PC INDEX AS A PROXY OF THE SOLAR WIND ENERGY THAT ENTERED AND ACCUMULATED IN THE MAGNETOSPHERE

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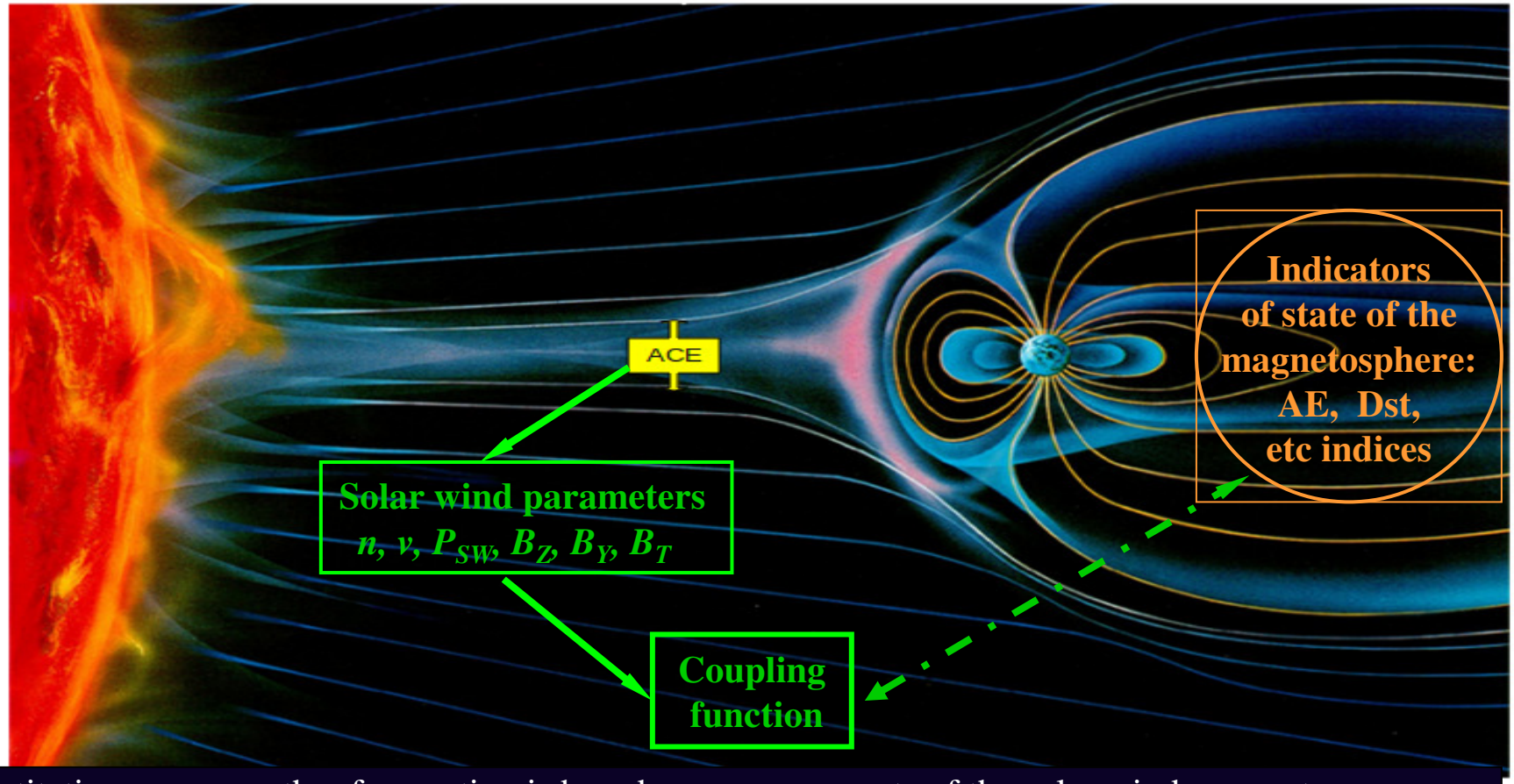


Quantitative space weather forecasting is based on measurements of the solar wind parameters on board ACE spacecraft spaced 1.5 M km apart the Earth in the Lagrange point L1.

The solar plasma parameter and interplanetary magnetic field detected in point L1 are used to derive a hypothetic "coupling function" which is designed to monitor the solar wind geoefficiency and forecast the magnetosphere state (space weather).

State of the magnetosphere is commonly evaluated by the magnetic Dst and AE indices, which characterize the energy realized in magnetosphere as storms and substorms.

The different "coupling functions" (to extent of more 10!) have been suggested to establish a link between the solar wind parameters and magnetosphere state.

Coupling function is determined as a such combination of the solar wind parameters which provides the best correlation of the function with indicators characterizing the magnetosphere state.

Various combinations were repeatedly examined to reveal the optimal coupling function:

- $\varepsilon = l_0^2 v B^2 \sin^4((\theta c/2)$ [Perreault and Akasofu (1978)]
- $E_{KL} = v B_T \sin^2(\theta c/2)$ [Sonnerup, 1974; Kan and Lee, 1979]
- $Erect = v B_S$ [Reiff and Luhmann, 1986]
- $E_{WAV} = v B_T \sin^4(\theta c/2)$ [Wygant *et al.*, 1983; Liou *et al.*,1998]
- $E_{SR} = v B_T \sin^4(\theta c/2) p^{1/2}$ [Scurry and Russel, 1991; Coumans *et al.*, 2006]
- $E_{WEI} = v B_T^{2/3} \sin^2(\theta c/2)$ [Weimer, 2001]
- $E_{SDS} = v B_T \sin^3(\theta c/2)$ [Shukhtina *et al.*, 2005]
- $E_{TL} = n^{1/2} v^2 B_T \sin^6(\theta c/2)$ [Temerin and Li, 2006]
- $E_{CBG} = P^{1/3} v B_T \sin^4(\theta c/2)$ [Coumans *et al.*, 2006]
- $E_{PZ} = v(B_Y^2/2 + B_Z^2)^{1/2} \sin^2(\theta c/2) + \alpha v^2$ [Petrukovich and Zakharov,2007]
- $E_{PAR} = v B_T \sin(\theta c/2)$ [Pulkkinen *et al.*, 2010]
- $E_{K\text{-}R} = E_{KL} 2 \Sigma_A / (\Sigma_P + \Sigma_A)$ [Kivelson and Ridley, 2008].

All these coupling functions are not based on any reliable experimental evidences of physical mechanisms determining the solar wind-magnetosphere interaction.

The comprehensive analysis of Newell et al. (2007, 2008) revealed that different variables, characterizing the magnetosphere state, show the best correlation with diverse coupling functions.

To monitor in reality the solar wind geoefficiency and the magnetosphere state we have to know the actual solar wind energy that entered into magnetosphere.

The PC index has been proposed as an adequate proxy of this energy [Troshichev and Janzhura, Space weather monitoring by ground-based means, Springer/Praxis, 2012]

XXII Scientific Assembly of International Geomagnetism and Aeronomy Association (12th IAGA), Merida, Mexico, August 2013

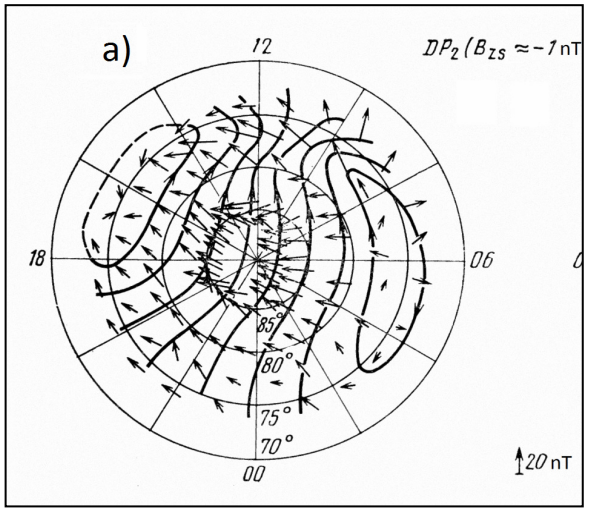
Resolution No. 3 (2013): Polar Cap (PC) index

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. *[*

PC index is a single index of magnetic activity officially approved by IAGA for last 50 years (following to AU/AL/AE and Dst indices)

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

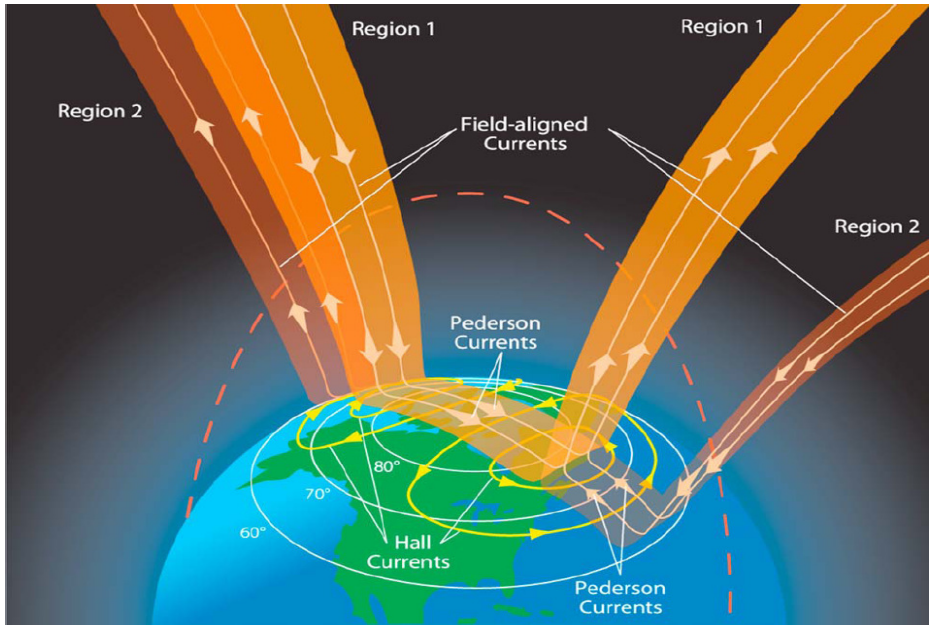


The PC index has been introduced [*Troshichev and Andrezen,* 1985; *Troshichev et al.,* 1988] to characterize the polar cap magnetic activity (DP2 disturbances) produced by the geoeffective solar wind coupling with the magnetosphere**.**

DP2 dsturbances are generated by the field-aligned currents (Troshichev and Tsyganenko, 1979; Troshichev et al., 1979), which are permanently presented on the poleward boundary of the auroral oval (Region 1 FAC) and responsible for cross-polar cap potential difference.

Experimental data are evidence that the field-aligned currents are strongly dependent on the soutward IMF and interplanetary electric field (Langel, 1975; McDiarmid et al.,1977; Iijima & Potemra, 1982; Bythrow & Potemra, 1983).

The concept of the magnetic disturbances in the polar cap, controlled by interplanetary electric field E_{KL} determined by Kan and Lee (1979), served as a basis for the method of the PC index calculation.



Method for calculation of the PC index

[Troshichev et al., 1988]

1. Vector of magnetic disturbances δF is determined using the data of magnetic observations from near-pole station

$$\delta F = \delta D \cdot \sin\gamma \pm \delta H \cdot \cos\gamma,$$

where $\gamma = \lambda \pm D_E + \varphi + UT,$

δD and δH are deviations of the magnetic horizontal components from the quiet level,

D_E is the mean declination angle for the given station,

λ is geographycal longitude and φ is angle between the transpolar current, typical of the given UT, and the noon-midnight meridian.

2. The correlation between values of δF and merging electric field Em is calculated for each month and UT

$$\delta F = \alpha Em + \beta$$

where α and β the coefficients of regression.

3. Coefficients α, β and φ, ensuring the best correlation between δF и Em are used for calculation of the PC index

$$PC = \xi\, Em = \xi\, (\delta F - \beta)/\, \alpha$$

where ξ is the scale coefficient.

The PC index has been defined as a value, which is proportional to intensity of the polar cap magnetic disturbance, calibrated for geoffective electric field E_M, and parameterised by season, UT and hemisphere.

PC index and development of magnetospheric substorms

- To analyze relationship between the polar cap magnetic activity and substorm development the behavior 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

- Under magnetic substorm with sudden onset we examined steep increases of magnetic disturbance in the auroral zone with magnitude more than 100nT for time lapse < 10 min.

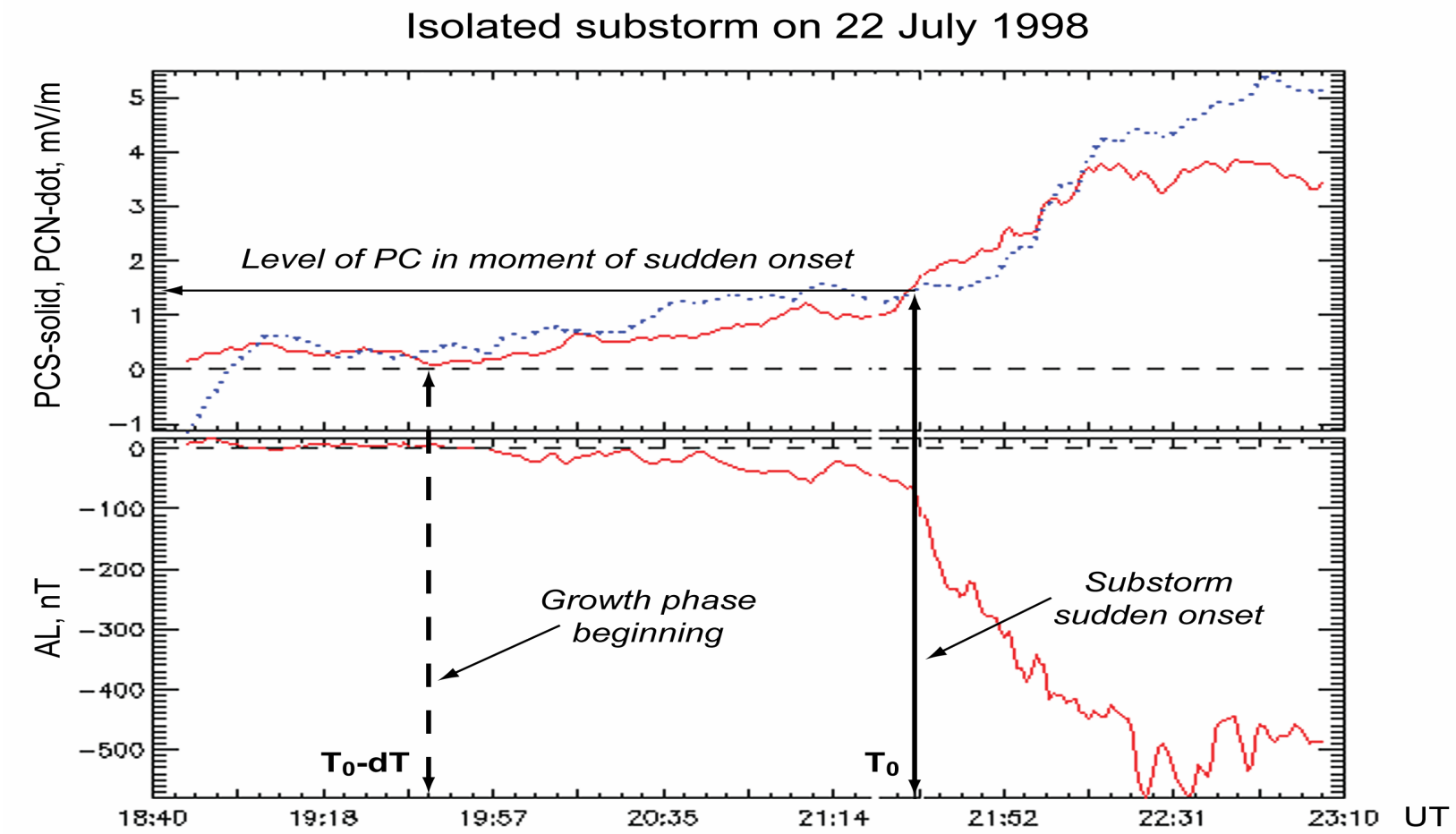
- **1641** events answering to this requirement were separated:

  195 disturbances (12 %) starting against the background of quiet magnetic field were qualified as **isolated substorms**.

