PC INDEX
AS INDICATOR OF THE SOLAR WIND ENERGY ENTERED INTO THE MAGNETOSPHERE: RELATION TO INTERPLANETARY ELECTRIC FIELD AND MAGNETIC DISTURBANCES

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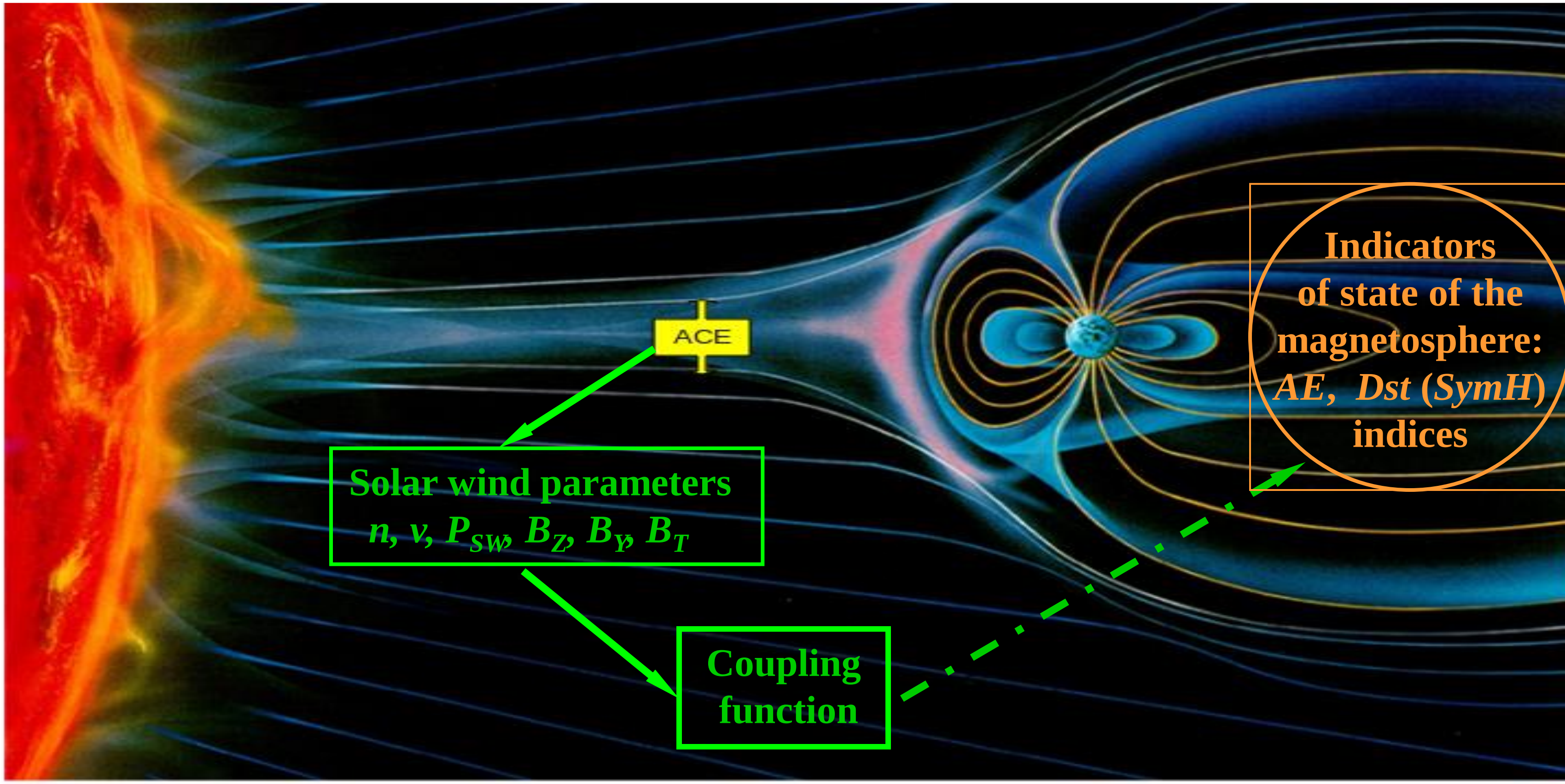
1. *Motivation: requirements of readily available and reliable means for monitoring and nowcasting the magnetosphere state*



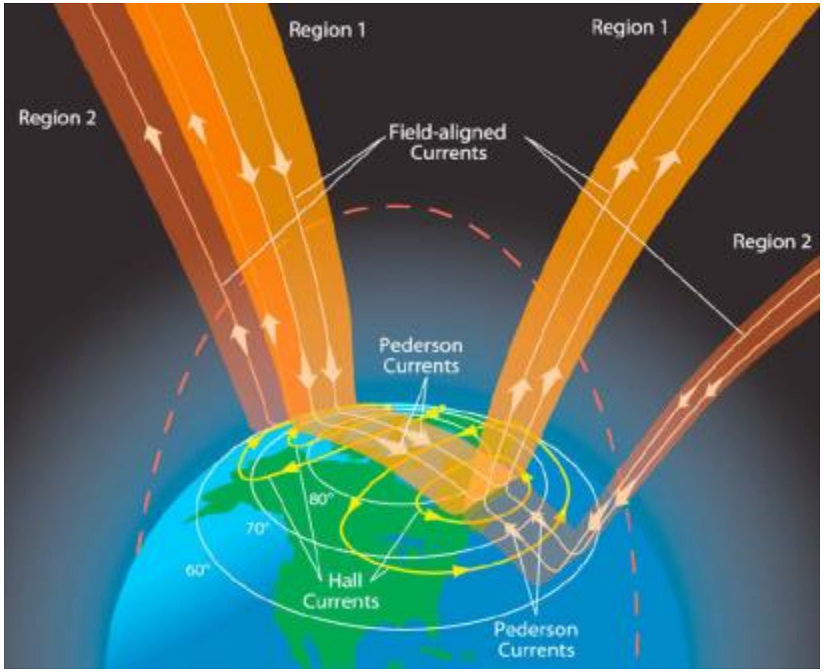
Quantitative space weather forecasting and monitoring is based on measurements of the solar wind parameters on board ACE spacecraft spaced 1.5 M km apart the Earth in the Lagrange point L1

State of the magnetosphere is commonly evaluated by the magnetic *Dst* (*SymH*) and *AE*(*AL*) indices, which characterize the energy realized in magnetosphere in form of storms and substorms.

The different "coupling functions" (N>20) have been suggested to establish a link between the solar wind parameters and the magnetosphere state, but no one of them is not universal.

The *PC* index has been proposed [Troshichev et al., 2012] as indicator of efficiency of the solar wind – magnetosphere coupling.

2. *Physical backgrounds for PC index: magnetic activity in the polar caps uniquely responds to the solar wind geoeffective variations*



The variable solar wind coupling with the geomagnetic field constantly generates the "magnetospheric 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]

$$E_{KL}=Vsw*B_T$$

where ***Vsw*** **–** solar wind speed, B_T – the IMF tangential component.

