PC index as a proxy of the solar wind energy that entered into the magnetosphere: relationships between the interplanetary shocks and PC, AL indices

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Introduction

Interplanetary shocks denote the sudden and strong enhancements of solar wind dynamic pressure (Pd) occurring when the high-speed solar plasma flows are propagated through the space with low-speed plasma. Impact of interplanetary shock on the Earth's magnetosphere initiates the magnetosphere compression which displayed as the geomagnetic field impulse. If the impulse is followed by magnetic storm it is classified as a storm commencement (SC), in the opposite case it is classified as a sudden impulse (*SI*).

Effects of the compression waves propagated in the magnetosphere were detected in oscillations of magnetic field and energetic particle flux at geosynchronous orbit [***Erlandson et al.*, 1991; *Lee et al.*, 2004**], in geomagnetic field fluctuations coherent with pressure variations and appeared at the stations located from polar to equatorial regions [***Motobu et al.* 2003**], in increase of the cusp and LLBL area projection [***Newell, and Meng*, 1994]**, in occurrence of aurora near the local noon and their propagation along the auroral oval [***Zhou et al.*, 2003; *Meurant et al., 2004***].

Apart from interplanetary shocks there are also observed the rarefaction waves propagating through the space, which are displayed as negative impulses in global geomagnetic field. These impulses have not drawn attention because they are not followed by magnetic disturbances.

In this study we examine relationships between the solar wind parameters (such as solar wind dynamic pressure Pd, IMF vertical component B_Z, solar wind velocity Vsw and interplanetary electric field E_{KL}) and the magnetic activity indices (*PC*, *AL*, *SymH*) in course of interplanetary shocks.

A rise time of SC is one to six minutes and an amplitude of several tens of nT. The initial phase produced by currents flowing on magnetopause (DCF) typically lasts few hours, during which the field remains compressed by the solar wind pressure increase following the discontinuity.

Evidences on influence of the solar wind pressure impulses Pd on substorms and magnetic storms development are ambiguous.

It has long been known that large magnetic storms are usually preceded by sudden storm commencements (SSC), which are associated with arrival of an enhanced solar wind stream to the dayside magnetopause [***Chapman and Ferraro,* 1932**].

The particle injection into the ring current is proportional to the solar wind dynamic pressure with a power index equal to 0.2 during southward IMF [***Wang et al.,* 2003**].

Response of high-latitude ionosphere to sudden impulse events during the northward IMF conditions was noted by **[*Moretto et al*., 2000]**.

Geomagnetic fiels fluctuations coherent with pressure variations appeared on a global scale at the stations located from polar to equatorialregions [***Motobu et al.,* 2003**].

A shock-induced aurora starting in the noon sector may eventually trigger auroral substorm development on the nightside [***Zhou et al*., 2003; *Meurant et al.*, 2004**]. As this takes place, the latitudes of the substorm onset are shifted poleward in correlation with the solar wind dynamic pressure [***Gerard et al.,* 2004**], the auroral oval width increases and the global intensification of auroral particle precipitation occurs [***Boudouridis et al*., 2003**].

The energy transfer into the magnetosphere is controlled by solar wind density [***Lopez et al*., 2004]**.

Shock compression is not likely to trigger substorms, but enhances magnetospheric currents and auroral particle precipitation**,** contributing equally with IMF Bz to the westward auroral electrojet [***Liou et al.,* 2003, 2004**].

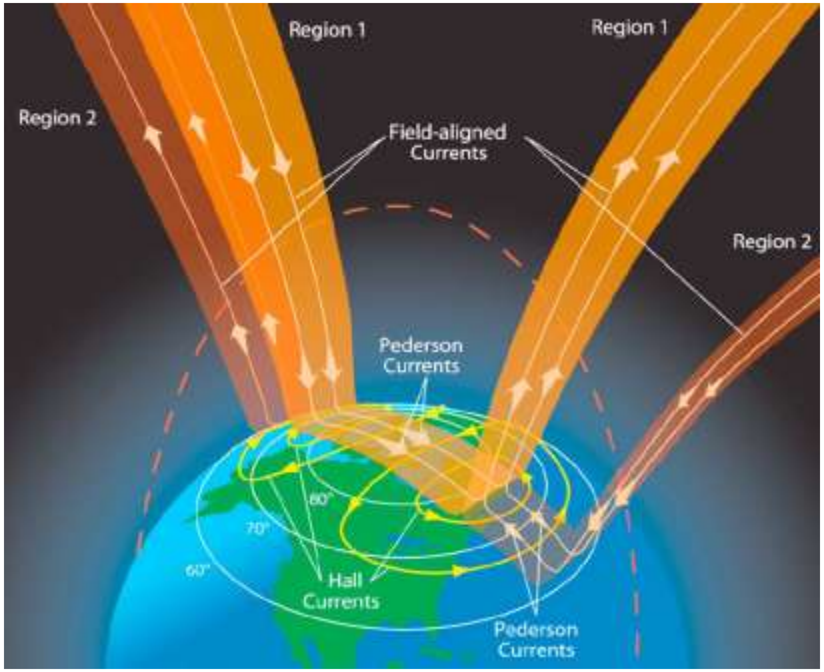
The *AE* index increases in response to solar wind pressure impulses only under conditions of a steady southward IMF **[*Palmroth et al.,* 2004]**.

Even a modest dynamic pressure enhancement can result in significant changes in the magnetosphere if the IMF stays strongly southward for a long interval **[*Lee et al.,* 2004]**.

Interplanetary electric field E_{KL} determines behavior of the *PC* index, whereas the solar wind pressure growth rate seems to be decisive for the *PC* index increase under conditions of the northward IMF B_Z [***Troshichev et al.,* 2007]**

The majority of the shock events do not lead to magnetic disturbances (magnetic bays) [***Liou et al.,* 2017].**

PC index: Physical backgrounds



The variable solar wind coupling with the geomagnetic field constantly generates in magnetosphere the "field-aligned electric currents" flowing along the geomagnetic field lines [*Langel, 1975; McDiarmid et al.,1977; Iijima & Potemra, 1982; Bythrow & Potemra, 1983*].

The currents are distributed along the poleward boundary of the auroral zone (Region 1 FAC) and flow into the polar ionosphere on the dawn side and flow out of the ionosphere on the dusk side of the auroral zone.

These currents are responsible for the cross-polar cap potential difference and ionospheric currents producing the polar cap magnetic disturbances [*Troshichev and Tsyganenko, 1979*].

PC index has been introduced [*Troshichev and Andrezen, 1985; Troshichev et al.*, 1988] to characterize the polar cap magnetic activity produced by the interplanetary electric field E_{KL} [Kan and Lee, 1979]

$$E_{KL}=Vsw*(By^2+Bz^2)^{1/2}\sin^2\theta/2$$

where ***Vsw* –** solar wind speed, ***By, Bz*** –azimuthal and vertical IMF components.

***PC* index is determined as a value of the E_{KL}-produced magnetic disturbances at the near-pole stations (Thule and Vostok) with allowance for UT time, season and hemisphere.**

Data and Method of the analysis

Selection of magnetic storms events with distinctive initial phase was carried out by data on the solar wind dynamic pressure (Pd), obtained from the GSFC/SPDF OMNI/Web interface at http://omniweb.gsfc.nasa.gov. The SC event was identified as a Pd increase by value more than 10 nP within 5 minutes. The events with gaps in the solar wind data were excluded from the analysis if the gaps were in excess of 30% of the event data series.

The 1-min solar wind parameters, such as radial solar wind speed (Vx), vertical IMF component (Bz) and interplanetary electric field (E_{KL}), fixed in the point of libration and reduced to the magnetopause, are regarded as indicators of the solar wind geoefficiency.