  1418 events were regarded as **expanded substorms**

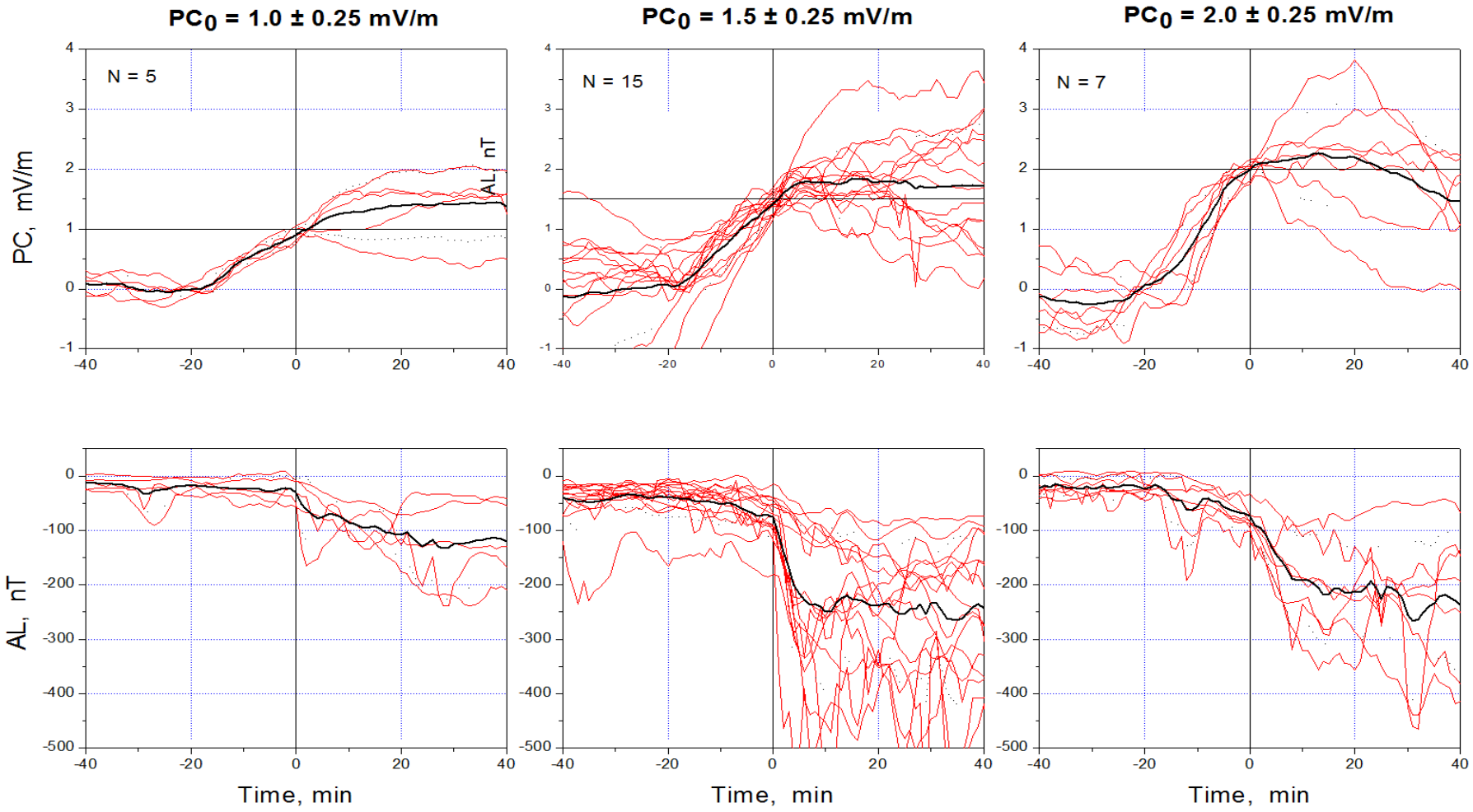
  32 events (<2 %) were excluded from examination for lack of any evident connection between changes in PC and AL.

1. Isolated substorms: Separation of magnetic substorms according to length of growth phase and level of PC index



- Moment of substorm sudden onset (SO) is taken as a key date (**To**).
- Value of the PC index at a moment To is fixed as PC_O.
- Moment when the PC index starts to increase is taken as a beginning of growth phase.
- Time interval between the growth phase beginning and key date is determined as the growth phase duration (**dT**).
- All substorm events are classified into 4 groups according to the growth phase duration (dT<10 min, 10<dT<20 min, and 20<dT<45 min, 45min<dT) and subdivided over the PC level at moment To.

Relationship between PC and AL indices in course of isolated substorms: growth phase duration is in range from 10 to 20 minutes

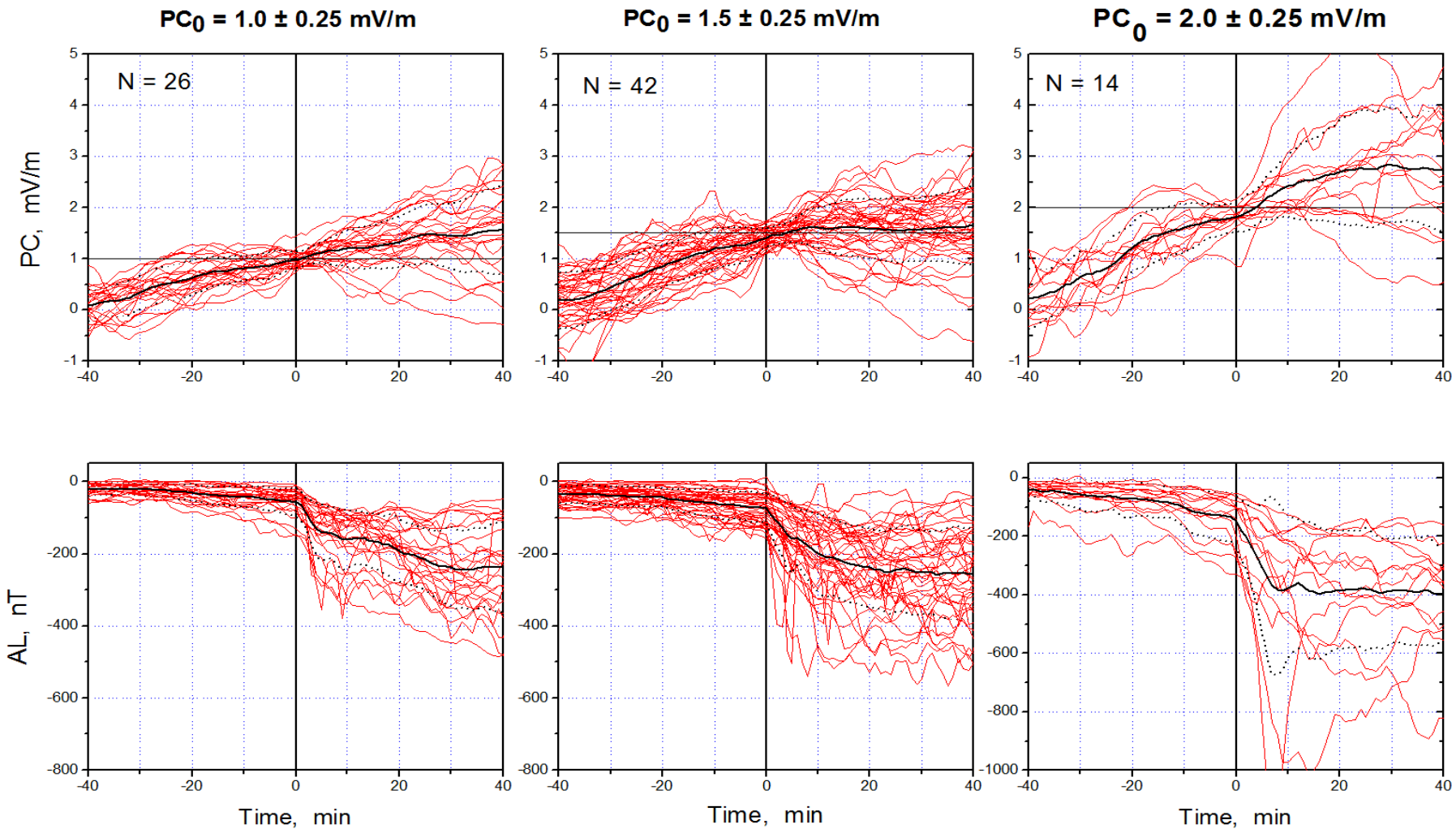


The PC index starts to grow prior to substorm sudden onset (dTave~18 min).

Magnetic disturbance in the auroral zone (AL index) does not essentially changed up to sudden onset (SO).

The PC index continues to grow after the sudden onset, and PC growth rate does not affected by SO.

Relationship between PC and AL indices in course of isolated substorms: growth phase duration is in range from 20 to 45 minutes

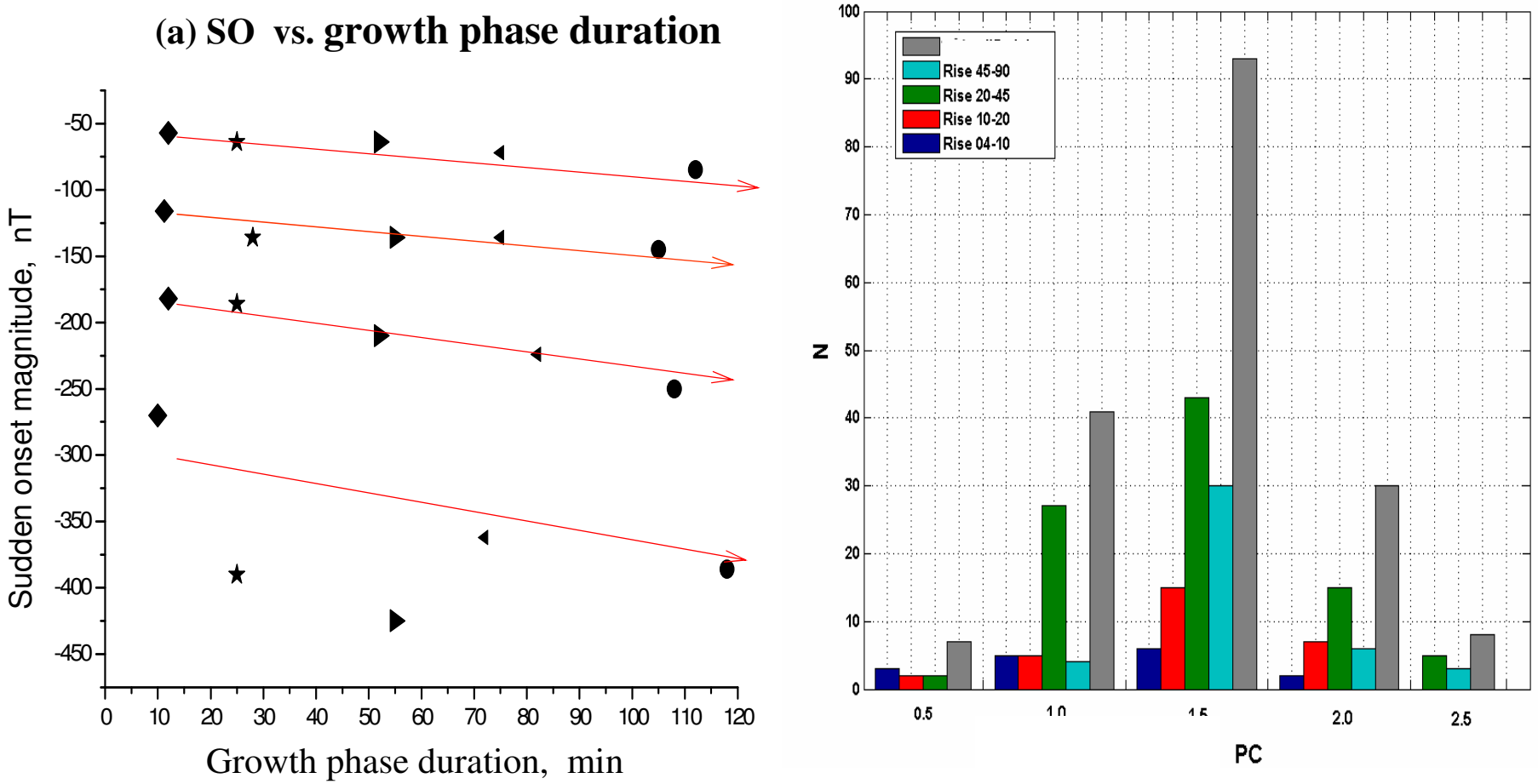


The PC index starts to grow prior to substorm sudden onset (dTave~30 min).
Magnetic disturbance in the auroral zone (AL index) does not essentially changed up to SO.
The PC index continues to grow after the sudden onset, and PC growth rate does not affected by SO.

Isolated substorms

(a) Relationship between the growth phase duration and magnitude of the sudden onset

(b) Distribution of substorms with different PC-value levels (in moment of SO)



Magnitude of the substorm sudden onset (SO) demonstrates a **slight tendency to decrease with a rise of the growth phase length.**

The great majority of substorms start when the PC value reaches the **threshold level PC = 1.5mV/m**

Results:

- **Development of magnetic disturbances in the auroral zone (magnetic substorms) is preceded by growth of magnetic activity in the polar cap.**
- **Substorms start as soon as PC index reaches some threshold level (~1,5 mV/m).**
- **Substorm intensty is not dependent on length of the growth phase before SO**

Thus, on the one hand, increase of the polar cap magnetic activity (growth of PC index) precedes the substorm development, but, on the other hand, the growth phase duration does not influence the sudden onset of substorm.

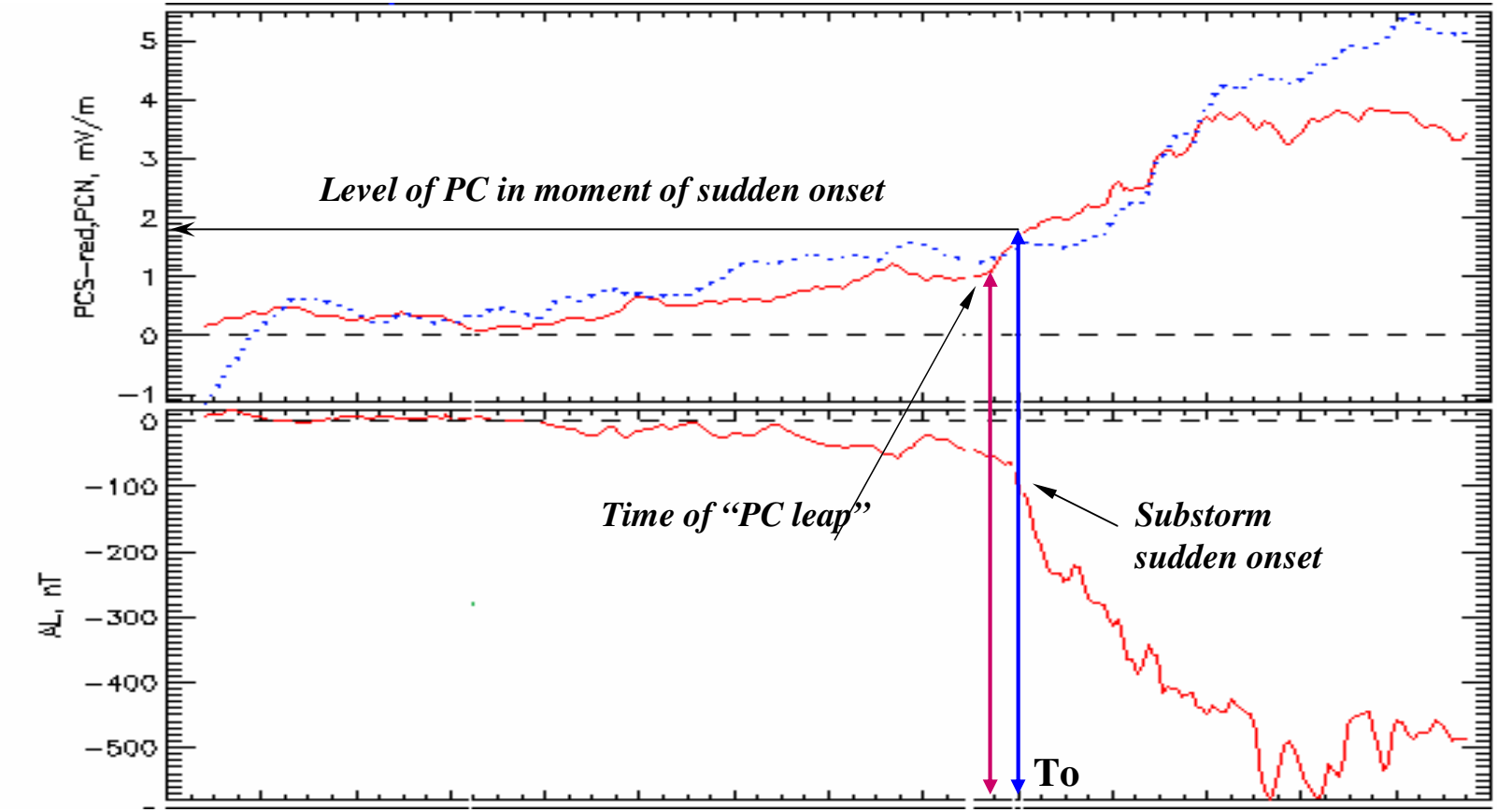
What are actual factors which really affect the sudden onset of substorm ??