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.**

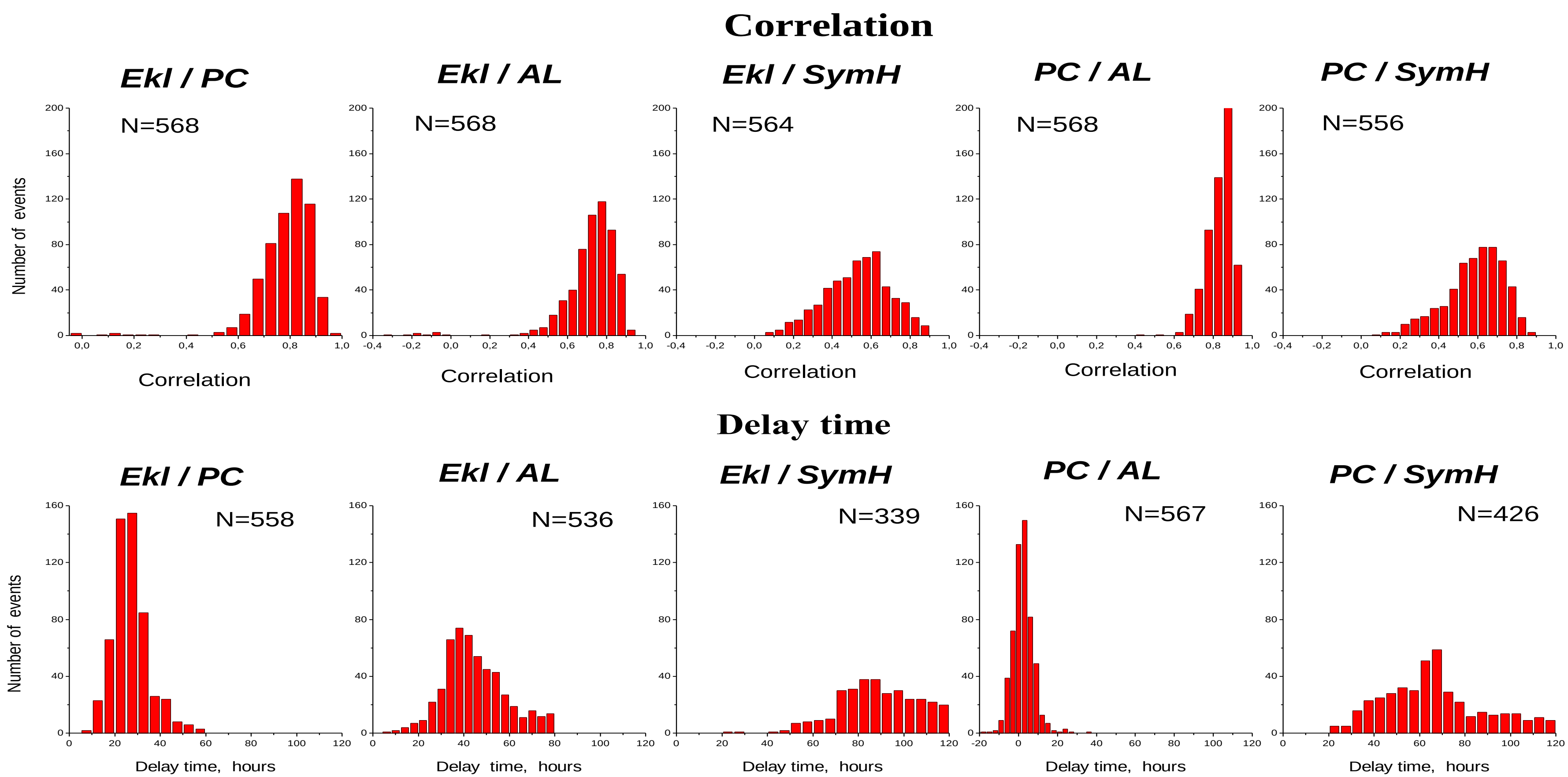
Resolutions of XXII Scientific Assembly of International Geomagnetism and Aeronomy Association (12th IAGA), Merida, Mexico, August 2013
No. 3: Polar Cap (PC) index

IAGA,

- **noting** that polar cap magnetic activity is not yet described by existing IAGA geomagnetic indices,
- **considering** that the Polar Cap (PC) index constitutes a quantitative estimate of geomagnetic activity at polar latitudes and **serves as a proxy for energy that enters into the magnetosphere during solar wind-magnetosphere coupling**,
- **emphasising** that the usefulness of such an index is dependent on having a continuous data series,
- **recognising** that the PC index is derived in partnership between the Arctic and Antarctic Research Institute (AARI, Russian Federation) and the National Space Institute, Technical University of Denmark (DTU, Denmark)
- **recommends** use of the PC index by the international scientific community in its near-real time and definitive forms, and
- **urges** that all possible efforts be made to maintain continuous operation of all geomagnetic observatories contributing to the PC index.

Therein lies the principal distinction of the PC index from various coupling functions (which are characteristics of the solar wind arriving to the Lagrange point L1) and from AL and Dst indices (which are characteristics of the energy realized in form of magnetospheric substorm and magnetic storms).

3. *Correlation between the interplanetary electric field E_{KL} and PC index and between PC index and magnetic disturbances (AL and SymH indices)*



Correlation between the 30-min smoothed values of E_{KL} field and the *PC*, *AL*, *SymH* indices has been estimated within the storm intervals (Tmax ± 2 days), where Tmax is moment of the storm maximal intensity.

Correlation (R > 0.5) between ***E_{KL}* and *PC*** index is observed in 98% of events with **delay ~ 20-30 min in response of *PC***.

Correlation (R > 0.5) between ***E_{KL}* and *AL*** index is observed in 94% of events with **delay ~ 30-50 min in response of *AL***.

Correlation between **E_{KL} and *SymH*** index is observed in 94% of events with **delay ~ 70-100 min in response of *SymH*.**

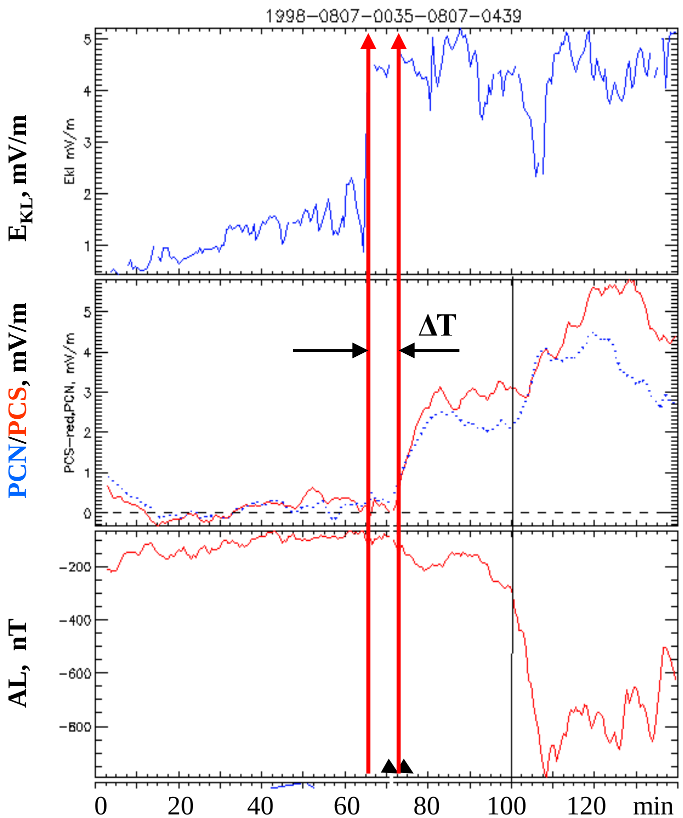
Correlation between ***PC* and *AL*** indices is observed in 99.8% of events with **delay ~ 0-10 min in response of *AL***.

Correlation between ***PC* and *SymH*** indices is observed in 75% of events with **delay ~ 30-90 min in response of *SymH*.**

Conclusion: **E_{KL} field is a driver of the *PC* growth and subsequent substorm (*AL*) and storm (*SymH*) development.**

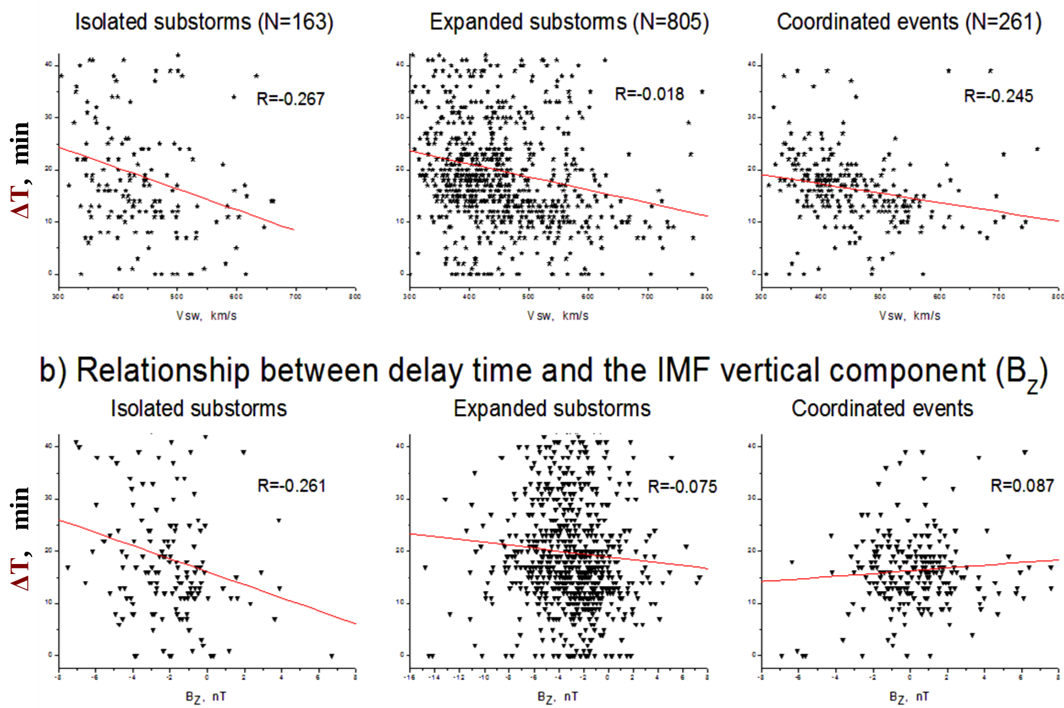
4. *Interplanetary electric field E_{KL} and PC index*

PC index unambiguously responds to variations of the interplanetary electric field *E_{KL}* but delay time (ΔT) in response of *PC* to *E_{KL}* is not dependent on the solar wind parameters, such as the solar wind speed (*Vsw*) and dynamic pressure (*Psw*). IMF vertical (*Bz*) and azimuthal (*By*) components.



