PC index as a proxy of the solar wind energy incoming into the magnetosphere

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Outline:

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1. *Physical backgrounds for PC index: magnetic activity in the polar caps responds to the solar wind geoeffective variations*
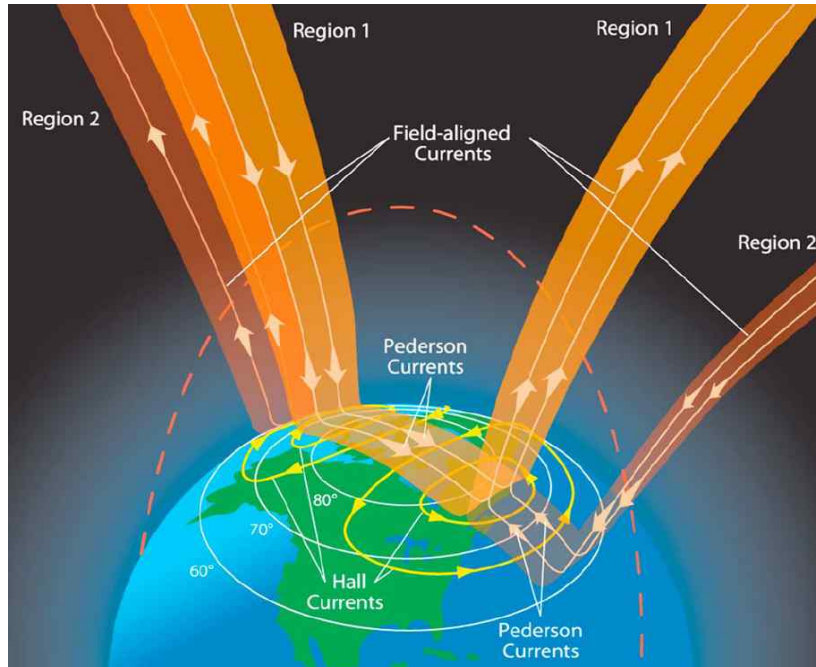
The variable solar wind coupling with the geomagnetic field constantly generates the "magnetospheric field-aligned electric currents" flowing along the geomagnetic field lines [Langel, 1975; McDiarmid et al.,1977; Iijima & Potemra, 1982; Bythrow & Potemra, 1983]. The currents are distributed along the 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]

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

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.

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).

PC index –relation to the interplanetary electric field E_{KL} and to magnetospheric substorms
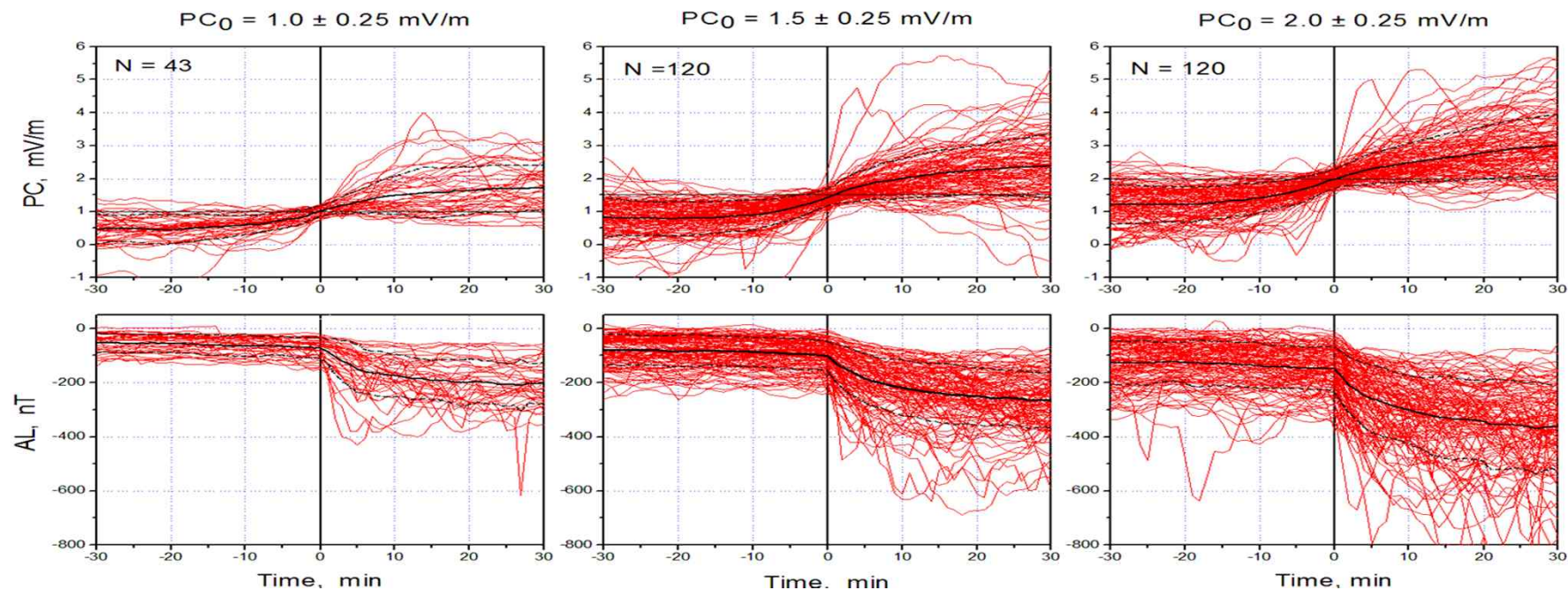
[*Troshichev et al.,* 2011b; *Troshichev et al.,* 2014; *Troshichev and Sormakov,* 2015]

The **PC** index strongly follows the E_{KL} field variations with time delays ΔT lying in the range from 8 to 24 minutes. Value of ΔT is dependent on the E_{KL} growth rate dE_{KL}/dt), not from **any one particular solar wind parameter (such as IMF Bz, Vsw, Psw)**
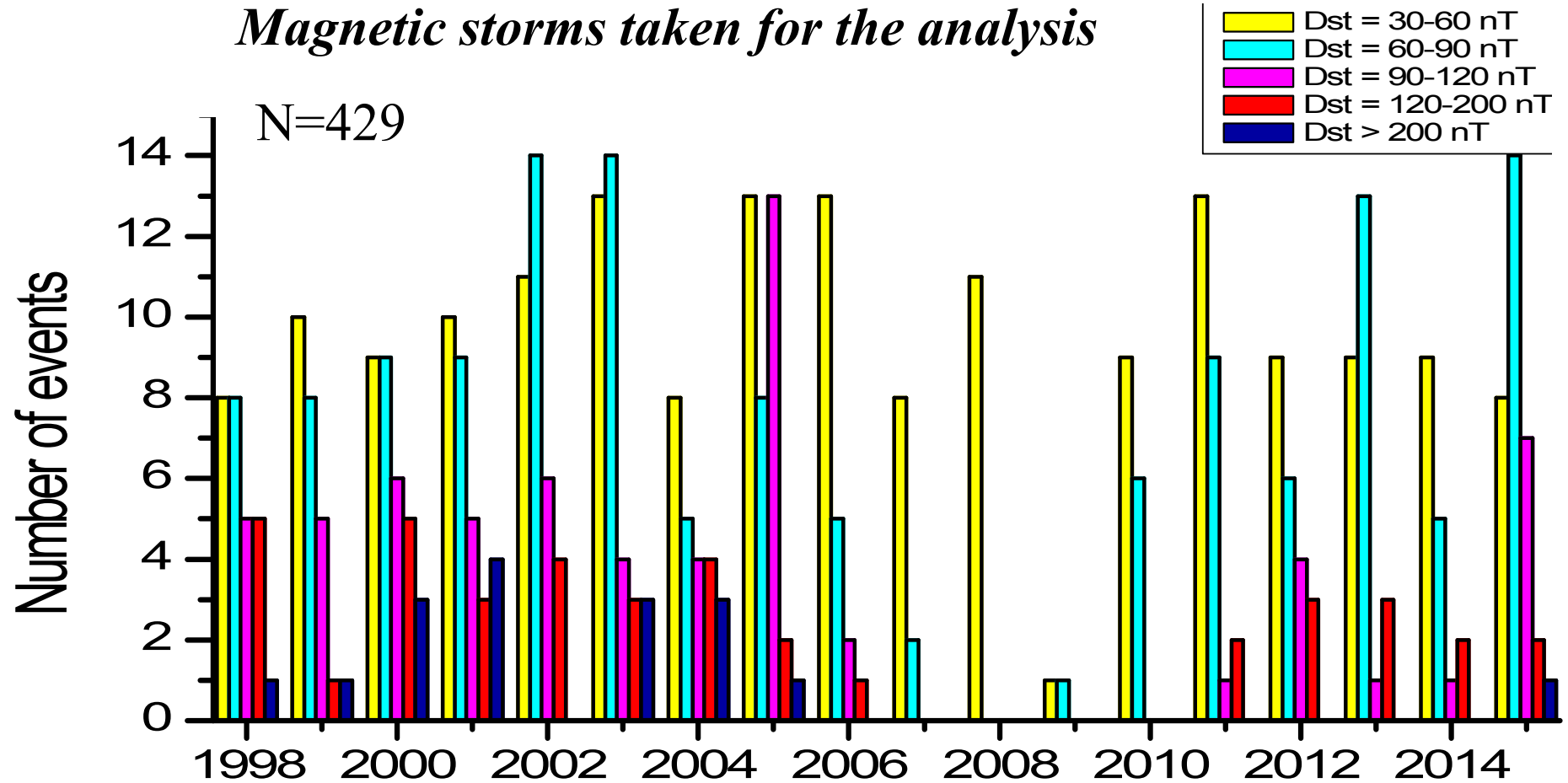
Magnetic substorms are always preceded by the **PC** index growth, the substorm sudden onsets (SO) being related to distinct **PC** value leap;

