, for SW of two types. Figure 1, *a*, *c* shows that in magnetic storm main phases during CIR and ICME events SME_{aver} increases with $|\Delta Dst|/\Delta T$; SME_{aver} increasing more sharply for ICME events (see Table). We have obtained close correlation coefficients between SME_{aver} and $|\Delta Dst|/\Delta T$ for CIR ($r=0.5$) and ICME ($r=0.54$) events. For CIR ($r=0.67$) and ICME ($r=0.6$) events, high correlation coefficients are also observed between SME_{aver} and $|Dst_{min}|$ (Figure 1, *b*, *d*). Regression equations for SME_{aver} and $|Dst_{min}|$ for CIR and ICME events are similar (see Table): the angular coefficients that determine the slope of straight lines relative to the X-axis differ slightly.

Among the IMF and SW parameters, the electric field is the main driver of magnetic storms [Burton et al., 1975; Gonzalez et al., 1994; Kane, 2005]. The SW electric field is related to the SW plasma velocity V_{sw} and one of the significant geoeffective interplanetary medium parameters — the southward IMF B_z component. In terms of SW type, we have performed a correlation analysis of SME_{aver}, the SW electric field, and the southward B_z component.

Figure 2 exhibits the correlation between SME_{aver} and E_{swaver} and $|B_{z\,aver}|$ for CIR- and ICME-induced magnetic storms. Figure 2 indicates that for SW of both

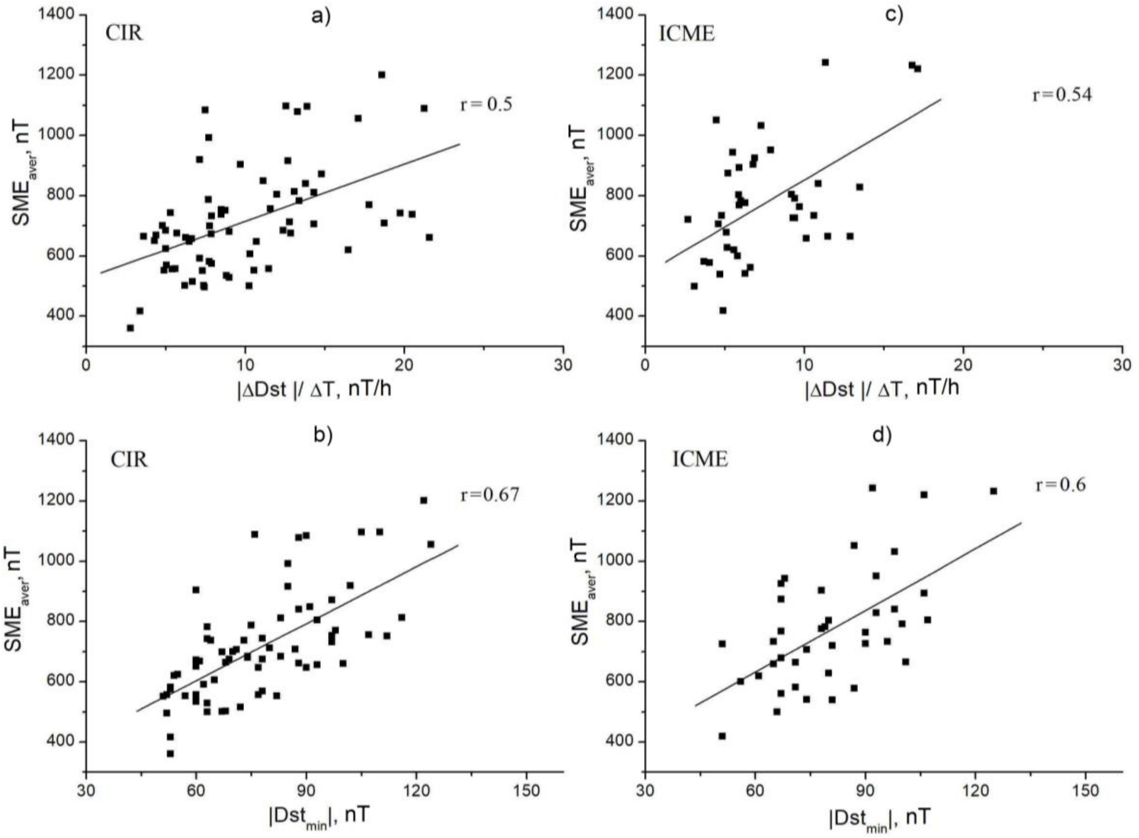

Figure 1. SME_{aver} as a function of the magnetic storm development rate and the $Dst_{\min}$ modulus during main phases of CIR- and ICME-induced magnetic storms: squares — separate magnetic storms; straight lines — linear approximation; r — correlation coefficient