The 1-min *PC* index used in the analysis presents the mean value of magnetic activity in the northern (*PCN*) and southern (PCS) polar caps. The value of magnetic disturbances in the auroral zone (*AL* index) is examined as indicator of the magnetospheric activity.

The actual moment of the solar wind contact with magnetosphere was identified by sharp jump in the SymH index, as SC moment (T_0). All separated events were examined at interval of $T_0 \pm 40$ minutes.

To minimize the influence of preceding disturbances on course of SC events the following criteria were used while separating the events for analysis:

- SC jump should start against the background of steady quiet geomagnetic field lasting over 45 min,
- magnitude of SC jump should raise more than 8 nT over the 8 minutes after the jump beginning.

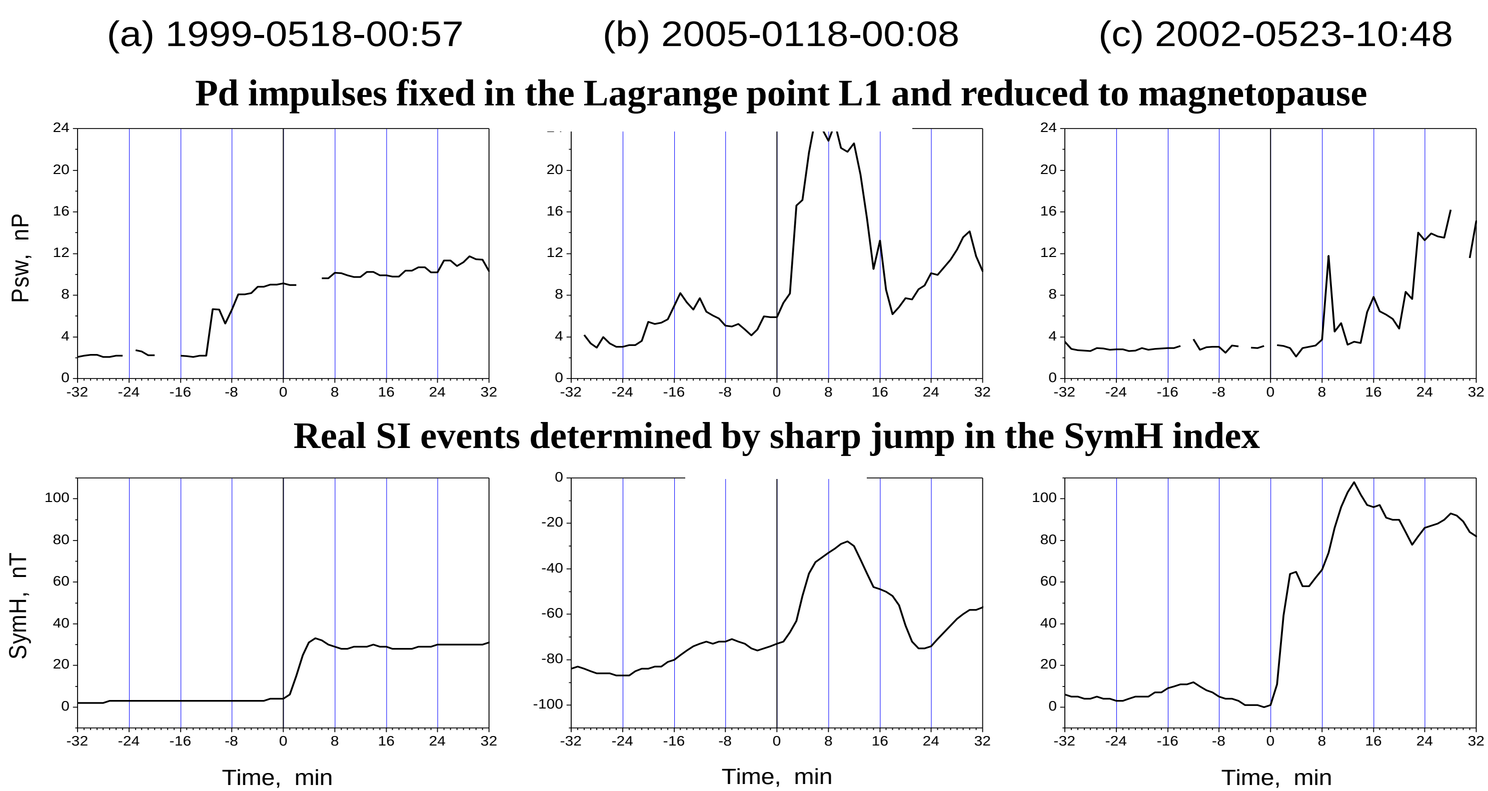
The SC events matching these requirements were subjected for the analysis: 108 events with positive sudden impulses (leaps) and 35 events with negative sudden impulses (drops).

The superposed epoch method is used to analyze effects of the solar wind pressure impulses, the moment of the SI beginning being taken as an epoch zero time T_0.

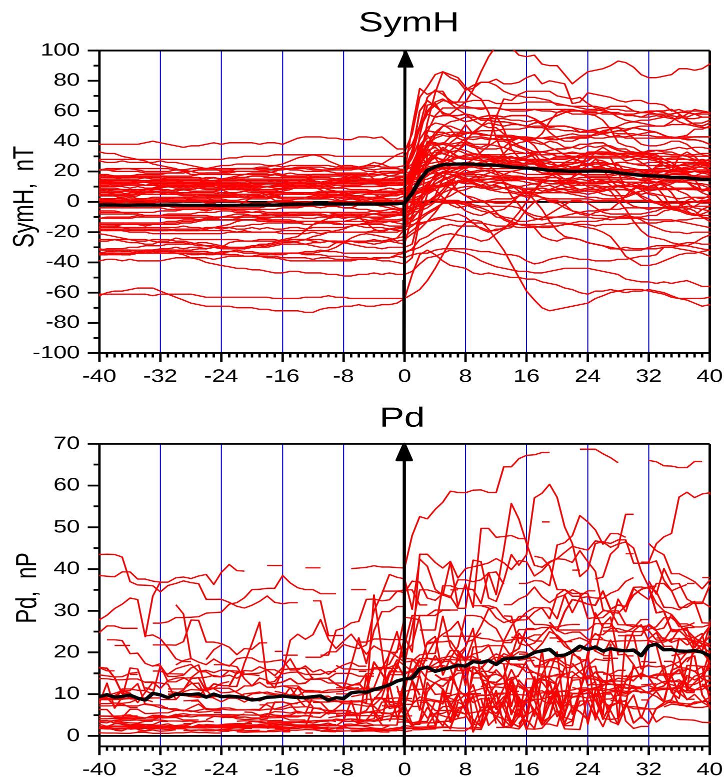
Data and method of the analysis

Thus, the SC events, determined by sharp jump in the SymH index, were regarded as indicator of the actual impact of the Pd impulse on the magnetosphere, the impulses power being expressed in the geomagnetic field units (nT).

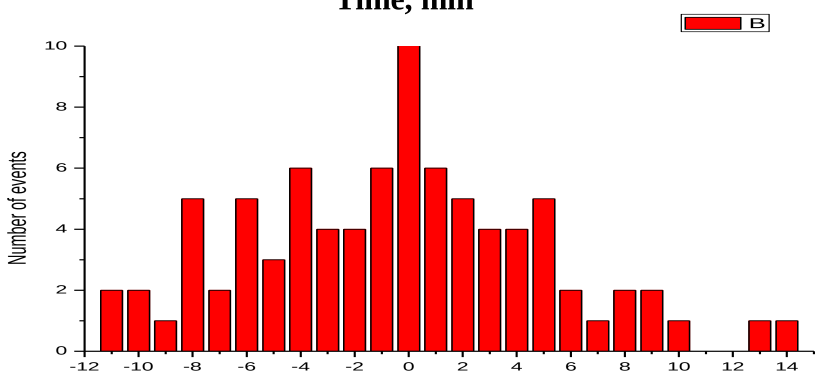
Comparison of the appropriate Pd and SC events showed that features of the **actually observed SC events (moment of beginning, time evolution, intensity) can be significantly different from characteristics of the Pd impulses** estimated by solar wind data fixed in the Lagrange point, far upstream the Earth (~1.5 million km) and reduced to magnetopuase.



