Relation of PC index to the geomagnetic storm Dst variation

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1. Introduction

Geomagnetic storms are the result of joint action of the magnetopause currents (DCF), which are proportional to the square root of the dynamic pressure of the solar wind, and magnetospheric ring currents (DR). The ground effect of DR current typically far exceeds the effect of DCF currents, that is why the magnetic storm intensity is evaluated by the Dst index depicting the longitudinally averaged magnetic field depression at low latitudes (Sugiura, 1976).

It is well known (Burton et al., 1975; Akasofu, 1981) that the intensity of magnetic storms is dominantly controlled by the southward IMF component \( B_Y \), whereas the solar wind velocity \( V \) and density \( n \) are of minor importance. It was also suggested (McPherron, 1997) that substorms or substorm-like activations can play a part in the ring current intensification and decay. In models for operational forecasting of the Dst index (O’Brien and McPherron, 2000; Lundstedt et al., 2002), simultaneous observations of \( B_Z \), \( n \) and \( V \) were used. While investigating the solar wind-magnetosphere-coupling functions, the best result has been obtained for functions including the geoeffective interplanetary electric field \( E_m \) (Newell et al., 2008; Spencer et al., 2009).

The PC index was introduced (Troshichev and Andrezen, 1985; Troshichev et al., 1988) as an indicator of magnetic activity in the polar caps generated by the geoeffective interplanetary electric field \( E_m \) (Kan and Lee, 1979):

\[
E_m = \frac{v_{SW} (B^2_2 + B^2_Y)}{2} \sin^2 (\Theta/2),
\]

where \( v_{SW} \) is the velocity of the solar wind, \( B_2 \) and \( B_Y \) are the components of the interplanetary magnetic field (IMF), and \( \Theta \) is the angle between the IMF transverse component and the geomagnetic dipole. The PC index is estimated independently for the northern (PCN) and southern (PCS) polar caps, basing on data from two near-pole stations Thule in Greenland (at 85.4° corrected geomagnetic latitude) and Vostok in Antarctica (at 83.4°).

The PC index is a reliable proxy characterizing the solar wind energy having been entered into the magnetosphere.
intensity (AE index) (Vennerstrom et al., 1991; Vassiliadis et al., 1996; Takalo and Timonen, 1998), the cross polar cap voltage and polar cap diameter (Trostchev et al., 1996; Ridley and Kihn, 2004), ionospheric electric field in the near-pole region (Trostchev et al., 2000; Ridley and Kihn, 2004), ionospheric Joule heat production (Chun et al., 1999, 2002), the global auroral power (Liou et al., 2003). Influence of the solar wind pressure impulses on the PC index was shown in Lukianova and Troshichev (2002), Lukianova (2003), Lee et al. (2004), Liou et al. (2004) and Huang (2005). Thus, the results of the previous analyses made it possible to regard the PC index as a measure characterizing the current state of the magnetosphere activity.

In 2006 the unified procedure for derivation of the 1-min PCN and PCS indices was elaborated (Trostchev et al., 2006) to remove distinctions in the PCN and PCS indices caused by some differences in procedures of their calculation. The unified procedure ensures on-line derivation of the PC calculation provided that: (1) the unified PCN and PCS indices are in close agreement to one another, except the specific conditions; (2) the unified PCN and PCS indices are consistent with the electric field Em; (3) there is no daily variation in behavior of the PCN and PCS indices; and (4) there is no seasonal variation in behavior of the PCN and PCS indices. The comprehensive analysis of relationships between the polar cap magnetic activity behavior and the substorm development has been fulfilled with use of the unified 1-min PC index. It was found that the PC growth precedes the magnetic disturbance onset in the auroral zone, that the substorm sudden onsets occur when the PC index exceeds the threshold of ~1.5–2 mV/m, that the PC growth rate determines the substorm growth phase when the PC index exceeds the threshold of ~2 mV/m, that the pressure effects in the PC value (Stauning and Troshichev, 2008). The total conclusion has been made that the PC index can be considered as an indicator characterizing the solar wind energy input in the magnetosphere.

In this paper we examine the relationships between behavior of the PC index and development of the storm depression (Dst index) to support the above conclusion. If the relation of the PC index to magnetic storms is similar to that for the magnetospheric substorm, the PC index can be successfully applied to diagnose the development of the magnetospheric substorm and magnetic storms, and to monitor the current state of magnetosphere.

### Table 1

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Data on the Dst index for 1998–2004 were provided by the World Data Center B2 in Japan (http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html). The solar wind dynamic pressure behavior is not examined in the analysis, since our previous study (Trostchev et al., 2007) showed that PC index responds to the pressure gradient in direct proportion and in the same manner as to the electric field Em influence (PC increases for positive values ∆Em and ∆PSW, and decreases for negative values ∆Em and ∆PSW), the pressure gradient ∆PSW = 1 nPa being approximately equivalent to action of ∆Em = 0.33 mV/m.