Correlation between ΔT and the solar wind parameters averaged for 1-hour preceding the substorm onset

(a) Relationship between delay time and the solar wind speed (Vsw)



Results:

(a) There is only **slight tendency (R<0.30) to *ΔT* decrease with rise of the solar wind speed *Vsw*.**

(b) Delay time ***ΔT* does not depend on the IMF *B_Z* component.**

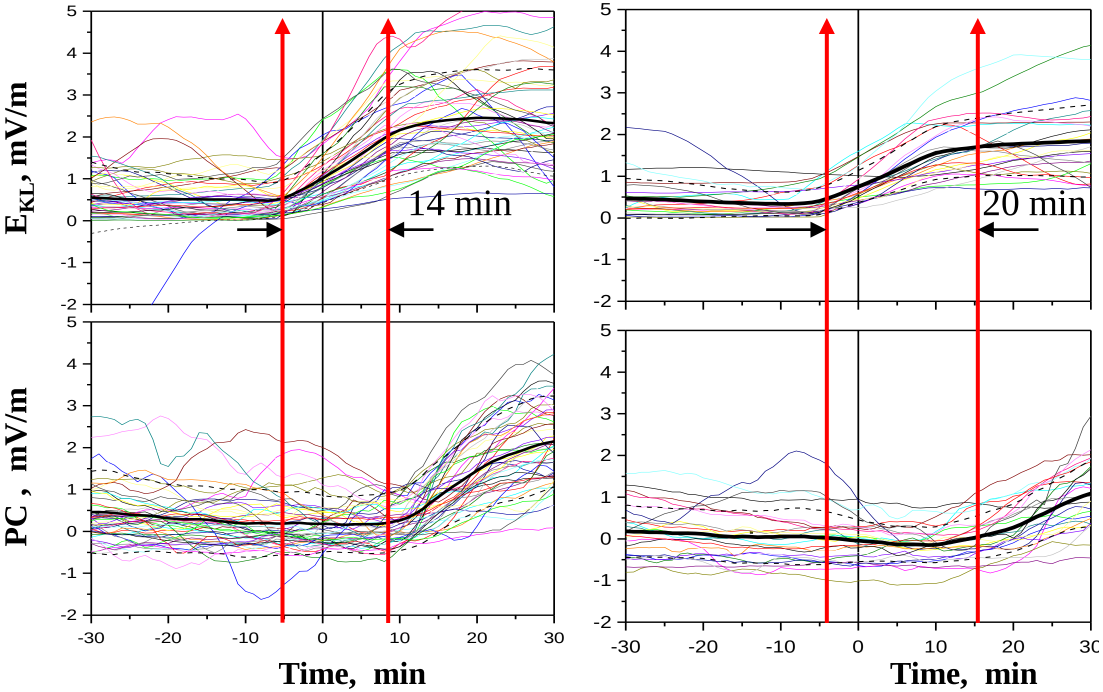
(c) Delay time ***ΔT* does not depend on** the IMF horizontal component ***$B_T=(B_Y^2+B_Z^2)^{1/2}$*** (is not shown)

(d) Delay time ***ΔT* does not depend on** the solar wind dynamic pressure ***Pd*** (is not shown).

Interplanetary electric field E_{KL} and PC index

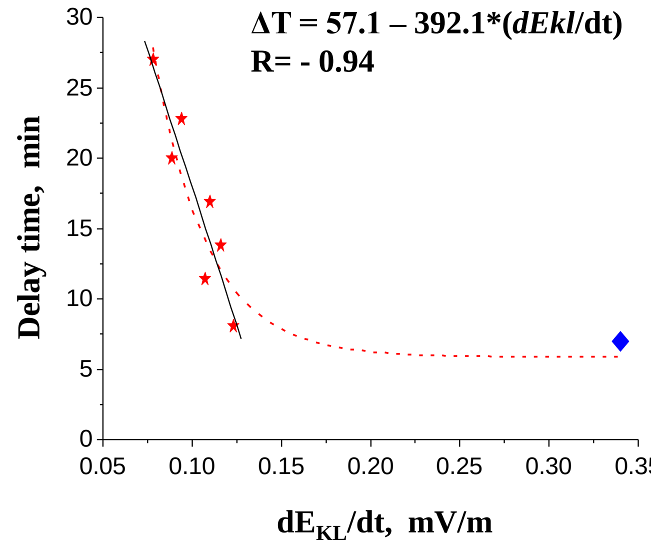
Delay time (ΔT) in response of the *PC* index to the solar wind variations is determined by the growth rate of the interplanetary electric field (*dE_{KL}/dt*), not by any one particular solar wind parameter.

ΔT = 13-15 min **ΔT = 19-21 min**



Thin lines present the time evolution of *EKL* and *PC* in course of individual events for each ΔT group. Sudden rise of the mean *EKL* field and the appropriate increase of the mean *PC* index are marked by vertical red lines.

ΔT vs. *dE_{KL}/dt*



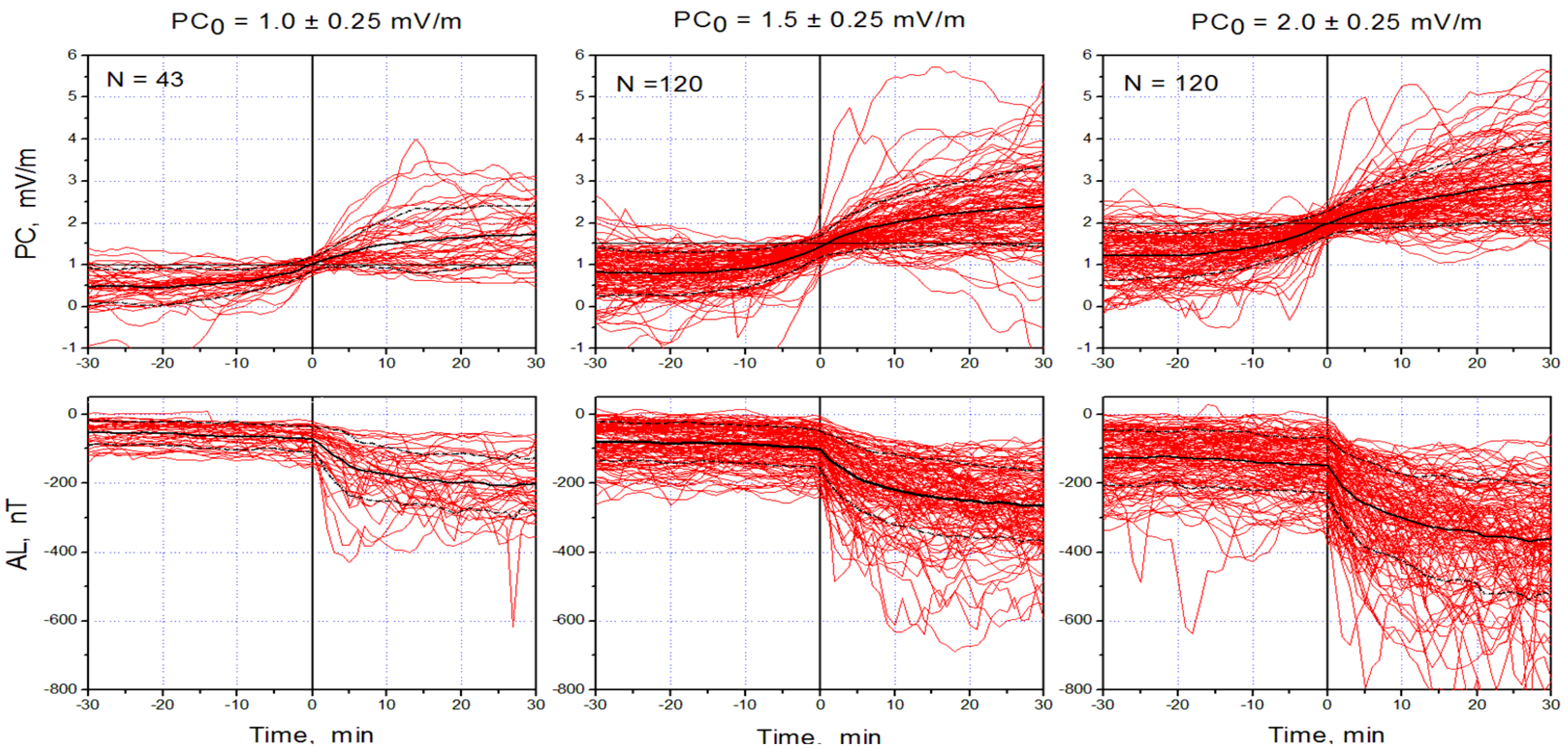
Delay time ΔT and growth rate ***dE_{KL}/dt*** are connected by the linear low (shown by ***asterisks*** and solid line). **The lowest limit ΔT** (marked by ***rhombs***) **is observed in case of the interplanetary shocks.**

These experimental facts are in fully contradiction with Dungey's concept, which regards the solar wind speed Vx and southward IMF component as a clue factors determining response of convection patterns in the polar cap to solar wind impact on the magnetosphere.