All substorms were reexamined with a special attention to time evolution of the PC index in relation to substorm sudden onset.

It was found that of the PC growth rate sharp increases in relation to substorm sudden onset (SO). Two distinctive features in behavior of PC index have been separated:

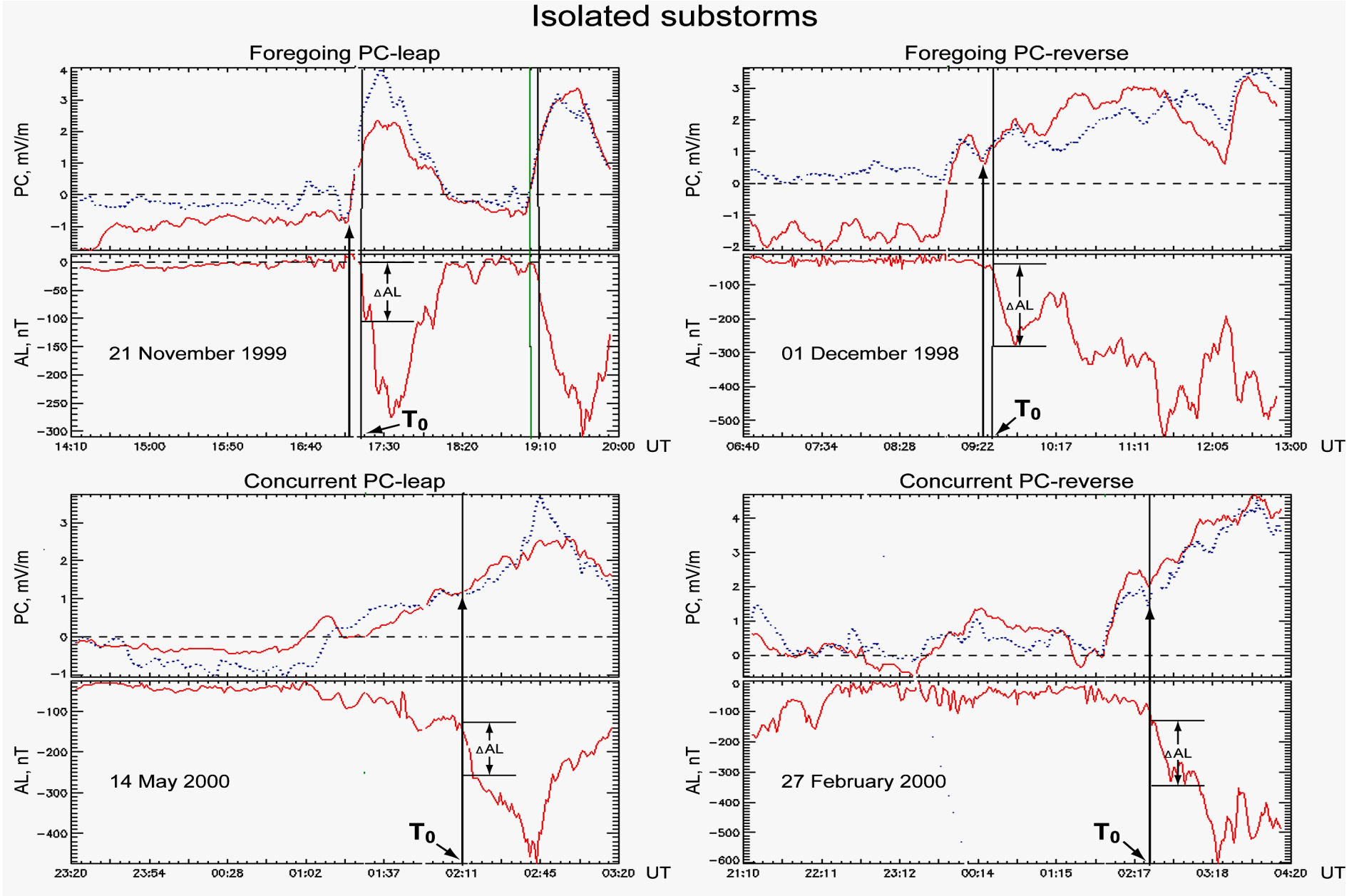
- "***PC leap***" – sharp rise of the PC value against the backgrounds of previously unchanged or slowly increasing PC,
- "***PC reverse***" – sharp rise of the PC value following the short (and sharp) PC decrease.

2. Isolated substorms: Separation of magnetic substorms according to the PC index features observed in connection with the substorm sudden onset

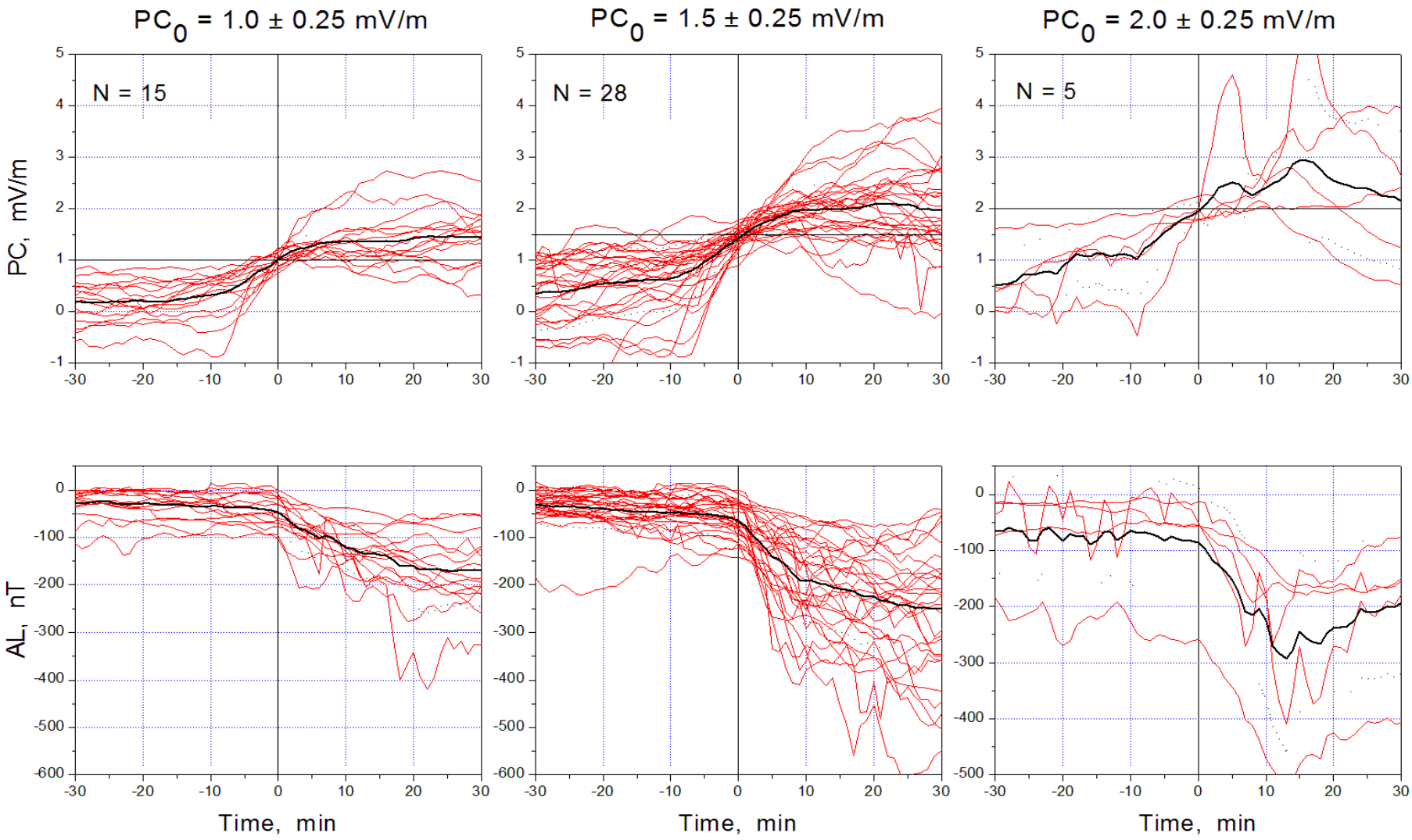


- Moment of substorm sudden onset is regarded as a key date (**To**).
- Sudden increase of PC index in connection with sudden onset is marked
- Value of the PC index at a moment To is fixed.
- All substorm events are separated according to type of PC change before SO and PC value at moment SO.

Examples of *"PC leaps"* and *"PC reverses"* observed ahead of SO (in range of 3-20 min) or concurrently with SO (in range of 0-2 min)

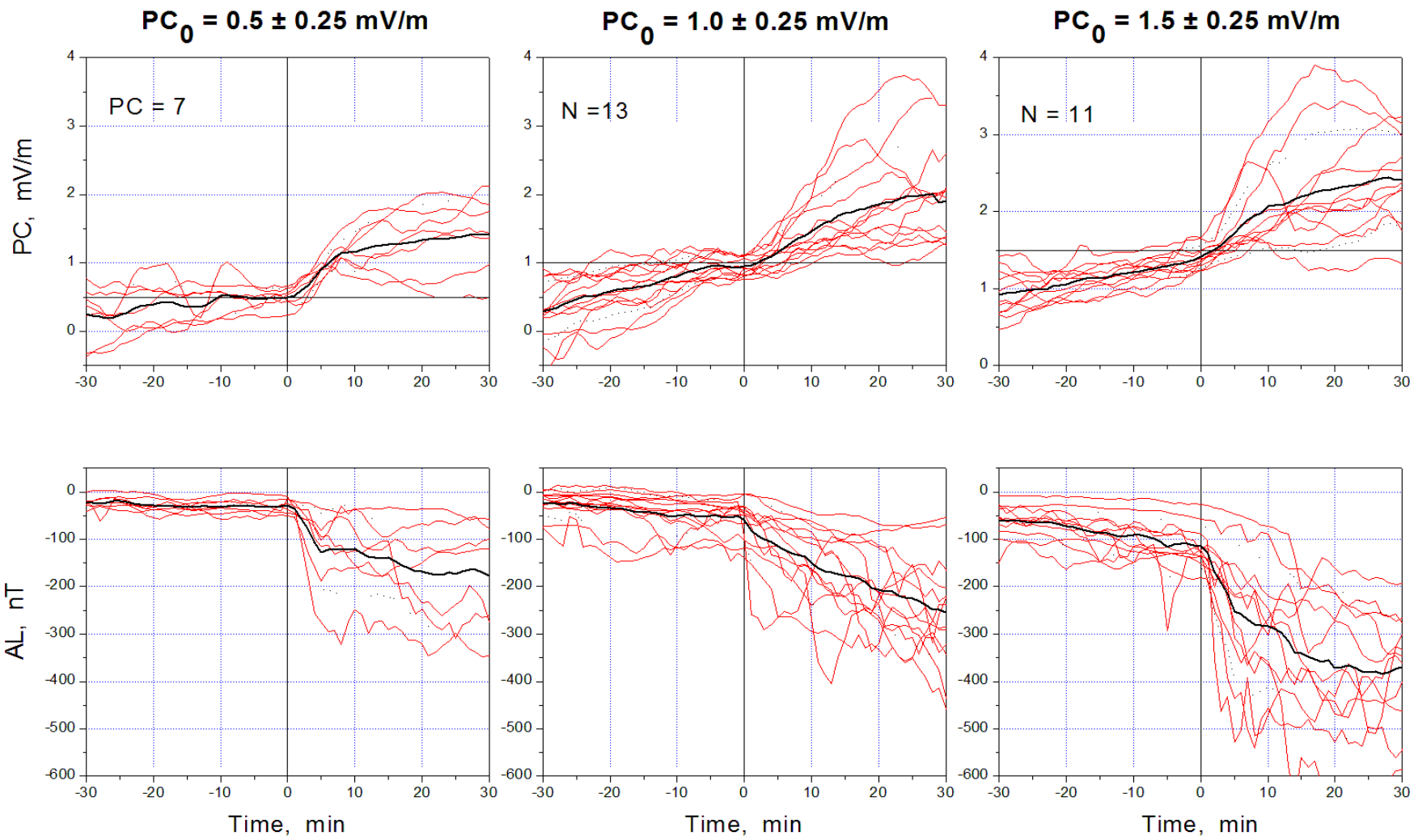


Isolated substorms with "*PC leap*" preceding SO (in range 3-20 minutes)



The substorm sudden onset is preceded by distinct PC value leap occurring 3-20 min ahead of SO.
Magnetic disturbance in the auroral zone (AL index) remains unchanged up to SO.
PC index continues to grow after the sudden onset, the PC growth rate being unaffected by SO.

Isolated substorms with "*PC leap*" coincident with SO (in range 0-2min)



PC index started to grow before sudden onset and continues to grow after the sudden onset.
The substorm sudden onset is coincident with the distinct PC value leap.
Magnetic disturbance in the auroral zone (AL index) remains almost unchanged up to SO.

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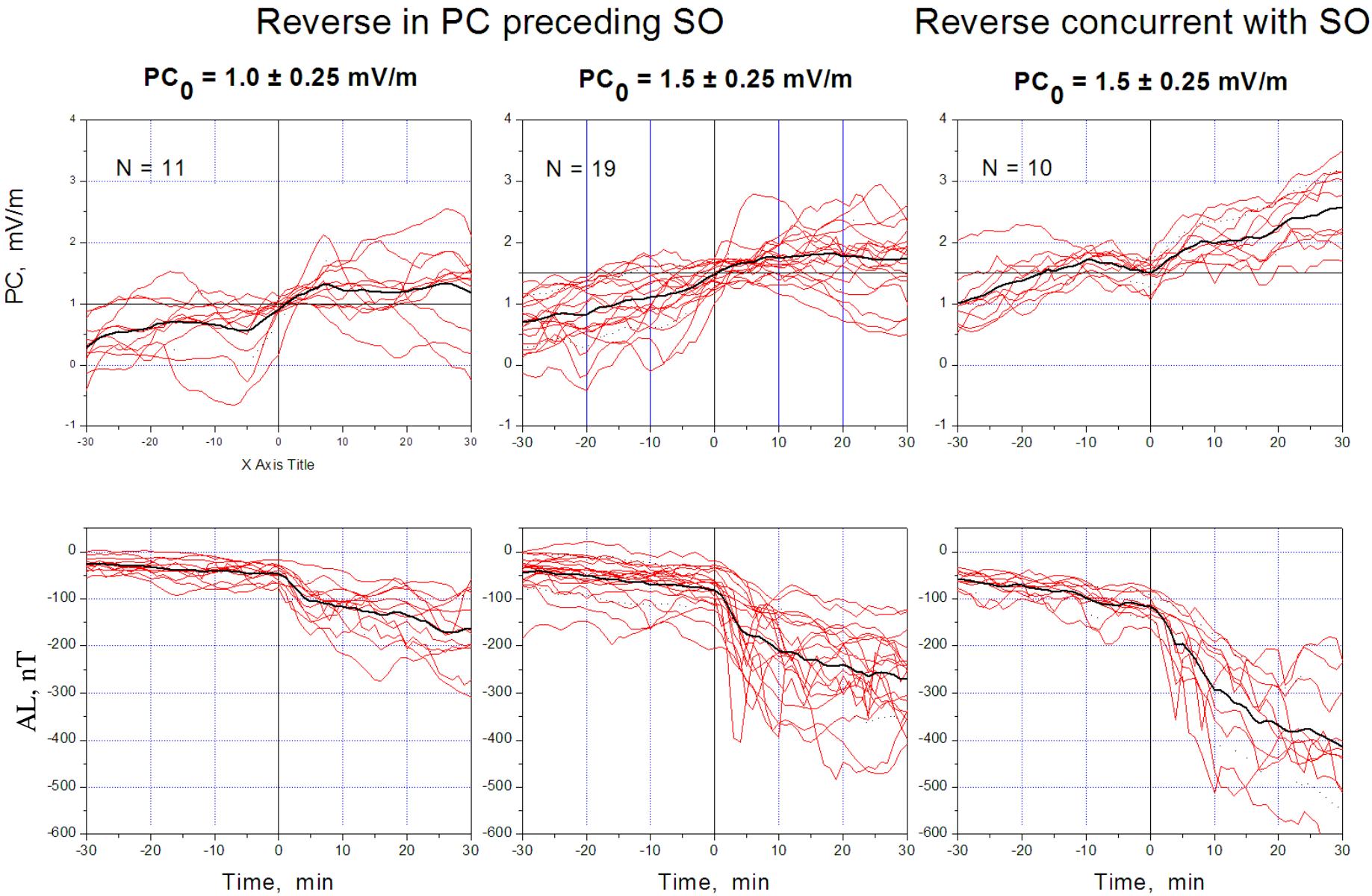
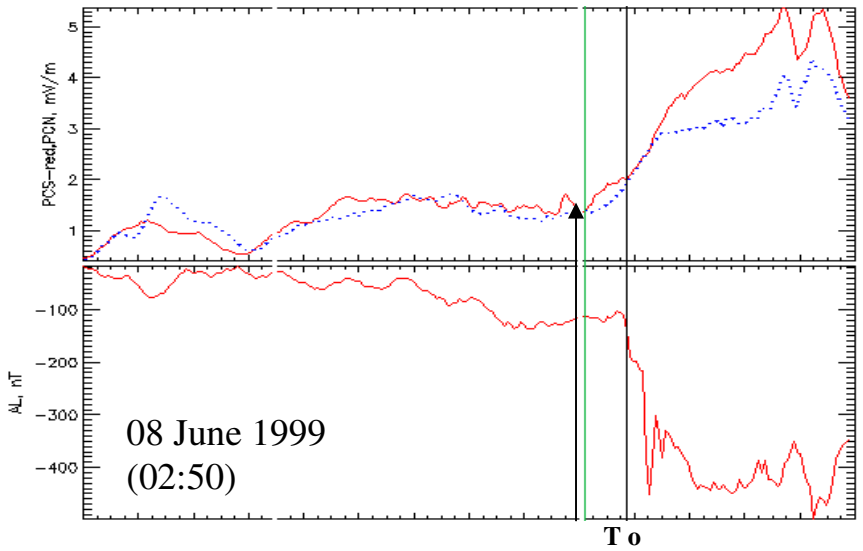
Isolated substorms with "*PC reverse*"