The following criteria were used as a basic guideline to choose the magnetic storms for the analysis: (1) duration of magnetic storm should be longer than 12 h; and (2) the depression of magnetic storm should be larger than Dst = –30 nT. Basing on these criteria we separated 54 magnetic storms for the period of 1998–2002 and 2004 with the maximal storm intensity varying in range from Dst = –30 to –373 nT. The list of the analyzed storms is given in Table 1. The list did not include the storms occurred in 2003, since the PCS index is not available for 2003, and one more storm observed in January of 2005 under conditions of the northward IMF was added. It was found once that all chosen storms occurred under condition PSW > 2 mV/m.

While studying the magnetic storms nature Chapman (1963) and Akasofu and Chapman (1972) examined exclusively storms with quickly developing and quickly damping depression of the magnetic field and subsequent slow restoration of the field to a...
quiet level. Correspondingly, the classical storm pattern includes a clearly delineated “main phase”, combining the fast depression and the initial fast recovery, and a “recovery phase”, demonstrating a slow restoration of geomagnetic field. The magnetic storm on April 11, 2001, shown in Fig. 1, is a typical example of the classical pattern. Meanwhile, other patterns of the Dst development are encountered, when the strong depression is developed, damped and amplified again and again. As an example, see in Fig. 2 the magnetic storms taking place on February 28, 1999 and on November 7–10, 2001. The latter storm lasted, without interruption, four days with the several strong depressions of magnetic field: the first largest peak value of Dst equal to \(-373\) nT was reached on November 08, afterwards the depression was damped up to \(-100\) nT on November 8, and then was amplified again to \(-150\) nT, then to \(-225\) nT on November 9, and at last up to \(-279\) nT on November 10, 2004. In these cases the concept of a single clearly delineated main phase becomes not only indefinite, but even contradictory.

For convenience of comparison of the PC (Em) behavior with the storm development we divided the main phase into two parts: the “growth phase”, which is consistent with a progressive depression of the geomagnetic field and the “damping phase”, which is consistent with an initial fast recovery of geomagnetic field. Period of the magnetic field slow restoration to the previous undisturbed level is denoted by “recovery phase”, as before. These three phases are shown in the same Fig. 1, where numbers 1, 2, and 3 denote the times of the storm depression beginning, the storm depression peak, and the end of the damping phase, when the main phase is changed for the recovery phase.

The Dst index value is determined mainly by joint action of two current sources: by the magnetopause currents (DCF) increasing the geomagnetic field, and magnetospheric ring currents (DR), decreasing the geomagnetic field. A noticeable input in Dst value can be also produced by the dawn-dusk currents in the near-Earth plasma sheet and by Region 2 FAC closing currents in the equatorial magnetosphere. Since these latter currents are confined to definite LT sectors in the magnetosphere, their effect is revealed mainly in the asymmetric development of the geomagnetic field depression (with use of the ASYM-H index). As a consequence, the time and value of the initial decline of the Dst index can be dependent on different reasons not only on the DR current growth. In addition, during the solar maximum epoch (1998–2004) the magnetic storms were often following one after another, when a new magnetic storm is started against the background of recovery phase of the previous storm. Under these conditions the value of Dst, as itself, could not be regarded as an adequate indicator of the storm depression beginnings. In a similar way, the exact identification of the transition time from “depression damping” to “slow restoration” turned out to be problematic in many cases owing to either very smooth changes in Dst or to multiple fluctuations in the Dst reduction rate.

As a result, it would be well to look for another characteristic, independent on the peculiarities of the certain magnetic storm development. Referring to results (Janzhura et al., 2007; Troschichev and Janzhura, 2009) and suggesting that a similar threshold of the solar wind energy input is acting for both magnetospheric substorm and magnetic storms, the value \(PC = 2\) mV/m has been tested as a threshold level. The time when the PC index persistently rises above the level \(2\) mV/m was taken as a time \((T = 0)\) of the disturbance beginning, and the time when the PC index persistently falls below the level \(2\) mV/m was taken as a time of the recovery phase beginning.

3. Results of the analysis

3.1. Threshold level of Em and PC conforming to the storm beginning

Fig. 2 shows behavior of the PC index (upper panel) and run of the magnetic storm Dst index (lower panel) for 8 storms of different intensity. The summer PC is used in the analysis, that means the PCN index for period May/June/July/August and the PCS index for period November/December/January/February. For the equinox periods March/April and September/October both indices are usable. At the upper panel the behavior of the corresponding geoeffective interplanetary electric field Em, reduced to the magnetopause, is also shown. The time of storm development in Fig. 2 is counted from moment \(T = 0\), when the PC index persistently rises above the threshold \(Em = 2\) mV.