The great majority of substorms (>75%) occur under conditions **PC**>1.5 mV/m;

The intensity of magnetic disturbances in the auroral zone (*AL* index) is linearly related to the *PC* value before as well as after the substorm onset;

Magnetic storms taken for the analysis

N=429

(Chart showing Number of events versus years 1998–2014, with five Dst categories:)

- Dst = 30-60 nT
- Dst = 60-90 nT
- Dst = 90-120 nT
- Dst = 120-200 nT
- Dst > 200 nT

Magnetic storms with intensity *Dstmin* more than = -30nT, and duration longer than 12 h, observed in 1998-2015 have been taken for the analysis (N=429); storms were divided into 5 categories by their intensity: 30-60nT, 60-90nT, 90-120nT, 120-200nT, 200-400nT.

The following parameters were used to characterize magnetic storm: (1) beginning of the geomagnetic field depression is regarded as a magnetic storm beginning, (2) maximum of the geomagnetic field depression (*Dstmin*) is regarded as a magnetic storm intensity, (3) time interval between the moments of storm beginning and storm intensity is regarded as a storm growth phase.

The Sym H index as a storm indicator: Choice of the smoothing window width

Correlation between *PC* and *SymH* indices
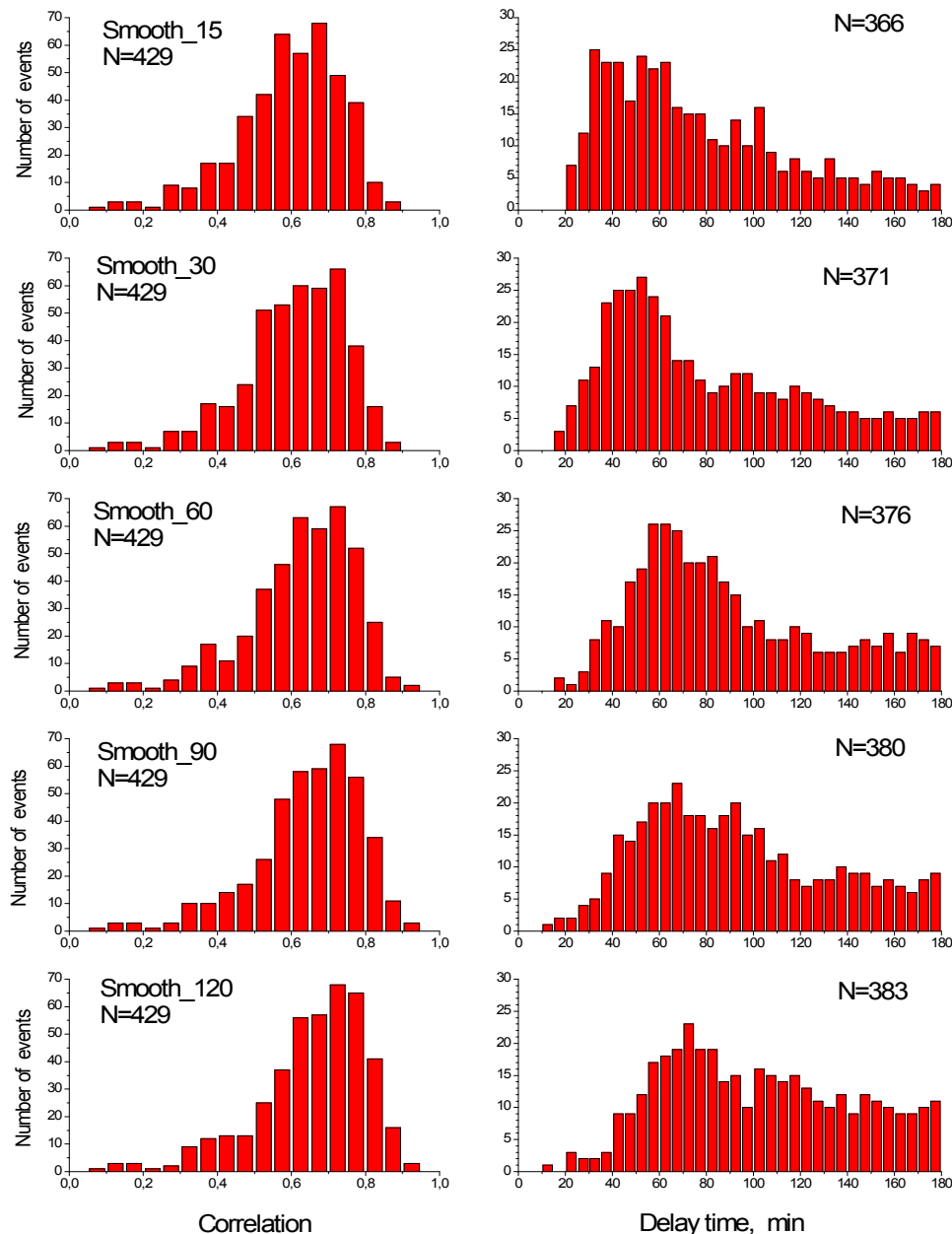
In our study we used the SymH index, which is 1-min analogue of the 1-hour Dst index.

To reveal conditions of the best correlation between processes with quite different time scale (~ 1 min in the polar cap and ~ tens minutes in the inner magnetosphere), **the all 1-min indicators were smoothed using the averaging running window of different width** (from 0 to 180 min).

Correlation between 1-min PC and SymH indices was calculated with different time shifts between them. **The shift value providing the best correlation was identified as a real delay time ΔT.**

Figure demonstrates **correlation between the smoothed *SymH* and *PC* indices and the corresponding delay times ΔT** for 429 magnetic storms in 1998-2015 under condition of different width of the smoothing windows (15, 30, 60, 90,120 minutes).

Results:

 Correlation between the smoothed *SymH* and *PC* indices is optimal under condition of delay times ΔT=30-90 min.

 Correlation is obviously improved while widening the smoothing interval, but maximum at ΔT=30-90 min is also progressively smoothed.

Taking into account these two oppositely acting tendencies, the running window width of 30 min was taken as optimal one.

