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

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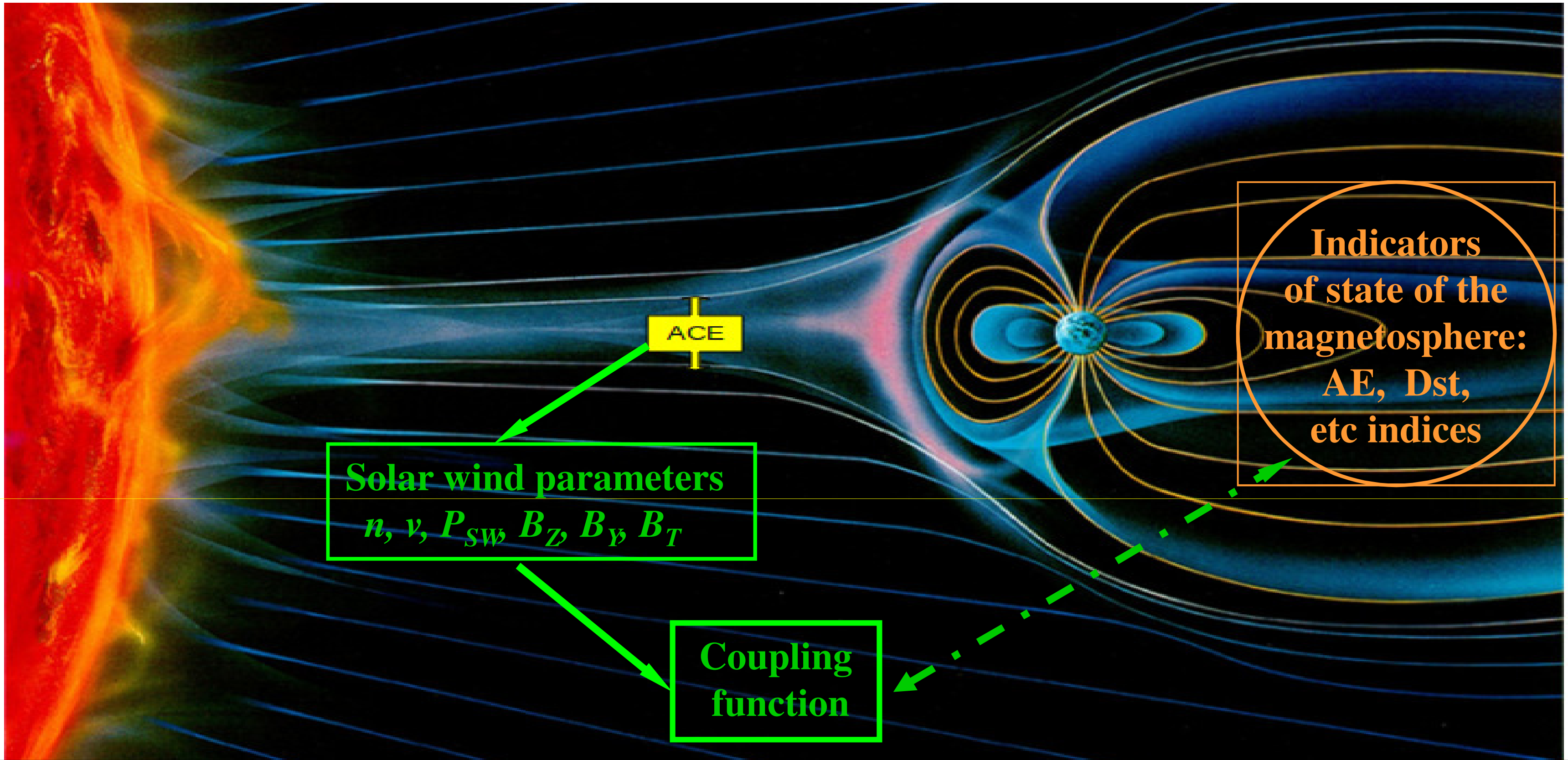
Motivation: need in reliable means for monitoring and nowcasting the space weather and magnetosphere state



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 and AE indices, which characterize the energy realized in magnetosphere in form of storms and substorms.

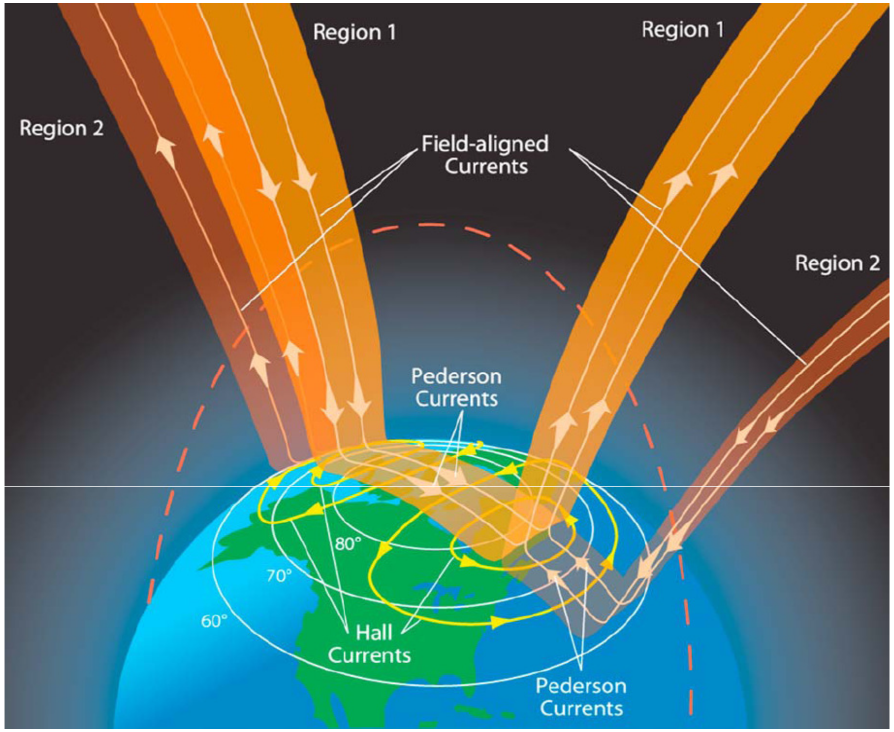
The different "coupling functions" (N>20) have been suggested to establish a link between the solar wind parameters and the magnetosphere state, but no one of them is not universal.

The PC index is proposed as indicator of efficiency of the solar wind – magnetosphere coupling.

Outline:

1. **Physical backgrounds of the *PC* index derivation**
2. ***PC* index and development of magnetospheric substorms**
3. **Relationship between *PC* and the interplanetary electric field E_{KL}**
4. **Relationship between the *PC* index and magnetic storms**
5. **Summary of results**

Physical backgrounds for PC index: the polar cap magnetic activity responds to the geoeffective variations of solar wind



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

The currents distributed along the poleward boundary of the auroral zone (Region 1 FAC) 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]

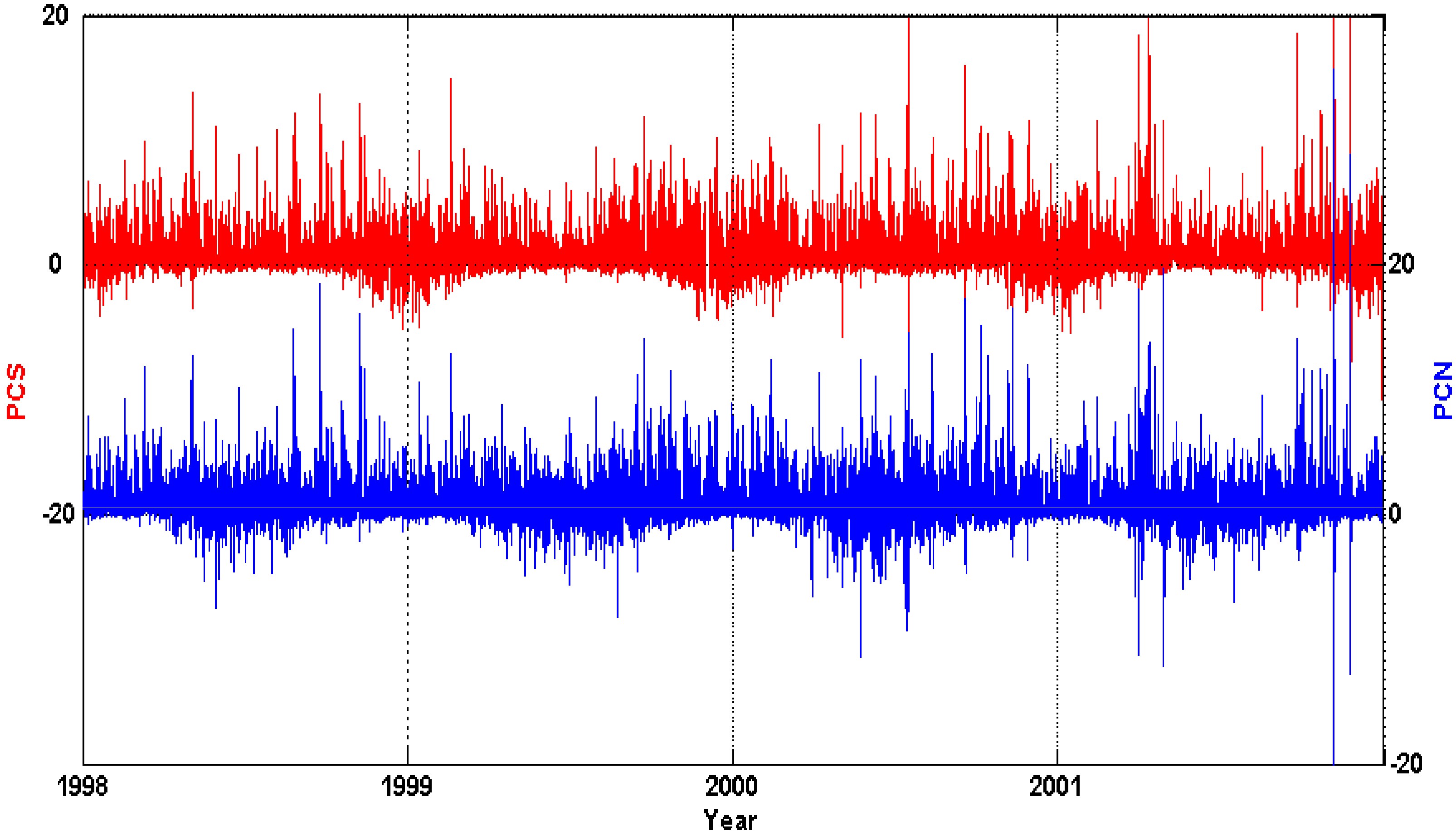
PC index has been introduced [*Troshichev et al.,* 1988] to characterize the polar cap magnetic activity produced by the interplanetary electric field E_{KL} [Kan and Lee, 1979]

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

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

PC index is determined as a value of magnetic disturbance in the near-pole region normalized by the EKL field intensity with allowance for UT time, season and hemisphere.