Fig. 2(a) shows development of the weak magnetic storm on July 28, 1999 with maximal depression \(Dst = -38\) nT. In this case the value \(PC = 2\) mV/m was reached at first at 11.55 UT (moment \(T = 0\)), but the PC excess above the threshold was small and PC fluctuated around \(2\) mV/m till 15.53 UT. The Dst value is kept on level about \(-3\) nT during this 4 h interval. The persistent PC increase began at 15.53 UT, and just at this time the magnetic depression started to grow. As for the interplanetary electric field Em, it reached the threshold \(2\) mV/m about 3.5 h later than PC (at 15.26 UT), without any obvious response in the Dst value. The PC index kept, in average, the value higher than \(2\) mV/m till 02.53 UT on July 29, 1999, after that the PC and Em finally descend below the level of \(2\) mV/m, marking the end of the magnetic field depression.

Fig. 2(b) shows development of magnetic storm on December 10, 1998 with maximal depression \(Dst = -67\) nT. The PC index firstly exceeds the threshold \(2\) mV/m at 13.15 UT, with 7 min delay relative to Em, when Dst index was about \(1\) nT. However, the PC exceeding above the threshold was insignificant and about 2.5 h later PC was again returned to values below \(1.5\) mV/v. At 18.08 UT (moment \(T = 0\)) the PC index secondly exceeds the threshold \(2\) mV/m and fluctuated around this level during next 4 h. The quick increase of PC and Em started only at 22.07 UT being followed by the essential growth of the magnetic field depression. The depression quickly stopped as soon as PC fell below \(2\) mV/m at 16.08 UT on December 11, 1998.

Fig. 2(c) shows development of magnetic storm on February 28, 1999 with maximal depression \(Dst = -95\) nT. In this case PC and Em crossed the threshold simultaneously at 17.48 UT (moment \(T = 0\)), when Dst index was about \(7\) nT. Afterwards the magnetic field depression began to grow quickly in evident connection with the increase of PC (and Em). The remarkable

![Fig. 1. Separation of the storm growth and damping phases on the example of storm development on April 11, 2001: (1) — the magnetic storm beginning; (2) — maximum of the magnetic depression (Dst (peak)); and (3) — transition from the dumping to recovery phase.](image-url)
peculiarity of this magnetic storm is appearance of three clearly seen extremes (three growth and damping phases) in the run of Dst index: on the 7th hour after the beginning (Dst = 94 nT during 00.00–01.00 UT on March 01, 1999) and on the 25th hour and 32nd hour after the beginning (Dst = 95 nT at 19.00 UT on March 01 and Dst = 80 nT at 02.00 UT on March 02, correspondingly). The end of each of three damping phases was related to the PC (and Em) back crossing the threshold 2 mV/m (at 07.17 UT and 21.00 UT on March 01, and about 03.00 UT on March 02, 1999). Fig. 2(d) shows development of magnetic storm on November 07, 1998 with maximal depression Dst = 149 nT. PC and Em simultaneously crossed the threshold at 11.02 UT (moment $T = 0$), when Dst index was about –10 nT. Like to the previous case, two clearly detected maximal depressions are observed in this event: with Dst = –81 nT at 16.00 UT on November 07 and Dst = –149 nT at 06.00 UT on November 08. The end of first depression was related to the persistent PC descending below the threshold at 18.53 UT on November 07, which was followed by the next strong and long Em and PC increase up to values >10 mV/m. The end of the second depression was related to the final PC falling at 13.15 UT on November 08, 1998.