5. *PC index and development of magnetospheric substorm*

Development of magnetospheric substorms is always preceded by the *PC* index growth

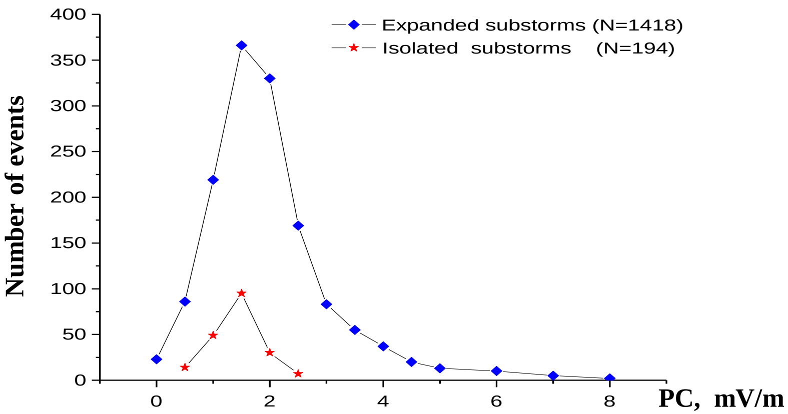
Substorms are separated by groups by value of PC_0 in time of substorm sudden onset; the moment of substorm onset (SO) being taken as a key date (T=0). Thin red lines present a run of *PC* and *AL* in course of individual events. Thick black line presents variation of mean *PC* and *AL* values for each group



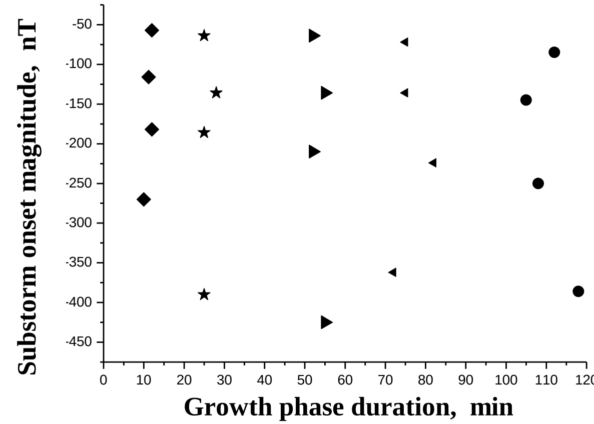
The substorm onset is related to distinct *PC* leap occurring in range 0-10 min ahead of SO.
The *PC* growth rate is not affected by the substorm sudden onset.

Relationship between PC and AL indices

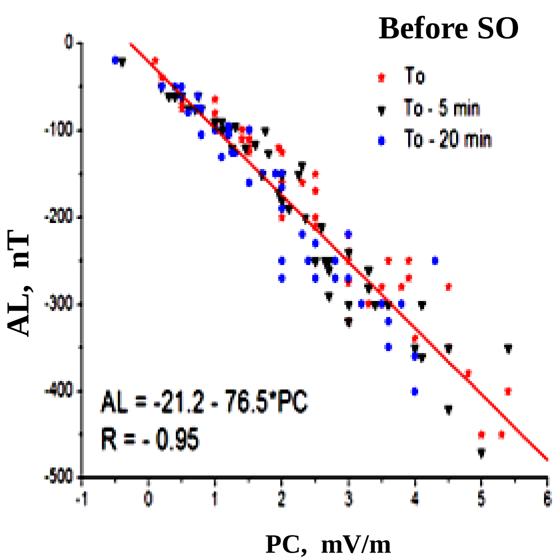
Time evolution and intensity of magnetospheric substorms are controlled by value and dynamics of the *PC* index

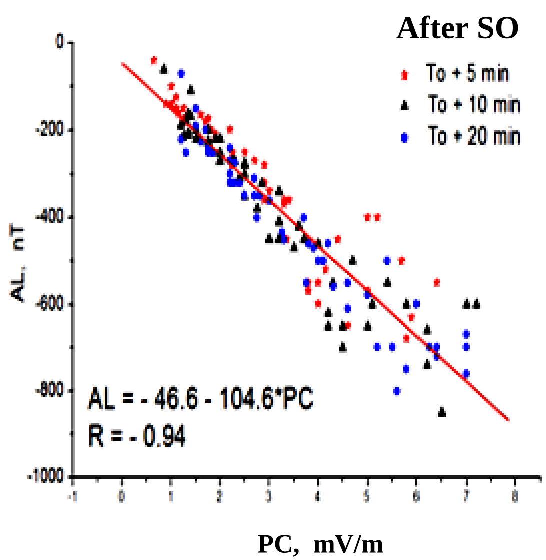


Magnetospheric substorms generally start as soon as the *PC* index exceeds the threshold level *PC*=1 mV/m. Occurrence of substorms reaches maximum under conditions of PC =1.5 ÷ 2 mV/m



Duration of growth phase does not affect the substorm intensity. Magnitude of the substorm sudden onset (SO) shows tendency to decrease with a rise of the growth phase length.



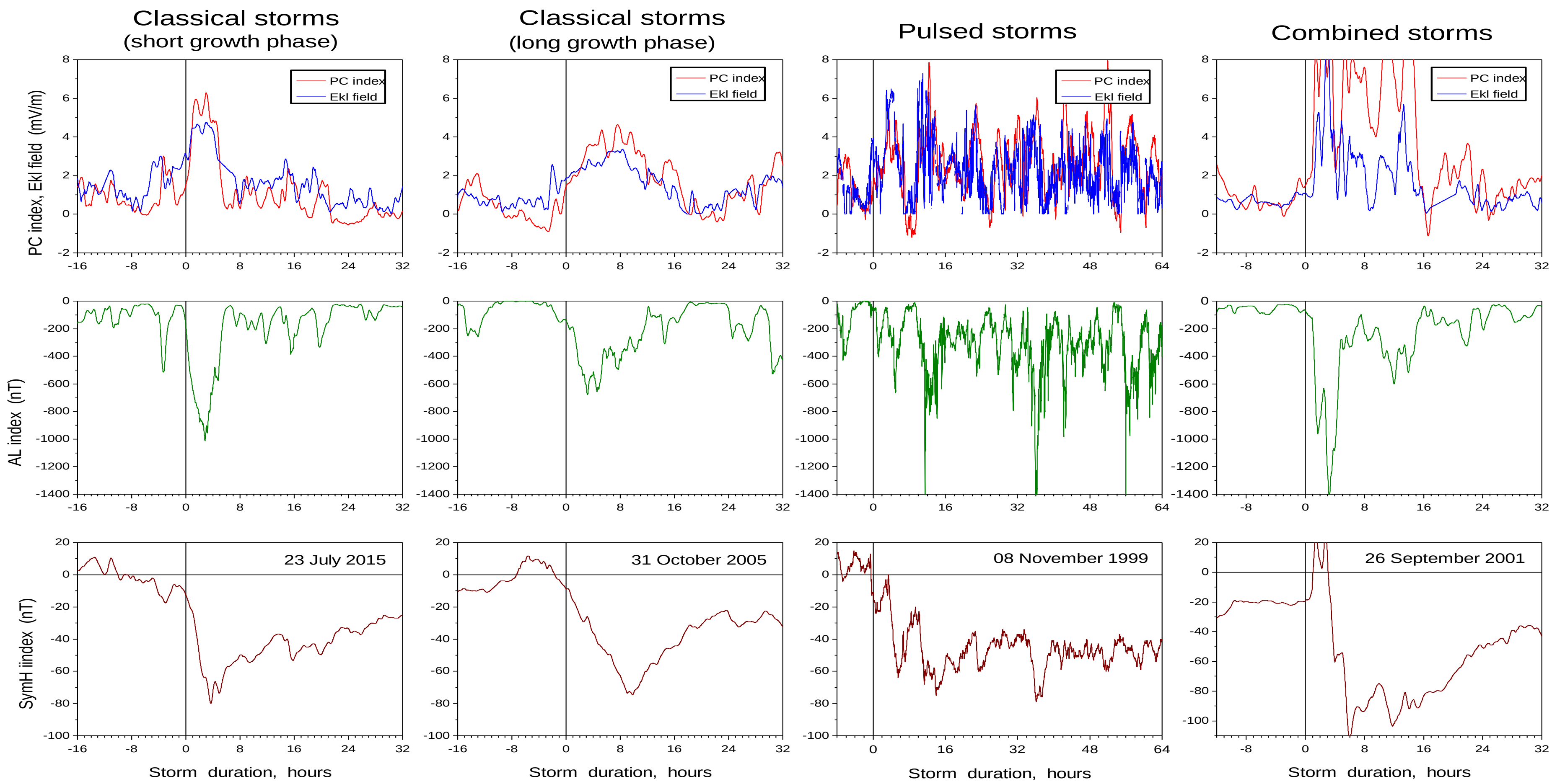


Value of magnetic disturbances in the auroral zone (*AL* index) before and after the substorm sudden onset is linearly related to *PC* value.