Run of the PCN and PCS indices in 1998-2002



PC index is calculated by magnetic data from stations Thule (Greenland) and Vostok (Antarctic).

- There is remarkable agreement in behavior of the positive PC values in the northern and southern hemispheres.
- The positive PC index can reach so large value as 20 at both Thule and Vostok station.
- Occurrence of the negative PC index is typical only of the local summer under conditions of the northward IMF (Bzn) influence in both hemispheres.

2. *PC index and development of magnetospheric substorms*

Development of the magnetospheric substorms was estimated by the AL index, characterizing magnetic activity in the auroral zone.

Under the substorm sudden onset we examined steep increases of the AL index with magnitude more than 100nT for time lapse < 10 min.

To analyze relationship between the PC index and substorm development the time evolution of the PC and AL indices **in course of all magnetic substorms with sudden onset** observed in epoch of solar maximum (1998-2001) was examined.

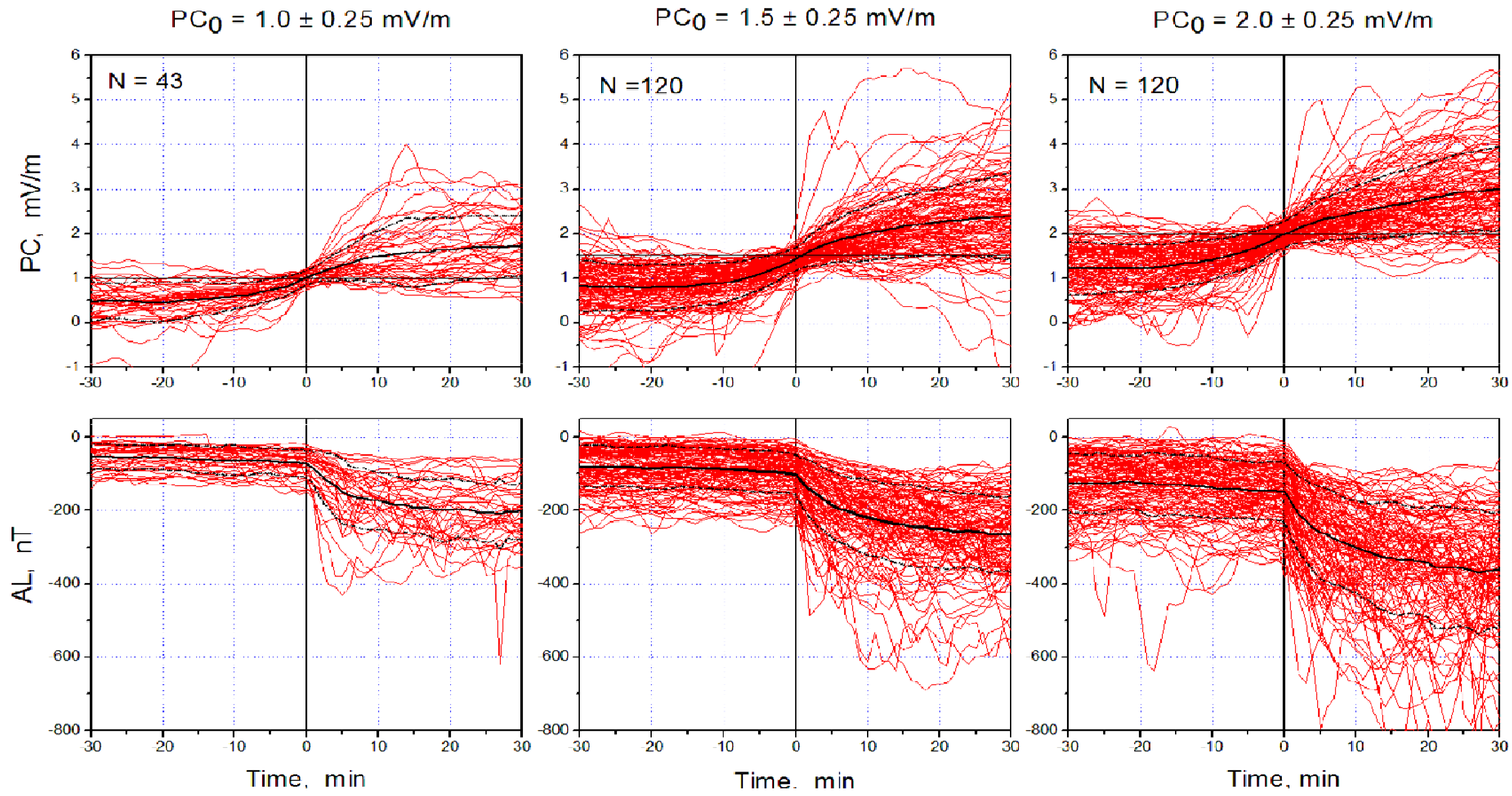
Magnetic substorms have been divided into two classes:

Isolated substorms are disturbances, which are developed against the background of quiet magnetic field ($AL \leq 200$nT) lasting not less than 3 hours prior to SO **(N=194),**

Expanded substorms are disturbances, which occurred during the enhanced magnetic activity in the polar cap and aurora zone **(N=1418).**

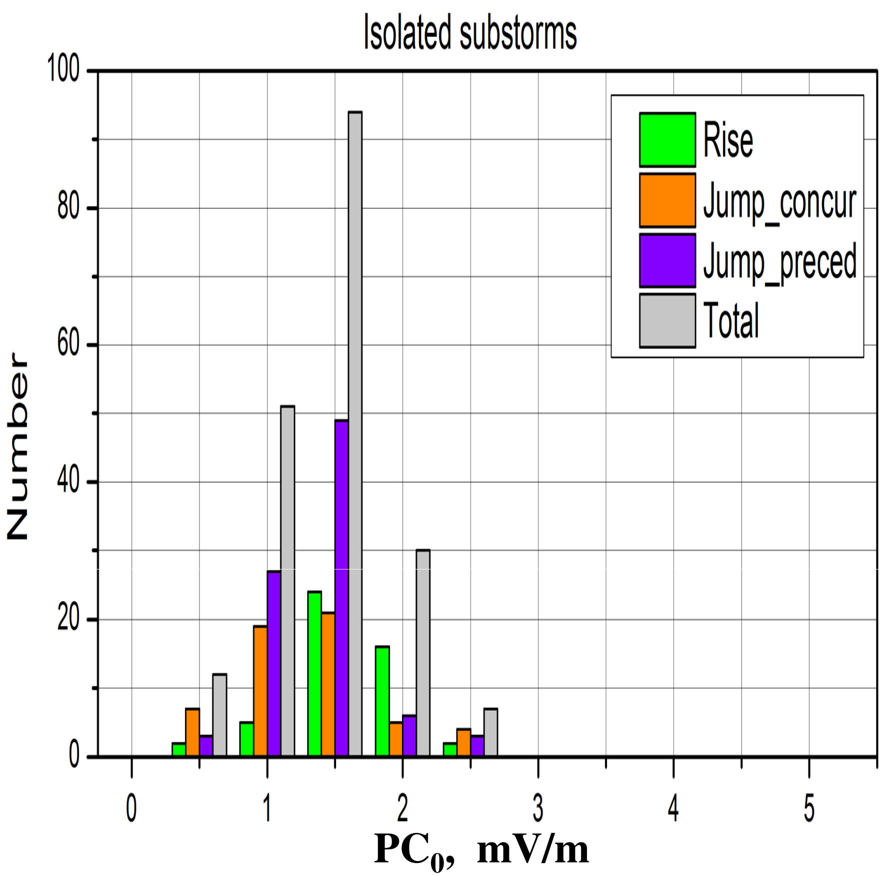
PC index and substorm development

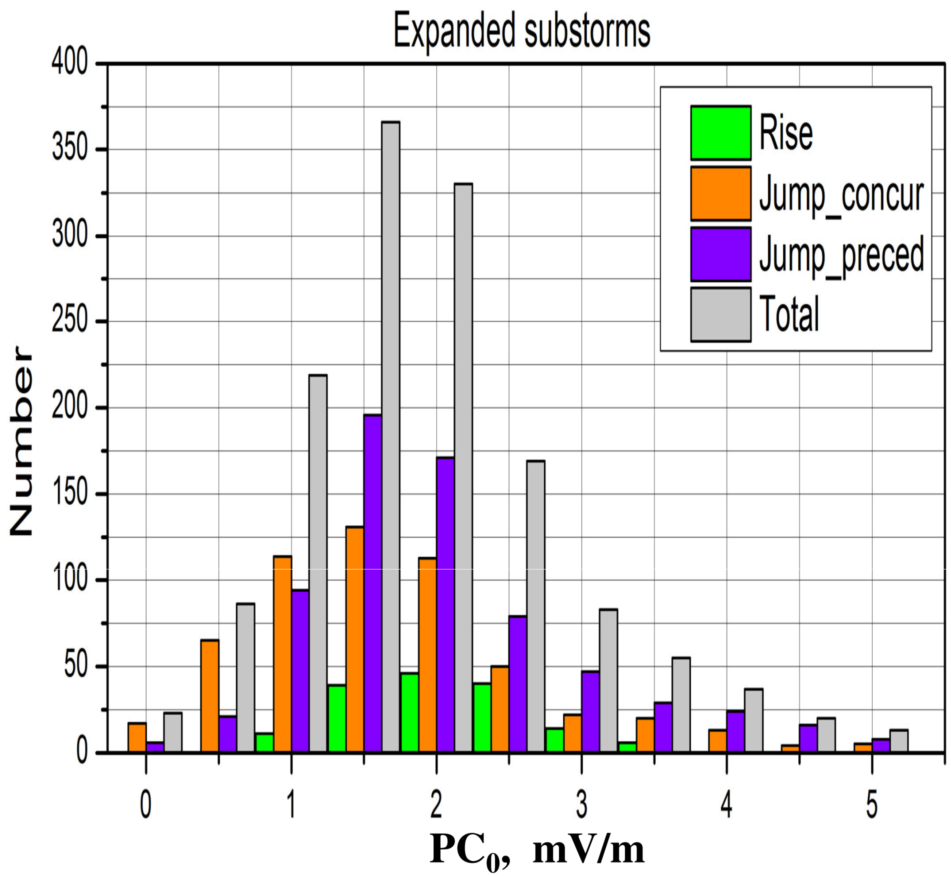
Substorm separated by groups by value of PC_0 in time of substorm sudden onset; the moment of substorm onset (SO) is taken as a key date (T=0). Thin red lines present a run of *PC* and *AL* in course of individual events.Thick black line presents variation of mean *PC* and *AL* values for each group