Fig. 2(e) shows development of magnetic storm on October 01, 2002 with maximal depression Dst = –176 nT. The threshold 2 mV/m was crossed by Em at 04.10 UT, more than one hour ahead PC at 05.34 UT, but Dst value weakly changes (from –20 to –25 nT) during this time. The sharp increase of the magnetic field depression began in connection with the quick PC growth after 05.34 UT (moment $T = 0$). The high and stable level of depression (Dst > 150 nT) was held about 10 h in evident response to the high (> 4 mV/m) and stable level of PC and Em quantities. The PC index falling below 2 mV/m after 10.45 UT on October 2 was accompanied by the magnetic depression damping. Fig. 2(f) shows development of magnetic storm on April 11, 2001 with maximal depression Dst = –270 nT. The threshold 2 mV/m was crossed by PC at 13.00 UT (moment $T = 0$), two hours ahead Em (15.00 UT), the Dst value being increased from –17 to –4 nT during this time. Depression of the magnetic field started only at 16.00 UT in evident relation to the sharp growth of PC and Em quantities, which reached in this event so large values as 20 mV/m. The quantities PC and Em kept the high value (> 4 mV/m) during 22 h in course of this event. The storm damping phase was ended at 12.06 UT on April 06 in relation to final descend of the PC index below the threshold 2 mV/m. Fig. 2(g) shows development of magnetic storm on November 07, 2004, the most powerful storm during the last solar maximum epoch (Dst = –373 nT). PC crossed the threshold at 18.30 UT (moment $T = 0$), against the background of the enhanced DCF currents caused by the high solar wind pressure (Dst = +24 nT). The geomagnetic field depression was displayed only at 20.11 UT, when PC and Em started to grow persistently. Five hours later the Em field reached to the extremely high value 33 mV/m that was followed by the deepest geomagnetic field depression. In that
time the PC index varied in range from 6 to 12 mV/m, demonstrating "the PC saturation effect", which is typical of relations between the very high values of PC and Em (> 10 mV/m). The storm damping phase come to the end about 15.30 UT in relation to the firm descend of Em and then PC below the threshold 2 mV/m.

Fig. 2(h) shows development of magnetic storm on November 09, 2004, which started against the background of recovery phase of the previous November 07 storm. In this case a new magnetic depression started at 11.00 UT at level of Dst = 90 nT in relation with sharp jump of PC higher 6 mV/m. We can see three successive strong depressions: the first depression (Dst = −155 nT) at 15.00–16.00 UT on November 09 was related to spike in the PC index up to ~12 mV/m at 14.56 UT, the second depression (Dst = −223 nT) at 21.00 UT on November 09 was preceded by the simultaneous spikes in both Em (~26 mV/m) and PC (~13 mV/m) quantities at 19.57 UT, and the third depression (Dst = −289 nT) at 09.00–10.00 UT on November 10 was better agreed with the 6 h enhancement of Em above 17 mV/m in interval from 01.52 to 08.15, whereas the PC index fluctuates in range from 6 to 12 mV/m during this time. "The PC saturation effect" is evident in this case again. The third damping phase was terminated by descend of PC and Em below 2 mV/m about 19.00 UT on November 10, 2004.

To demonstrate that features, displayed in Fig. 2, are typical of relationship between PC (Em) changes and the magnetic storm development, we separated the magnetic storms into six gradations according to their intensity and examined relationship between the averaged PC (Em) and Dst quantities for these gradations. The gradations, determined by minimal Dst value, are the following: (a) −30 > Dst > −50 nT; (b) −50 > Dst > −80 nT; (c) −80 > Dst > −100 nT; (d) −100 > Dst > −120 nT; (e) −130 > Dst > −160 nT; and (f) −160 > Dst > −240 nT. Three magnetic storms of the larger intensity Dst = 271, −289, and −373 nT are presented in Fig. 2(f–h), respectively. The method of the superposed epochs has been used, the key date (T = 0) being taken as a time of the persistent transition of the PC index over the level of 2 mV/m.

Fig. 3 shows the behavior of the averaged geoeffective interplanetary electric field Em and PC index and the corresponding changes in the Dst index for these 6 gradations. The behavior of the averaged quantities obviously demonstrates that the Dst index starts to decline, on the average, as soon as the value of the interplanetary electric field Em (and PC index) exceeds the threshold of ~2 mV/m. It is remarkable that the

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**Fig. 3.** Behavior of the averaged PC index (black curve) and Em field (grey curve) and the corresponding run of the averaged Dst index given in the appropriate upper and lower boxes given for six gradations of the magnetic storm intensity: (a) −30 > Dst > −50 nT; (b) −50 > Dst > −80 nT; (c) −80 > Dst > −100 nT; (d) −100 > Dst > −120 nT; (e) −130 > Dst > −160 nT; and (f) −160 > Dst > −240 nT. The key date (T = 0) is taken as the time of the persistent transition of the Em value over the level of 2 mV/m.
averaged PC and Em display the abrupt simultaneous jump at $T=0$ for storms with depression more than $-50$ nT. It should be reminded in this connection that the point ($T=0$) was determined as a time, when the PC index rises above the level PC = 2 mV/m, along with the following criteria: duration of the storm interval should be longer than 12 h and the mean PC (Em) value during the interval should be higher than 2 mV/m. We suggest that these conditions are typical of interplanetary shocks demonstrating the sharpening effect of Em at their fronts.