# PC index and different types of magnetic storms: Classic storms
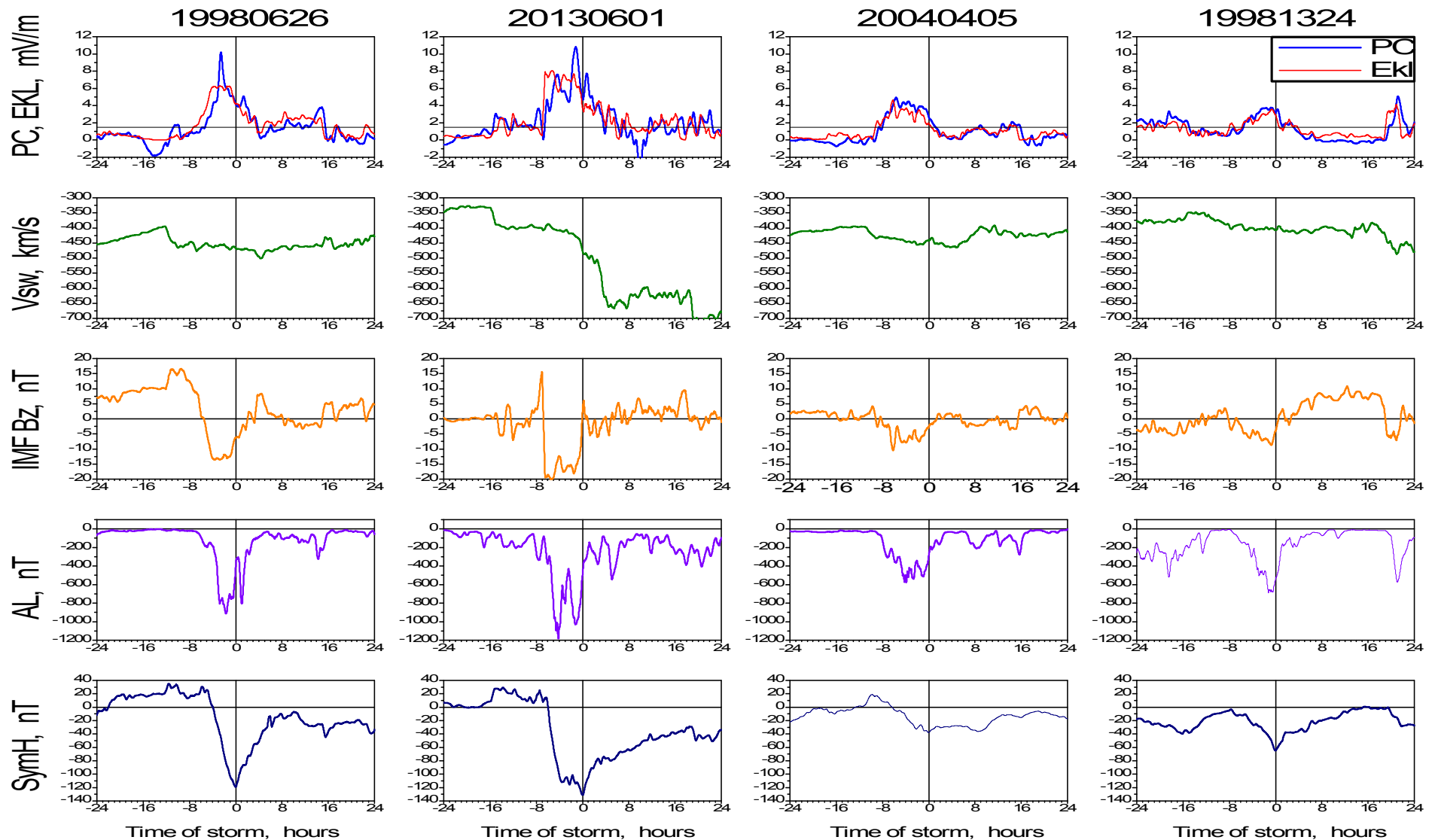
The *PC* index increases systematically after exceeding the threshold level (*PC*=1.5 mV/m) during few or many hours and does not drop below this level. The *PC* behavior is mainly controlled by the southward IMF turning, which determines, in combination with the solar wind velocity, the value of E_{KL} field. **Classic storms demonstrate development of "classical Dst variation", which was described by *Chapman* [1963],** and just this reason determines the name of these storms.

Pulsed storms
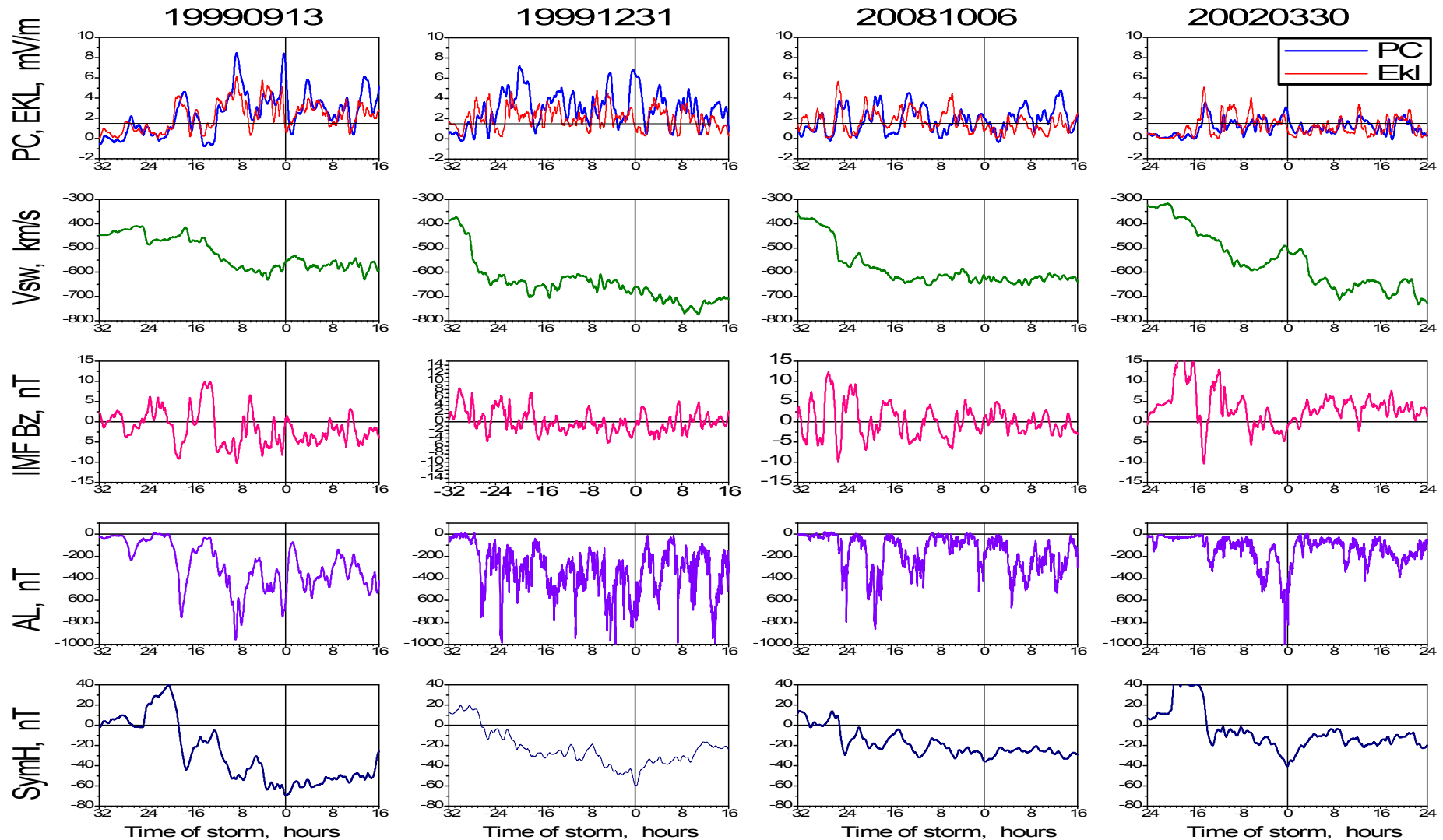
The PC index behavior represents a succession of the repeating *PC* oscillations with different amplitudes and periods. Duration of successions can vary from some hours to 3 days, the magnitude of oscillations can be either near-invariant, or diversified, or progressively decreased in the course of storm. These *PC* oscillations are due to the IMF BZ fluctuations occurring relative to zero level against the background of the solar wind "high speed streams" (HSS). **The pulsed storms demonstrate, in contrast to classic storms, a prolonged main phase lasting many hours with many unexceptional maxima in the geomagnetic field depression.**