Relationship between actual SI moments (derived from SymH data) and SC moments estimated from the Pd measurements on board ACE spacecraft



Time, min



Delay time

The actual contact of solar wind with the magnetosphere (T_0) is determined by moment of sharp jump of the ground-based SymH index.

The “estimated” contact of the Pd impulse with magnetosphere is calculated by the solar wind parameters fixed in the Lagrange point and reduced to the magnetopause. Solar wind can accelerate or delay on the way from Lagrange point to magnetosphere being dependent on special features of the propagating SW structures. As a result, the “estimated” SC moments will be late or forestall relative to real SC moments.

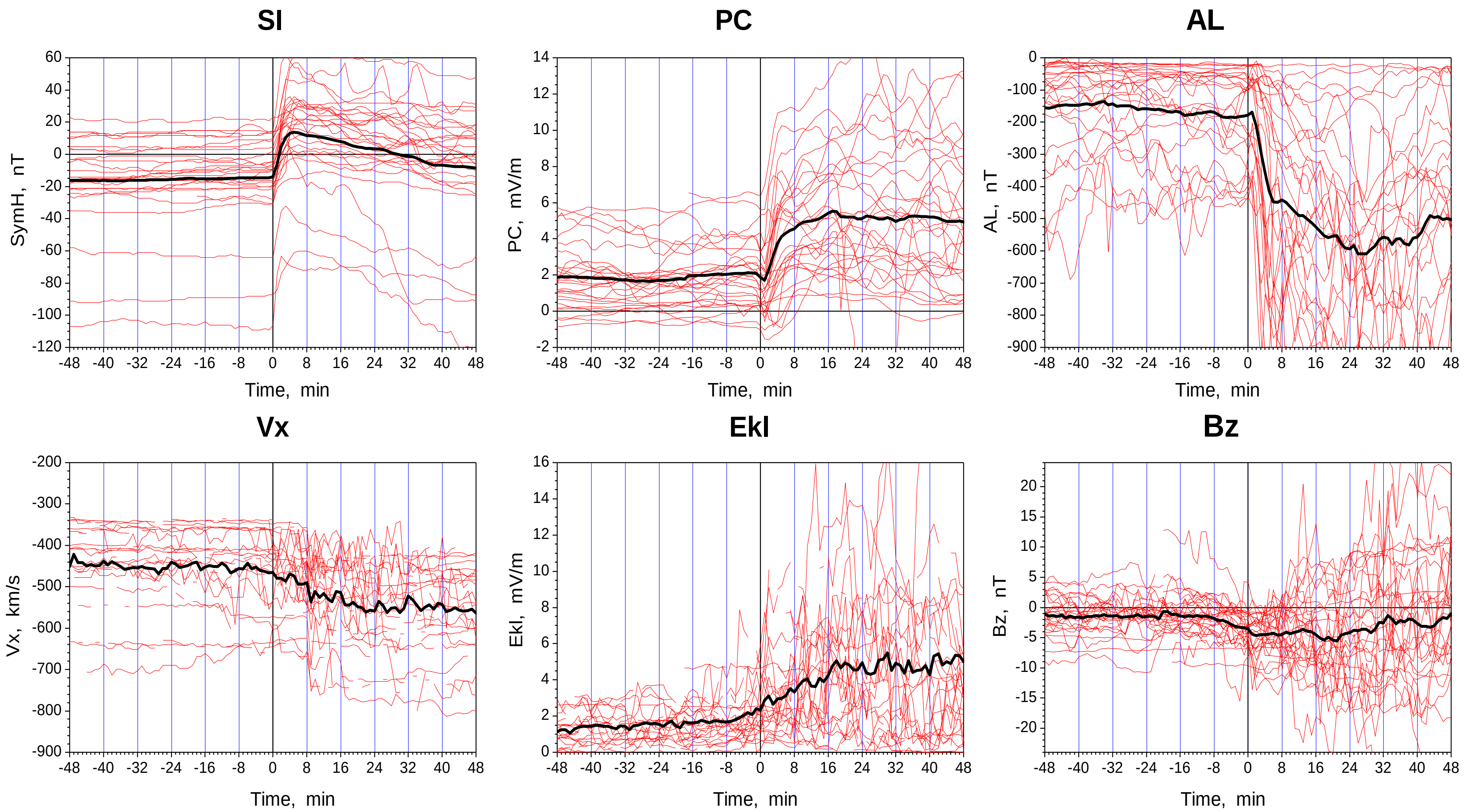
Comparison of actual and estimated SC moments demonstrates that both options meet in reality. The lower panel shows distribution of number of events over the delay times dT, where the negative ΔT are for estimated SC, which are late relative to real SC, whereas positive ΔT are for estimated SC, which are overtake real SC. One can see that acceleration process is a little excess of deceleration one.

Results of the analysis

Results of the analysis are presented as graphs summing up the time evolution of the actual Psw impulses (identified with the ground-based SI events) and *PC* and *AL* indices, on the one hand, and such solar wind parameters, as the solar wind speed Vx, interplanetary electric field E_{KL}, IMF component Bz, on the other hand, under different solar wind conditions, as follows :