The Dst magnetic field depression is considered as a primary magnetic field depression caused by the solar wind and solar storm events. It is characterized by the sharp enhancement of Em at its fronts. In the process of the solar wind undulation, the Dst magnetic field depression is at its maximum and the magnitude of the PC (Em) values below the threshold level (statistical relationships).

3.2. Dependence of the storm dynamics on the em and PC value (statistical relationships)

As Figs. 2 and 3 show the moment of the firm descent of Em or PC quantities below the threshold level $\sim 2$ mV/m approximately corresponds to transition from the damping phase to the recovery phase. We determined the value of Dst observed in moment, when Em or PC firmly descend below 2 mV/m, as a magnetic field depression, corresponding to transition from the damping phase to the recovery phase (Dst (trans)). To derive the statistical relationships between Dst and the mean PC (Em) values two sets of the averaged PC and Em quantities were calculated. In the first set, the quantities PC (growth) and Em (growth) were averaged over the growth phase duration (the interval from the time $T=0$ to the time of the peak Dst value). Quantities Em (growth) and PC (growth) were compared with Dst (peak). In the second set, the quantities PC (damp) and Em (damp) were averaged over the damping phase duration (the interval from the time of the minimal Dst value to the time of the final descent of the PC (Em) quantities below the threshold level $\sim 2$ mV/m). Quantities PC (damp) and Em (damp) were compared with Dst (trans).

The 1-min data for Em, PC and Dst have been taken for the analysis, and the comparison was carried out for each of the storm events.

Fig. 4 shows the relationship between the values of Dst (peak) and the mean quantities Em (growth) (left column) and PC (growth) (right column) for different gradations of Em: (a) Em $< 6$ mV/m; (b) Em $> 6$ mV/m; and (e) all available values of Em, the relations for the appropriate values of PC being shown in Fig. 4(b,d, and f). It should be noted that all scales for PC are equal, whereas scales for Em in Fig. 4e and e are double in comparison with Fig. 4a. One can see that for low values of Em and PC (cases: (a) and (b)), the relationship between Dst (peak) and PC (Dst = 24.8–31.8PC) is of the same character as between Dst (peak) and Em (Dst = 24.9–30.9Em), although correlation of Dst with Em ($R = -0.74$) is much lower, than with PC ($R = -0.87$). While Em field growing the correlation between Dst (peak) and Em (growth) arises up to $R = -0.95$, but the efficiency of Em strongly decreases (Dst $= 35.6–16.05$Em). It is evident from Fig. 4c that rise of the correlation coefficient is attained at the cost of 3 far removed points of Em with values 12.1, 16.3 and 20.6 mV/m. The same is true for Fig. 4e, where the high level of correlation ($R = -0.90$) is determined also by these three far removed points. Indeed, if these three points are excluded from examination, the correlation between Dst (peak) and Em (growth) falls up to $R = -0.77$. At the same time, the relationship between Dst and PC remains practically invariant under conditions of Em $< 6$ mV/m (Fig. 4b), Em $> 6$ mV/m (Fig. 4d) and for values of Em (Fig. 4f). Thus the link between PC and Dst is characterized by the same relationship regardless to Em and PC value, whereas the character of link between Em and Dst changes with Em value, the Em efficiency being strongly decreased while exceeding the level Em $\sim 6$ mV/m.

Fig. 5 shows the relationship between two series of Dst (trans), demonstrates the high level of correlation ($R = 0.95$) between the Dst (trans) quantities derived for Em and PC, with a slightly more negative values of Dst (trans) obtained from the PC index. It means that both parameters, Em and PC, provide closely related times of the final threshold intersection, the PC being descended slightly sooner.

Correlation of value Dst (trans) with c quantities Em (damp) and PC (damp) turned out to be much worst than correlation of value Dst (peak) with quantities Em (growth) and PC (growth). Decline of correlation in case of Dst (trans) seems to be reasonable, if we take into account that value Dst (trans) should be strongly dependent on deepness of the storm magnetic depression Dst (peak) for the certain storm. Indeed, as Fig. 6 shows the correlation between values Dst (trans) and Dst (peak) is so high as $R = 0.825$. It means that transition from damping phase to recovery phase can occur at different levels of Dst being dependent primarily on the storm intensity and only secondly on the average PC value during the damping phase.