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

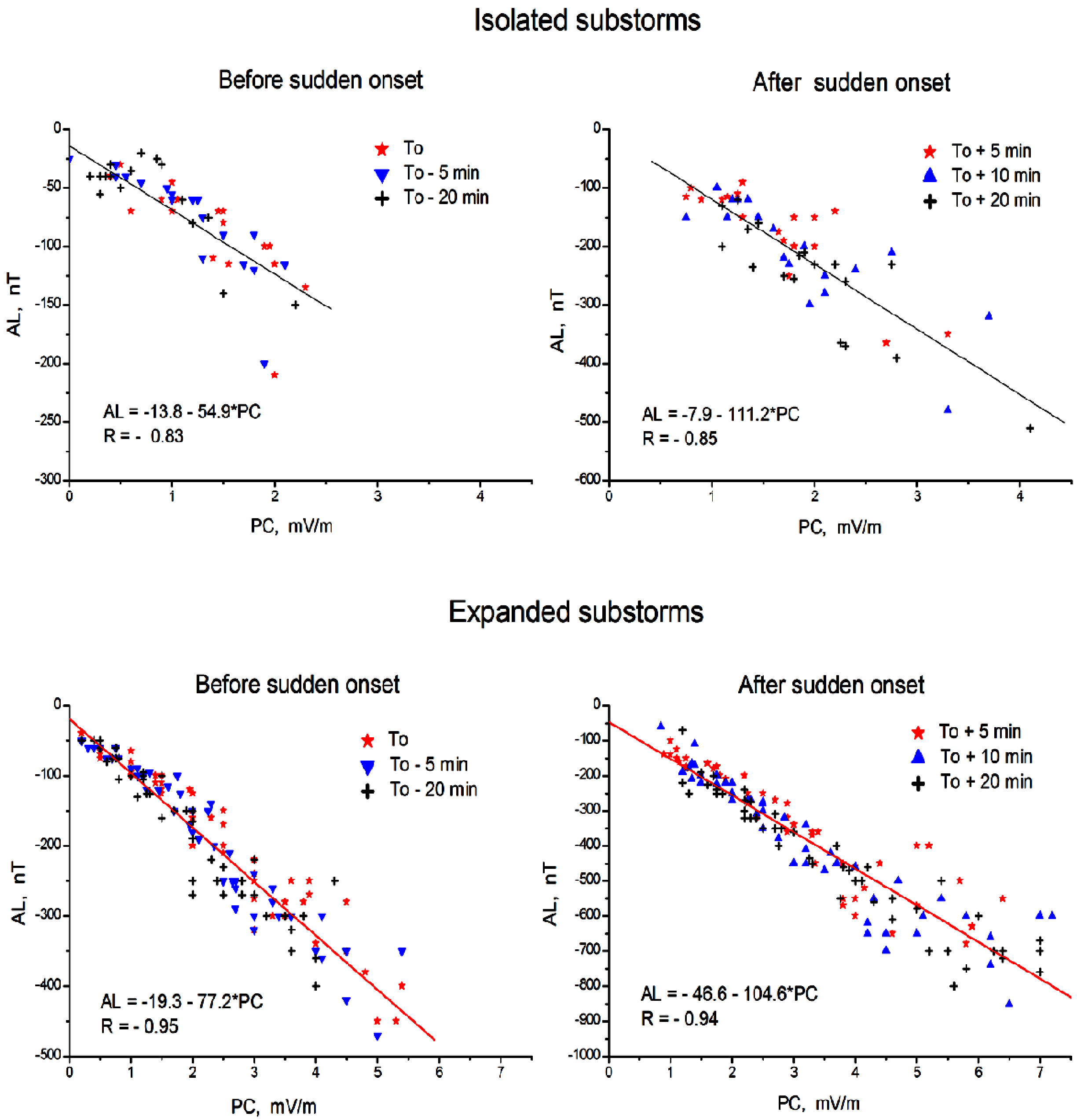
Distribution of substorms over the values PC_0





Substorms are developed against the backgrounds of gradually increasing *PC* index.
Sudden onset of isolated and expanded substorms is observed, as a rule (for >75%), when the *PC* index exceeds the threshold level *PC*=1÷1.5 mV/m.
Under conditions of high activity (PC_0>3.5 mV/m), the substorms start exclusively in association with strong jump of the *PC*.

Relationship between AL and PC indices before and after substorm onset



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

In case of isolated and extended substorms the slope coefficient after SO turned out to be much higher than before SO.

Thus, the time evolution of magnetic disturbances in the auroral zone is controlled by the *PC* value, but dependence of AL on PC 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.

3. *Relationship between PC and the interplanetary electric field* E_{KL}

The analysis of relationship between PC and E_{KL} was carried out for the same events with isolated and expanded substorms for period 1998-2001 which were examined above.

Values *PC* and E_{KL} were smoothed using the 15 min averaging running window.

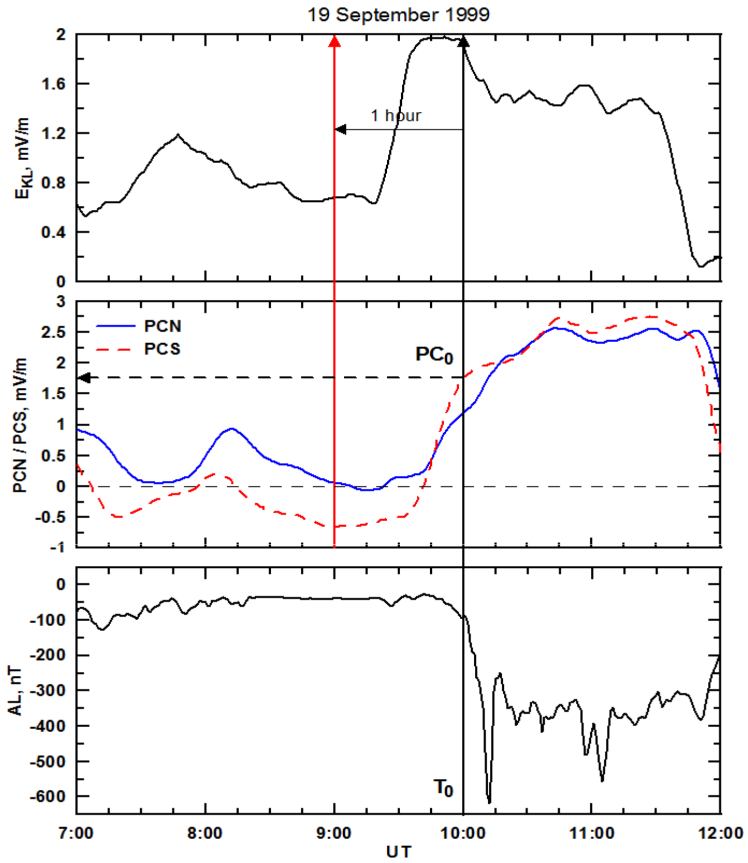
The time of substorm onset (SO) was identified by *AL* index a zero time (T_0) for events with isolated and expanded substorms and correlation between the smoothed E_{KL} and *PC* was calculated for 1-hour term preceding SO.

Besides, the events with coordinated E_{KL} and *PC* changes during 2-hour interval preceding SO have been separated as the **coordinated events.** In this case the moment of the sudden rise of E_{KL} was taken as a zero date (T_0).

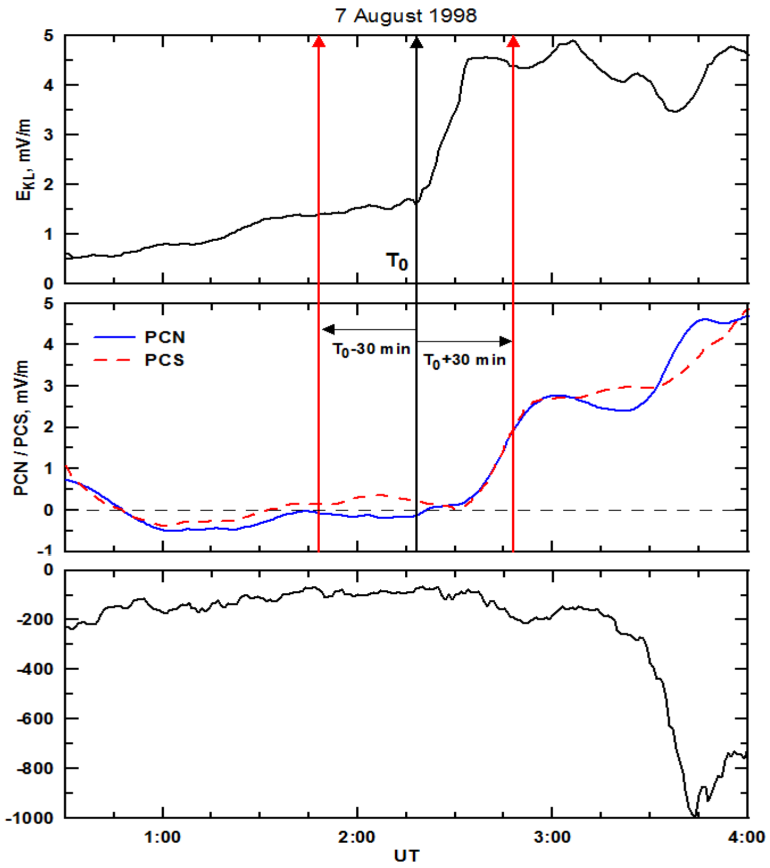
The event with the gap in data more than 40% of the data body were excluded from examination. As a result, amount of the examined events was N=163 for isolated and N=983 for expanded substorms, and N=261 for coordinated events.

Examples of events with substorm onset and coordinated events

Event with isolated substorm



Coordinated event

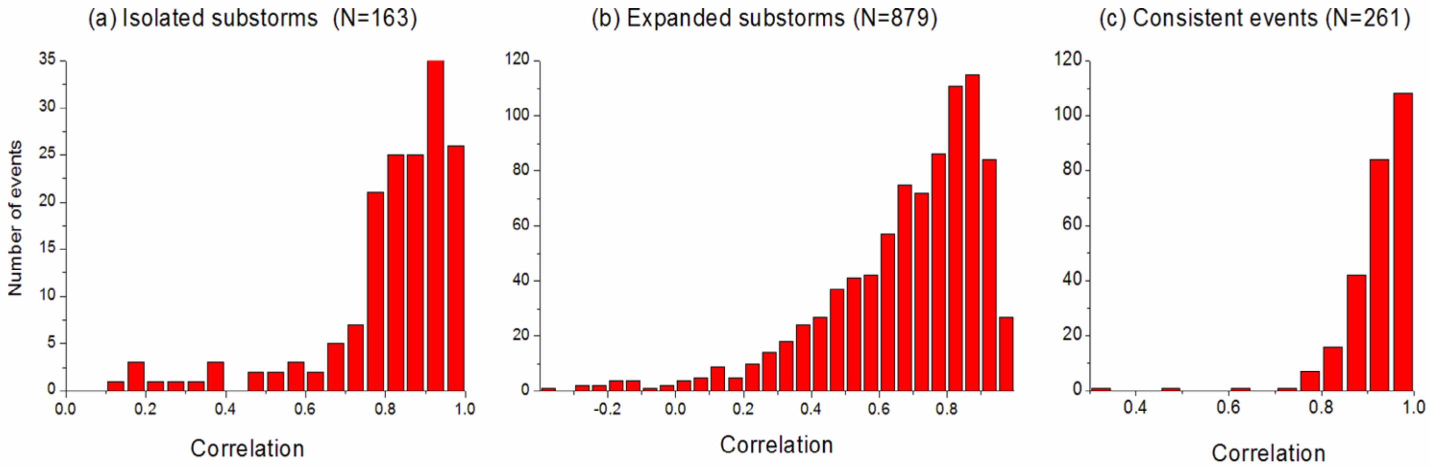


In case of events with SO the correlation between the smoothed E_{KL} and *PC* was calculated for 1-hour term preceding SO separately for each event. In case of coordinated events the correlation between E_{KL} and *PC* quantities was calculated in range from T_0–30 to T_0+30, irrespective of substorm sudden onset.