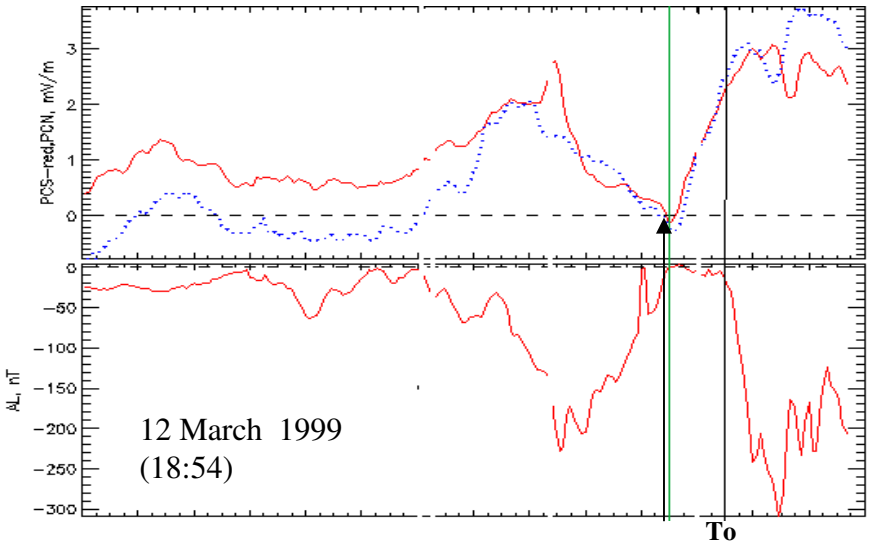
The unique feature uniting both "*PC-leap*" and "*PC-reverse*" signatures is a sharp rise of the *PC* growth rate (*PC-jump*) following the interval of unchanging, decreasing or gradually increasing *PC* value.

3. Expanded substorms: examples of PC index behavior

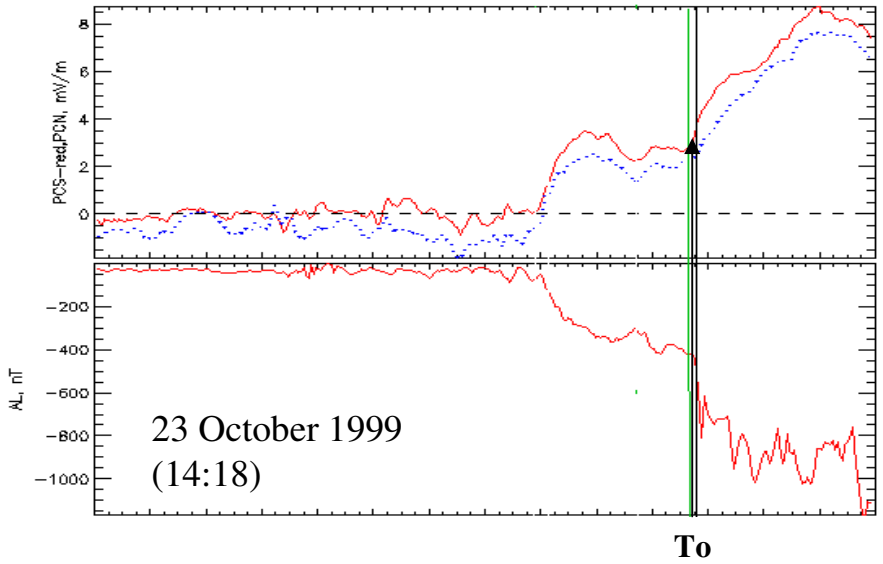
Leap **of PC prior to sudden onset**



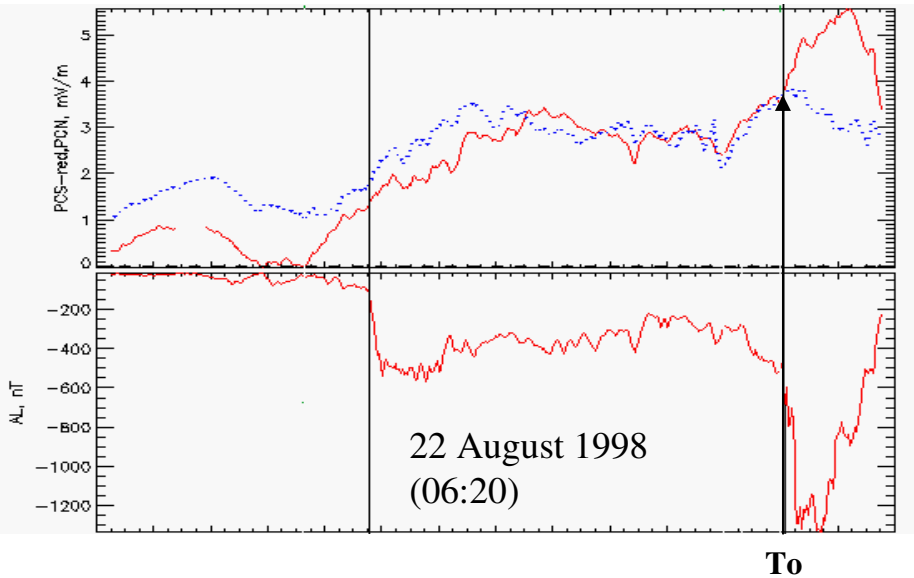
Reverse **of PC prior to sudden onset**



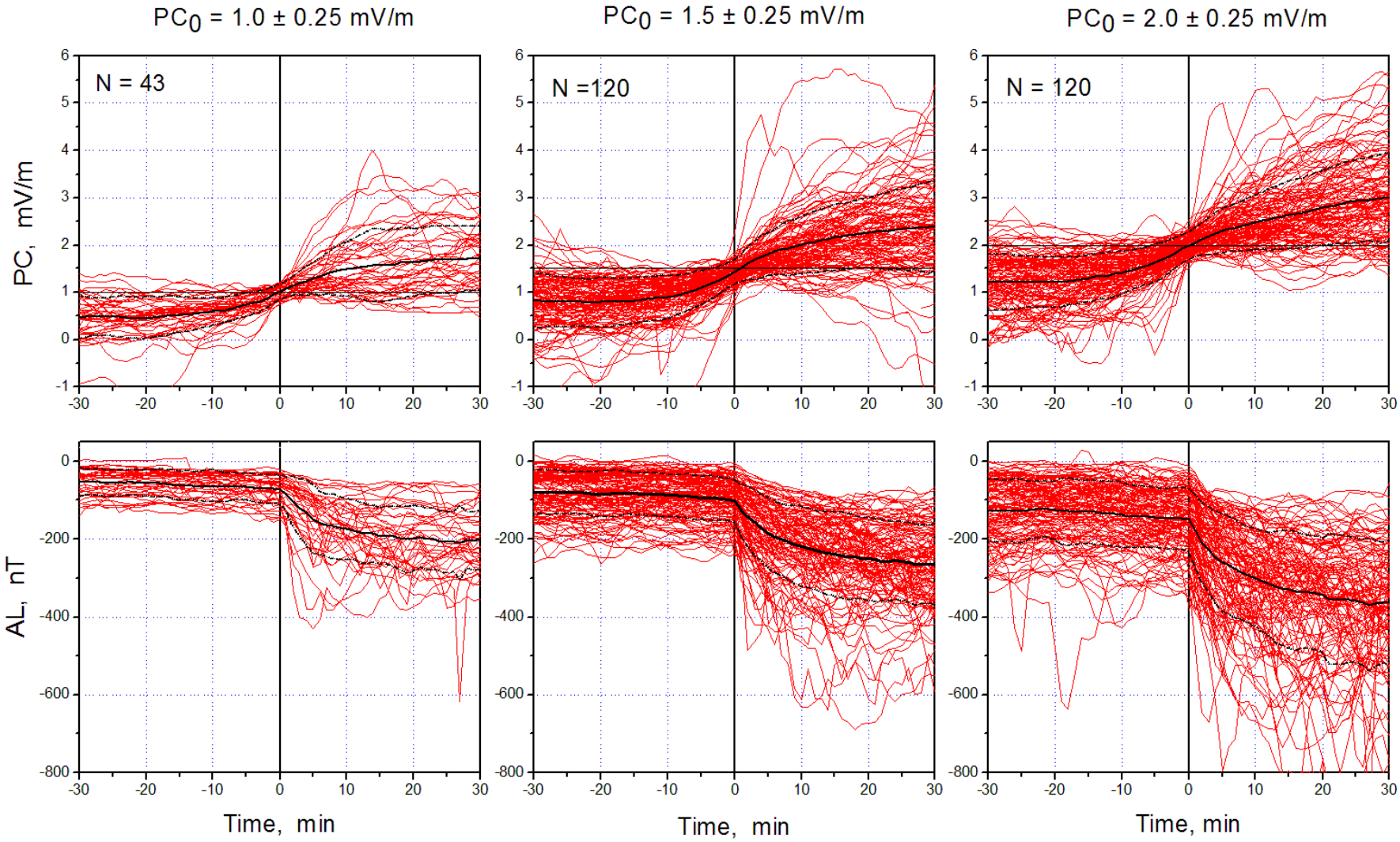
Leap **of PC coincident with sudden onset**



Reverse **of PC coincident with sudden onset**

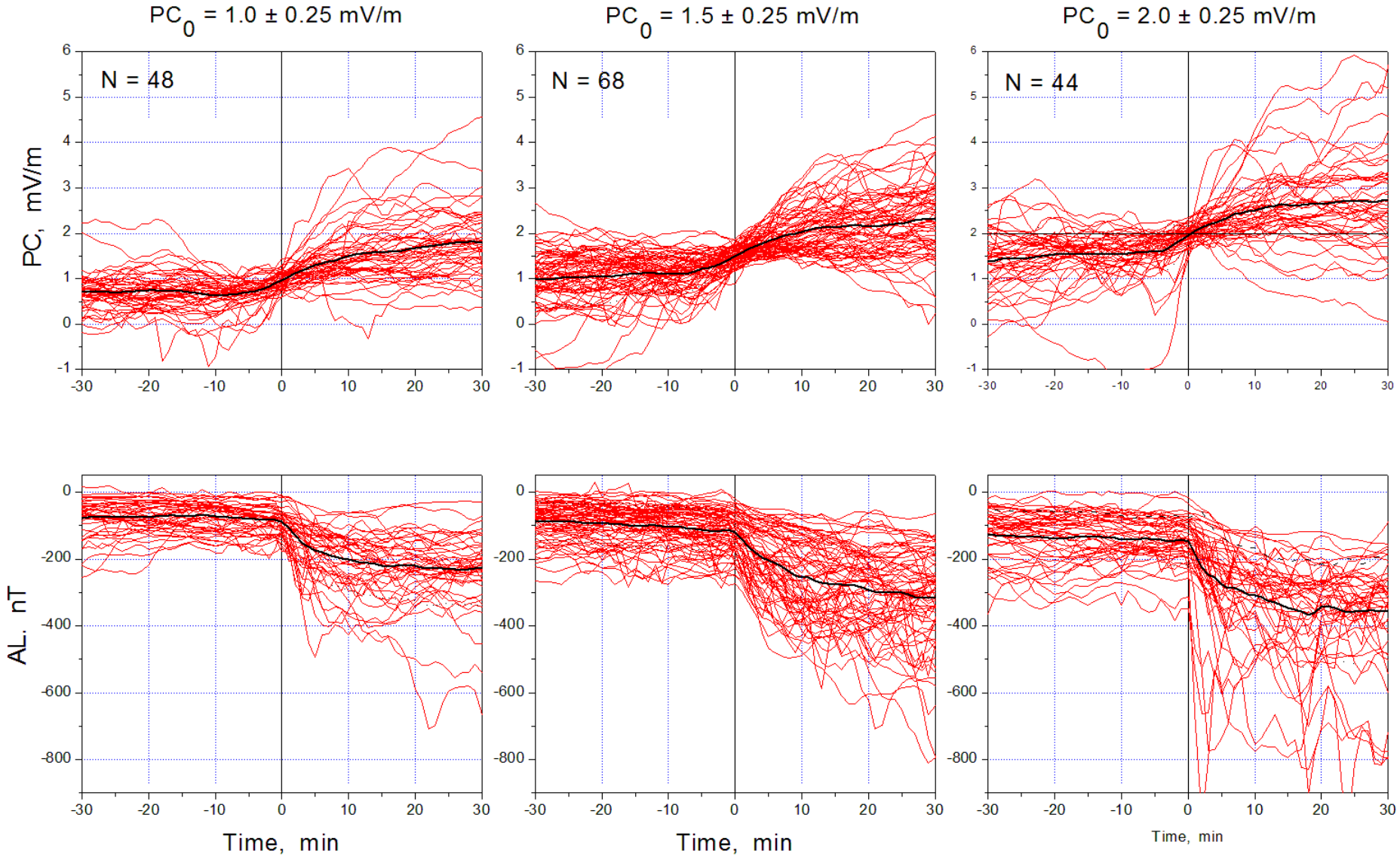


Expanded substorms with "*PC leap*" preceding SO



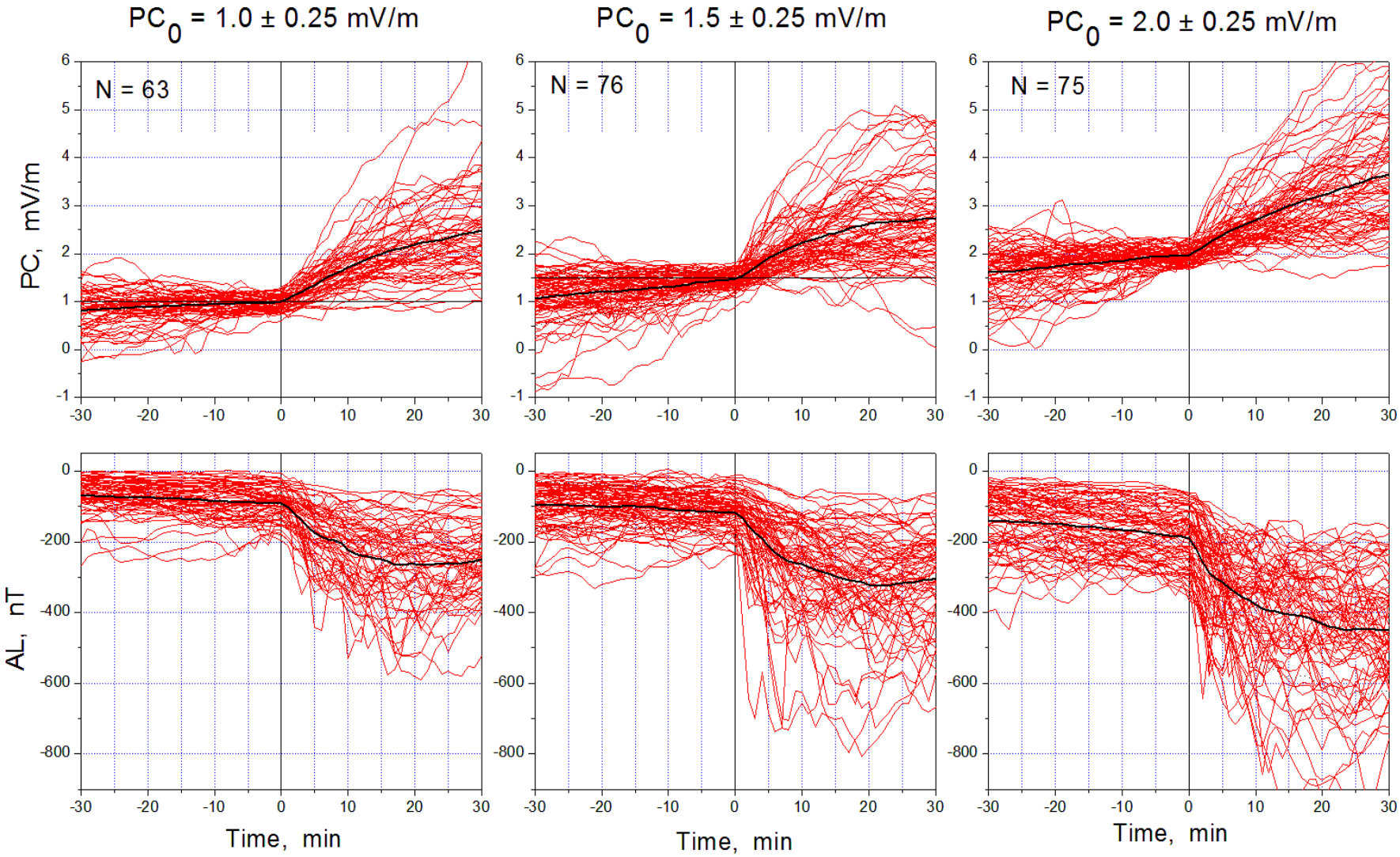
Substorm sudden onsets are preceded by distinct PC value leap occurring 3-20 min ahead of SO.
Magnetic activity in the auroral zone (AL index) remains almost unchanged up to SO.
PC index continues to grow after the sudden onset, the PC growth rate being unaffected by SO.