Slope coefficient characterizing linear linkage between PC and AL sharply increases after the substorm onset as an evident consequence of the auroral particle precipitation giving rise to the ionospheric conductivity and powerful westward auroral electrojet in course of the substorm expansive phase.

6. PC index and development of magnetic storms

Different types of the magnetic storm development



Three basic types of magnetic storms have been determined taking into account the PC and Dst time evolution features :

- “**classical storms**”, which demonstrate the main phase with one well defined maximum of depression (>**40%**),
- “**pulsed storms**”, which consist of sequence of periodically repeating depressions, lasting during many hours (<**30%**),
- “**combined storms**”, which are composition of pulsations proceeding on the elevated background (“bank”) with a quite different ratio between the background and pulsation magnitude (>**30%**).

It is remarkable that the time evolution of Dst index is predetermined by the PC index behavior.

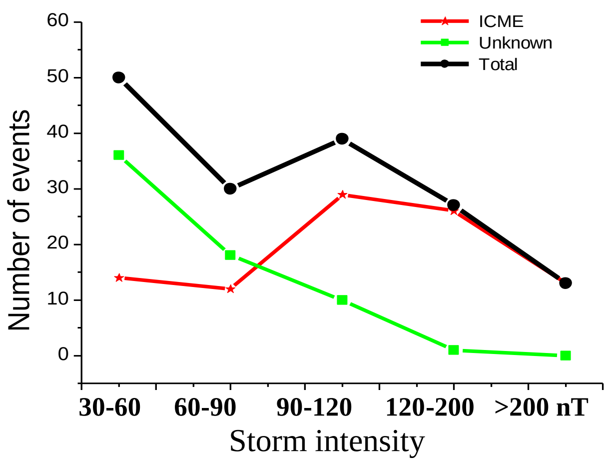
Relation of different types of the magnetic storms to the solar wind drivers (ICME and SIR)

Analysis of magnetic storms for 1998-2009 was carried out basing on the following catalogues:

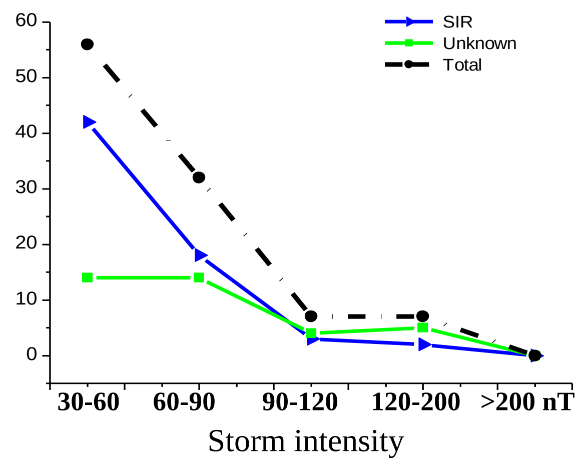
I. Richardson and H.Cane “List of Near-Earth Interplanetary Coronal Mass Ejections (ICME) for 1997-2015”

II. L. Jian “List of Stream Interaction Regions (SIR) for 1995-2009”

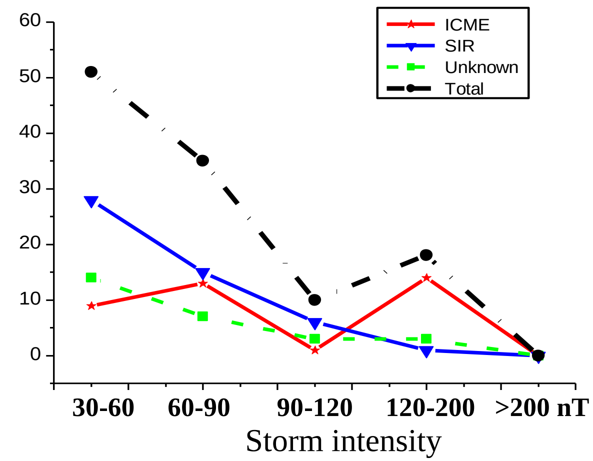
Classic storms



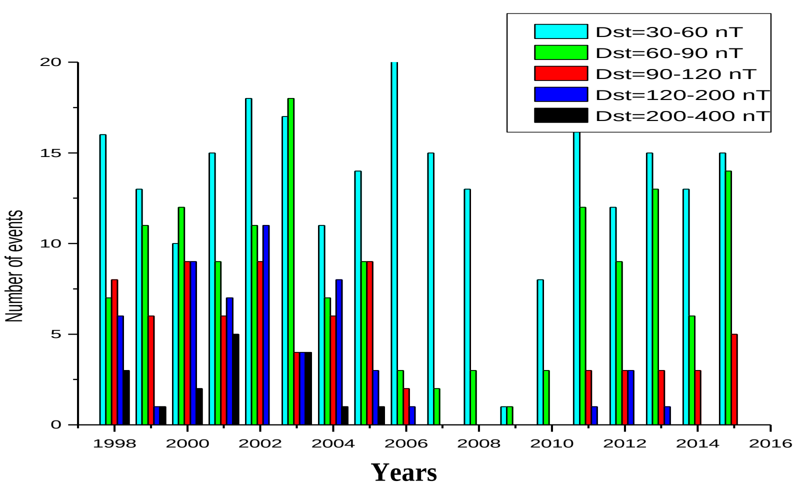
Pulsed storms



Combined storms



Magnetic storms taken for the analysis



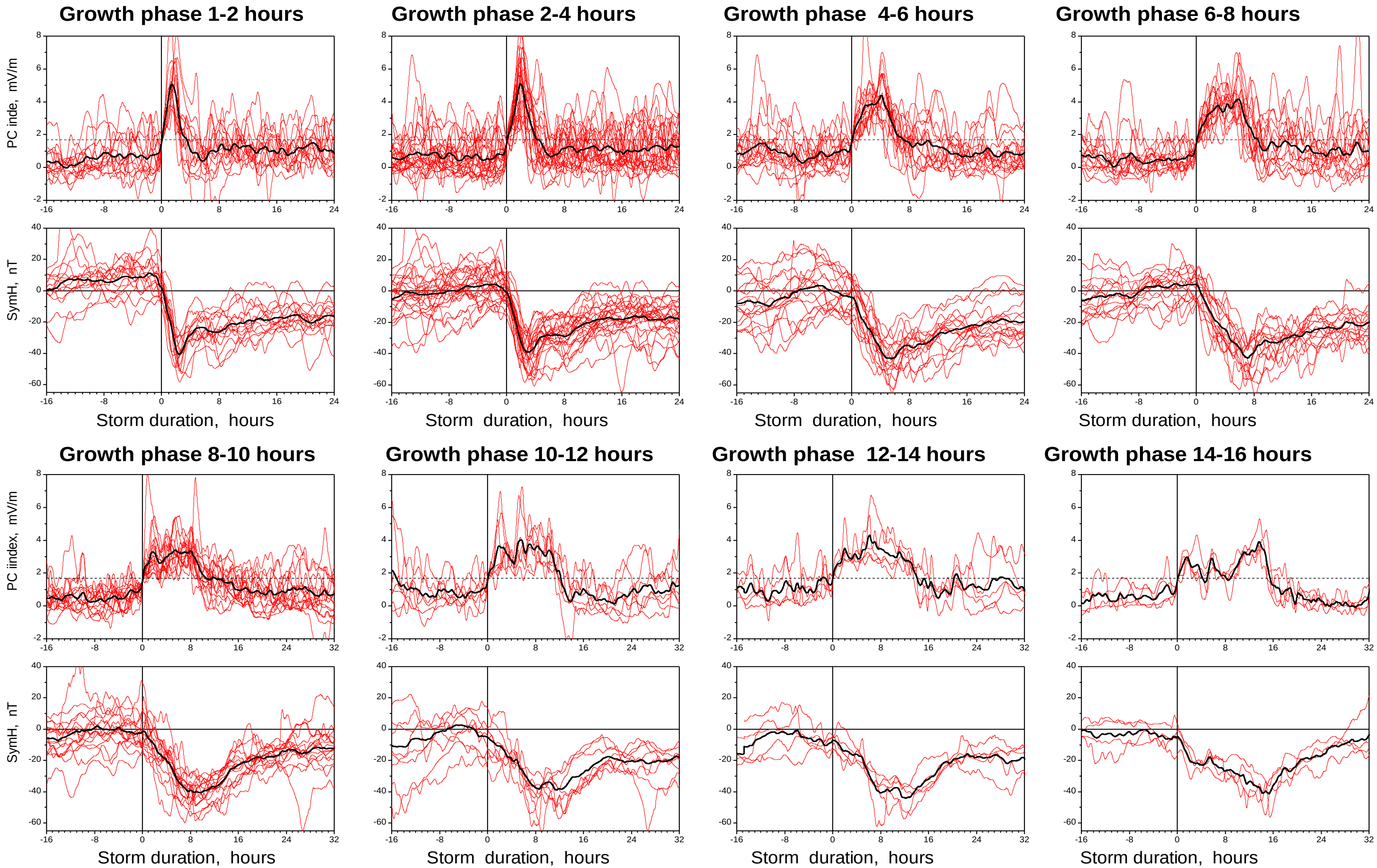
Classical storms are related mainly to Interplanetary Coronal Mass Ejections (59%); powerful magnetic storms (Dst>120 nT) are generated exclusively by ICME .