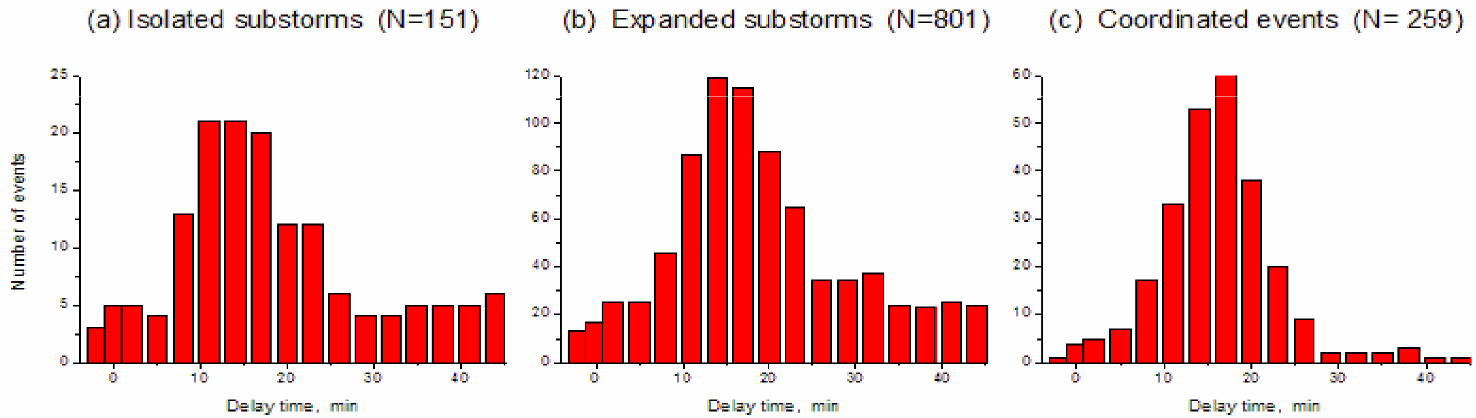
The correlation was calculated with variable shifts of E_{KL} relative to *PC*, the shift being taken in range of from 0 to 45 min in case of substorm and in range of ±30 minutes in case of coordinated events.

The delay time ΔT in response of *PC* to E_{KL} variation was identified for each specific event as a value of shift providing the maximal correlation between E_{KL} and *PC*.

Correlation between *PC* and E_{KL} in period preceding the substorm sudden onset



Delay time ΔT in response of *PC* to E_{KL} variation

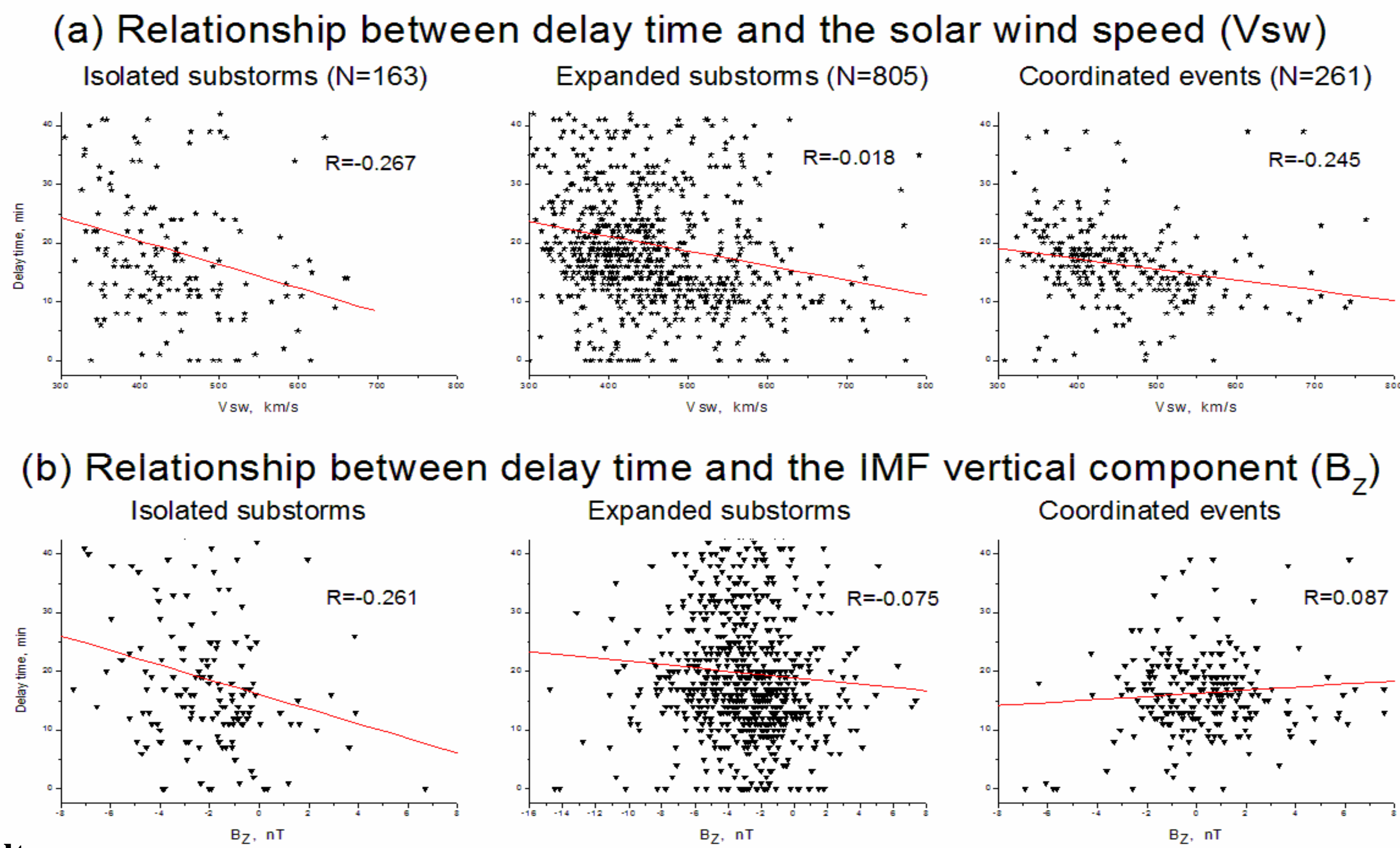


The high correlation between E_{KL} and *PC* (R>0.75) was observed in ~70% of events with isolated substorms, in ~50% of events with expanded substorms, and in > 90% of coordinated events testifying that ***PC* index strongly follows the time evolution of E_{KL} field** in period preceding the substorm onset.

The low (R<0.50) or negative correlation between E_{KL} and *PC* observed for another part of examined events suggesting that the magnetosphere in these cases was not touched by the solar wind, those parameters were measured on board ACE spacecraft in the Lagrange point L1.

Delay times in response of *PC* to E_{KL} are extended in range from 0 to 40 min with the very pronounced peak at ΔT=12-18 min irrespective of type of the examined events.

Relationship between the solar wind parameters and delay times ΔT for isolated and expanded substorms and coordinated events with R>0.75



Results:

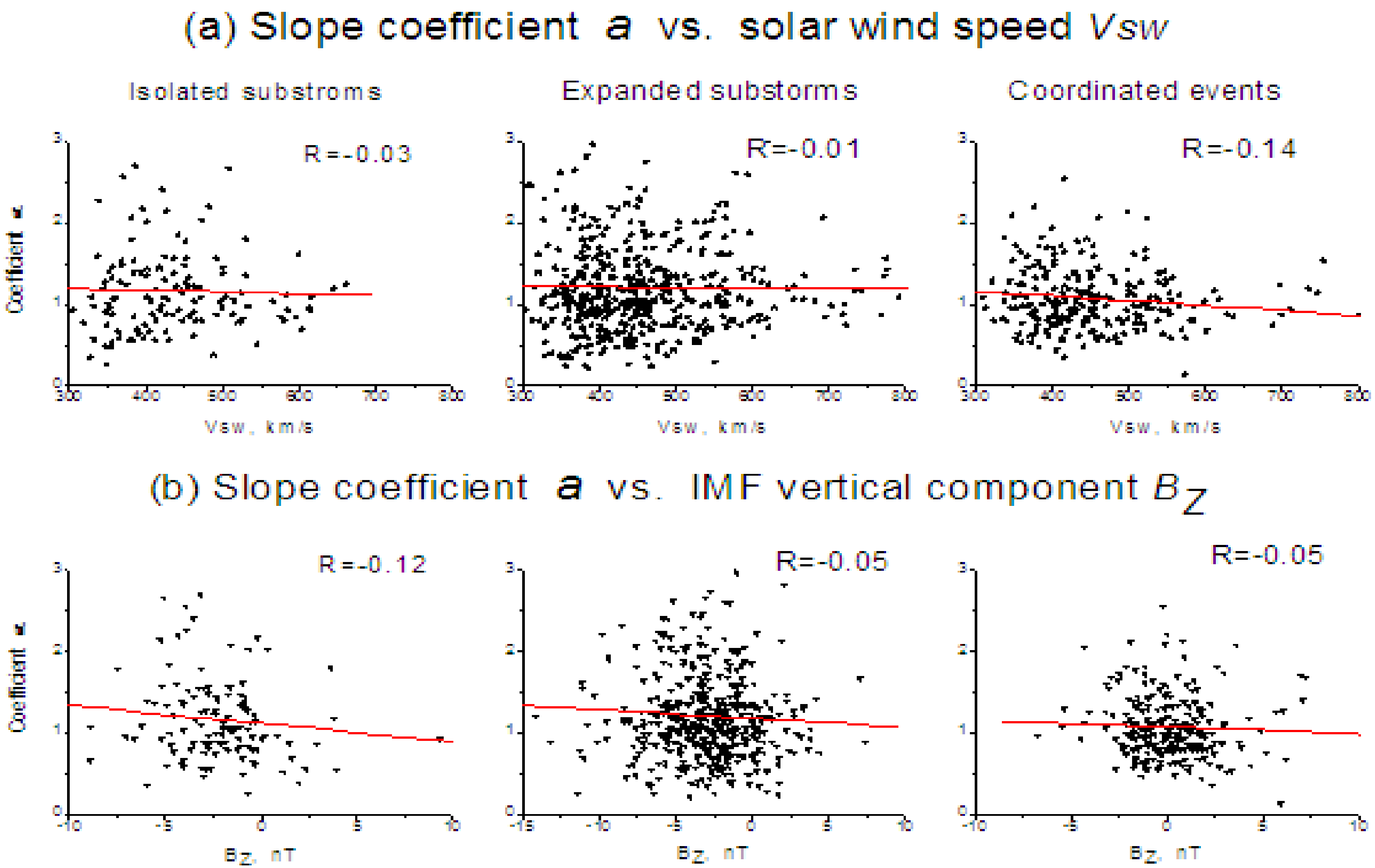
(a) There is only **slight tendency (R<0.30) to *ΔT* decrease with rise of the solar wind speed *Vsw*.**

(b) Delay time ***ΔT* slightly (R=0.26) increases under conditions of northward IMF B_Z component.**

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

(d) Delay time ***ΔT* is not affected** by the solar wind dynamic pressure ***Pd*** (is not shown).