Composite storms
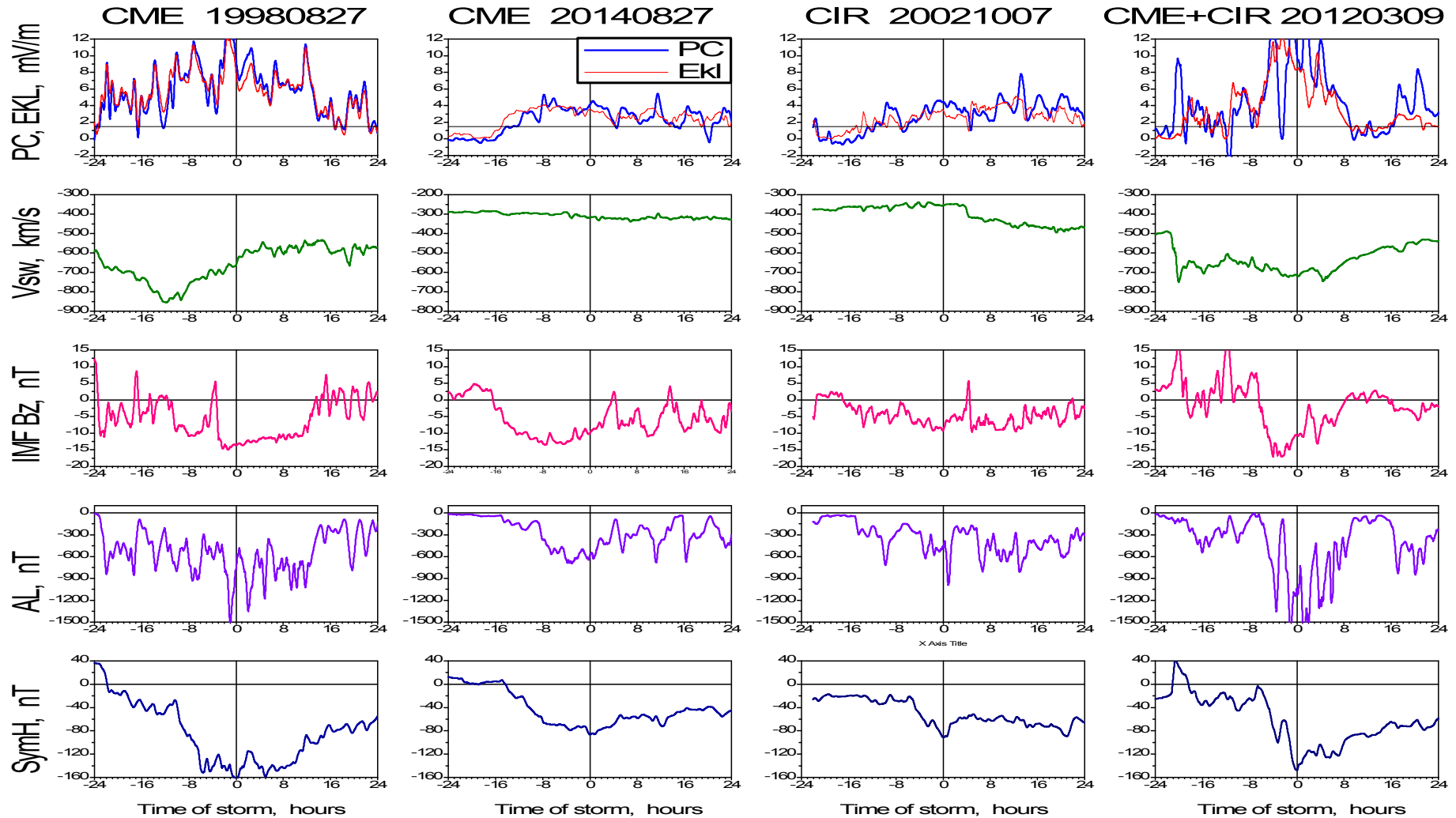
These storms are observed, when the *PC* oscillations proceed against the background of "humpbacked" *PC* level (when the IMF Bz fluctuations occur against the background of pronounced southward IMF). The combination of the fluctuating southward IMF and low speed solar wind (Vx~300-400 km/s) can provide the same effect as a combination of the fluctuating IMF Bz and high speed solar wind (HSS). **The composite storms demonstrate correspondence between average levels of the *PC* "hump" and the *SymH*.**

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

Analysis of magnetic storms for period of 1998-2015 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"
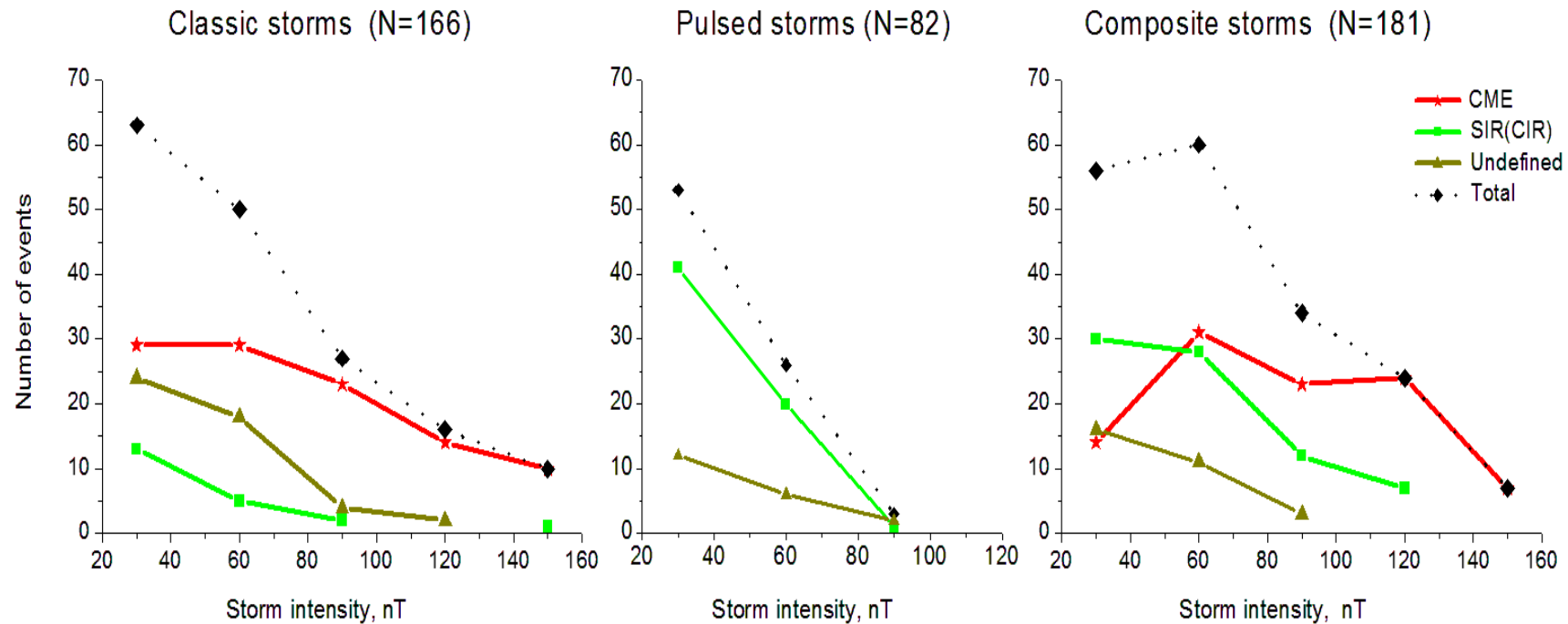
Classical storms are related mainly to Interplanetary Coronal Mass Ejections (59%); powerful magnetic storms (Dst>120 nT) are generated exclusively by ICME .