Pulsed storms are related (64%) to Stream Interaction Regions (SIRs) or Corotating Interaction Regions (CIRs); it is evident in case of weak magnetic storms (Dst<90 nT),

Combined storms are produced by joint action of ICME (32%) and SIR (44%), the weak storms (Dst<60 nT) being mainly related to SIR, the strong storms (Dst>120 nT) being related to ICME.

Relation of the classic magnetic storms to the PC index

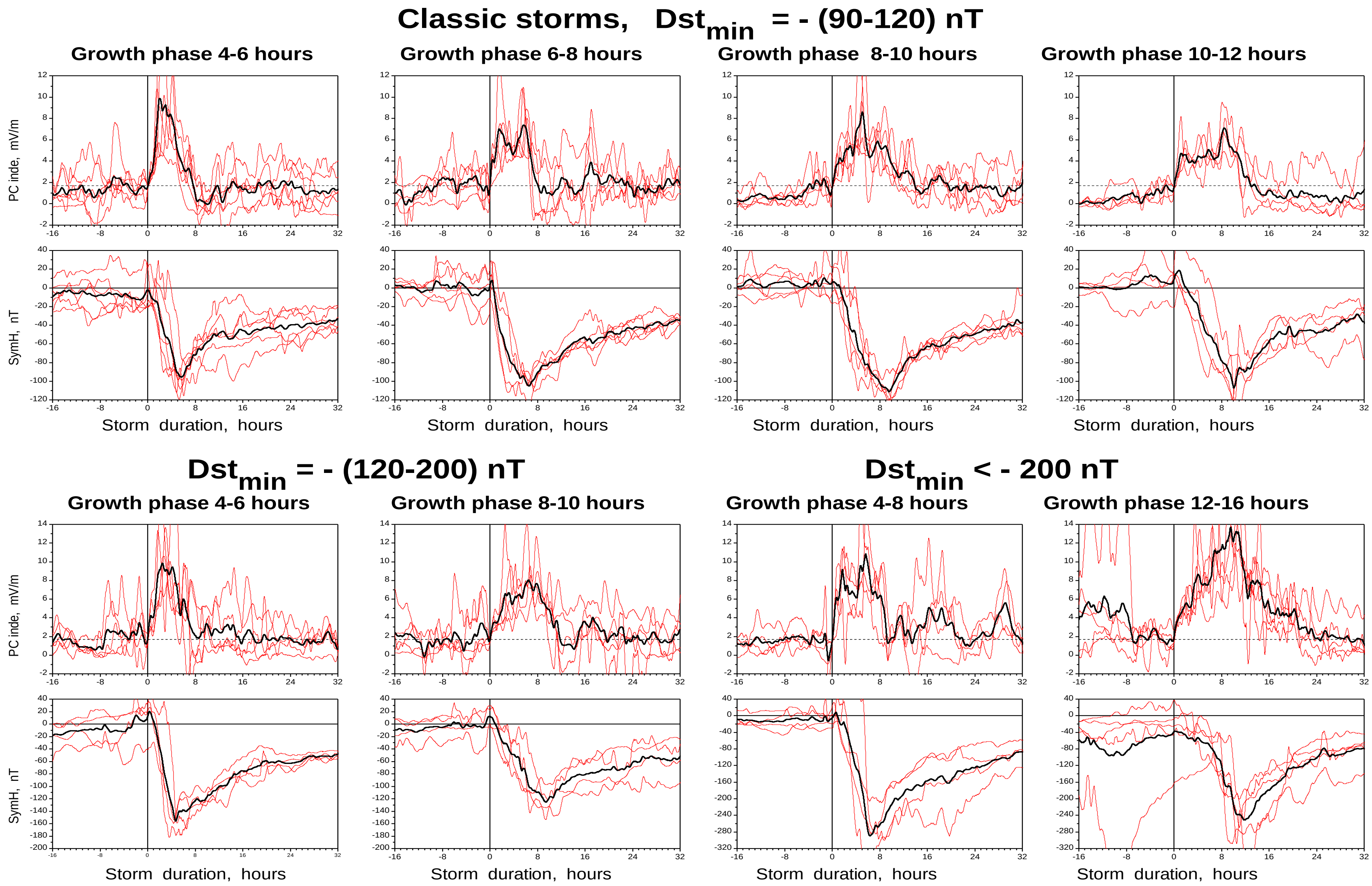
Classic storms with intensity Dst_{min} = - (30-60) nT



Development of classical magnetic storm is determined by time evolution of the PC index:

- **Magnetic storm starts (T=0) when PC index steadily exceeds the threshold level PC~1.5 mV/m.**
- **Magnetic storm continues till PC index stays higher the threshold level, as a result, the storm growth phase duration is determined by time period with PC>1.5 mV/m.**

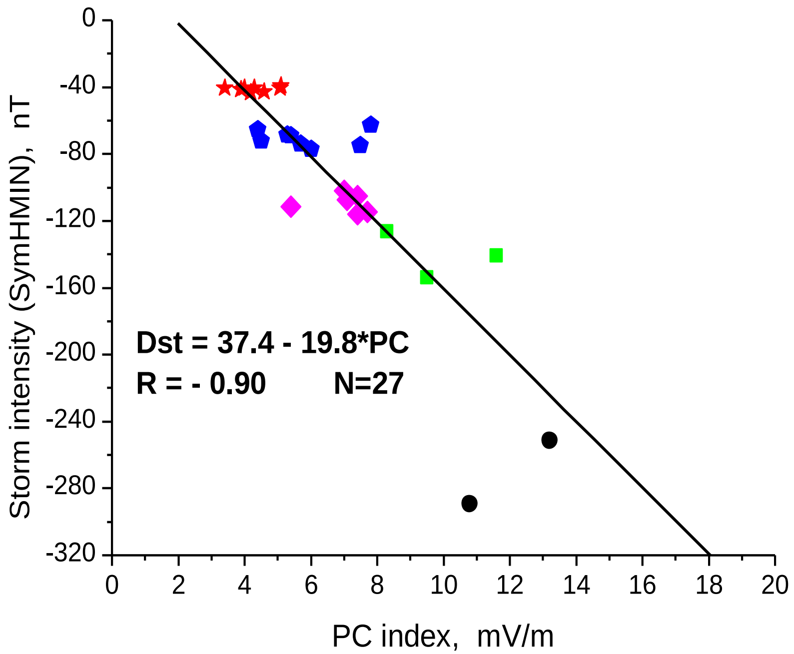
Relation of the classic magnetic storms to the PC index