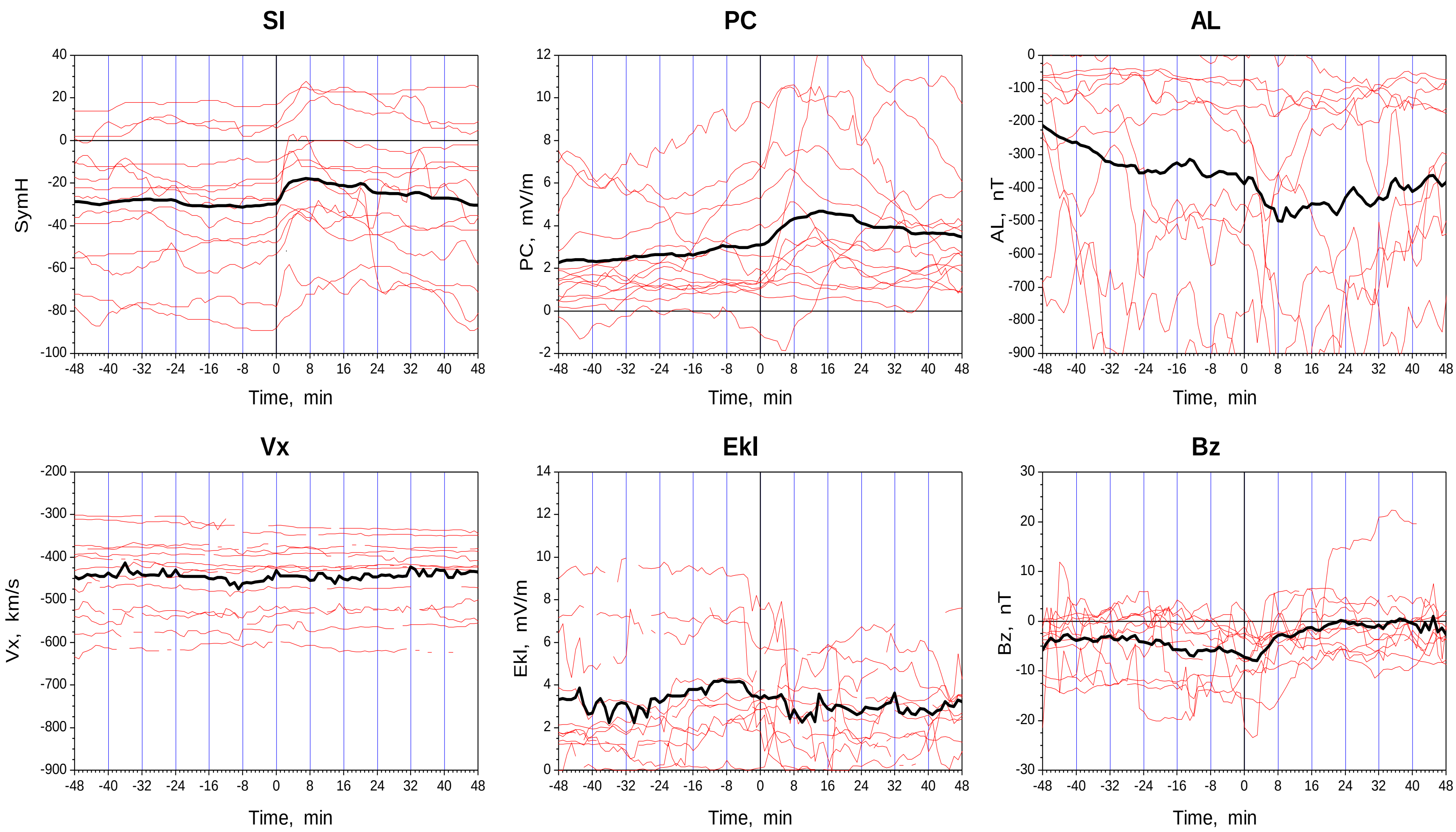
- Pd leaps under conditions of **growing solar wind speed** and negative IMF **Bz<0**,
- Pd leaps under conditions of **growing solar wind speed** and positive IMF **Bz>0**,
- Pd leaps under conditions of **steady solar wind speed** and negative IMF **Bz<0**,
- Pd leaps under conditions of **steady solar wind speed** and positive IMF **Bz>0**,
- Pd leaps under conditions of **steady solar wind speed** and **Bz =0**,
- Pd leaps under conditions of **fluctuating Bz** and **fluctuating solar wind speed**.
- Pd drops under conditions of **growing solar wind speed** and negative IMF **Bz<0**,
- Pd drops under conditions of **growing solar wind speed** and positive IMF **Bz>0**,
- Pd drops under conditions of **steady solar wind speed** and negative IMF **Bz<0**,
- Pd drops under conditions of **steady solar wind speed** and positive IMF **Bz>0**,

Pd leaps under conditions of southward IMF Bz<0 and growing Vsw



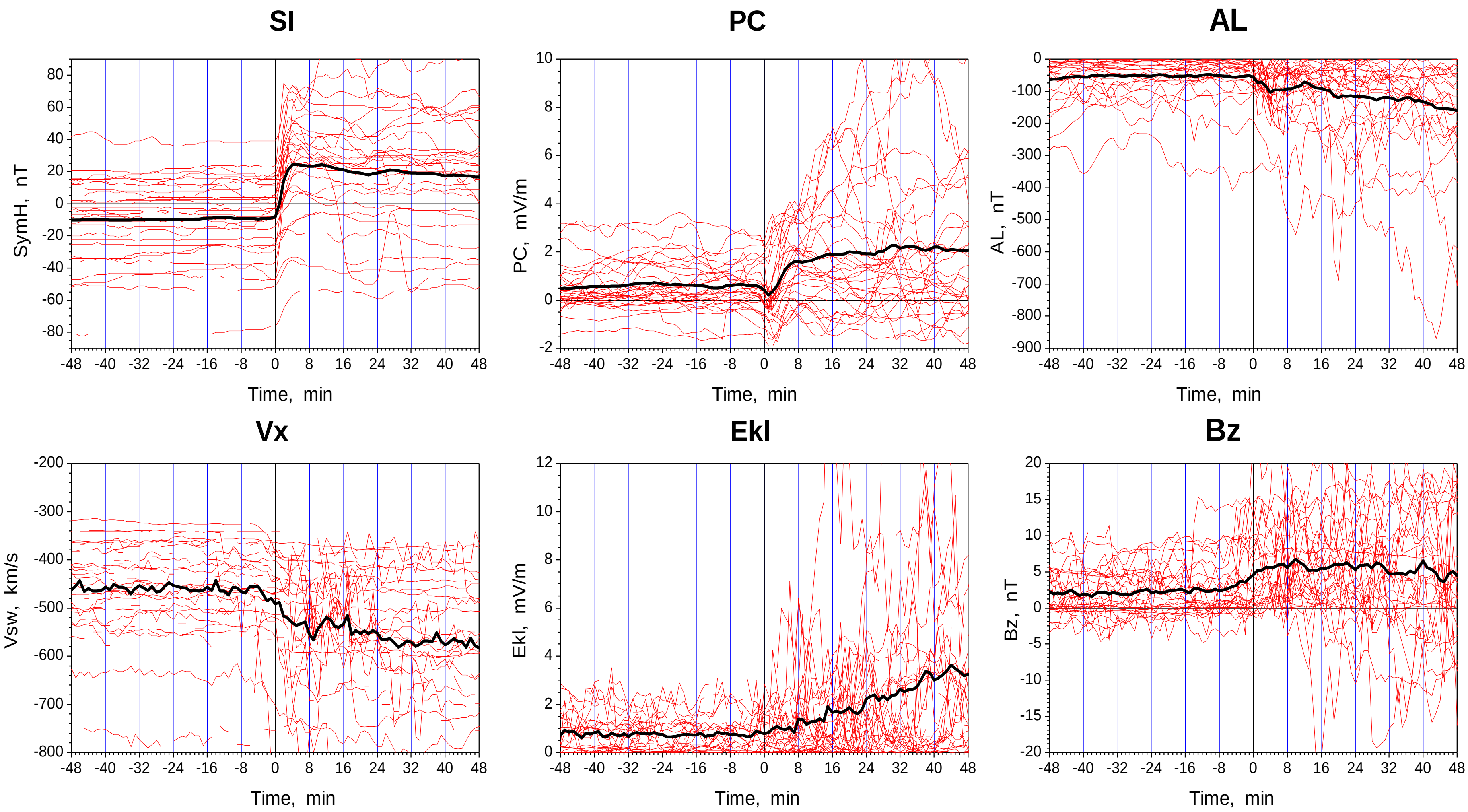
The ***PC* index** and magnetic disturbances in the auroral zone (***AL* index**) **reach maximum** values under conditions of ***southward IMF*** (***Bzmean~-3 nT)*** and ***growing solar wind velocity*** *from 200 to >600 km/c (mean Vsw increases during initial phase).*