Fig. 7 shows the relationships between parameter Dst (trans) and the mean quantities Em (damp) (left column) and PC (damp) (right column) for the following gradations of Em: Em $< 5$ mV/m, Em $> 5$ mV/m and for all available values of Em, the appropriate values of PC being examined. Like to Fig. 4, the relationships between Dst (trans) and Em quantities and between Dst (trans) and PC quantities turned out to be similar only for low values of Em $< 5$ mV/m (Dst $= 6.8–17.4$Em and Dst $= 8.2–21.25$PC), with coefficients of correlation $R = 0.415$ for Em and $R = 0.66$ for PC. For values of Em $> 5$ mV/m, efficiency of the link between Dst (trans) and Em sharply decreases (Dst $= -34.3–7.6$Em), however the correlation is the same ($R = 0.415$). On contrary, the link between Dst (trans) and PC changes insignificantly (Dst $= 36.2–22.7$PC), and correlation increases up to $R = -0.80$. The same regularity is valid for all body of Em and PC data: Dst $= 36.1–8.1$Em with $R = -0.46$ and Dst $= -4.8–16.9$PC with $R = -0.71$. 

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3.3. **Effect of “Dst saturation”**

As Figs. 4 and 7 show the regression equations describing the relationship between interplanetary electric field $E_m$ and Dst index sharply change while overstepping the $E_m$ level $\approx 5–6$ mV/m. The same effect is observed for relationship between the storm intensity $D_{st}$ (peak) and value $E_m$ averaged for the growth phase, and for relationship between the storm parameter $D_{st}$ (trans) and value $E_m$ averaged for the damping phase. To clearly demonstrate this regularity we calculated the values $D_{st}$ (peak) and $D_{st}$ (trans) for different values of $E_m$, referring to the regression equations, presented in Figs. 4(a, c) and 7(a,c). Results presented in

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**Fig. 4.** Relationships between the storm intensity $D_{st}$ (peak) and the quantities $E_m$ (grow) and PC (grow), averaged over the interval of the storm growth phase, derived for three categories of $E_m$ and PC values: (a) and (b) $E_m < 6$ mV/m; (c) and (d) $E_m > 6$ mV/m; (e) and (f) all values of $E_m$. 

**Legend:**
- **(a)** $D_{st}$ = 24.9 - 30.9$^\circ$ $E_m$
  - $R$ = -0.074  $N$ = 39
- **(b)** $D_{st}$ = 24.8 - 31.8$^\circ$ PC
  - $R$ = -0.87  $N$ = 42
- **(c)** $D_{st}$ = -35.6 - 16.06$^\circ$ $E_m$
  - $R$ = -0.95  $N$ = 13
- **(d)** $D_{st}$ = 8.2 - 32.6$^\circ$ PC
  - $R$ = -0.91  $N$ = 13
- **(e)** $D_{st}$ = -26.5 - 17.2$^\circ$ $E_m$
  - $R$ = -0.90  $N$ = 52
- **(f)** $D_{st}$ = 32.2 - 34.6$^\circ$ PC
  - $R$ = -0.915  $N$ = 55
It should be noted that it is commonly supposed that the ring current injection rate does not increase linearly with VBZ and shows no evidence of saturation (Lopez et al., 2009), although the polar cap potential saturation is well documented phenomena (see, for example, Reiff and Luhmann, 1986; Boyle et al., 1997; Kivelson and Ridley, 2008; Newell et al., 2008). So, our results demonstrating the saturation phenomena for the magnetic storm parameters Dst (peak) and Dst (trans) is the first evidence that rates of the ring current injection and damping are differ for large and low values of Em. The analogous effect of "PC saturation" is observed for relations between the interplanetary electric field and PC index (Nagatsuma, 2002; Troshichev et al., 2006; Fiori et al., 2009; Lyatsky et al., 2010).

The same Fig. 8 shows the corresponding Dst values calculated by the PC index, according to the regression equations presented in Figs. 4(b,d) and 7(b,d). One can see that the growth rate for quantities Dst (peak) and damping rate for Dst (trans) practically do not change while passing the crucial level of PC=5–6 mV/m. As a result, the Dst parameters, estimated by the PC index under conditions of large Em and PC values, can be two times as much as estimated by Em field. Thus, “saturation effect” in Dst is evident only for relations with the interplanetary electric field Em. In this connection we have to emphasize that PC and Dst indices characterize magnetic disturbances occurring in the quite different regions of the magnetosphere and generated by the quite different physical processes: PC index is related to the electric currents or fields in the polar ionosphere, whereas Dst index is related to the ring currents flowing in the inner magnetosphere. The source, the solar wind, providing energy for these disturbances is a single thing, which is common for them. It means that “Dst saturation” like to “PC saturation” is manifestation of peculiarities taking place in process of coupling between the interplanetary electric field and magnetosphere. Both saturation effects are indicative on the same regularity: the coupling between the solar wind and magnetosphere is more effective for Em < 5–6 mV/m than for Em > 6 mV/m. The PC index, as an indicator of the actual solar wind energy transferring into the magnetosphere, and the Dst index, as a characteristic of energy stored in the magnetosphere and expended for magnetic storms, both adequately responds to changes in efficiency of the coupling function. Just this circumstance ensures the linear correlation between the PC and Dst values regardless to value of Em seen in Fig. 8.