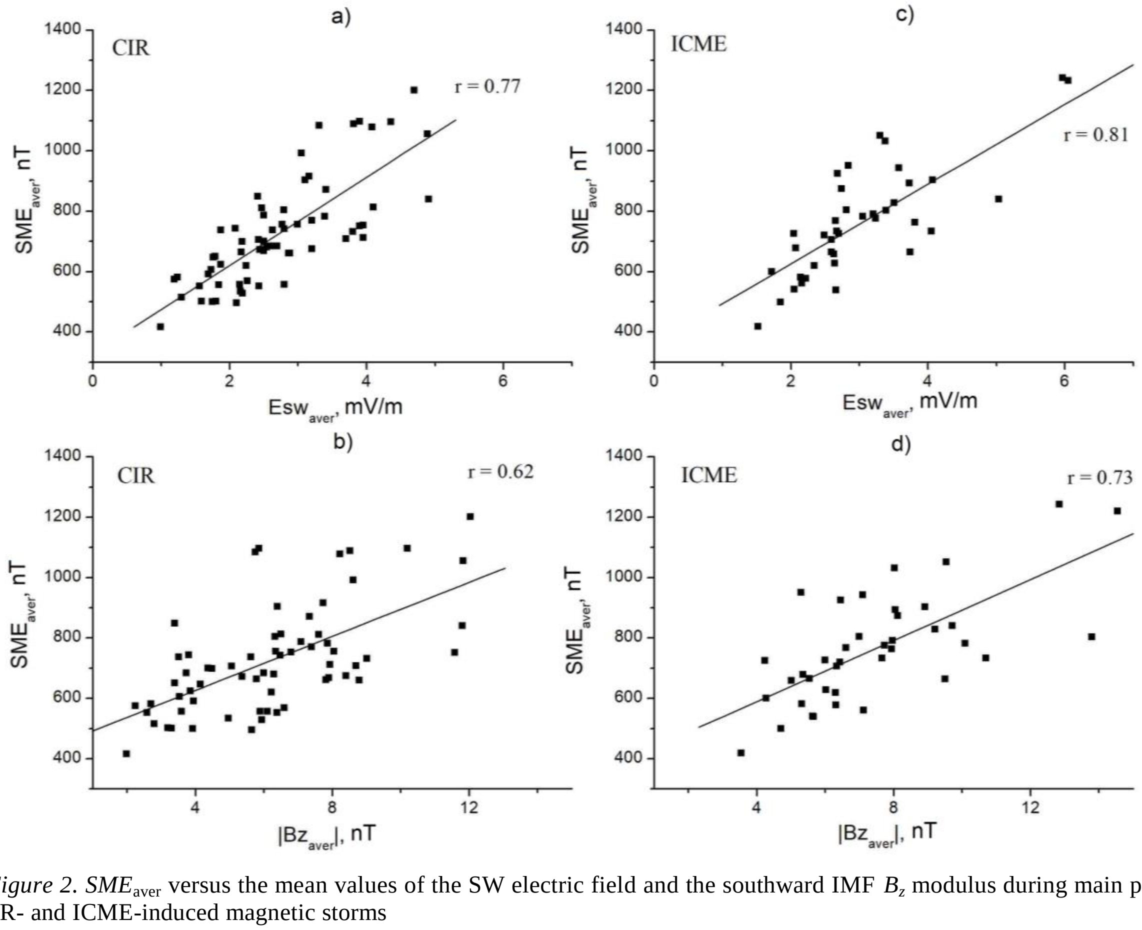

Figure 2. SME_{aver} versus the mean values of the SW electric field and the southward IMF B_z modulus during main phases of CIR- and ICME-induced magnetic storms

Pearson correlation coefficients r between SME_{aver}, magnetic storm characteristics, and interplanetary medium parameters, calculated with a significance level p=0.01, in magnetic storm main phases during CIR and ICME events, as well as regression equations. The correlation coefficients and regression equations for AE and K_{p} have been taken from [Boroyev et al., 2020]