Pd leaps under conditions of southward IMF Bz<0 and steady Vsw



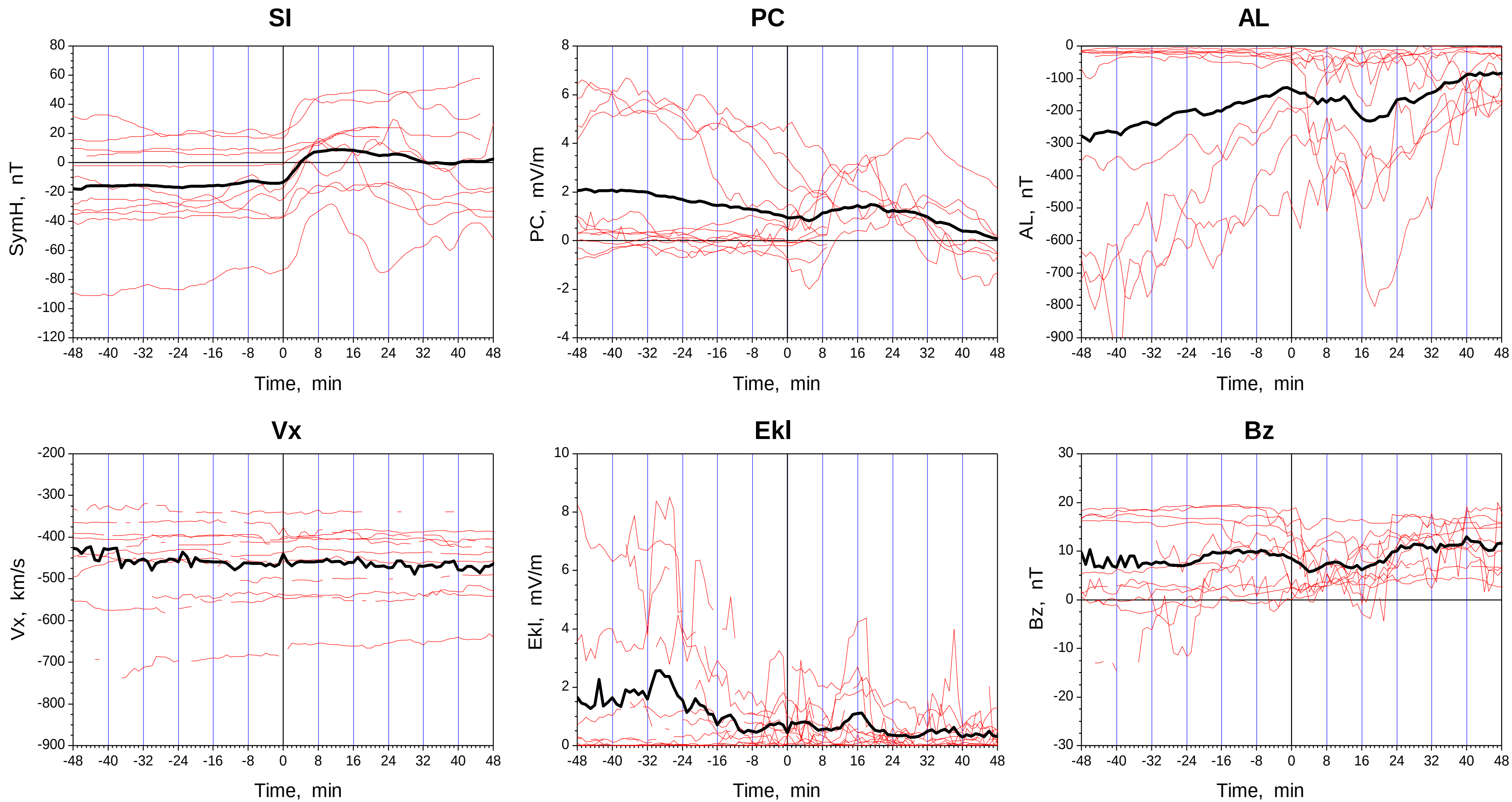
Under conditions of ***southward IMF*** (***Bzmean~-3 nT)*** and ***steady solar wind velocity (Vswmean ~ 380km/c)*** during initial phase the intensity of magnetic disturbances in auroral zone (**AL index) decreases** from ~-300 nT to ~-500 nT for the same values of Pd impulse.

Pd leaps under conditions of northward IMF Bz>0 and growing Vsw



Under conditions of ***norththward IMF*** (***Bzmean~ 4 nT)*** and ***growing solar wind velocity (Vswmean ~ 475km/c)*** the mean intensity of magnetic disturbances in auroral zone (**AL index)** during initial phase **negligibly increases** (from 50 to 100 nT).

Pd leaps under conditions of northward IMF Bz>0 and steady Vsw



Under conditions of ***norththward IMF*** (***Bzmean~ 4 nT)*** and ***steady solar wind velocity (Vswmean ~ 475km/c)*** the mean intensity of magnetic disturbances in auroral zone (**AL index**) **did not increase** during initial phase (in spite of action of same Pd impulse).