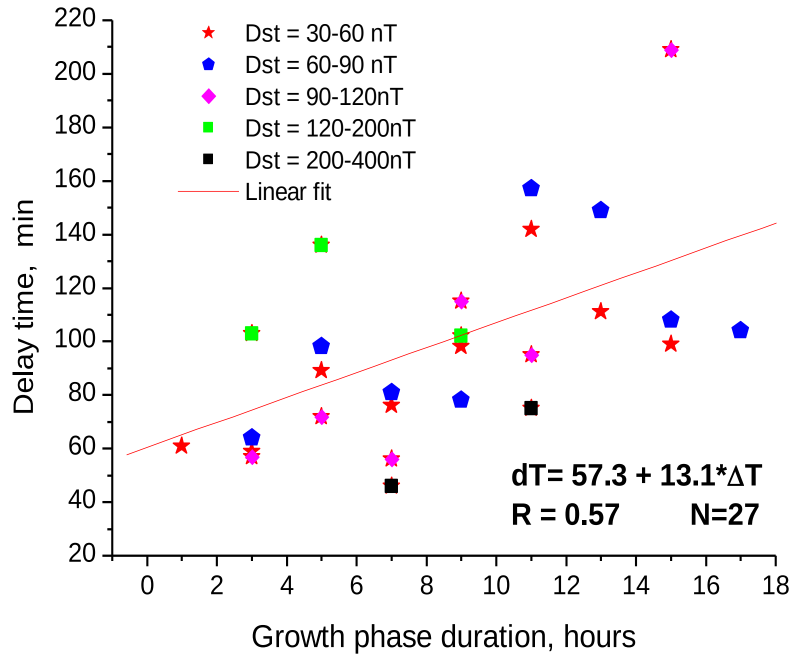
Development of classical magnetic storm is determined by time evolution of the PC index:

Relationship between PC and SymH indices in case of classic storms

Dst_{MIN} vs. PC_{MAX}



Delay time (dT) vs. growth ph. length (ΔT)



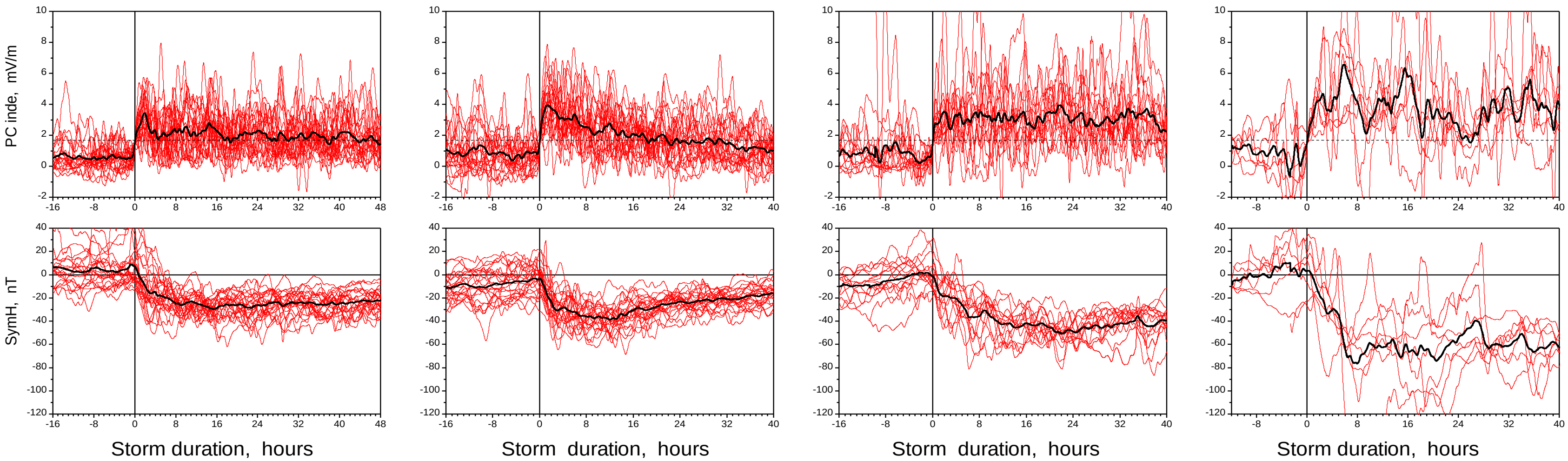
- **The maximal depression of magnetic field (storm intensity) follows to maximum value of the 30-min smoothed *PC* index with time delay dT~ 1- 2 hours**
- **The maximal depression of geomagnetic field *DstMIN*) is linearly related to preceding maximal PC value (*PCMAX*).**
- **The higher the *PCmax* value, the larger is magnetic storm intensity (Dstmin).**
- **Delay time dT seems to be dependent on the storm growth phase duration (the longer the growth phase, the larger is delay time in response of Dst to PC increase)**

Relation of the pulsed and combined storms to the PC index

Pulsed storms

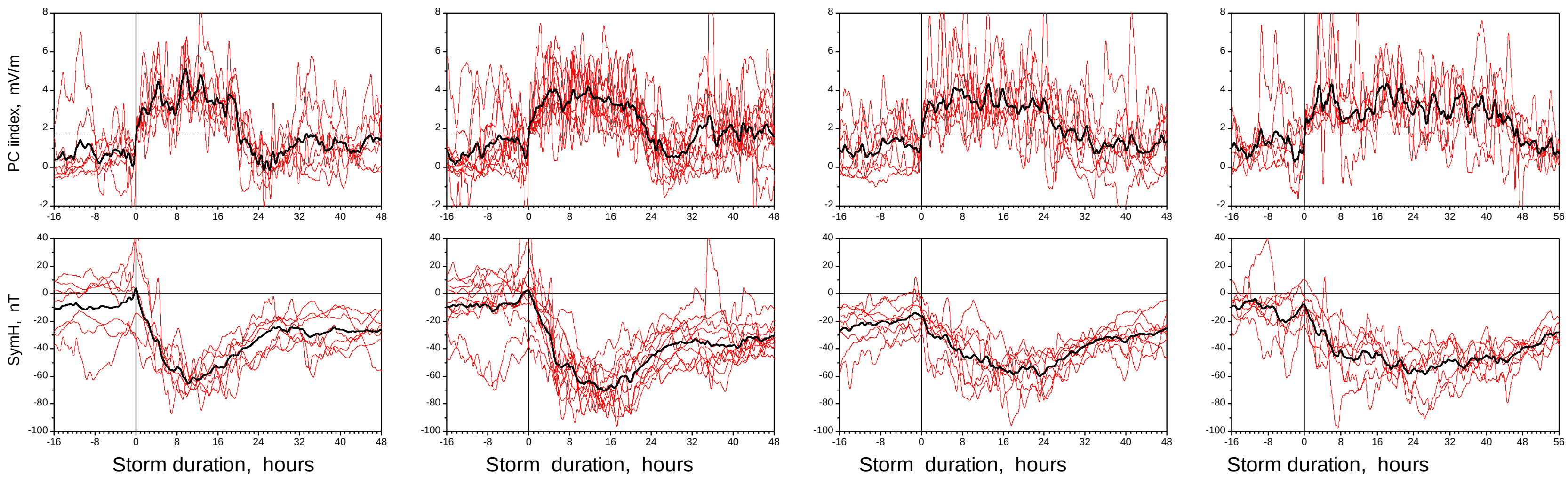
Dst_{min} = - (30-60) nT | **Dst_{min} = - (60-90) nT** | **Dst_{min} = - (90-120) nT**

Permanent oscillation | **Weakining oscillation** | **Permanent oscillation** | **Varying oscillation**

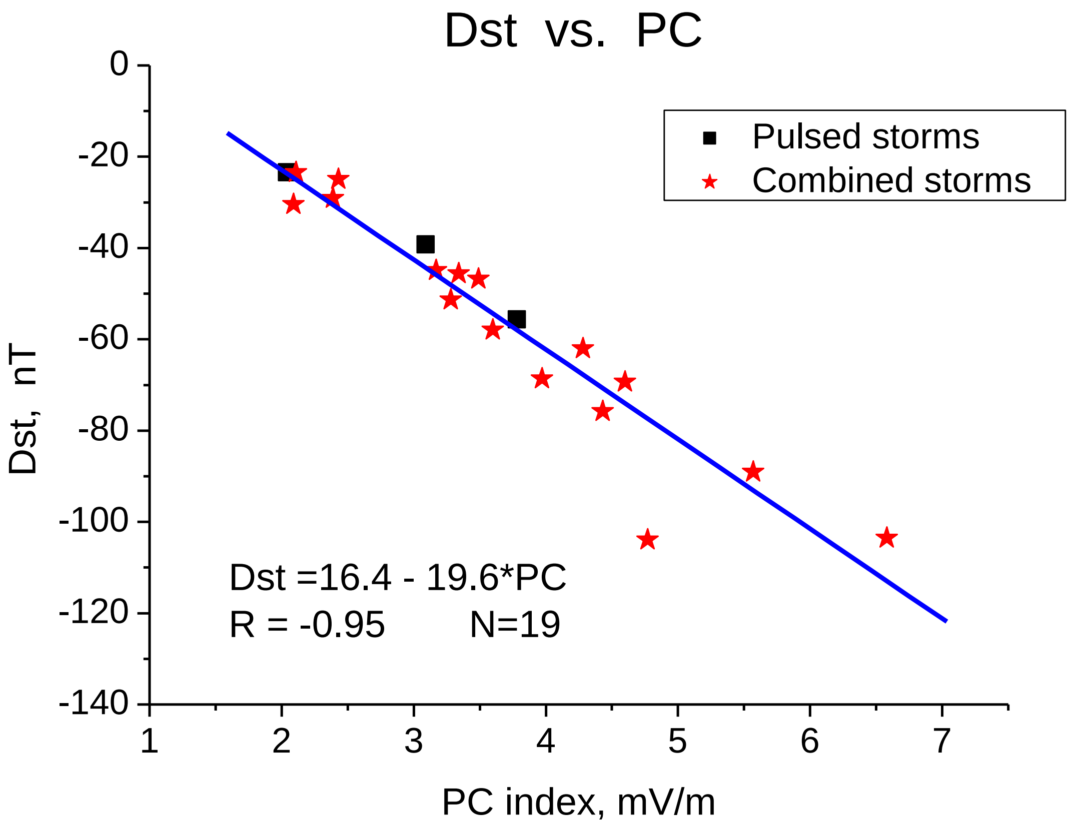


Combined storms with intensity Dst_{min} = - (60-90) nT

Bank width 18-20 hours | **Bank width 20-24 hours** | **Bank width 24-32 hours** | **Bank width 40-48 hours**