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.

**Distribution of the classic, pulsed and composite storms over years**

N=429

Classic
Pulsed
Composite

Number of events
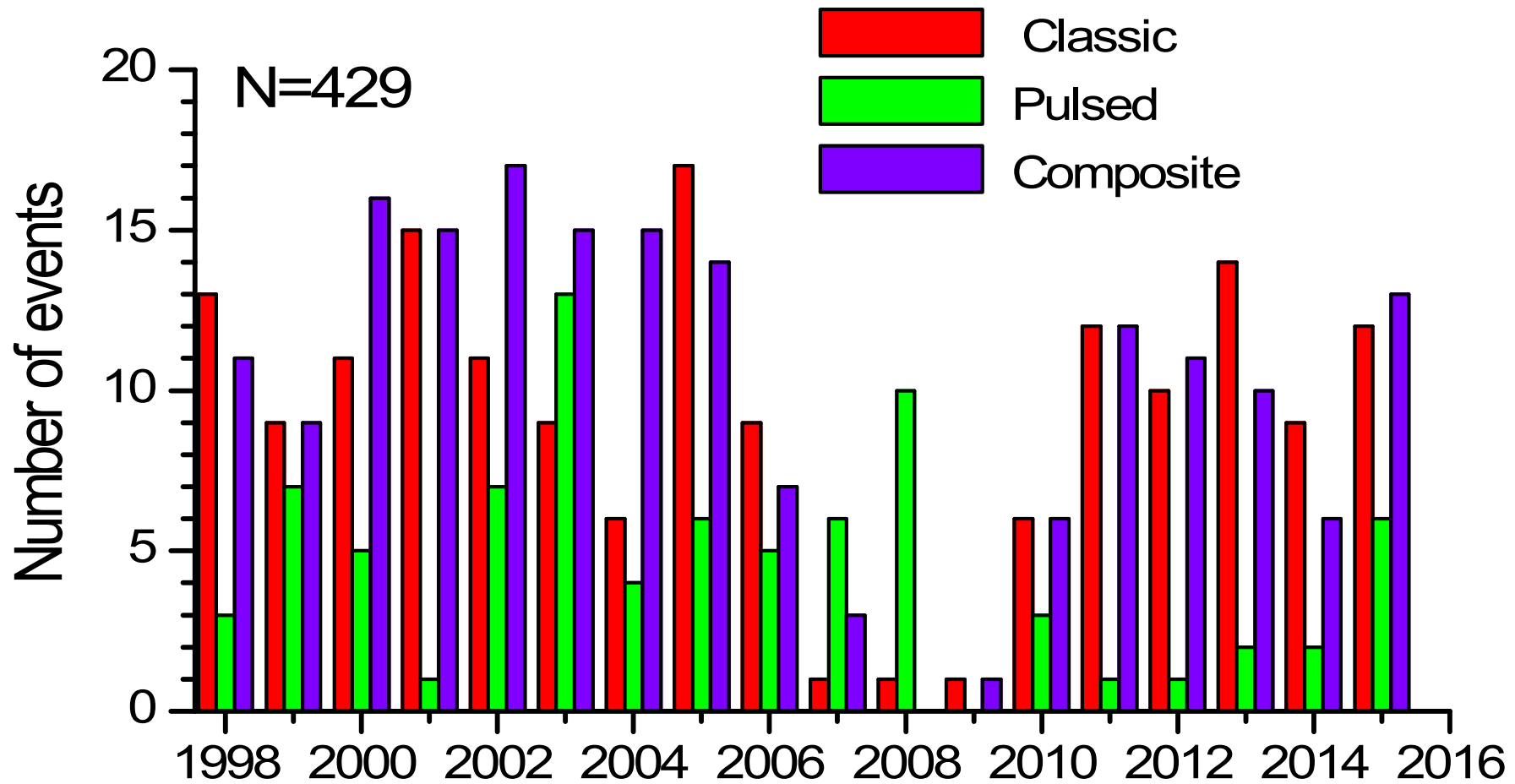
The classic and composite storms were observed throughout the whole period, with maximum rate
(N≥10 in year) in 1998, 2000-2002, 2005, 2011-2013, 2015 and minimum rate (N<3) in 2007-2009.
The pulsed storms reached a peak incidence (N≥10) in 2003 and 2008, being absent in 2009.

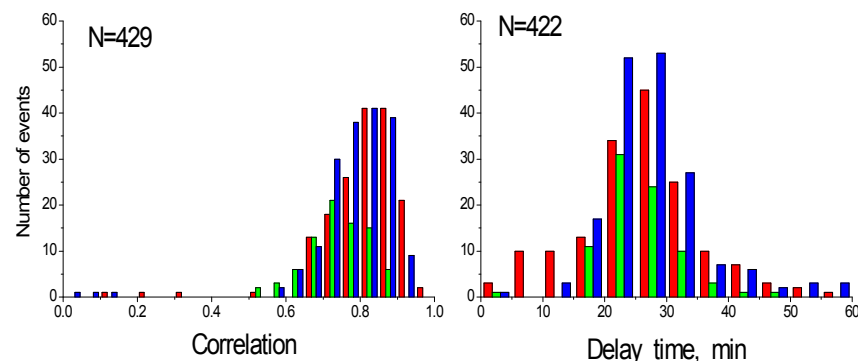# Correlation between PC and the solar wind parameters (Bz, Vx, EKL)