Extended substorms with "*PC reverse*" preceding SO

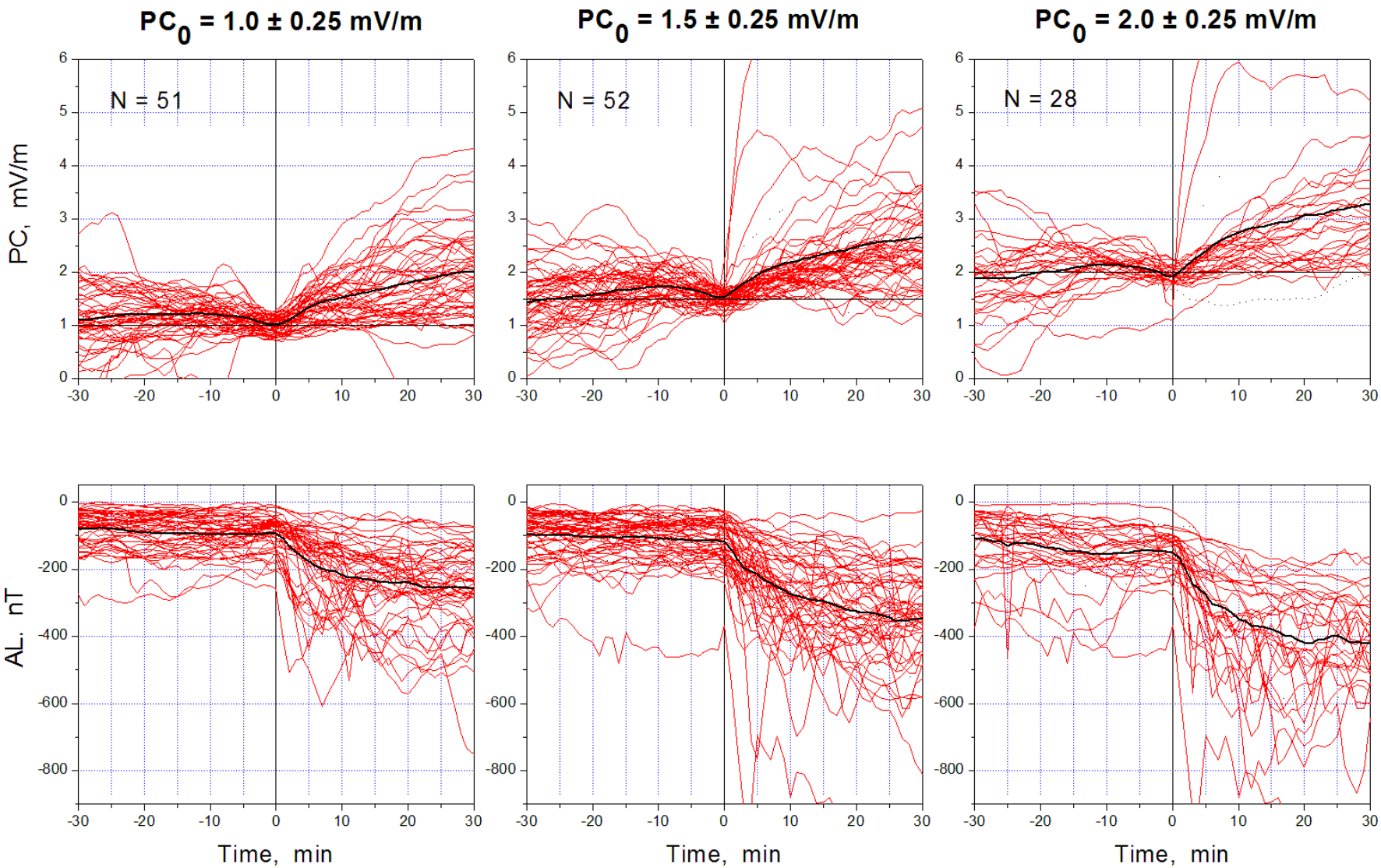


There is no difference between statistical effects of "PC leap" and "PC reverse" preceding SO. The obvious *PC-jump* turned out to be related to substorms sudden onset in the most cases.

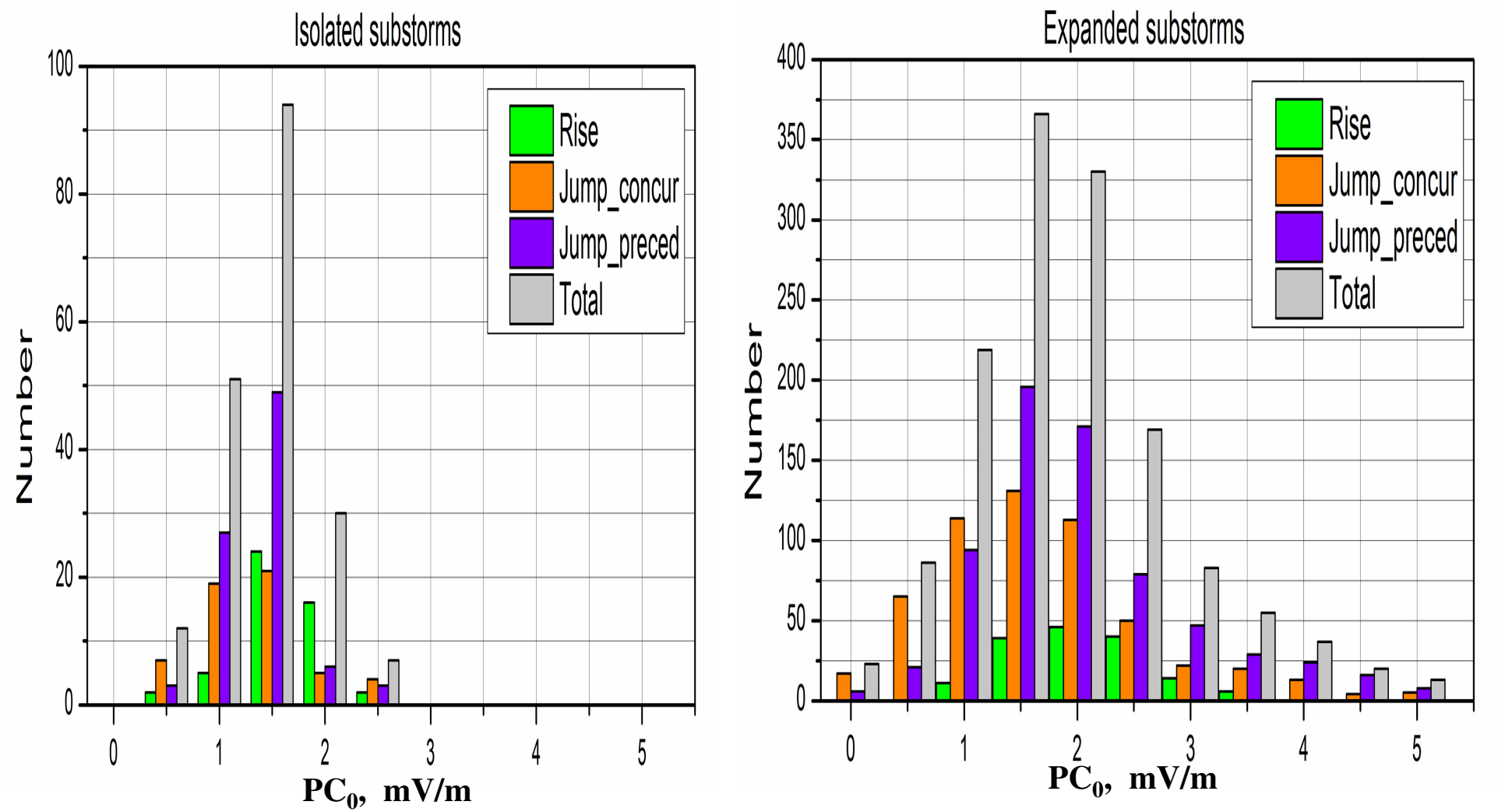
Expanded substorms with "*PC leap*" coincident with SO



Expanded substorms with "*PC reverse*" coincident with SO

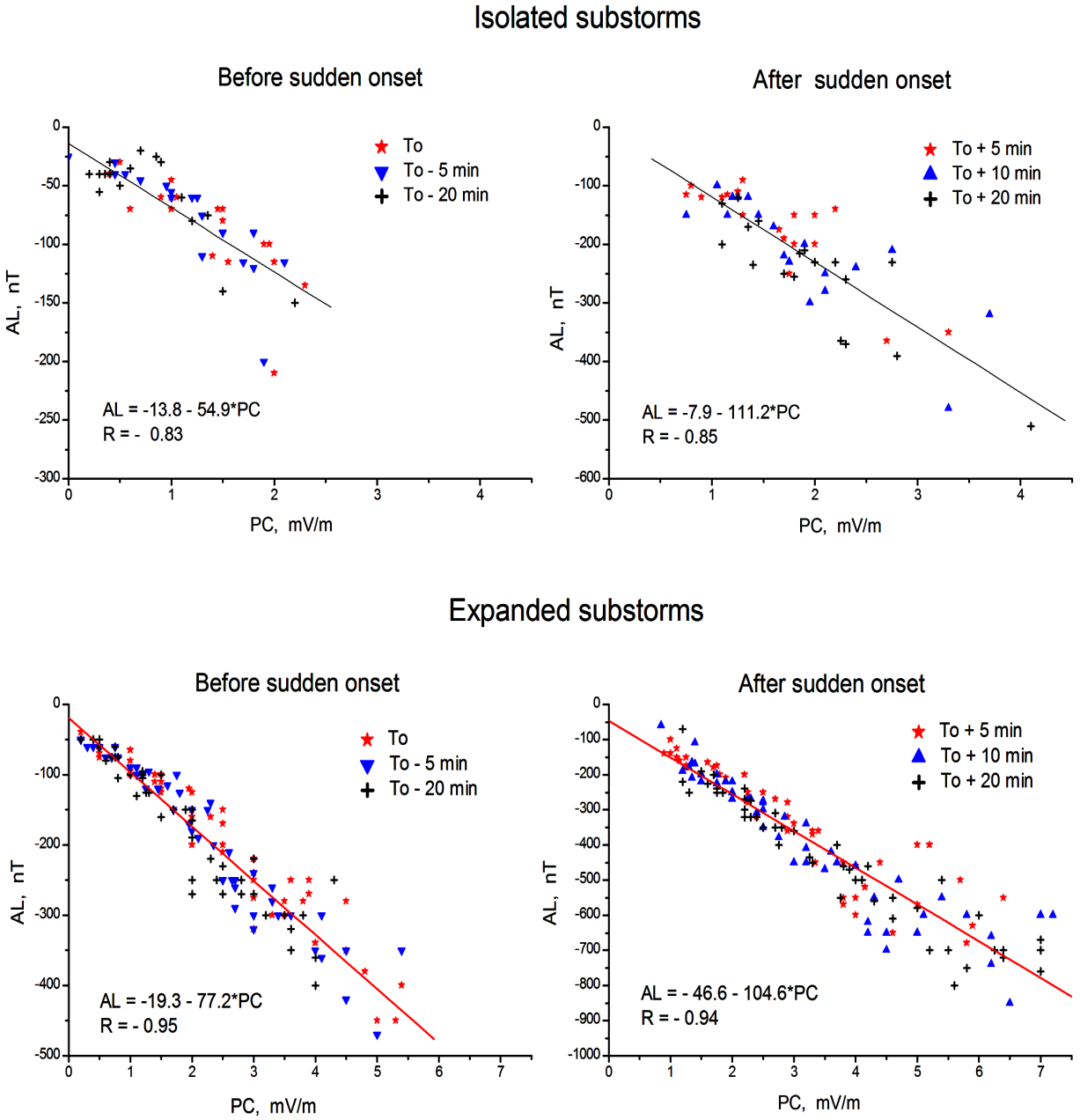


4. Isolated and expanded substorms: distribution of over the values PC_0



Substorms start against the backgrounds of gradually increasing PC index. The great majority of isolated and expanded substorms (>75%) occur under conditions PC>1.5 mV/m. The most part of the isolated substorms (45%) and expanded substorms (49%) started in relation to the foregoing *PC-leap* or *PC-reverse* signatures. Number of substorms with concurrent *PC-leap* or *PC-reverse* signatures is about 29%. Under conditions of high activity (*PC0*>3.5 mV/m) the substorms start exclusively in association of the *PC*-jumps.

Relationships between AL and PC indices before and after sudden onset (SO) for isolated and expanded substorms



Intensity of magnetic disturbances in the auroral zone (AL index) is linearly related to value of the polar cap magnetic activity (PC index) before as well as after the substorm sudden onset.

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

It implies that dependence of magnetic activity in the auroral zone on *PC* index sharply enhances 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.

5. Development of substorms: relation to PC index
(summary of results)

- Magnetospheric substorms and storms are always preceded by the *PC* index growth.
- Magnetospheric substorms generally start to develop when the *PC* index exceeds the threshold level ~ 1.5 mV/m, irrespective of the substorm growth phase duration and type of substorm (isolated or extended).
- The substorm sudden onsets are definitely related to sharp changes (leap or reverse) in the PC growth rate. The substorm sudden onset magnitude is a function of the PC index value in moment of sudden onset.

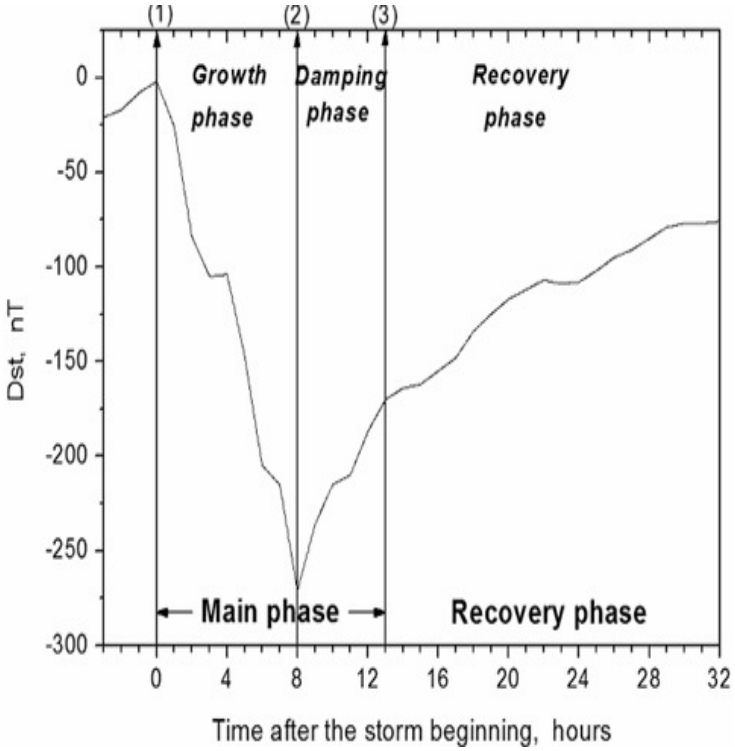
Other experimental evidences on relation of PC to the magnetosphere state

PC index adequately responds to the solar wind dynamic pressure impulses *(Troshichev and Janzhura, 2007),*

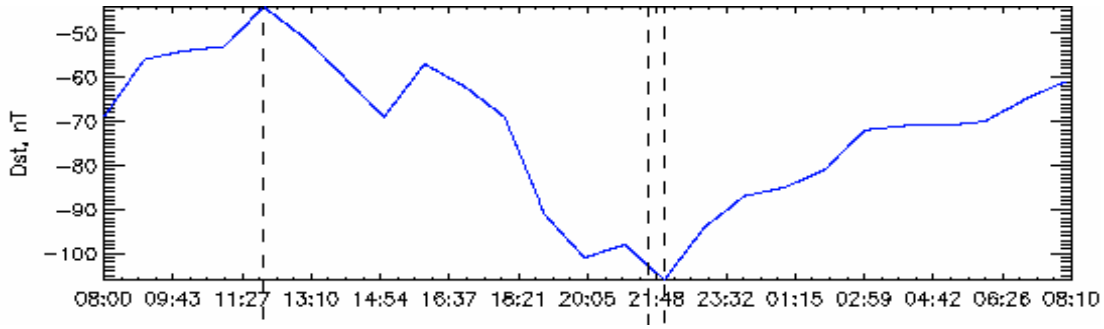
"Extraordinary" substorms observed under conditions of northward IMF are strictly associated with influence of the effective PC index (PC≥ 2 mV/m) *(Troshichev et al, 2011a, 2011b),*

6. Relationship between the PC index and magnetic storms Separation of magnetic storms into "classical", "retarded" and unqualified types.