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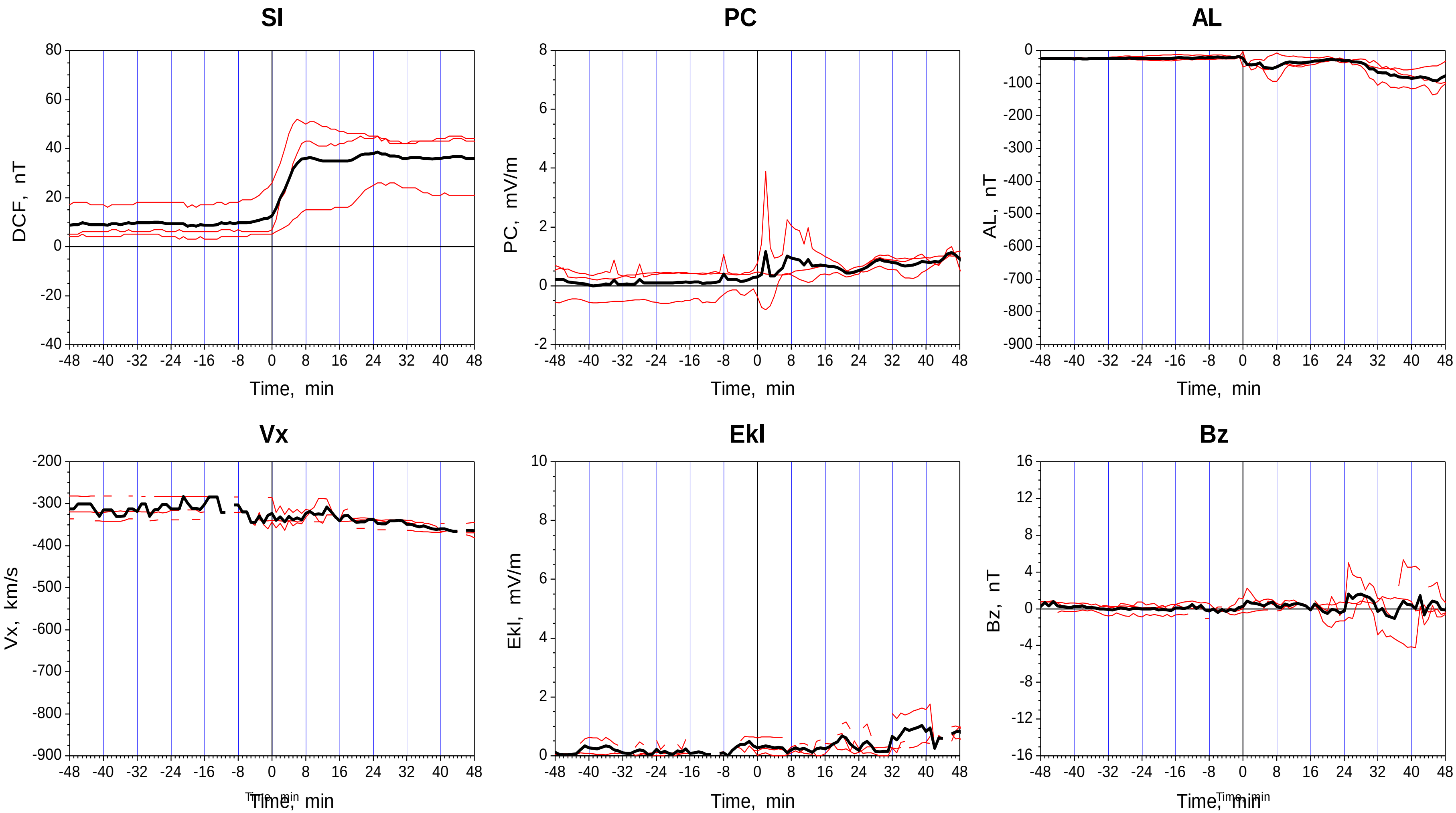
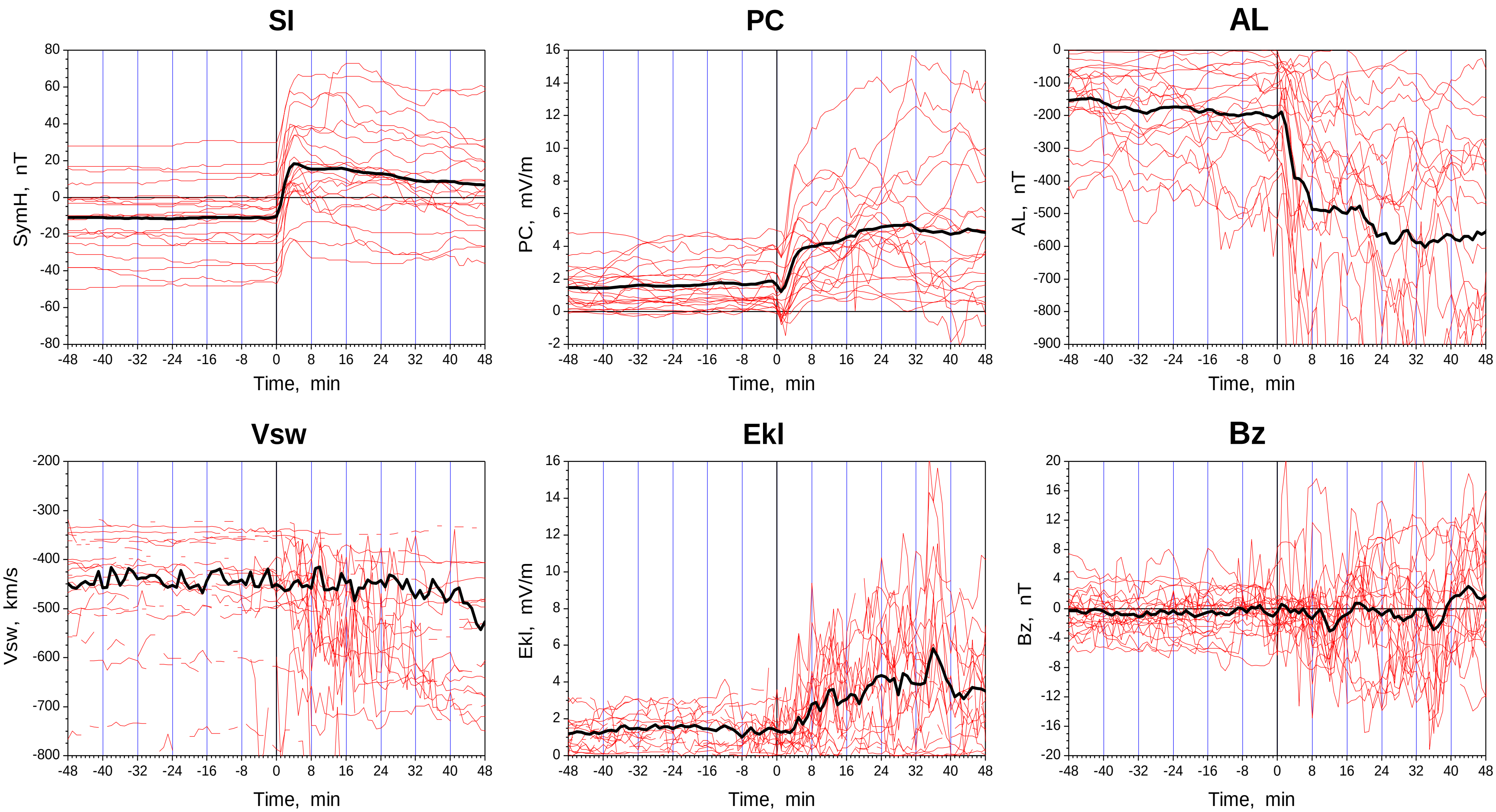
Pd leaps under conditions of IMF Bz=0 and steady Vsw



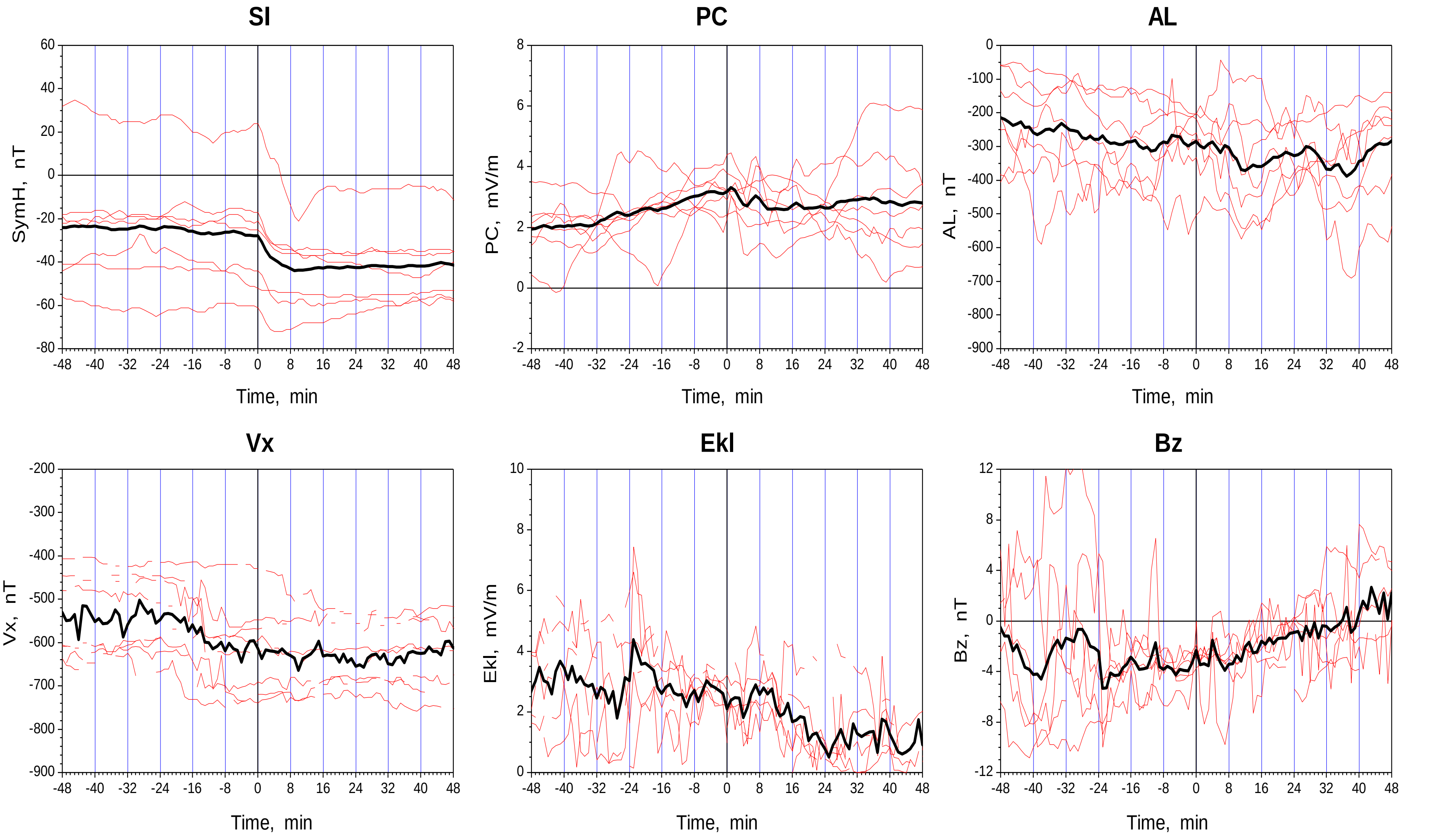
When the **s**olar wind dynamic pressure impulses occur under conditions of steady solar wind speed and IMF BZ≈0**,** the mean values of ***PC*** and ***AL* indices** were**,** correspondingly**, 0.7 mV/m and -50 nT,** in spite of sufficiently high magnitude of the SC leap (ΔSC~25nT). **.**