Efficiency of linkage between PC and E_{KL} ($PC = \alpha E_{KL} + \beta$) : relation to the solar wind speed Vsw and IMF vertical B_Z component

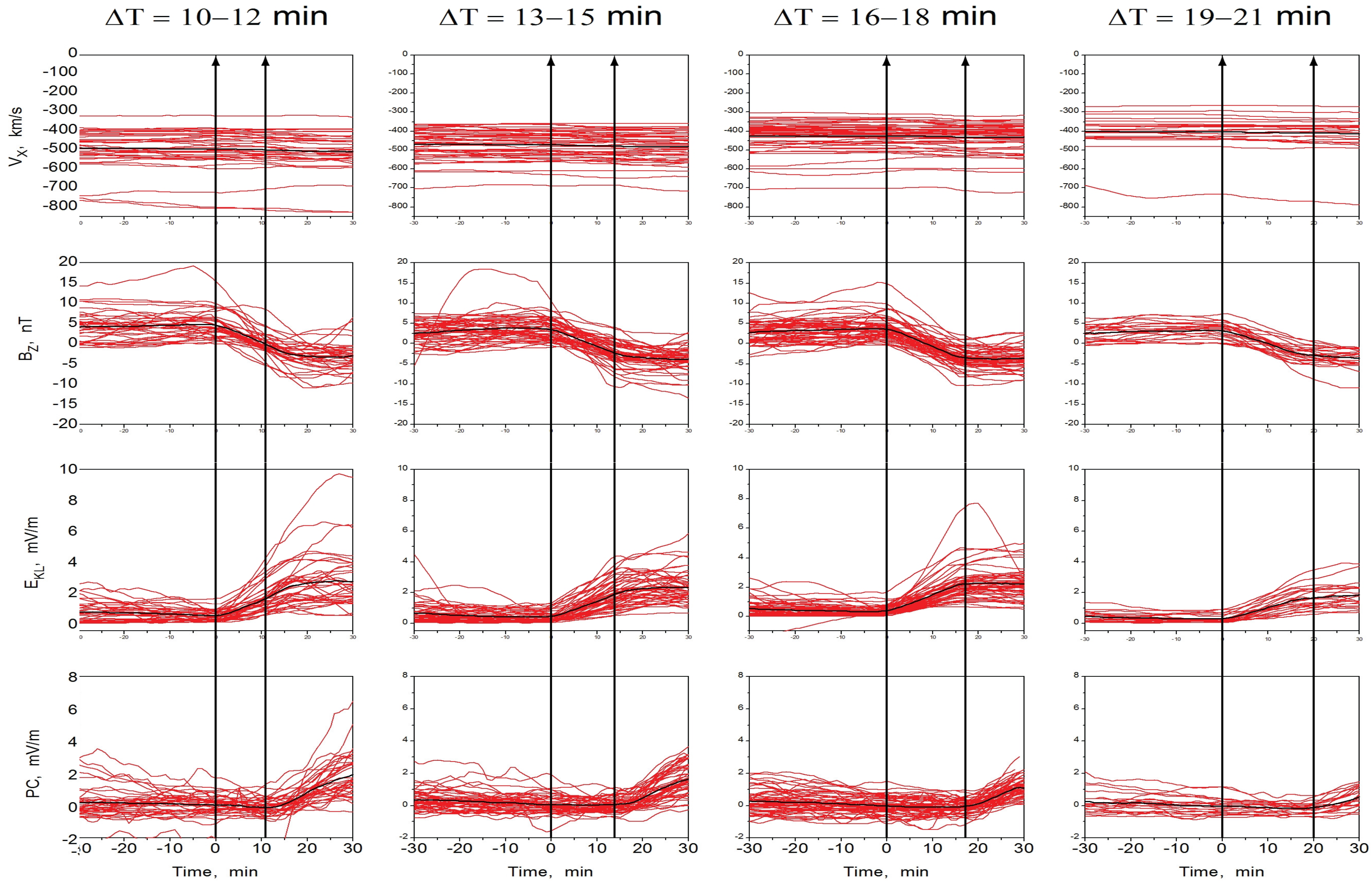


It is seen the negligible small tendency for the α value decrease with the solar wind speed increasing and the IMF B_Z component northward turning.

Conclusion:

The slope coefficient *α* and, therefore, the efficiency of relation between *PC* and E_{KL} is not directly affected by the solar wind parameters *Vsw* and B_Z.

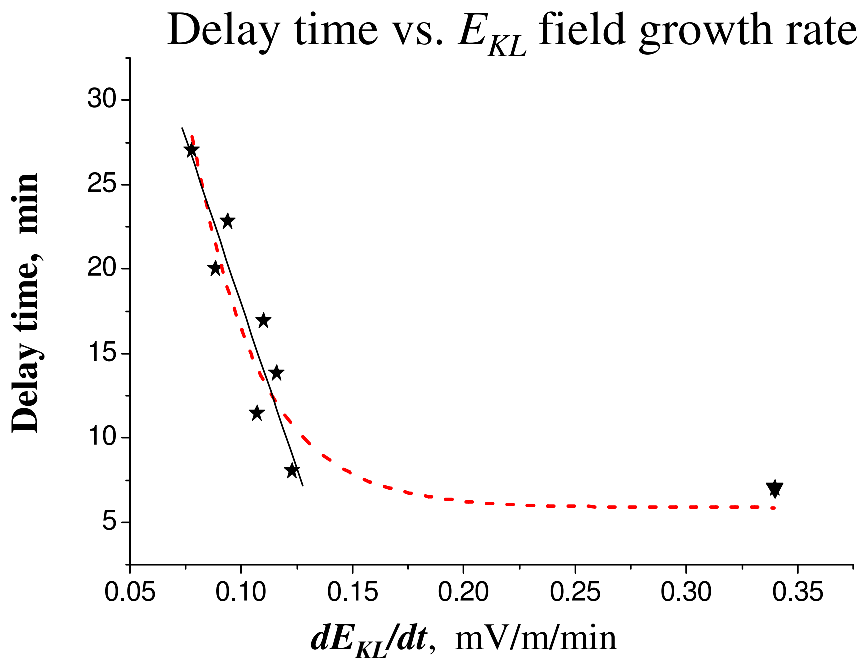
Time evolution of values V_X, B_Z, E_{KL} and PC for groups with different delay times ΔT



Moments of sudden rise of E_{KL} field (T=0) and *PC* jumps (T=0+ΔT) are marked by the vertical black lines.

Increase ΔE_{KL} during delay time ΔT is identified as the E_{KL} growth rate (dE_{KL}/dt).

Delay time ΔT as a function of the E_{KL} field growth rate



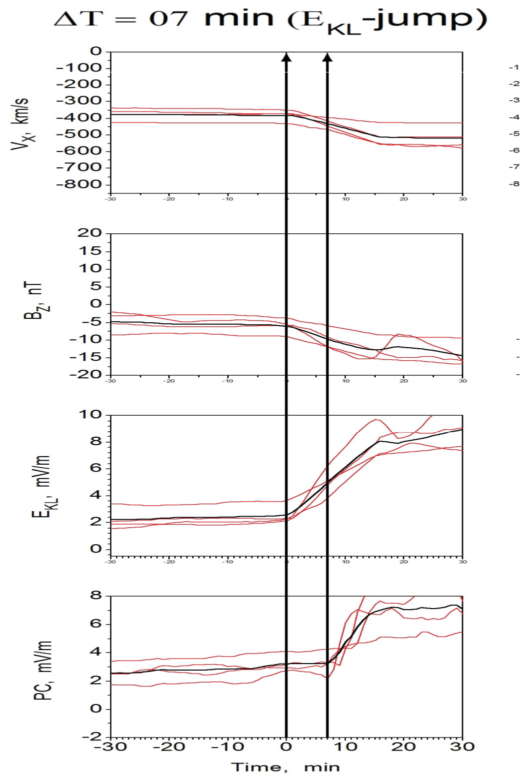
The events with high correlation between *PC* and E_{KL} (R>0.75) are only examined.

Knowledge of E_{KL} growth rate for any delay time interval ΔT makes it possible to derive relationship between delay time and the E_{KL} growth rate (*shown by asterisks and solid line*).

Delay time ΔT and growth rate of E_{KL} field are connected by the linear low:

$$\Delta T = 57.1 - 392.1*(dE_{KL}/dt)$$

R= - 0.94   N=7



A lower limit of ΔT is reached in events with extremely high jumps E_{KL} (from ~2.5 to ~5 mV/m instead of the usual rising from ~0.5 to 2 mV/m).

These extreme jumps of E_{KL} were due to strong rising the southward IMF component (from -7 to -13 nT) and to strengthening the solar wind speed by about 150 km/s, both started synchronously at moment T=0.

The corresponding jumps in *PC* index was observed in range from ~ 3 to ~7 mV/m with mean delay times ΔT ~7 min.

It provides the E_{KL} growth rate as high as 0.34 mV/m/min (*triangle*).

Conclusion:

Delay 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*).

4. Relationship between the PC index and magnetic storms

Criteria used to choose magnetic storms for the analysis: (1) depression of magnetic field during storm should be larger than *Dst* = -30nT, and (2) magnetic storm duration should be longer than 12 hours.