	CIR	ICME	Regression equations for SME_{aver}	
	r	r	CIR	ICME
SME_{aver} and $\lvert\Delta Dst\rvert/\Delta T$	0.50	0.54	$y = 20x + 526$	$y = 29x + 551$
AE_{aver} and $\lvert\Delta Dst\rvert/\Delta T$	0.51	0.29	$y = 14x + 485$	$y = 9.7x + 572$
$K_{\text{p aver}}$ and $\lvert\Delta Dst\rvert/\Delta T$	0.54	0.62	$y = 0.8x + 40$	$y = 1.2x + 34$
SME_{aver} and $\lvert Dst_{\text{min}}\rvert$	0.67	0.6	$y = 6.3x + 226$	$y = 6.8x + 223$
AE_{aver} and $\lvert Dst_{\text{min}}\rvert$	0.53	0.41	$y = 4x + 320$	$y = 2x + 464$
$K_{\text{p aver}}$ and $\lvert Dst_{\text{min}}\rvert$	0.59	0.67	$y = 0.2x + 30$	$y = 0.2x + 26$
SME_{aver} and $E_{\text{sw aver}}$	0.77	0.81	$y = 146x + 328$	$y = 131x + 362$
AE_{aver} and $E_{\text{sw aver}}$	0.67	0.66	$y = 97x + 367$	$y = 95x + 353$
$K_{\text{p aver}}$ and $E_{\text{sw aver}}$	0.66	0.77	$y = 5x + 34$	$y = 6x + 24$
SME_{aver} and $\lvert B_{z\,\text{aver}}\rvert$	0.62	0.73	$y = 45x + 447$	$y = 50x + 387$
AE_{aver} and $\lvert B_{z\,\text{aver}}\rvert$	0.57	0.59	$y = 32x + 433$	$y = 37x + 370$
$K_{\text{p aver}}$ and $\lvert B_{z\,\text{aver}}\rvert$	0.44	0.53	$y = 1.3x + 40$	$y = 1.9x + 30$

types SME_{aver} increases linearly with E_{swaver} and $|B_{z\,\text{aver}}|$. There are high and close correlation coefficients between SME_{aver} and E_{swaver} for CIR (r=0.77) and ICME (r=0.81) events, whereas the correlation coefficients between SME_{aver} and $|B_{\text{zaver}}|$ for CIR (r=0.62) and ICME (r=0.73) are lower and markedly different (Figure 2, *b*, *d*).

DISCUSSION AND CONCLUSIONS

In this paper, we have examined the geomagnetic index of auroral activity *SME*, which, unlike *AE* and K_{p}, takes into account the equatorward drift of ionospheric currents and allows for a more accurate assessment of the intensity of ionospheric currents during magnetic storms. As magnetic storm parameters, we took the rate of magnetic storm development and Dst_{min}. Figure 1, *a*, *c* shows that the *SME* index correlates with the magnetic storm development rate for CIR (r=0.5) and ICME (r=0.54) events. There is however a difference in angular coefficients in the regression equations between SME_{aver} and $|\Delta Dst|/\Delta T$ (see Table). Unlike *SME*, the correlation coefficients between $|\Delta Dst|/\Delta T$ and *AE* and K_{p} differ greatly for CIR and ICME events. For *AE*, the correlation coefficient for ICME (r=0.29) is significantly lower than that for CIR (r=0.51), whereas for K_{p}, on the contrary, the correlation coefficient for ICME is slightly higher than that for CIR (see Table).

The magnetic storm velocity, or rather its variation $\Delta Dst/\Delta T$, depends on interplanetary medium parameters. A set of coupling functions for different combinations of SW/IMF parameters, including those determining *Dst*-index variations, has been proposed (e.g., [Burton et al., 1975; Newell et al., 2007; Borovsky, Birn, 2014; Dremuhina et al., 2018b]). Analysis has shown [Burton et al., 1975; Maltsev, Rezhenov, 2003] that there is a strong dependence of $\Delta Dst/\Delta T$ on southward IMF B_z. It is in the southward IMF B_z component that the SW type manifests itself. For example, in ICME (MC and ejecta), the magnetic field has a structure in the form of a rope, and inside it the magnetic pressure prevails over the thermal one β<1. The magnetic cloud, unlike ejecta, has a higher (>10 nT) and more regular magnetic field. In CIR, plasma has an increased density and temperature, and the thermal pressure prevails over the magnetic pressure β>1. Figure 2, *b*, *d* shows that some of CIR-induced magnetic storms have small values of southward IMF B_z. This is probably why for CIR the angular coefficient of the regression equation between SME_{aver} and $|\Delta Dst|/\Delta T$ is lower than for ICME.