Pd leaps under conditions of fluctuating IMF Bz and fluctuating Vsw



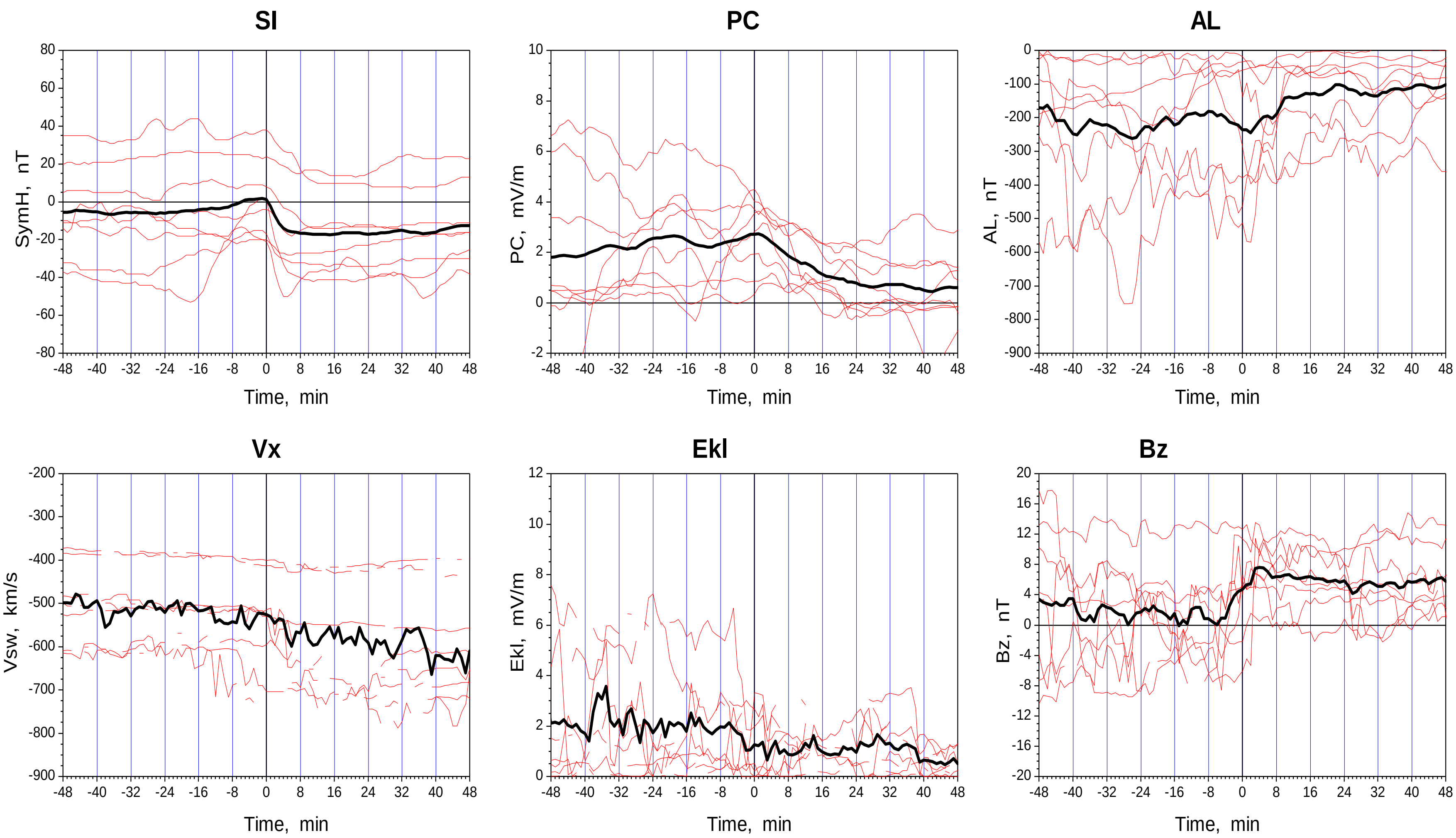
To the contrary, when leaps with similar magnitude, ΔSI~30nT, were observed under condition of highly fluctuating V_{SW} and B_Z, magnetic activity sharply increased (mean values of ***PC* and *AL*** were, correspondingly, **4 mV/m and -600 nT**).

Pd drops under conditions of growing Vsw and Bz<0



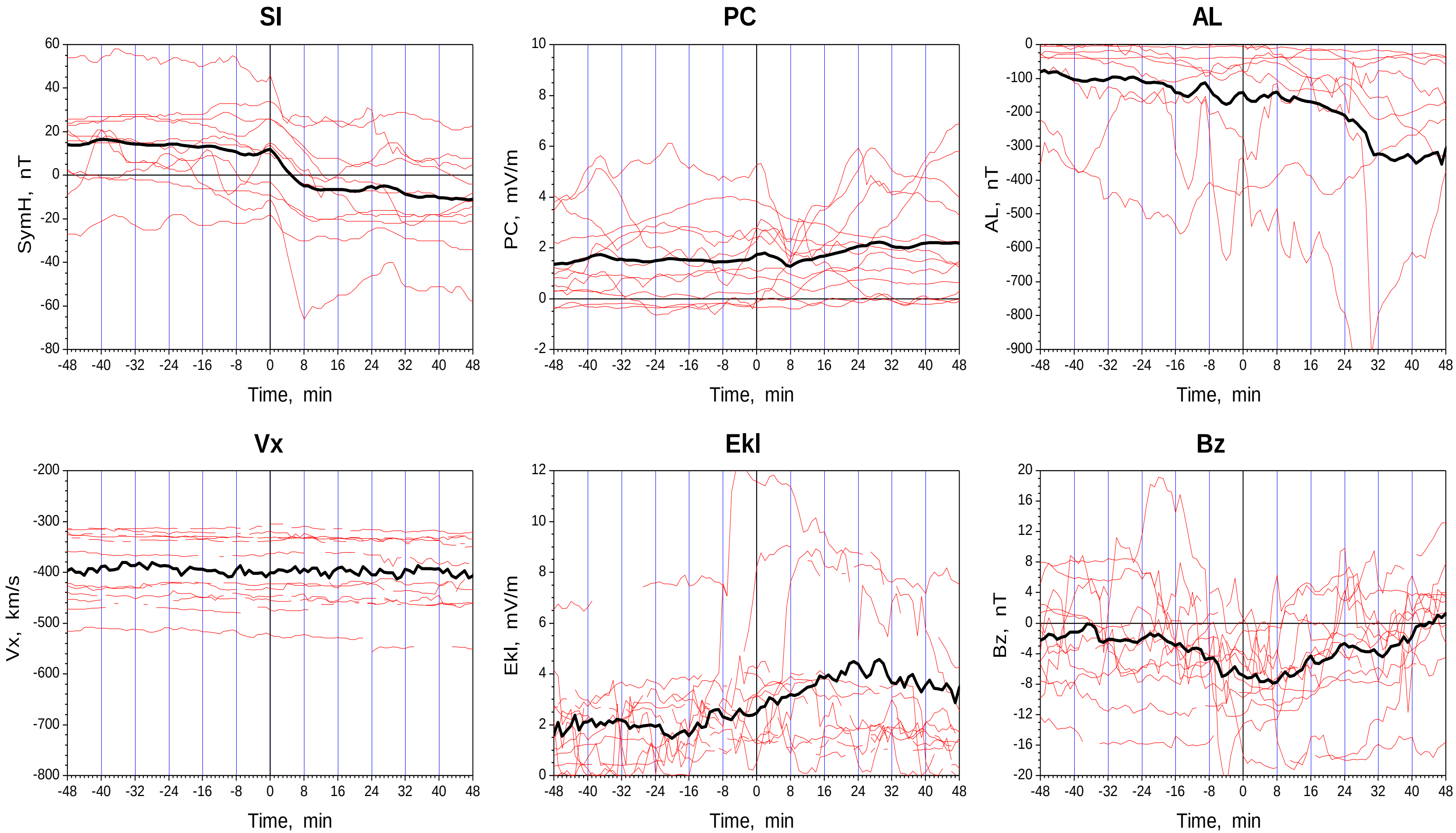
At the same SI drop magnitude (ΔSI ≈-15 nT) *the mean intensity of magnetic disturbances was highest (PC≈2.5 mV/m, AL≈-300 nT) under conditions of growing solar wind speed (V_{SW}≈620 km/s) at B_Z<0*