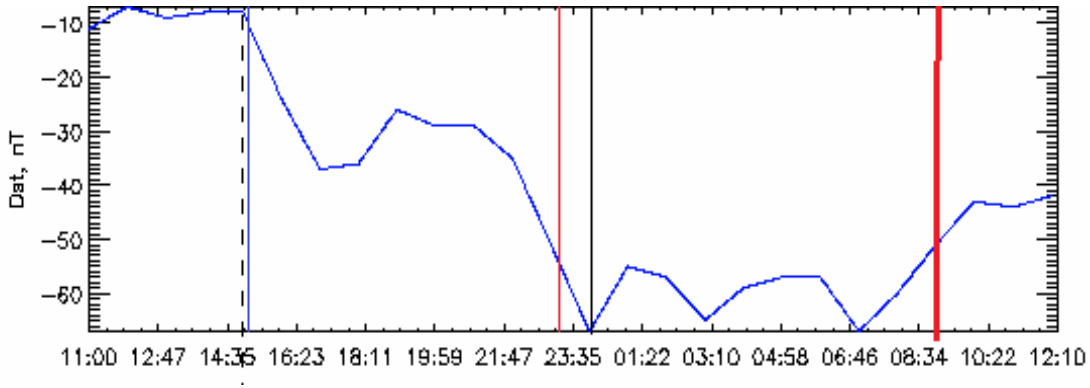
Example of classical storm
[*Akasofu and Chapman, 1972*]



Example of "retarded" storm of November 13, 1999



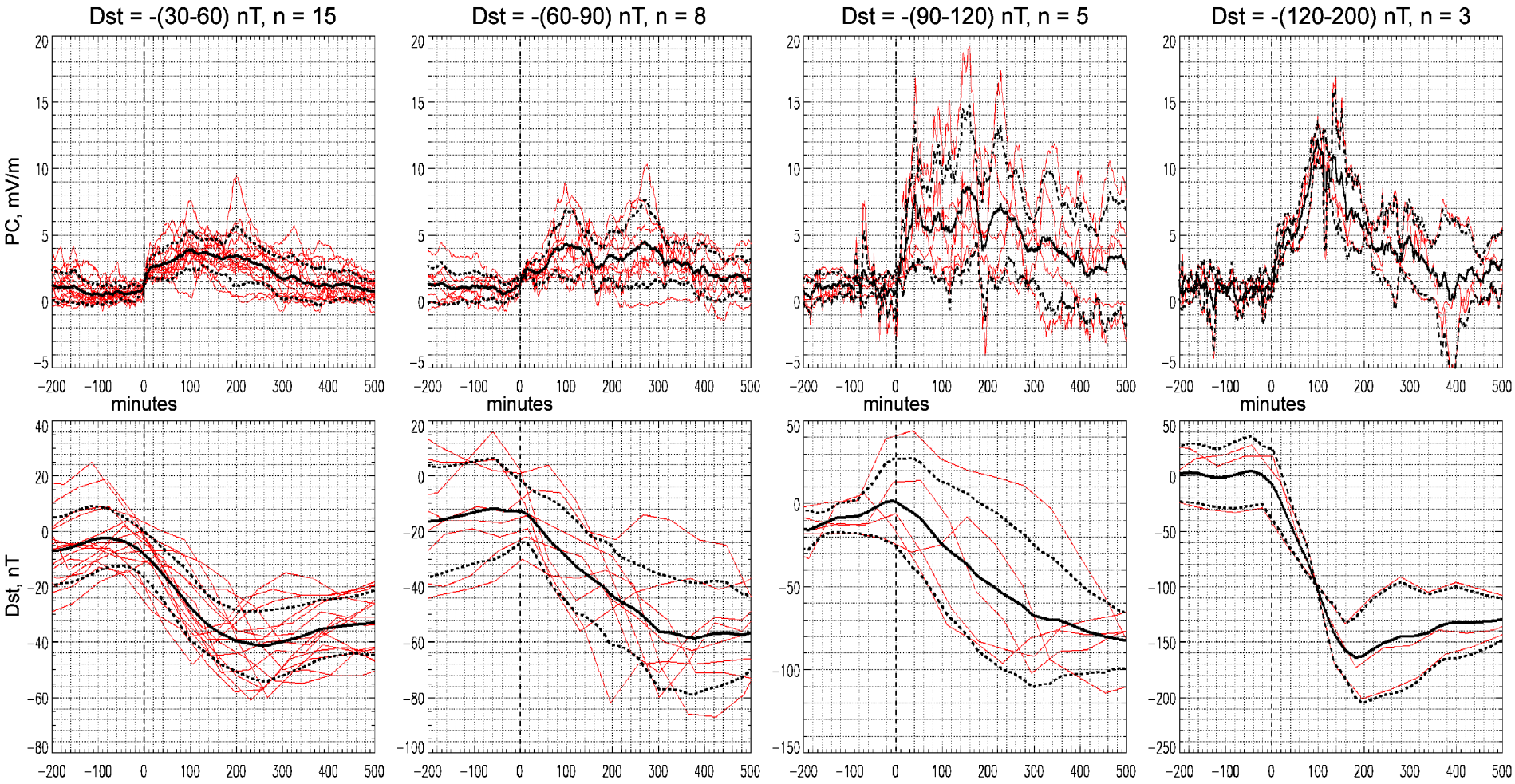
Example of unqualified storm of March 3, 2003



"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 distinquished main phase.
"Unqualified storms" are storms with smoothed or repeated main phase (were excluded from examination).
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 “classical” magnetic storms

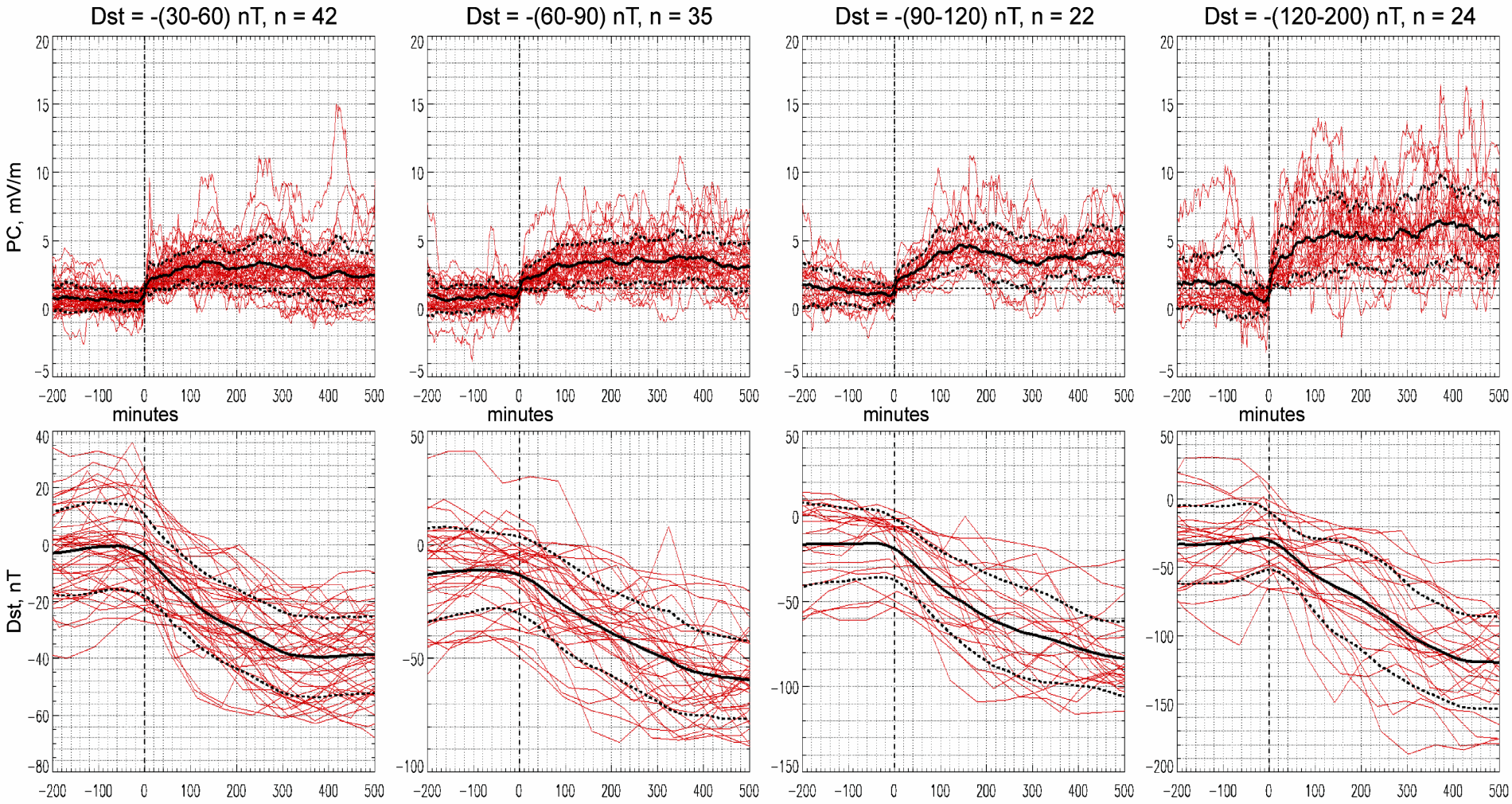
Intersection of the threshold level PC=1.5 mV/m is taken as a key date T=0



Depression of magnetic field starts to reveal when the threshold level PC~1.5 mV/m is steadily exceeded.

Beginning of the “retarded” magnetic storms

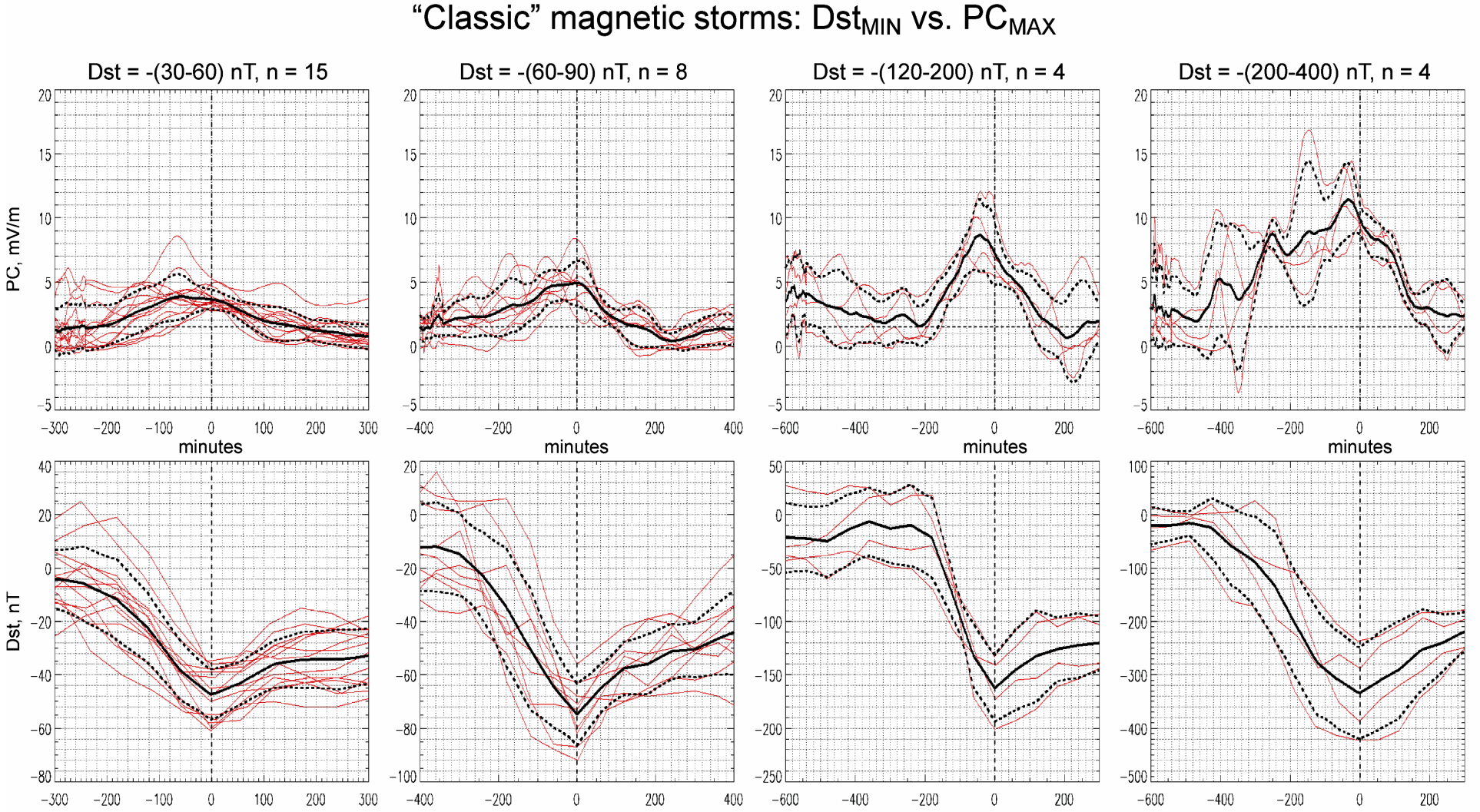
Intersection of the threshold level PC=1.5 mV/m is taken as a key date T=0



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

Relationship between PC_{max} and storm intensity (Dst_{min})

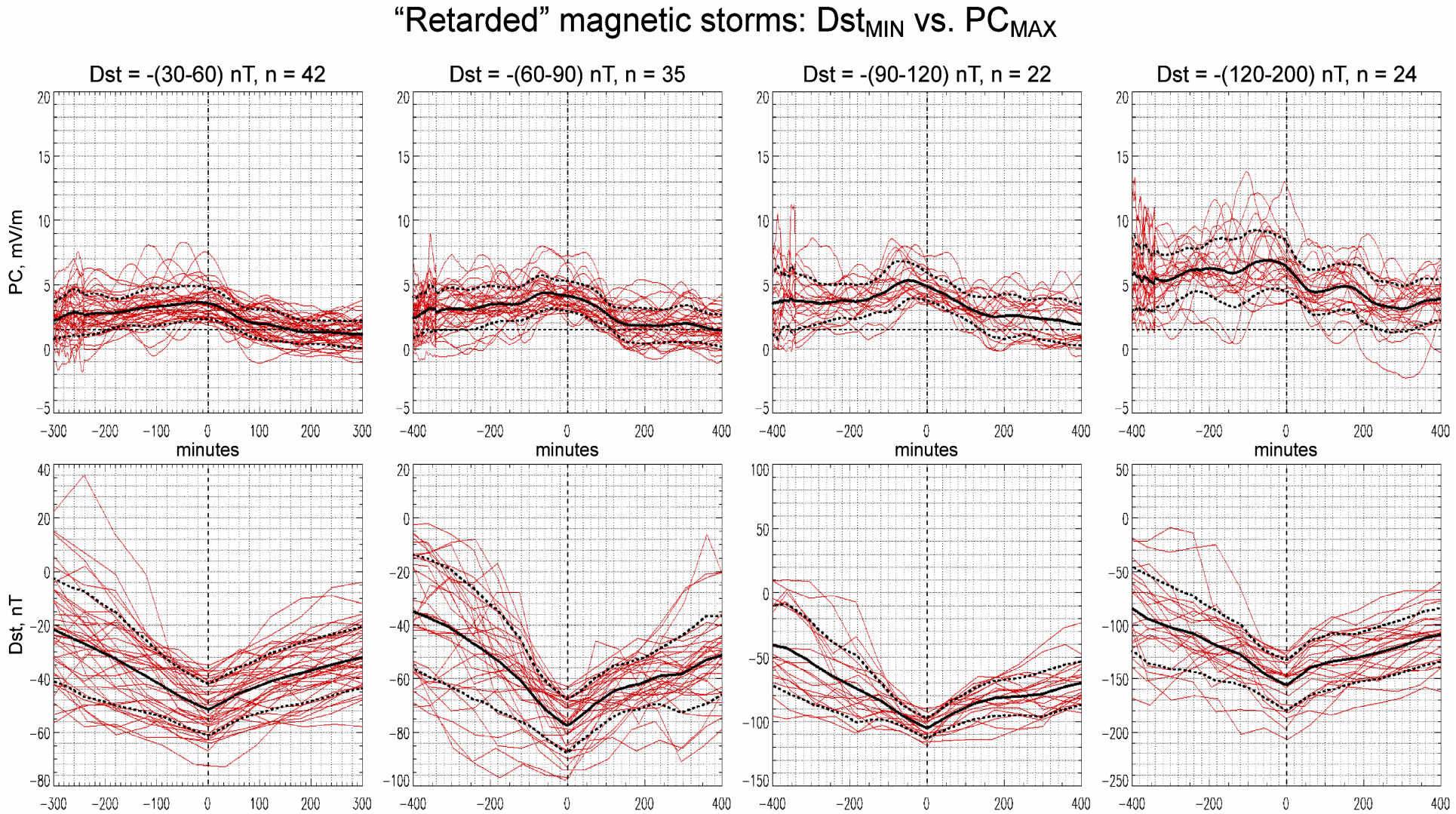
The moment of maximal depression is taken as a key date T=0, the hourly-mean PC values are shown



In case of "classical" storms the hourly-mean PC index reaches the maximum value ~60 minutes ahead the time of maximal depression (Dstmin).