3.4. Magnetic storms occurring under conditions of northward IMF

The storm of January 21–22, 2005 was remarkable by the high magnetic depression (Dst = −105 nT) developing under condition of the northward IMF. The storm was described by Du et al. (2008) as an anomalous event, the first reported in the literature. According to conclusion of Du et al. (2008), “there was first energy storage in the magnetotail and then a delayed energy injection into the magnetosphere".

Fig. 9 shows the development of the Dst storm of 21–22 January 2005 along with the behavior of the solar wind velocity VSW, IMF BY and BZ components, the interplanetary electric field Em and the summer PC index. One can see that the geomagnetic storm was initiated by the great enhancement of the geoeffective electric field Em with the initial input from the IMF southward component and the succeeding input from the IMF azimuthal BY component against the background of the very high solar wind speed VSW > 800 km/s. The Em drop below 2 mV/m is noted only for short period from 22:15 to 23:30 UT on January 21, but this drop is not confirmed by the PC index, which was larger than 4 mV/m at this time and started to decrease only after 00:00 UT on January 22. Dst responded to this decrease by deviation to recovery after 02:00 UT, but the Em and PC values grew again above 4 mV/m by 02:00 UT, as a result the geomagnetic storm was being continued.

Thus, if we examine the behavior of the geoeffective interplanetary electric field Em during 21–22 January 2005, instead of the IMF BY variations, the situation cannot to be regarded as anomalous. If we take into account the behavior of the PCS index, which remained in range from 2 to 5 mV/m after 20:20 UT on January 21, 2005, the storm of 21–22 January 2005 should be considered as an ordinary event. It is worthy of note again, that the storm development (Dst index) was much better matched by the PC index behavior, than the Em changes.

4. Discussion

It has long been known that geomagnetic storms are generated under conditions of southward IMF and the interplanetary electric field EV was considered as a direct driver of magnetic storms

\[ E_V = V_{SW} B_{Z \theta} \]  

(2)
The attempts were made to estimate a threshold of \( E_Y \) for the ring current to be fed. However, the large scatter of the observed threshold had been revealed at once: from \( E_Y \sim 2 \text{ mV/m} \) (Russel et al., 1974) to \( E_Y > 0.5 \text{ mV/m} \) (Burton et al., 1975). The attempt to summarize the thresholds in IMF \( B_z \) for magnetic storms was made in Gonzalez et al. (1994), who derived the threshold \( B_z < -5 \text{ nT} \) for the moderate magnetic storms. This estimation leads to threshold for the electric field \( E_Y \) of > 2.5 mV/m with the solar wind speed of > 500 km/s, which is typical of moderate storms (in our case the mean solar wind speed for storms with

![Figure 7](image-url)
Dst < 160 nT turned out to be about 550 km/s). Thus, estimations of the electric field \( E_Y \) threshold, required for the magnetic storm beginning, turned out to be differing by a factor of five.

The reason of this dispersion seems to be obvious: the westward electric field \( E_Y \) is not always the actual geoeffective interplanetary electric field. As evidenced by results (Troshichev and Andrezen, 1985) the geoeffective interplanetary electric field is best described by expression (1) given by Kan and Lee (1979). This conclusion is strongly supported by examination of the magnetic storm, occurring on January 21–22, 2005 under conditions of northward IMF \( B_Z \). Comparing expressions (1) and (2) we see that they differ by allowance for the IMF \( B_Y \) component input, the \( B_Y \) effect in expression (1) can be positive as well as negative depending on angle \( \theta \). In practice, if the \( B_Y \) value is close to zero, the both expressions provide almost the same values of the interplanetary electric field (and the appropriate threshold levels). As \( B_Y \) increases relative to \( B_Z \), the difference between the electric fields \( E_Y \) and \( E_m \) quickly grows giving rise to scatter in the threshold values for \( E_Y \) with the unchanged threshold level for \( E_m \). Input of azimuthal IMF component in the electric field \( E_m \) becomes decisive, with definite angles \( \theta \), under conditions of northward IMF component. The statistical relationship between field \( E_m \) and PC index presented for conditions of \( B_Z > 2 \) nT in Troshichev et al. (2006), clearly demonstrates that values of the field \( E_m \) and, correspondingly, PC index, increase proportionally to the By component growth. In exclusive cases the field \( E_m \) can be as large as 5–10 mV/m in spite of northward orientation of IMF. From this point of view an anomalous magnetic storm occurring under conditions of northward IMF \( B_Z \) on 21–22 January 2005 is rather usual phenomena taking place under influence of large interplanetary electric field \( E_m \) provided by the IMF By component.