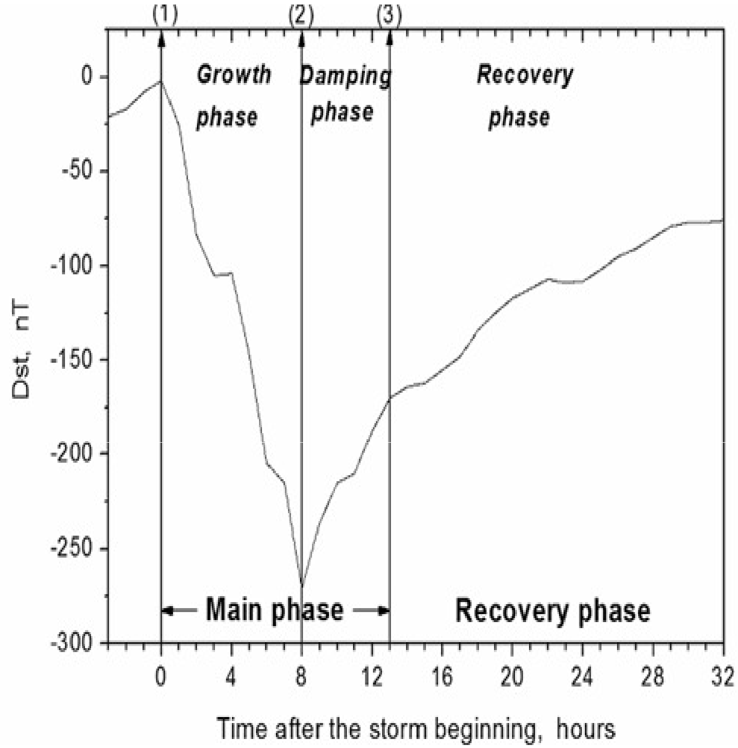
The depression advent is regarded as a beginning of the storm main phase, and the maximum of depression (Dst_{min}) is regarded as a magnetic storm intensity.

Magnetic storms are divided by their intensity into 5 categories: 30-60nT, 60-90nT, 90-120nT, 120-200nT, 200-400nT.

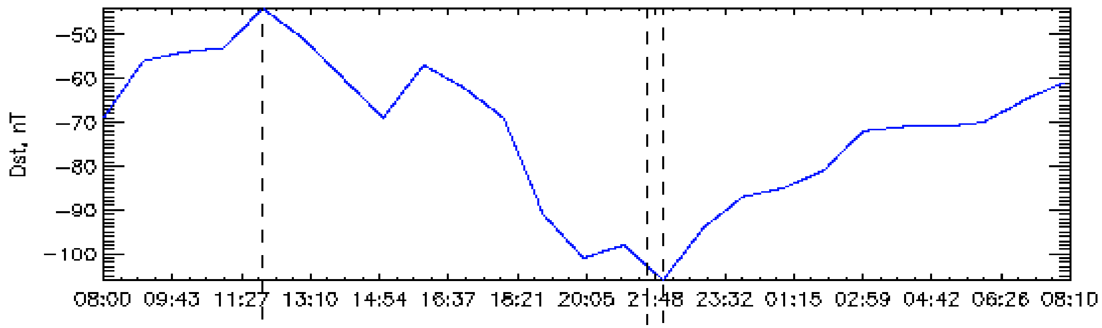
Basing on these criteria, 203 magnetic storms were separated for the epoch of solar activity maximum (1998-2004) with a maximal storm intensity varying in the range from *Dst* = -30nT to *Dst* = -400nT.

Separation of magnetic storms into "classical", "retarded" and unqualified types.

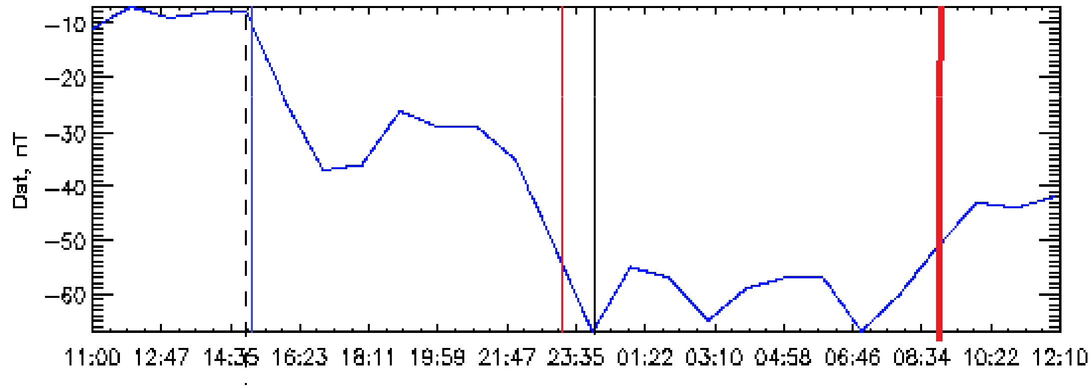
Example of classical storm
[*Akasofu and Chapman, 1972*]



Example of "retarded" storm of November 13, 1999



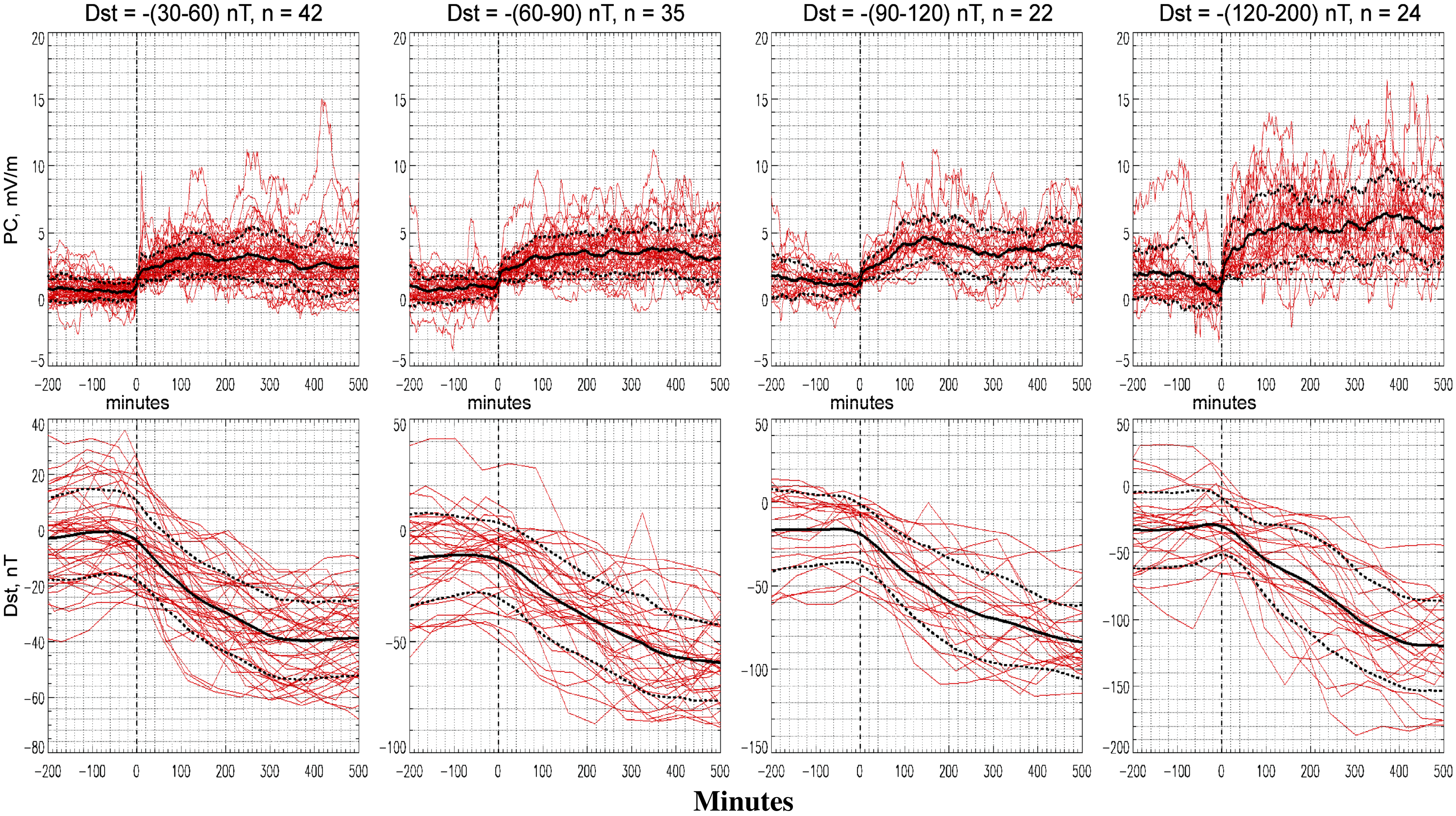
Example of unqualified storm of March 3, 2003



"Classical storms" are storms with a single clearly delineated strong depression of the magnetic field ("main phase") and a slow restoration of the field to the previous level ("recovery phase").
"Retarded storms" are storms with extended growth phase and distinguished main phase.
"Unqualified storms" with smoothed or repeated main phase were excluded from statistical analysis.
All magnetic storms with intensity >30nT and duration >12 hours were included in the analysis (N=230).
Magnetic storms were divided by their intensity : 30-60nT, 60-90nT, 90-120nT, 120-200nT, 200-400nT.