Relationship between PC_{max} and storm intensity (Dst_{min})

The moment of maximal depression is taken as a key date T=0, the hourly-mean PC values are shown

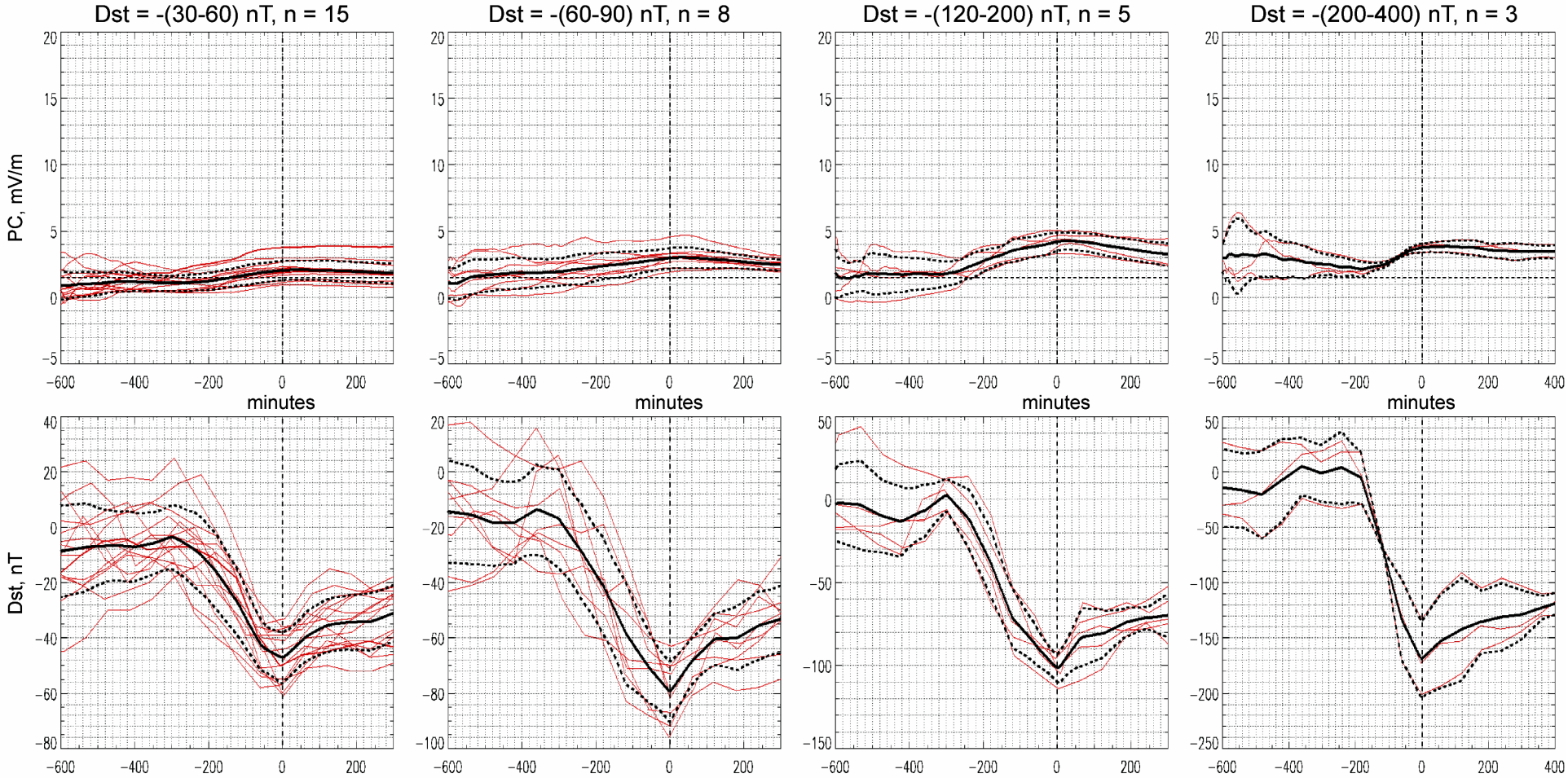


In case of "retarded" magnetic storms the hourly-mean PC index reaches the maximum value ~60 minutes ahead of time of maximal depression (Dstmin).

Accumulated-mean PC_{AM} index and development magnetic storms

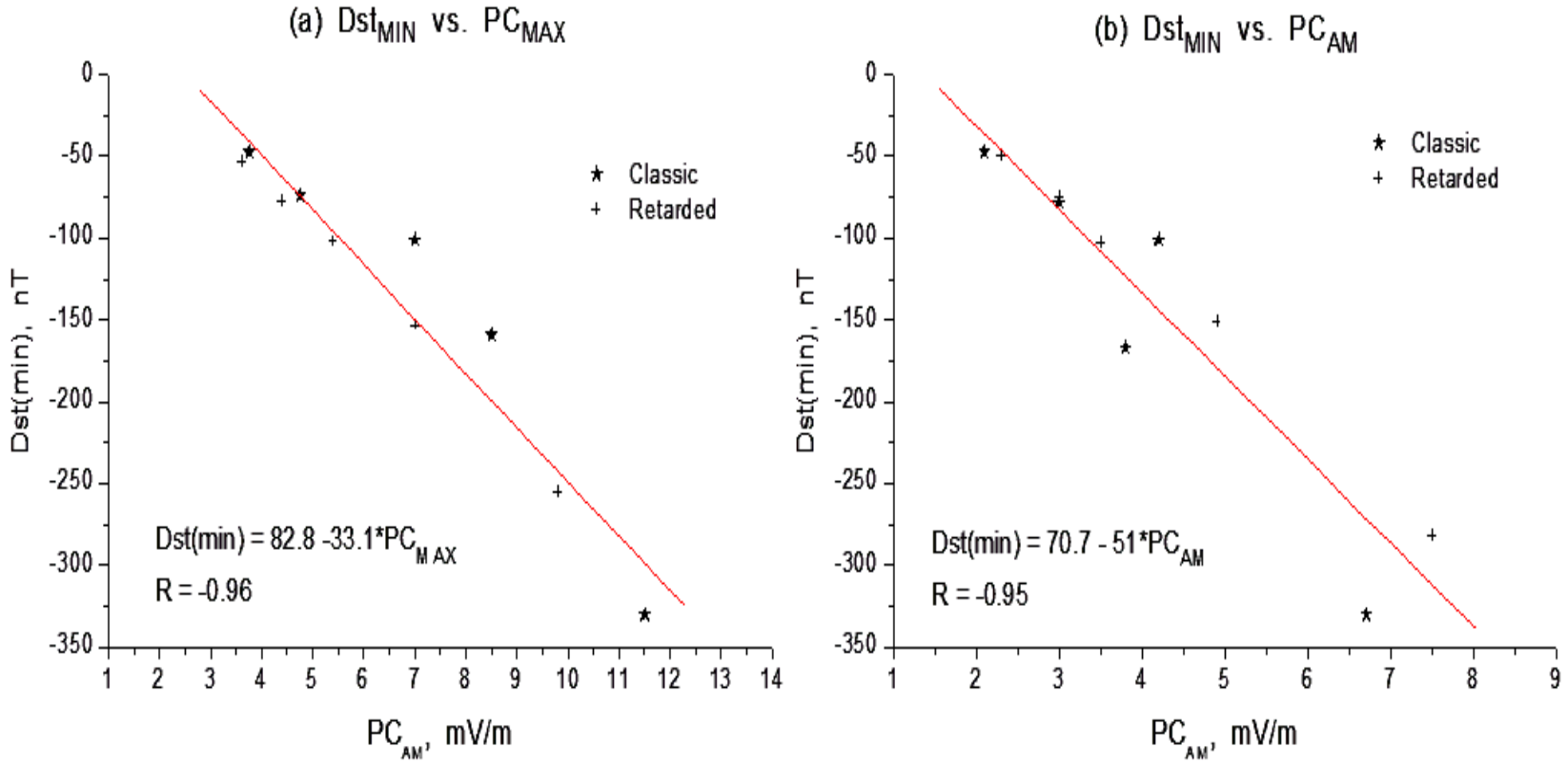
The moment of maximal depression is taken as a key date T=0. The accumulated-mean index $PC_{AM} = \Sigma PC/\Delta T$ is sum of 1-min PC values for the time interval ΔT divided by ΔT.

"Classic" magnetic storms: Dst_{MIN} vs. PC_{AM}



Behavior of the accumulated-mean value PC_{AM} determines the magnetic storm development: duration of the storm main phase and beginning of the recovery phase.

Relationship between the magnetic storms intensity Dst (min) to the accumulated-mean index PC_{AM}

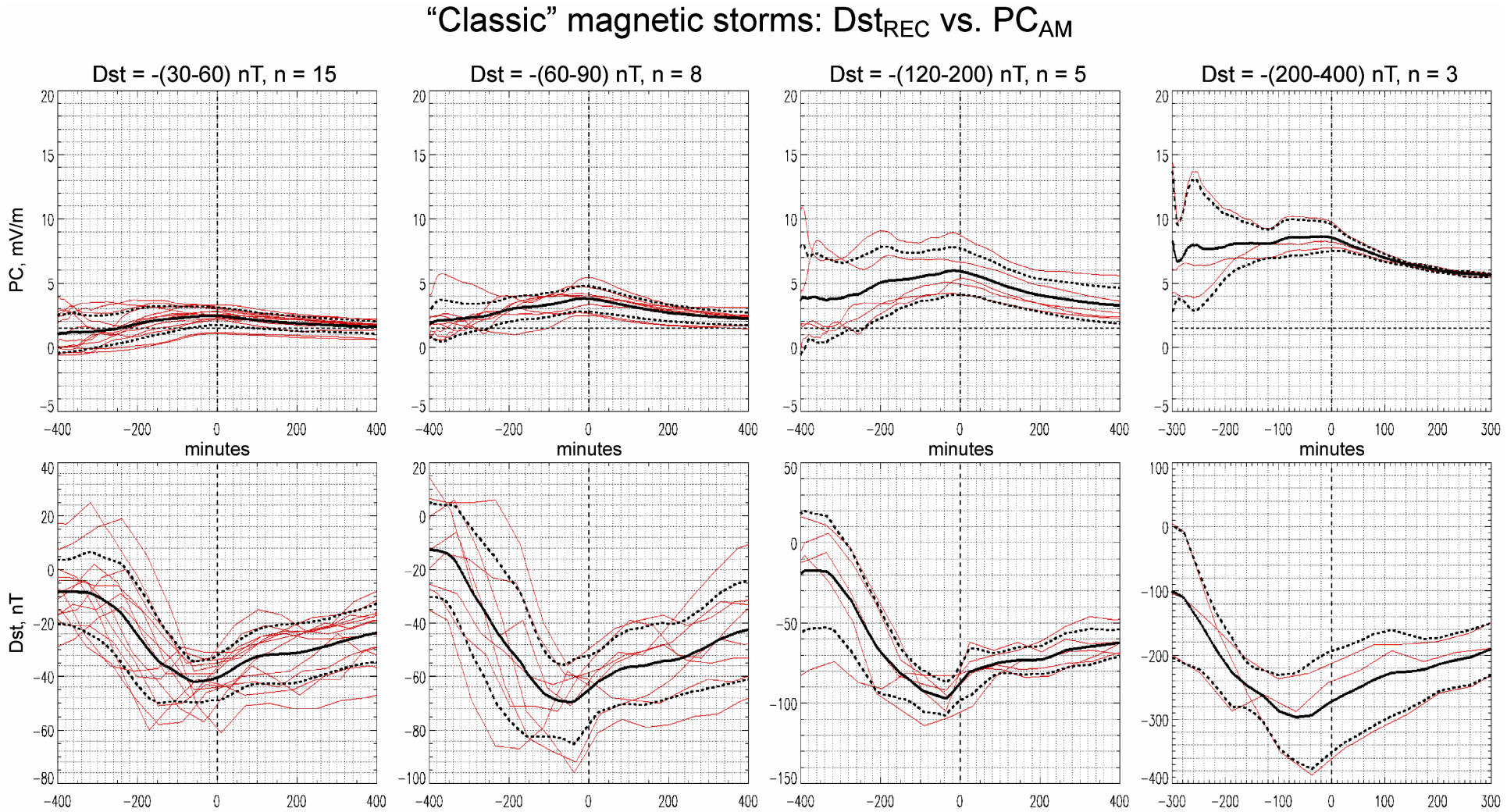


Correlation between the intensity of magnetic storms (Dstmin) and the accumulated-mean PCAM index is described by the linear law, irrespective of duration of storm main phase:

The evident link between the behavior of PC_{AM} index and the main storm characteristics such as rate of storm development, storm intensity, length of the main phase and transition to recovery phase, implies that PC_{AM} quantity characterizes the power accumulated in the magnetosphere in course of the solar wind – magnetosphere coupling.

Accumulated-mean PC_{AM} index and development magnetic storms

The moment of maximal value of accumulated-mean index PC_{AM} is taken as a key date T=0..



Behavior of the accumulated-mean value PC_{AM} determines the magnetic storm development: duration of the storm main phase and beginning of the recovery phase. As soon as the PCAM index ceases to increase, the storm main phase transforms to recovery phase

Relationship between the PC index and development of magnetic storms (summary of results)

- The magnetic storms main phase (i.e. magnetic field depression) starts to develop as soon as PC index steadily excess the threshold level 1.5 mV/m,
- The maximal depression of magnetic field follows the maximum of PC in course of the storm.
- Main features of magnetic storm are determined by the accumulated-mean PC value (PC_{AM}): storm is developed as long as PC_{AM} increases, comes to maximal intensity when PC_{AM} reaches the maximum, and transforms to recovery phase as soon as PC_{AM} value starts to decline.