Relationship between the magnetic storm intensity and mean PC index in case of pulsed and combined storms



Intensity of pulsed and combined magnetic storms is determined by the average PC index during the storm, the mean PC and Dst values being linearly connected.

In case of pulsed magnetic storms the relationship between the mean PC and Dst values averaged for the storm main phase are examined.

In case of combined storms the storm events were separated by the bank width and then the bank-average values of the PC and Dst indices were estimated.

7. Summary of results

The *PC* index strongly follows the time evolution of interplanetary electric field E_{KL} reduced to magnetopause (correlation **R > 0.6 in 98% of storm events and in 80% of substorm events**) with delay time lying in range from 0 to 35 min with prominent maximum at ΔT =15-20 minutes.

Value of delay time ΔT is determined by the E_{KL} growth rate (with coefficient of correlation R=-0.93), but is not affected by any one particular parameter of the solar wind.

Magnetic substorms are preceded by growth of the *PC* index. The substorm occurrence sharply increases when the *PC* index exceeds the threshold level ~1mV/m and reaches the maximum when *PC* ~ 1.5 mV/m, irrespective of the substorm growth phase duration and type of substorm.

The substorms sudden onsets are commonly associated with such peculiarities in time evolution of *PC* as *leap* or *reverse*, which are indicative of sharp increase in the *PC* growth rate. Sudden onset of magnetic substorms and substorm intensity are not affected by the *PC* growth phase duration.

PC index continues to grow after sudden onset, the *PC* growth rate being unaffected by SO.

Linear relationship between the *PC* and *AL* indices is typical of all classes of the substorms irrespective of their intensity and duration.

In ~ 20% of the substorm events the correlation between E_{KL} and *PC* is practically absent, in spite of actual substorm onset related to the *PC* index rise. It implies that in these cases the actual solar wind, measured in the Lagrange point, passes by the magnetosphere.

Steady exceeding the threshold level *PC*=1.5 mV/m is necessary and sufficient condition for development of the geomagnetic field depression. Respectively, the moment of the threshold exceeding determines the magnetic storm beginning.

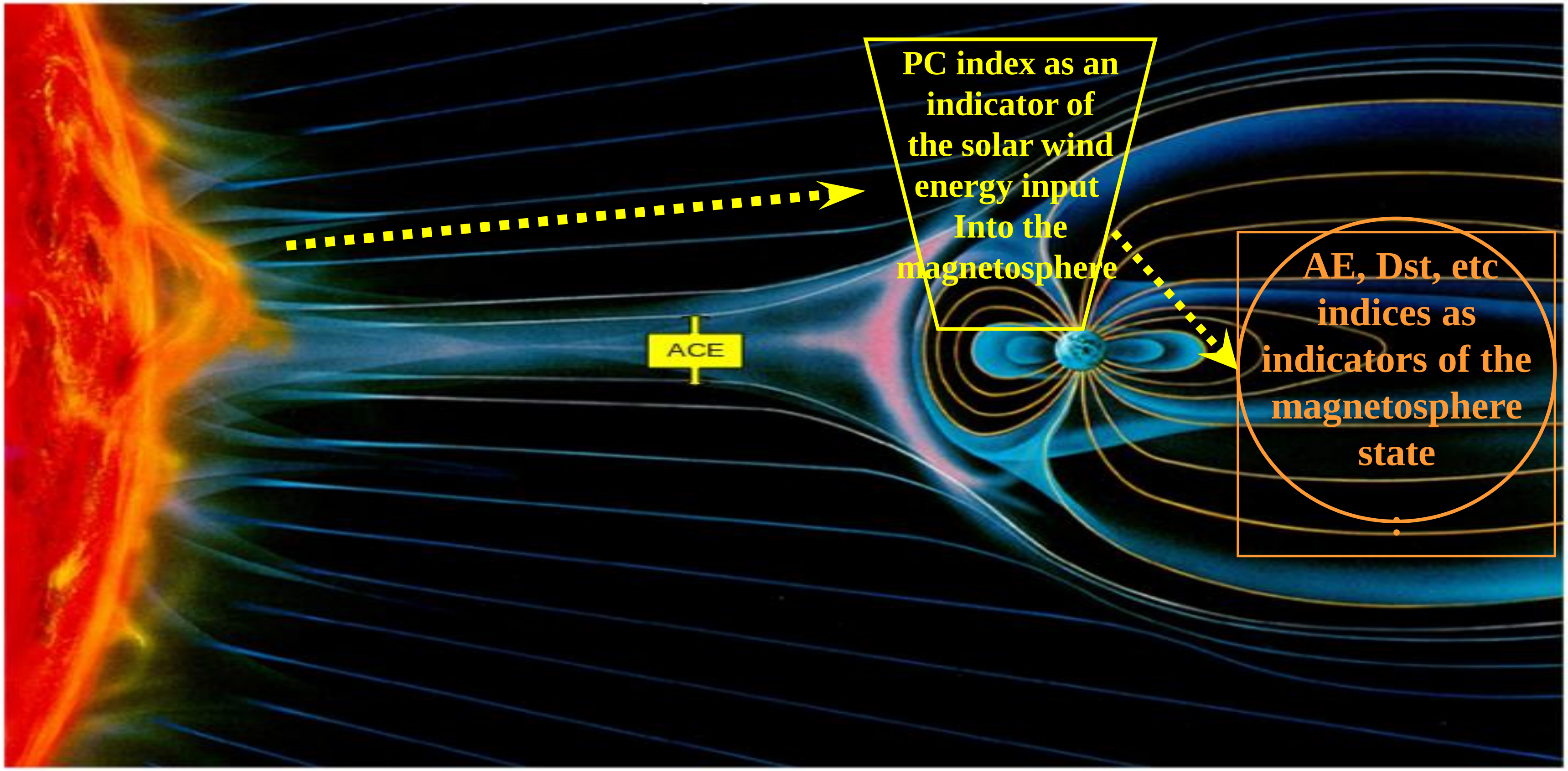
In course of magnetic storms the magnetic storm *SymH* index generally follows the time evolution of the 30-min smoothed *PC* index, irrespective of type and intensity of magnetic storms.

The basic types of magnetic storms are the following: "**classic storms**", related to ICME impact, with clearly expressed maximum of depression, "**pulsed storms**", related to SIR impact, with periodically repeating oscillations in *PC* and *SymH* indices, and "**combined storms**", which are regarded as effect of simultaneous ICME and SIR action. Linear relationship between the smoothed PC and Dst values seems to be independent on the solar wind drivers.

In case of classic storms the the magnetic storm intensity (i.e. the maximal depression of geomagnetic field Dst_{MIN}.) follows, with ~60 min delay, the maximal mean PC value (PC_{MAX}), the Dst_{MIN} value being linearly dependent on PC_{MAX} value.

The *AL* and *SymH* indices much better correlate with *PC* index than with E_{KL} field (which is estimated by the solar wind parameters fixed in the Lagrange point L1 and reduced to the Earth's magnetopause).

Conclusions



These experimental facts are strongly indicative of the *PC* index as an adequate indicator of the solar wind energy input into the magnetosphere.

The *PC* index might be useful for monitoring the space weather, nowcasting the actual state of the magnetosphere, fitting the solar wind-magnetosphere coupling function, and checking whether or not the solar wind fixed in Lagrange point L1 actually encounters the magnetosphere.

The historical *PC* indices (sets of data for 1997-2015) and current *PCN* and *PCS* indices calculated on-line by magnetic data from stations Thule and Vostok are presented at web site: http://pcindex.org

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Thank you for attention!

web site: http://pcindex.org