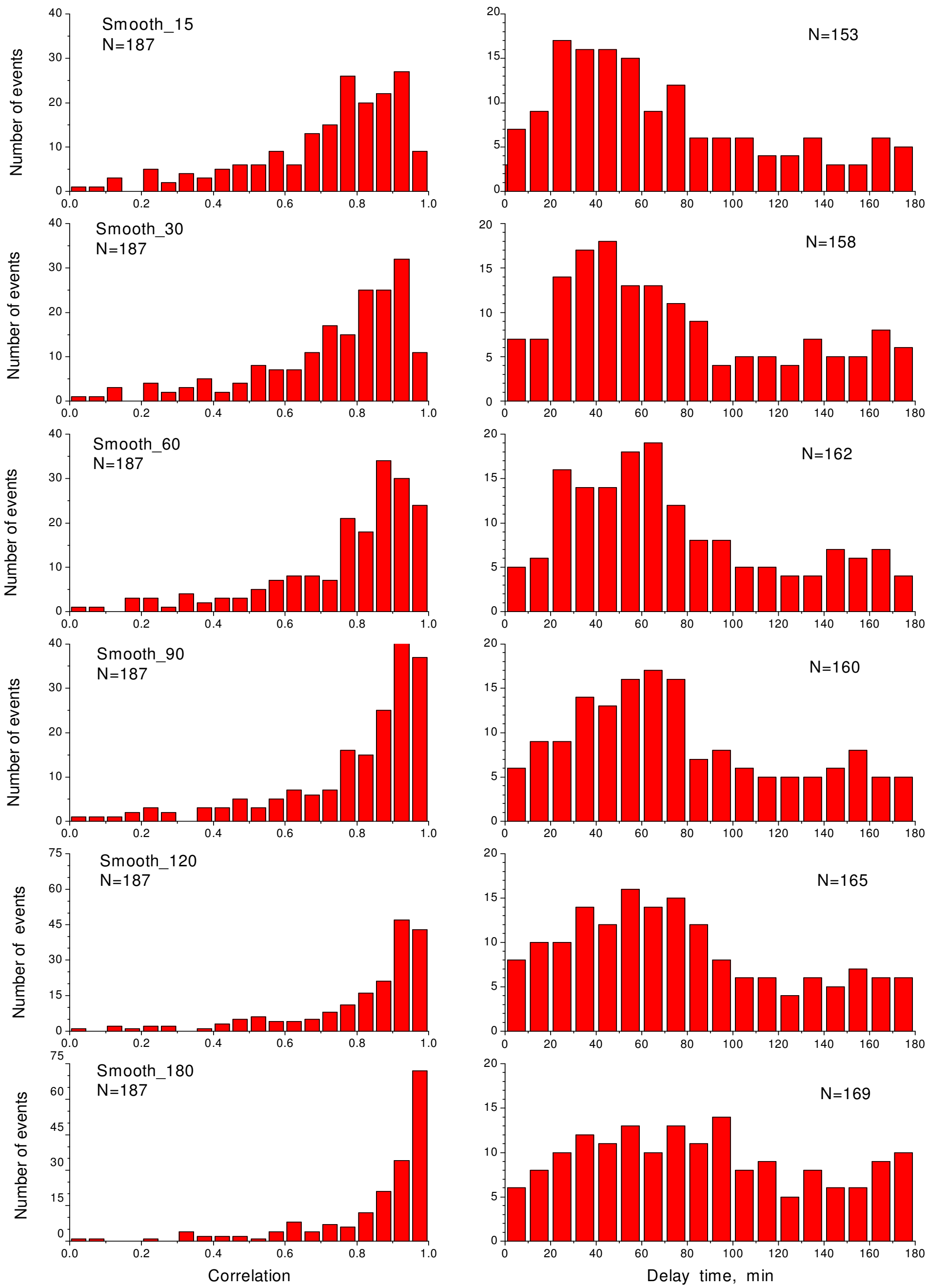
Beginning of the "retarded" magnetic storms

Intersection of the threshold level PC=1.5 mV/m was taken as a key date T=0



The moment when the PC index steadily exceeds the threshold level PC = 1.5 mV/m indicates the magnetic storm beginning.

Correlation between PC and Dst indices in course of magnetic storms



PC indices **were smoothed using the averaging running window** of different width (from 0 to 180 minutes).

Correlation between *Dst* and *PC* was calculated for different time shifts of *Dst* relative to *PC*. **The shift value providing the best correlation was identified as a delay time ΔT.**

Left column in Figure shows **occurrence of events with different correlation** between the *Dst* and smoothed *PC* indices for 6 fixed smoothing windows (15, 30, 60, 90, 120 and 180 minutes).

Right column shows **occurrence of events** with high correlation R>0.5 **over delay times ΔT**

.

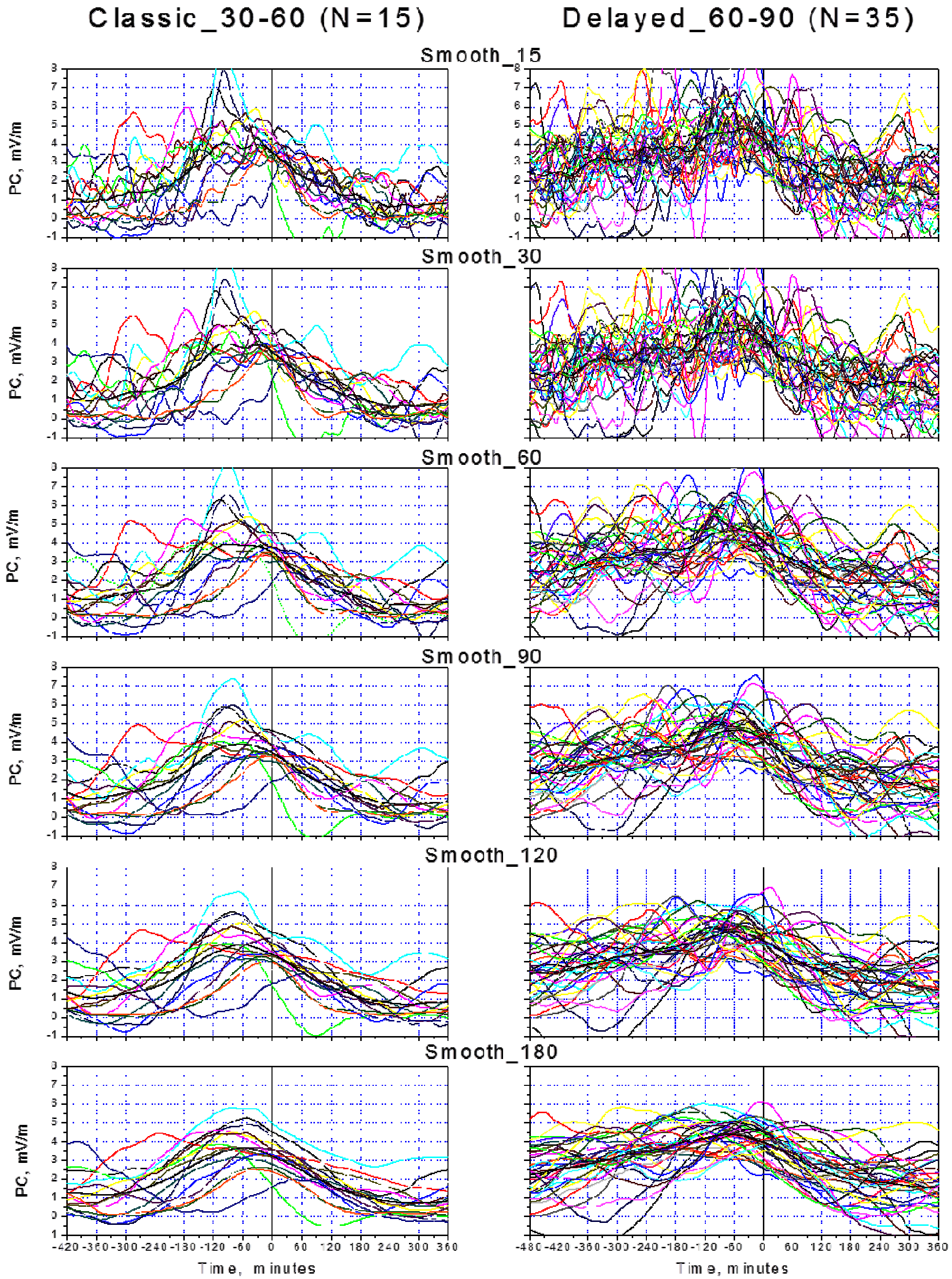
Results:

Correlation between *Dst* and smoothed *PC* reaches the maximum at delay times ΔT=30-90 min.

Correlation is obviously improved while widening the smoothing interval (fraction of well-correlated events increases from ~80% events for 15-min window to ~90% for 180 min window), but maximum at ΔT=30-90 min is also progressively smoothed.

Taking into account these two oppositely acting tendencies, the window width of 60-90 minutes seems to be optimal for further analysis.

Relation of storm intensity (*Dstmin*) to *PC* index value



Time evolution of the *PC* indices smoothed with different window widths (15, 30, 60, 90, 120, 180 minutes) is shown for classic storms with intensity *Dstmin*=30-60 nT and for delayed storms with intensity *Dstmin*=60-90 nT.

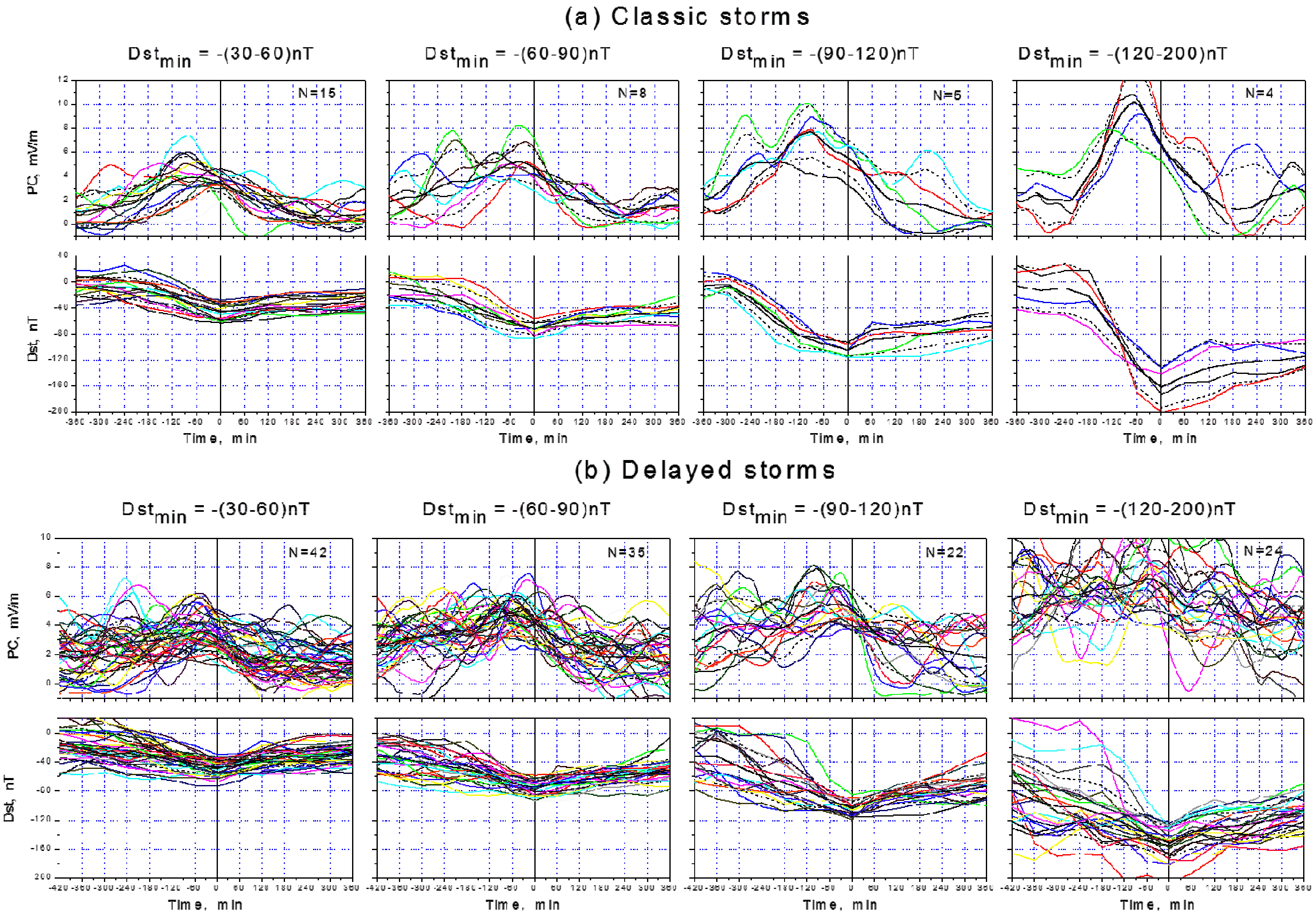
The moment of maximal depression *Dstmin* taken as a key date T=0 is marked by vertical line. Thin lines show the time evolution of smoothed *PC* indices in course of individual events, thick solid lines present variation of the mean *PC* values for each storm category.