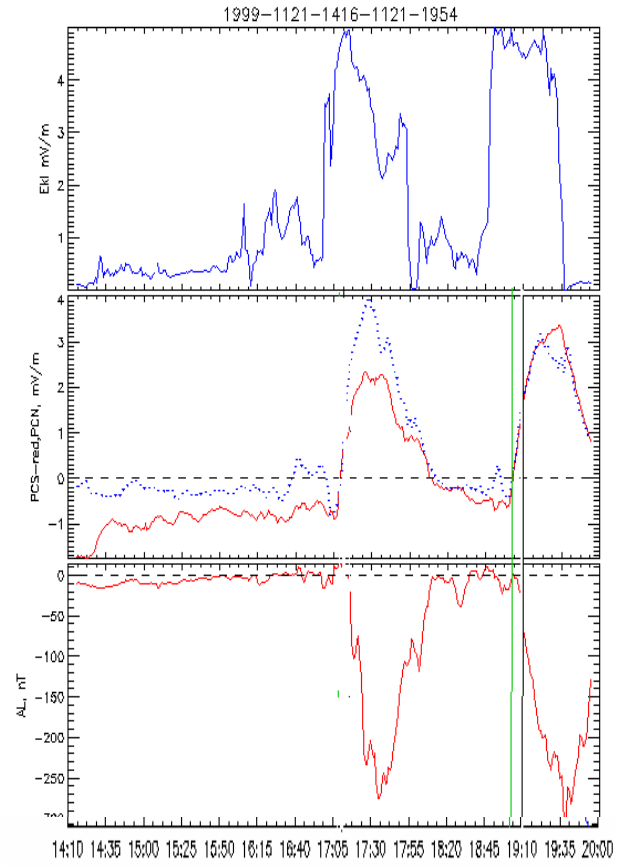
Magnetic storms observed under conditions of northward IMF are strictly associated with influence of the effective PC index (PC≥ 2 mV/m) *(Troshichev et al, 2011a, 2011b),*

All these experimental facts are indicative

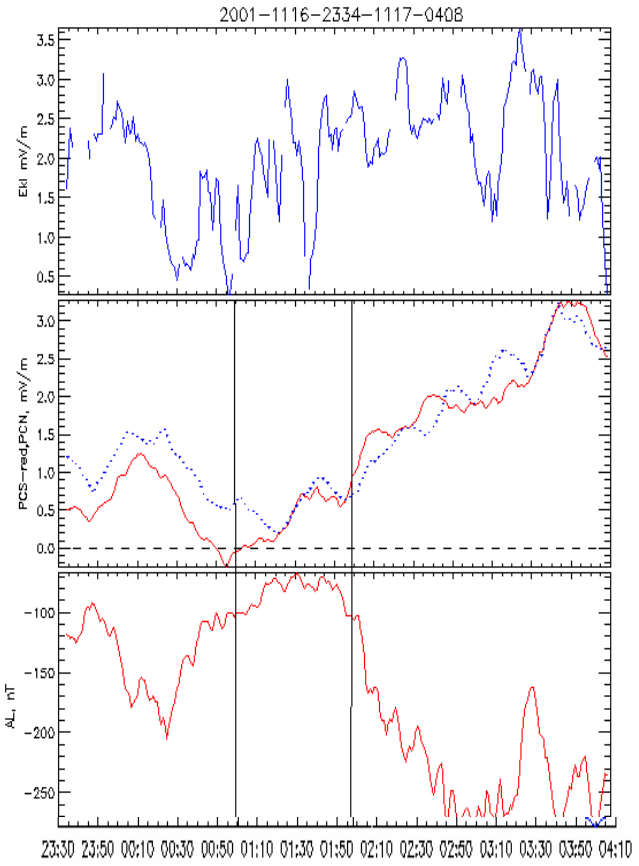
- **for PC index as a proxy of the solar wind energy that entered into the magnetosphere,**
- **for PC_{AM} value as a proxy of the solar wind energy that accumulated in the magnetosphere.**

7. Relationship between variations of the interplanetary electric field E_{KL} and the PC index behavior

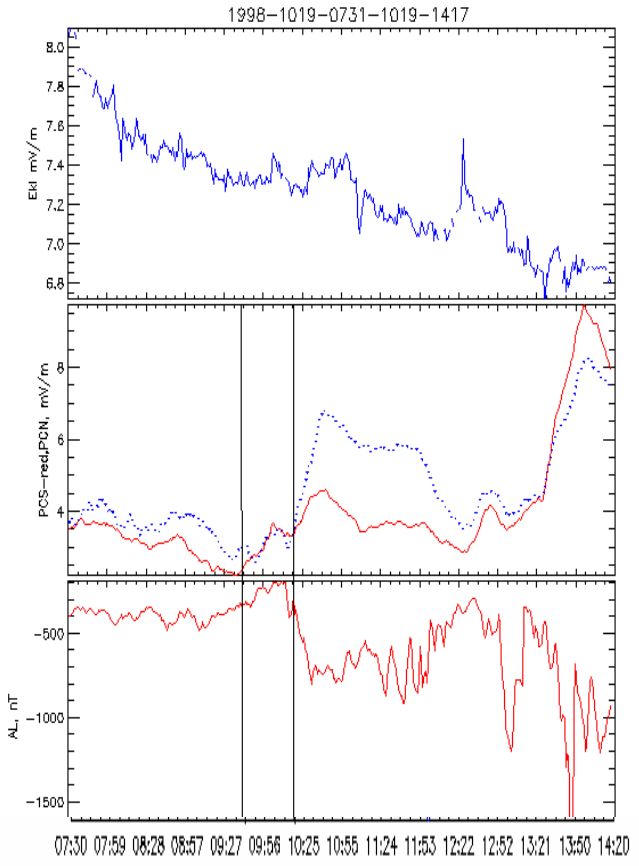
High correlation



Low correlation

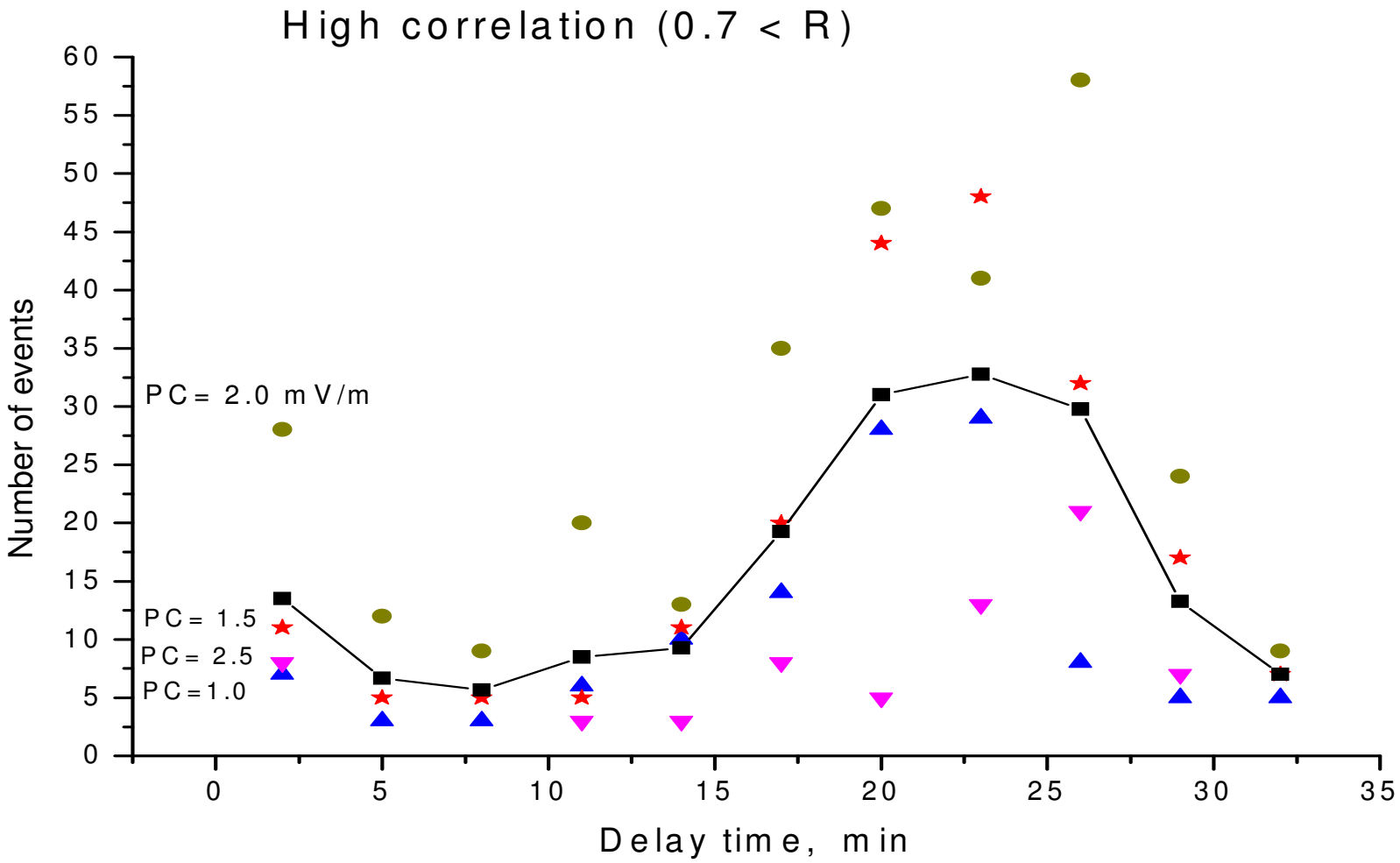


No correlation



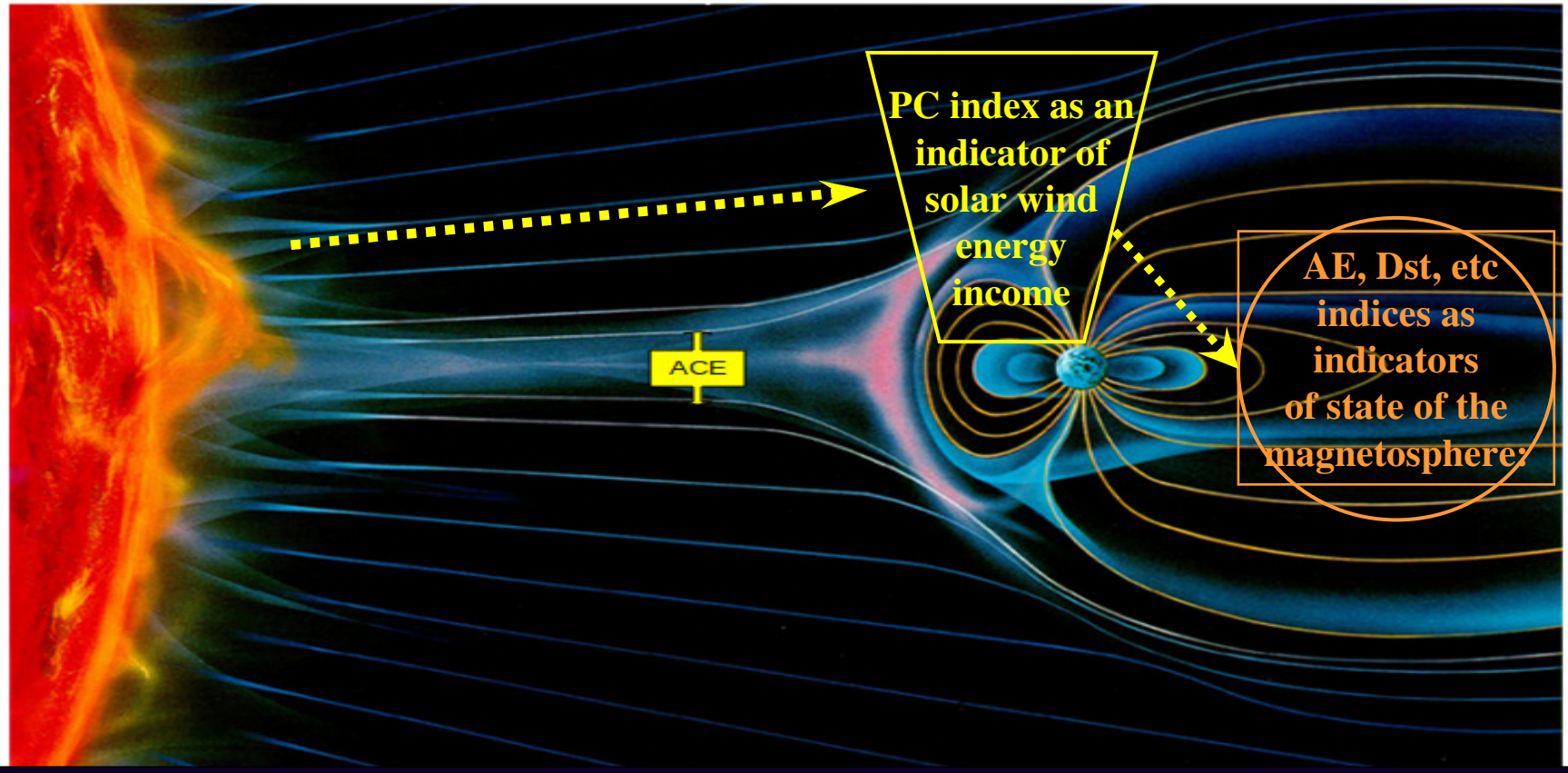
	High correlation ($R \leq 0.7$)	Low correlation ($0.5 \leq R < 0.7$)	No correlation ($R < 0.5$)
Isolated substorms	71 %	17 %	12%
Expanded substorms	56%	21%	23%

Relationship between variations of the interplanetary electric field E_{KL} and the PC index behavior: time delay



PC index correlates with the interplanetary electric field E_{KL} reduced to magnetopause with time delay ΔT in range from 0 to 35 minutes (coefficient of correlation R >0.7).
The most part of events occurs with ΔT= 18-28 minutes.

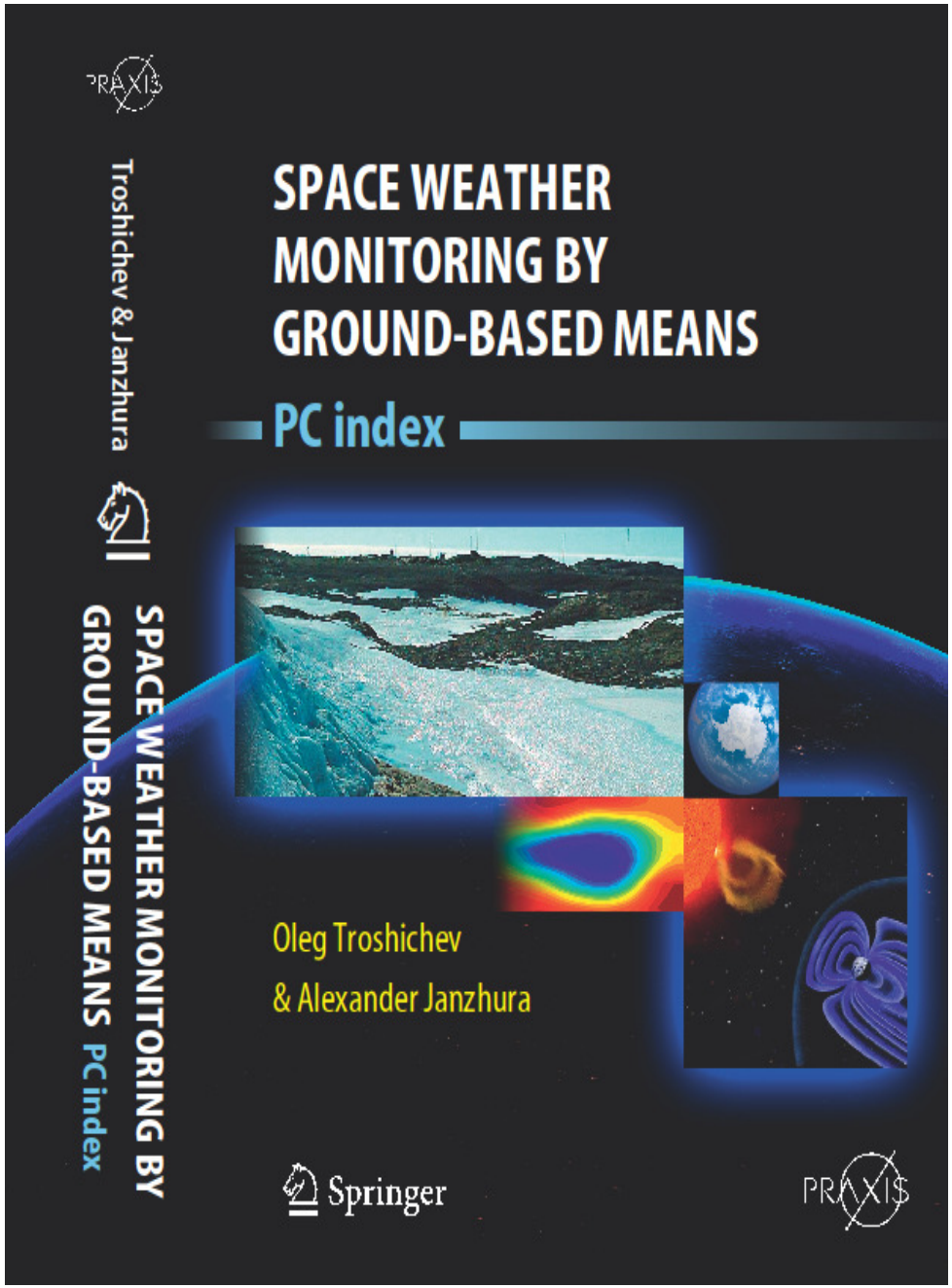
Space weather forecast and monitoring



The PC index provides the unique on-line information on solar wind energy that entered into magnetosphere and energy that accumulated in the magnetosphere.

Therein lies the principal distinction of the PC index from various coupling functions (which are characteristics of the solar wind arriving to magnetopause) 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 inspect different magnetospheric processes and to realize the quantitative space weather forecasting and monitoring.



This book includes a comprehensive description of the *PC* index and its application to the Space Weather monitoring

Thank you for attention!