Correlation between PC and IMF BZ
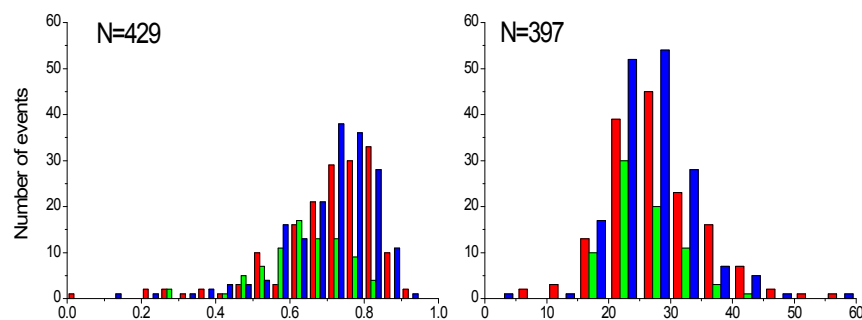
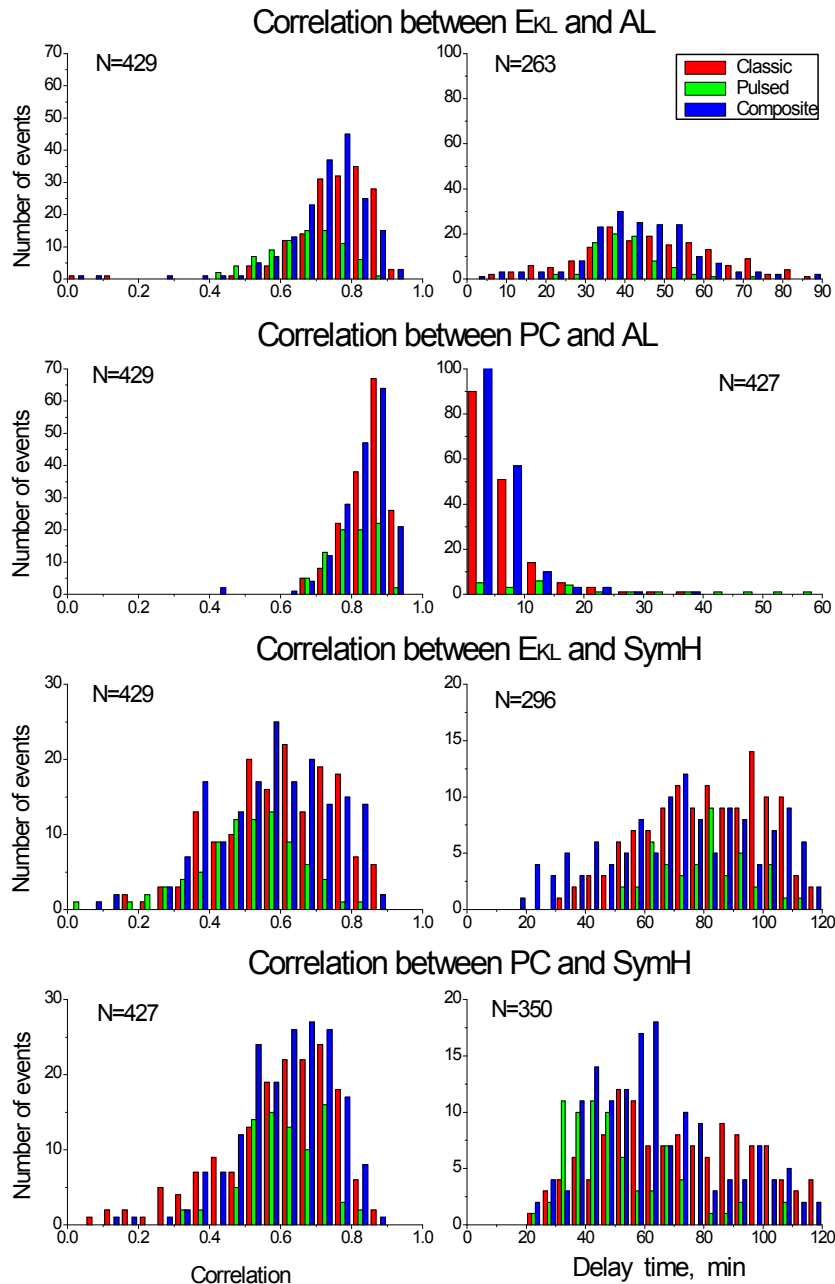Correlation between PC and Vx
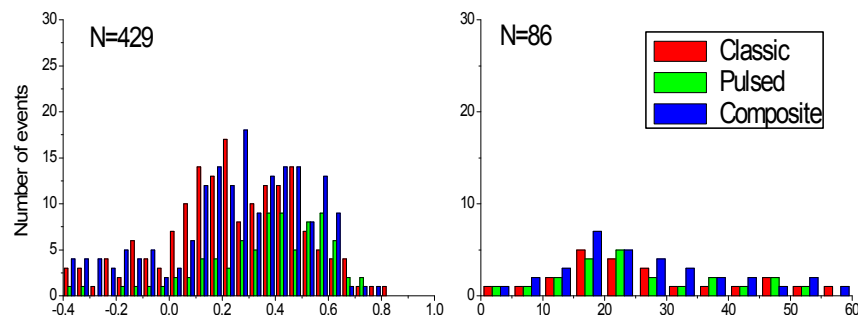
Correlation between PC and EKL

Correlation between the IMF Bz and _PC_ (R>0.5) is observed in 397 storm events of 429 **(92.5%),** with typical delay time **ΔT=20-30 min** in response of _PC_ to Bz changes.

Correlation between _PC_ and the solar wind velocity V_X R>0.5 is observed only in 86 events of 429 **(20%), the correlation for pulsed storms (~29%) being much better than that for classic and composite storms (17.6%).** The latter feature is related to exceptional role of the high speed solar wind streams (HSS) in generation of the pulsed storms.

The best connection is between _EKL_ and _PC_: correlation coefficients R>0.5 take place in 422 storm events of 429 **(98.4%),** the distribution of storms over ΔT being approximately the same as in case of Bz.

The correlation between the _PC_ and _EKL_ for classic and composite storms seems to be higher and the corresponding delay times to be longer than for pulsed storms, ΔT being slightly shifted from 10-25 min to 20-30 min.

Correlation between PC and AL/SymH indices

Correlation between E_{KL} and AL

Correlation between PC and AL

Correlation between E_{KL} and SymH

Correlation between PC and SymH

Correlation

Delay time, min

Correlation between the E_{KL} field and AL index (R>0.5) is observed in 411 storm events of 429 **(96%).** Correlation between the *PC* and *AL* indices is always better than R=0.5, in 72% of storms the correlatio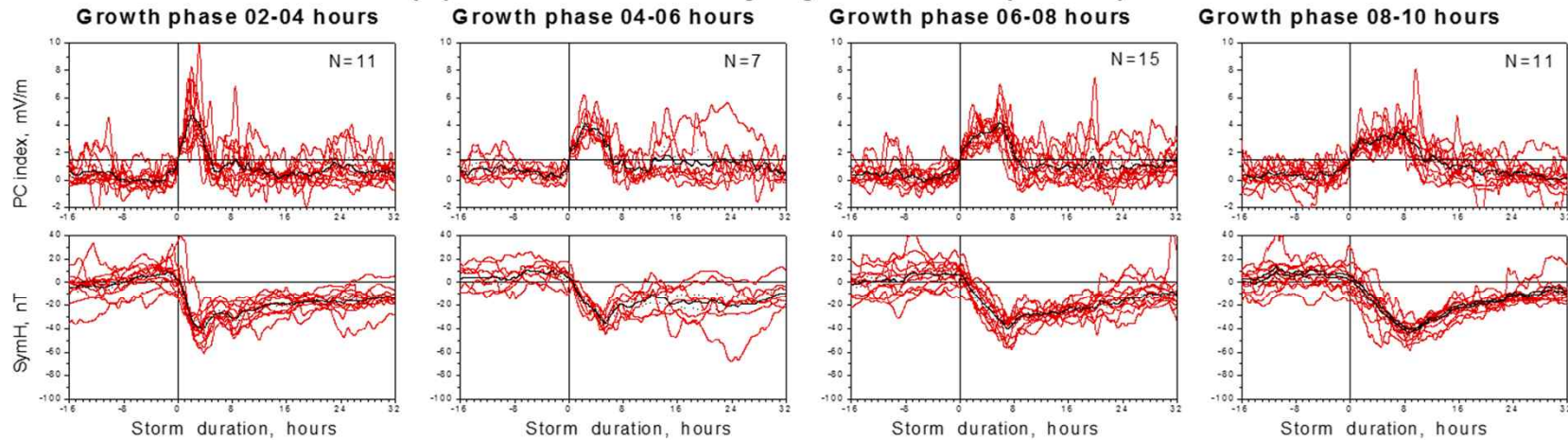n coefficients being higher than 0.75. The *AL* index responds to the *PC* index changes with delay times $\Delta T=0\div10$ min; this value is in a good agreement with delay time $\Delta T=25\div55$min in the *AL* response to the E_{KL} field evolution if the delay time between E_{KL} and PC ($\Delta T=15\div35$ min) is taken into account.