Pd drops under conditions of growing Vsw and Bz>0



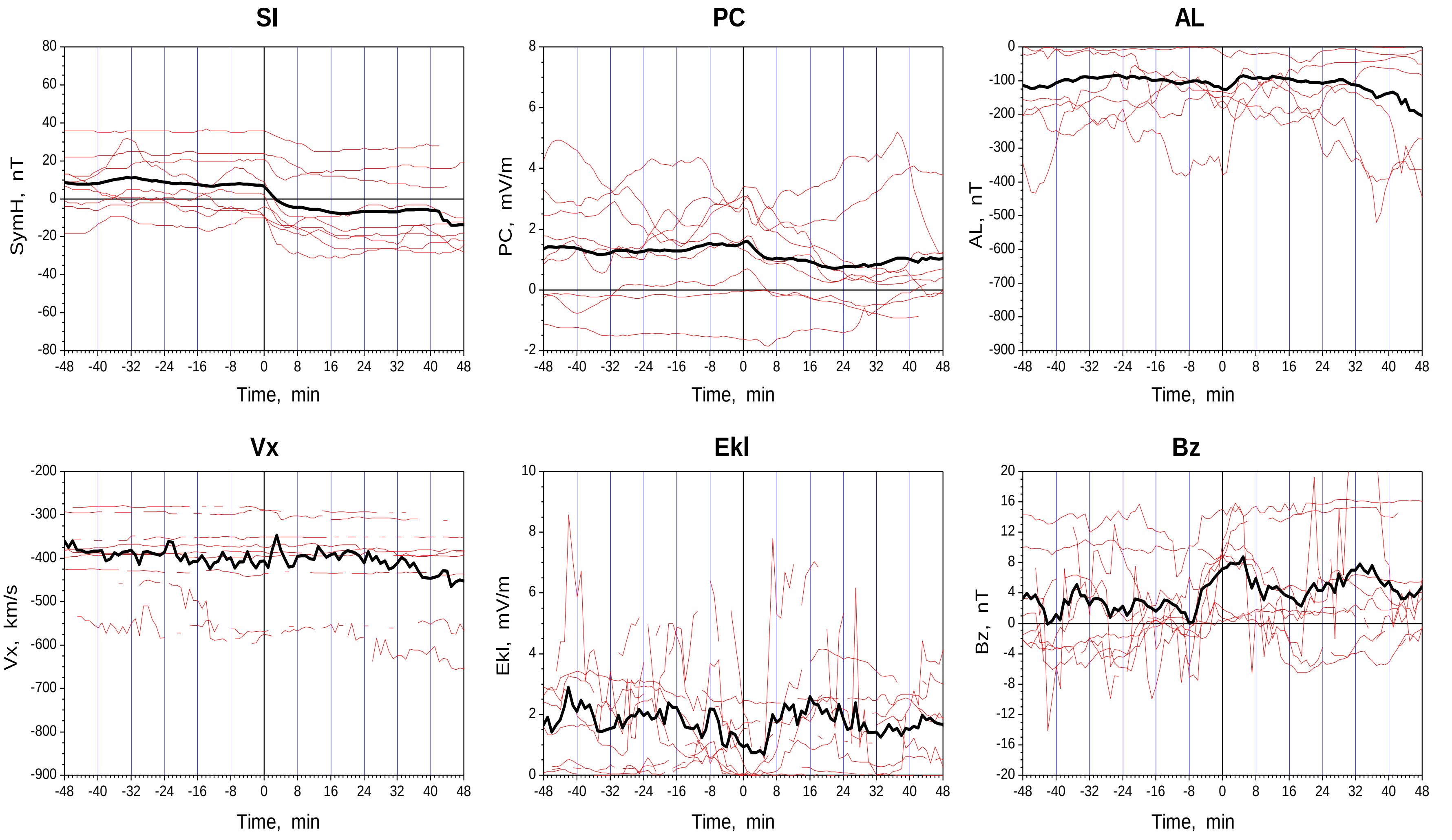
At the same SI drop magnitude (ΔSI ≈-15 nT) *the intensity of magnetic disturbances was on intermediate level (PC=1.5 ÷2 mV/m, AL=150 ÷180 nT) under conditions of growing solar wind speed and BZ>0*

Pd drops under conditions of steady Vsw and IMF Bz<0



At the same SI drop magnitude (ΔSI ≈-15 nT) *the intensity of magnetic disturbances was on intermediate level (PC=1.5 ÷2 mV/m, AL=150 ÷180 nT) under conditions of steady speed and* B_Z*<0.*

Pd drops under conditions of steady Vsw and IMF Bz>0



At the same SI drop magnitude (ΔSI ≈-15 nT) *the intensity of magnetic disturbances was lowest (PC≈0.7 mV/m, AL≈-50nT) under conditions of steady solar wind speed (VSW≈400 km/s) and* $B_Z>0$.

Total relationships between Pd, SymH, PC and AL during initial phase

	Growing Vsw		Steady Vsw	
	Bz<0	**Bz>0**	**Bz<0**	**Bz>0**
Pd (nP)	~10	~10	~10	~10
Sym H (nT)	30	30	18	20
PC (mV/m)	2.5	1.8	1.5	0.5
AL (nT)	300	50	75	~0

Conclusions:
Intensity of magnetospheric disturbances is strongly dependent on the IMF polarity and variability of the solar wind velocity and can be quiet different for the same power of the pressure impulses (Pd). The disturbances are maximal for conditions of southward IMF and growing solar wind velocity Vsw and fall to minimum under conditions of northward IMF and steady Vsw (with the same power of the solar wind dynamic pressure Pd!!!).

It means that the pressure shocks themselves are not promote (or insignificantly promote) the solar wind energy input into the magnetosphere, which is controlled mainly by the interplanetary electric field $E_{KL} \sim Vsw*(B_Y^2+B_Z^2)^{1/2}$ and displayed by the PC index.

PC web site: **http://pcindex.org**