Results:

When the smoothing window exceeds width of 60-90 minutes the value of delay time ΔT between the *PCmax* and *Dstmin* stops to change.

The largest magnetic field depression *Dstmin* (magnetic storm intensity) was observed with delay time ΔT ~ 60 minutes relative to maximal level of *PC*.

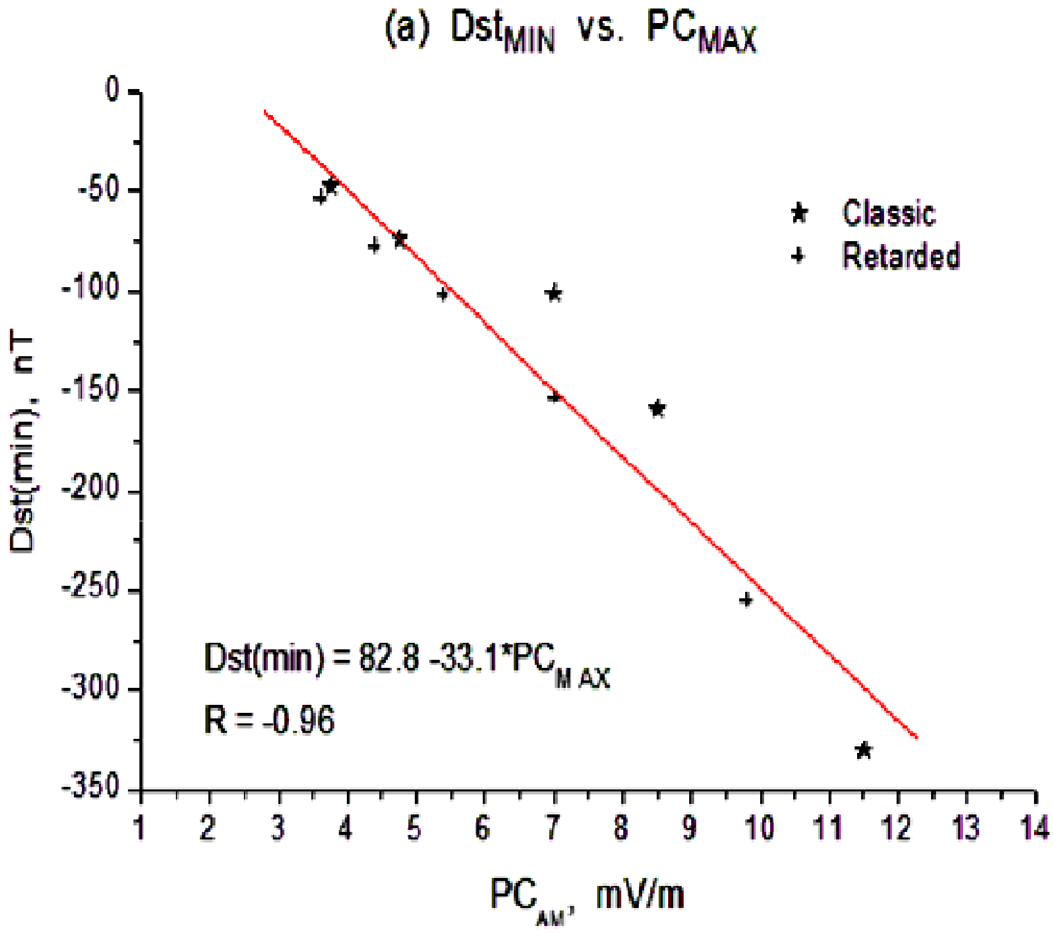
Relationship between PC and Dst indices in course of storms of different intensity



Irrespective of storm category, the maximal value of the 90-min smoothed *PC* index is followed with delay of 60±15 minutes by maximal intensity of the magnetic storm (Dst_{MIN}).

The higher the PC_{MAX} value, the larger is magnetic storm intensity.

Relationship between the magnetic storm intensity Dst_{MIN} and preceding maximal value PC_{MAX}

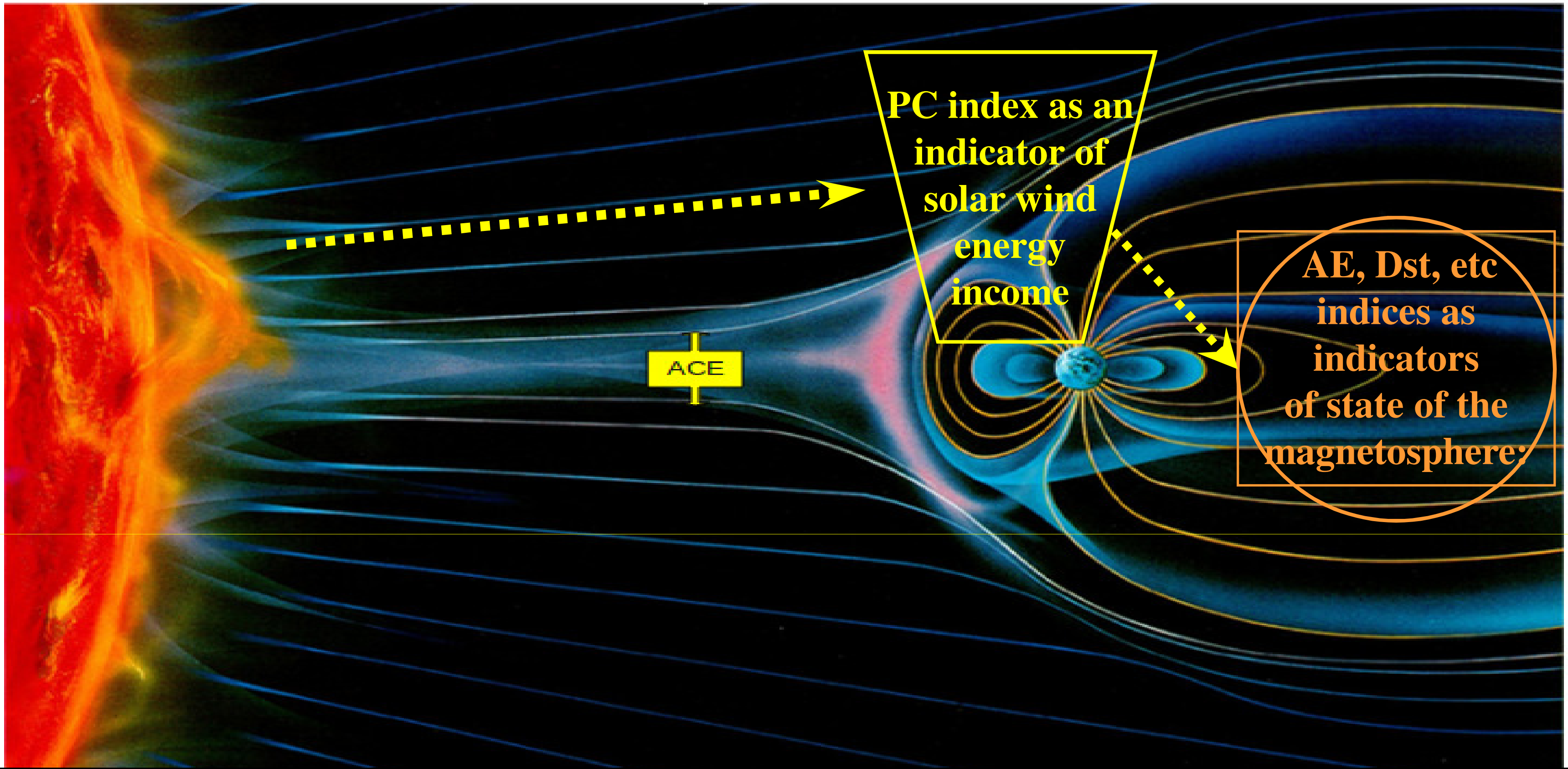


The magnetic storm intensity (Dst_{MIN}) and preceding maximal value PC_{MAX} are connected by linear relationship irrespective of the storm power and length of the storm main phase.

Summary of results

- In periods preceding the substorm onset the *PC* index strongly follows the time evolution of the interplanetary electric field E_{KL},
- Lack of correlation between E_{KL} and *PC* in those events when the PC growth is followed by the substorm development implies that magnetosphere in these cases was not touched by the solar wind, those parameters were measured on board ACE spacecraft in the Lagrange point L1.
- Delay times ΔT in response of *PC* to E_{KL} variations lie in range from 0 to 40 min with the very pronounced peak at ΔT=12-18 min, irrespective of type of examined events,
- Values of ΔT and efficiency of linkage between *PC* and E_{KL} are not directly related to the separate solar wind parameters such as *Vsw* and B_Z component, but are strongly controlled by the E_{KL} field growth rate.
- Magnetospheric substorms and storms are always preceded by the *PC* index growth,
- Magnetospheric substorms generally start when the *PC* index exceeds the level > 1mV/m, irrespective of the substorm growth phase duration and type of substorm (isolated or extended),
- If the PC index came to some crucial value (~ 1.5 mV/m), any sharp rise in the PC growth rate leads to the substorm sudden onset,
- The substorm sudden onset magnitude is a function of the PC index value in moment of sudden onset,
- Magnetic storms start to develop when the PC index steadily excess the threshold ~ 1.5 mV/m, and maximal intensity of the magnetic storm is reached with time delay of ~ 60±15 min after the moment of maximal *PC* index,
- Intensity of storm and substorm is linearly related to the *PC* index value
- Magnetic disturbances decay as soon as the PC index value falls below 1-1.5 mV/m.

6. Conclusions



The examined experimental facts are strongly indicative of the *PC* index as a proxy of the solar wind energy that actually entered into the magnetosphere.

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).

The *PC* index in this charge can be successfully used to study different magnetospheric processes and to realize the quantitative space weather forecasting and monitoring.

The historical PC indices (sets of data for 1997-2014) and current PCN and PCS indices calculated on-line by magnetic data from stations Thule and Vostok, are presented at web site: http://pc-index.org