Correlation between the *PC* and *SymH* indices (R>0.5) is observed in 81% of storm events) being better than between E_{KL} and *SymH* (in 68% of storm events). Delay time in response of *SymH* to the *EKL* changes ($\Delta T=50\div110$ min) is consistent with delay time $\Delta T=30\div80$ min in response of *SymH* to the *PC* changes with allowance for $\Delta T=15\div35$ min in response of *PC* to the *EKL* changes.
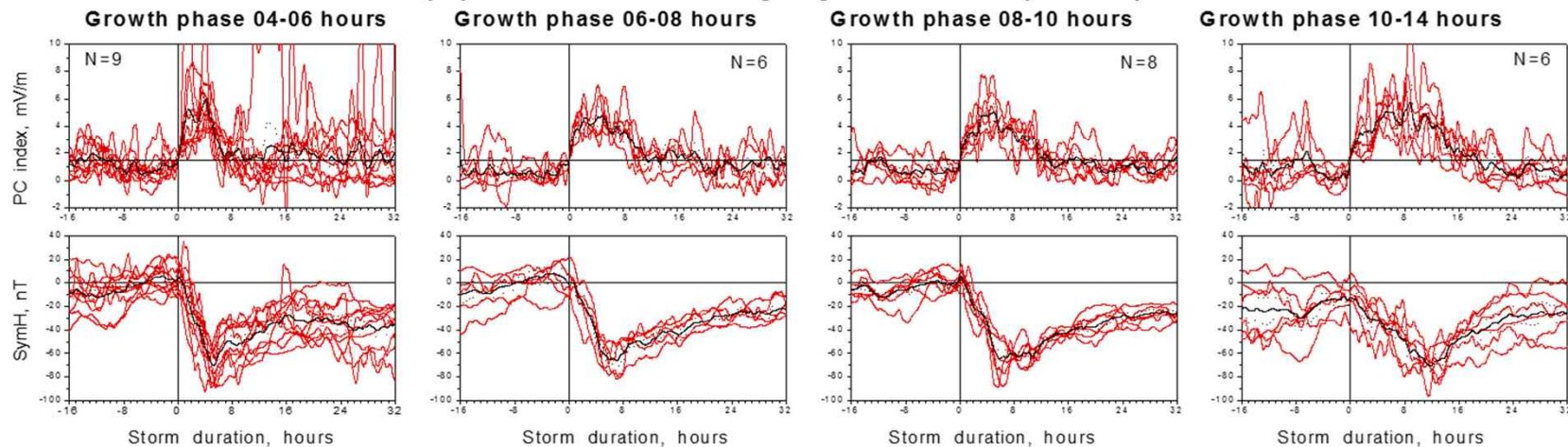
Figure demonstrates basically the same regularities for classic, pulsed and composite storms. It could be noted that correlation in case of pulsed storms is slightly worse than in case of classic and combined storms (distribution of the storm occurrence over the coefficients of correlation is more smoothed)

Time evolution of PC index and development of classic storms

(a) Storm intensity $SymH_{MIN} = -(30-60)$ nT

| Growth phase 02-04 hours | Growth phase 04-06 hours | Growth phase 06-08 hours | Growth phase 08-10 hours |

N=11   N=7   N=15   N=11

PC index, mV/m

SymH, nT

Storm duration, hours

(b) Storm intensity $SymH_{MIN} = -(60-90)$ nT

| Growth phase 04-06 hours | Growth phase 06-08 hours | Growth phase 08-10 hours | Growth phase 10-14 hours |

N=9   N=6   N=8   N=6

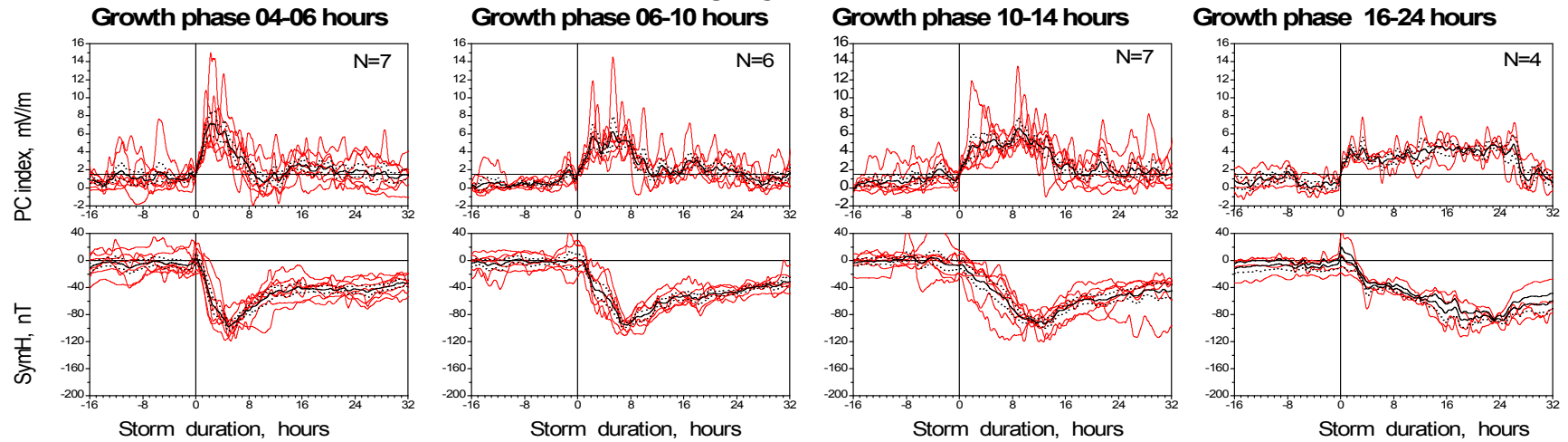PC index, mV/m

SymH, nT

Storm duration, hours

Magnetic storms were separated onto 5 categories according to their intensity.

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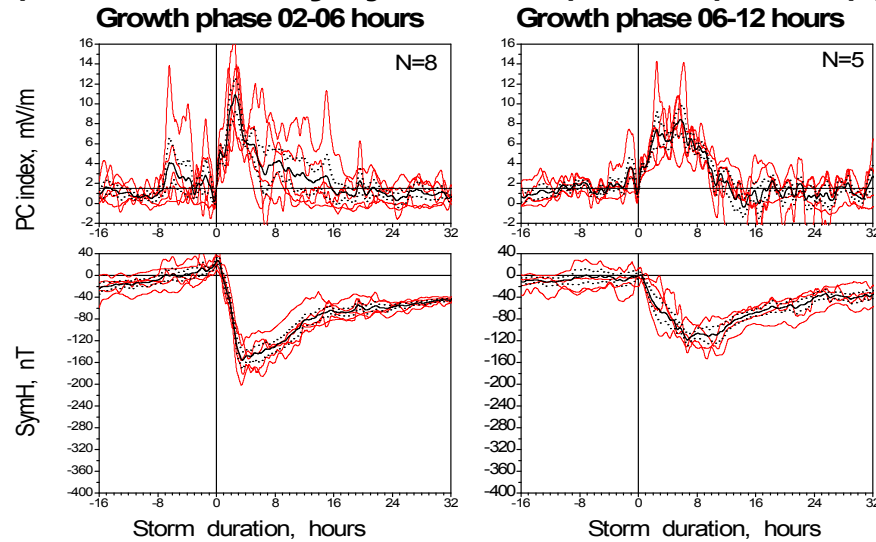
- **Magnetic storm starts (T=0) when PC index steadily exceeds the threshold level PC~1.5 mV/m.**
- **Magnetic storm continues till PC index stays higher the threshold level, as a result, the storm growth phase duration is determined by time period with PC>1.5 mV/m.**

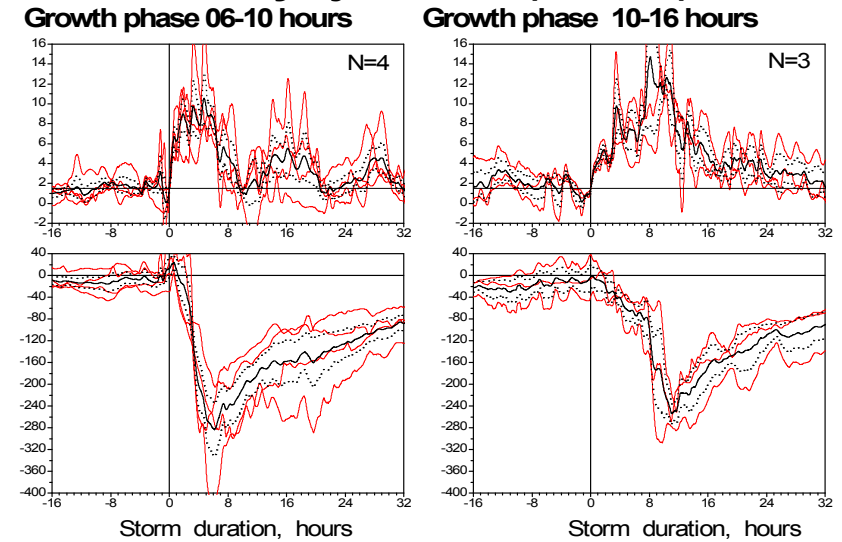# *Time evolution of PC index and development of classic storms*

(c) Storm intensity $SymH_{MIN}$ = - (90-120) nT

Growth phase 04-06 hours   Growth phase 06-10 hours   Growth phase 10-14 hours   Growth phase 16-24 hours