New results presented in our study demonstrate that the storm duration and intensity is directly related to the PC index value and there is a threshold level of \( ~ \sim 2 \) mV/m, above which the magnetic field depression is developed and below which the depression is damped (if we take into account the firm rise or drop of the PC index). The same level of PC \( ~ \sim 2 \) mV/m has been noted as a condition for the magnetospheric substorm development (Janzhura et al., 2007; Troshichev and Janzhura, 2009). It is worthy to note that in case of magnetospheric substorm the PC index begins to rise ahead of the magnetic disturbance and the PC growth rate infers the magnetic substorm power (Troshichev and Janzhura, 2009). As distinct from substorm development seen in AL, the magnetic storms respond to prolonged exposure to the average \( E_m > 2 \) mV/m and seem to be not evidently affected by the short-time (\(< 1\) h) fluctuations of \( E_m \) and PC. However, we did not examine specifically the question concerning the influence of the PC (Em) oscillations on magnetic storm Dst development, and the problem needs further investigation.

The PC index, based exclusively on the ground magnetic data, demonstrates the same relationship to the magnetic storm, as the geoeffective interplanetary electric field \( E_m \). This fact is not surprising by itself, since the PC index was derived as it had a high correlation just with \( E_m \). However, it should be accepted as a remarkable, if we take into account that the interplanetary field \( E_m \) is regarded as one of possible functions describing the coupling between the solar wind energy and magnetosphere. In such a case the ground-based PC index should be regarded as an indicator of the solar wind energy having been penetrated into the magnetosphere.

The most remarkable thing is that correlation of Dst index with the PC index is more steady and higher than with \( E_m \).
The same regularity has been noted for the magnetospheric substorms (Troshichev and Janzhura, 2009). This circumstance was explained by Troshichev and Janzhura (2009) with the following reasons: (1) the Em value is calculated based on the solar wind parameters measured far from the magnetosphere near the point of injection, and the actual Em value at the magnetopause might be different from that measured by the distant solar wind monitor; (2) very high level of turbulence of magnetic field is typical of magnetosheath near magnetopause (Rossolenko et al., 2008); hence, it is unlikely that changes in the solar wind parameters measured outside of bow shock are converted into the polar cap electric field changes in their true shape; and (3) the PC index makes allowance for the solar wind dynamic pressure effects in addition to Em influence (Troshichev et al., 2007).

The concept of the PC index as a proxy of the solar wind energy having been entered into the magnetosphere was put forward in Janzhura et al. (2007) on the example of the isolated substorms, and was confirmed in Troshichev and Janzhura (2009) on the example of the repetitive sawtooth substorms. The hourly averaged PC index was used as the input parameter in the time-delay neural network to forecast the ring index Dst variation (Stepanova et al., 2005). In this paper we demonstrate that the PC index is well correlated to the magnetic storm Dst dynamic features. This last result provides the weighty argument in support of the PC index use for monitoring the magnetospheric activity. The following peculiarities of the storm development could be evaluated:

- the beginning of ring current formation, evidenced by the firm rising of PC index above the threshold level 2 mV/m;
- the ring current magnitude, based on the relationship between the average PC (growth) and Dst (peak);
- the end of the damping phase (and, therefore, the end of the storm main phase), evidenced by the firm drop of PC below the threshold level of 2 mV/m.

5. Conclusion

We analyzed 54 magnetic storms occurring in 1998–2002 and 2004 with the duration more than 12 h and intensity Dst (peak) lying in range from −30 to −373 nT. All these storms started as soon as the geoactive interplanetary electric field Em and the corresponding PC index firmly exceeded the threshold of −2 mV/m and lasted until the Em and PC quantities firmly dropped below the threshold of −2 mV/m. The moment of the firm descent of the PC and Em quantities below the same level −2 mV/m is indicative on transition from the storm damping phase to the storm recovery phase. The storm intensity (Dst (peak)) demonstrates the steady linear correlation with the PC value, averaged for the growth phase (PCgrowth−mean), irrespective of PC value, whereas character of relationship between Dst (peak) and Em is dependent on the Em value (effect of “Dst saturation”). Respectively, the storm dynamics correlate better with values and changes of the PC index than with those of the Em field. An analogous peculiarity has been revealed for substorms (Troshichev and Janzhura, 2009), where the behavior of the Al index was also better related to the PC changes than to Em variations. Based on these results, the conclusion is made that the PC index is a reliable proxy, characterizing the solar wind energy having been entered into the magnetosphere. In this way, the PC index is well suited for the magnetic storm monitoring.

References