Khorosheva [2007] has reported findings of studies of the relationship between the shift of magnetospheric boundaries and the magnetic storm strength. According to this study, the *Dst* index makes it possible to estimate the position of boundaries of aurora and electrojets during magnetic storms. Dst_{min} determines the minimum latitude of the occurrence of auroras and electrojets during magnetic storms. The latitude of auroral electrojets during CIR and ICME events does not affect the *SME* index, as opposed to the *AE* and K_{p} indices. As seen in Figure 1, *b*, *d*, there are high and close correlation coefficients between *SME* and Dst_{min} during CIR (r=0.67) and ICME (r=0.6) events. There are no differences in the regression equations for CIR and ICME events either. The SW type has no effect on the relationship between SME_{aver} and $|Dst_{\text{min}}|$.

In this work, as in [Boroyev et al, 2020], to analyze the SW effect on auroral disturbances during magnetic storms, we have examined the SW electric field and IMF B_z. We have obtained higher and closer correlation coefficients between SME_{aver} and E_{swaver} (see Table) as compared to *AE* and K_{p}. There are no noticeable differences in the angular coefficients in the regression equations between SME_{aver} and $E_{\text{swaver},}$ and no relationship with the SW type (CIR/ICME) has been found either. The dependence of *SME* on E_{sw} is more pronounced than on *AE*. For SW of both types, a closer relationship is observed between SME_{aver} and $|B_{\text{zaver}}|$, yet the correlation coefficient for ICME events (r=0.73) is higher than for CIR events (r=0.62). Despite the difference in the correlation coefficients between SME_{aver} and $|B_{z\,\text{aver}}|$, the angular coefficients in the regression equations between SME_{aver} and $|B_{z\,\text{aver}}|$ for SW of both types have similar values (see Table). Comparative analysis of the correlation coefficients between SME_{aver}, AE, K_{p} and the magnetic storm and interplanetary medium parameters, as well as the respective regression equations, allows us to conclude that K_{p}, unlike AE, more accurately describes auroral activity in magnetic storm main phases during CIR and ICME events.

SW of each type has a certain set of parameters (see, e.g., [Yermolaev et al., 2010]). One of the important SW parameters is the southward IMF B_z component whose geoeffectiveness is associated with the SW electric field. It is at the southward B_z component that most magnetospheric-ionospheric disturbances are recorded, and the difference between SW types is manifested in its value. For example, Figure 2 indicates that during CIR events most magnetic storms have low values of the southward B_z component. Variations in the geomagnetic indices during the magnetic storm main phase depend on SW type. It has been shown [Plotnikov, Barkova, 2007; Yermolaev et al., 2010; Nikolaeva et al., 2011; Dremukhina et al., 2018a] that during magnetic storm main phases the dependences of AE, ap, K_{p} on E_{sw} are nonlinear for MC (possibly for all ICME events) and linear for CIR events. The nonlinear character is observed at high values of the SW electric field (E_{sw}>11 mV/m). According to [Plotnikov, Barkova, 2007; Yermolaev et al., 2017; Nikolaeva et al., 2017; Dremukhina et al., 2018a], the difference between variations in the indices for SW of different types may be due to the fact that along with southward IMF B_z it is also necessary to take into account other SW parameters (for example, SW pressure, IMF turbulence) whose values differ for SW of different types.

Unlike the dynamics of the AE and K_{p} indices, the dynamics of SME in magnetic storm main phases during CIR and ICME events does not depend on SW type. We have obtained high correlation coefficients between SME and the SW electric field (southward IMF B_z); and the regression equations between SME and E_{sw} (IMF B_z) for CIR and ICME events, taking into account the error in calculating the coefficients in the regression equations (within the error of ±10 %), differ slightly. It should however be noted that in this work we have selected magnetic storms with $|Dst_{\text{min}}|$<130 nT. In [Plotnikov, Barkova, 2007; Yermolaev et al., 2010, 2017; Nikolaeva et al., 2017; Dremukhina et al., 2018a], stronger magnetic storms $|Dst_{\text{min}}|$>130 nT have also been analyzed. It is possible that in magnetic storms with $|Dst_{\text{min}}|$<130 nT during CIR and ICME events, the dynamics of the geomagnetic indices is largely determined by southward IMF B_z. Other SW parameters have little effect on the geomagnetic indices.

The results of the analysis lead to the following conclusions:

1. In magnetic storm main phases during CIR and ICME events, a stronger correlation is shown to be between SME_{aver} and the interplanetary medium parameters, as compared to AE and K_{p}. We have obtained close correlation coefficients between SME_{aver} and the SW electric field (southward IMF B_z) for CIR and ICME events.

2. We have found that SME_{aver} correlates with the rate of magnetic storm development and $|Dst_{\text{min}}|$ for CIR and ICME events, while no relationship with SW type (CIR/ICME) is observed.

3. We have established that K_{p}, unlike AE, more accurately describes the dynamics of auroral currents in magnetic storm main phases during CIR and ICME events.

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