(d) Storm intensity $SymH_{MIN}$ = - (120-200) nT   (e) Storm intensity $SymH_{MIN}$ = - (200-450) nT

Growth phase 02-06 hours   Growth phase 06-12 hours   Growth phase 06-10 hours   Growth phase 10-16 hours

Time evolution of PC index and development of pulsed storms

(a) Storm intensity SymH$_{MIN}$ = - (30-60) nT   **(b) SymH$_{MIN}$ = - (60-90) nT**   **(c) SymH$_{MIN}$ = - (90-120) nT**

Permanent oscillation   Weakining oscillation   Permanent oscillation   Varying oscillation
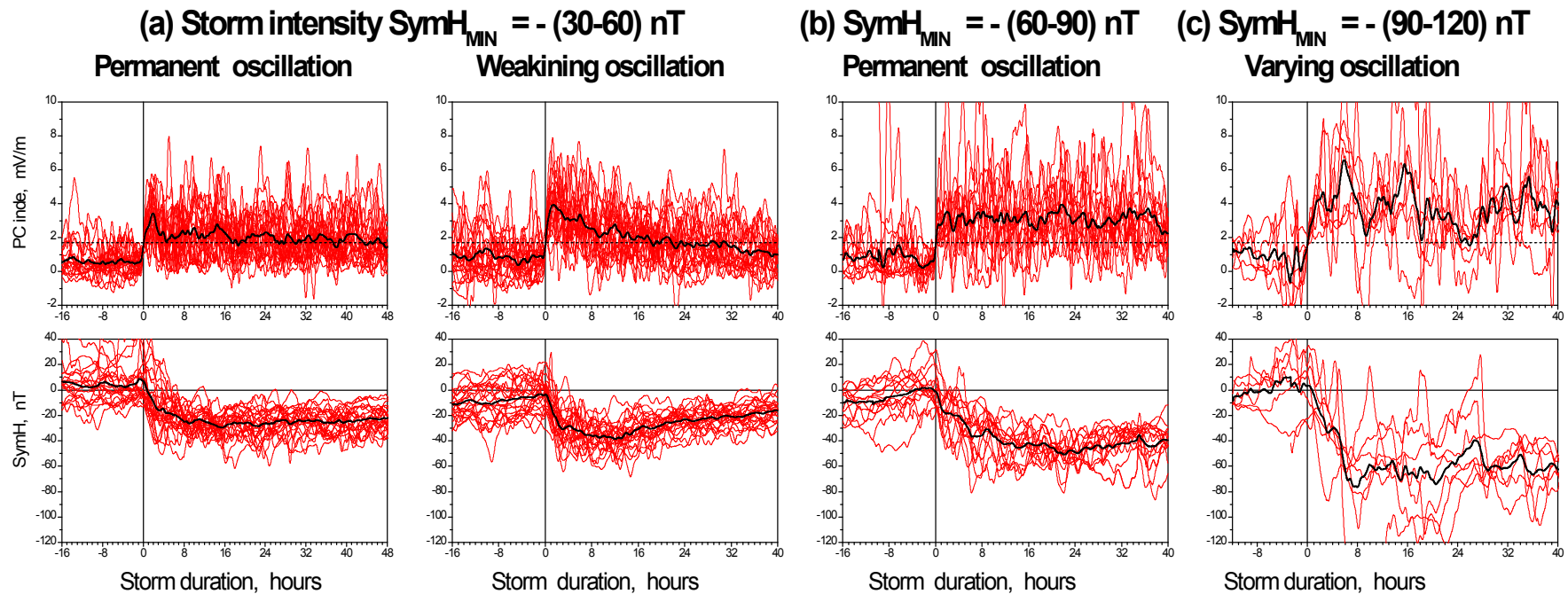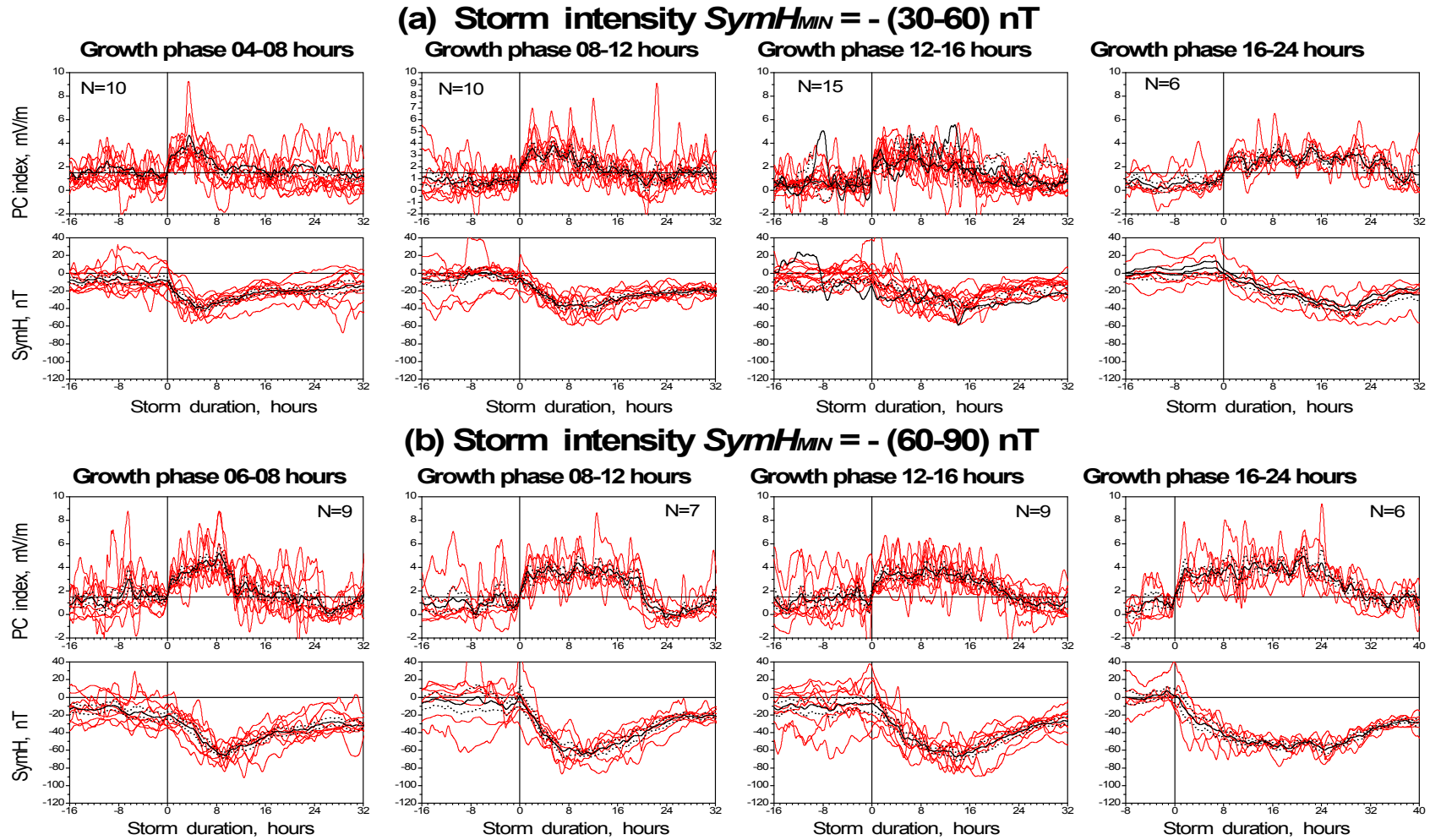
The beginning of the pulsed storms is determined, like to classic storms, by steady exceeding the *PC* index above the threshold level *PC* = 1.5 mV/m.

The geomagnetic field depression presents succession of *SymH* fluctuations of modified periods and smoothed amplitudes that implies the action of accumulating and smoothing processes.

Instead of a prominent *PC* maximum and a single distinct *SymH* minimum, typical of the classic storms, **the pulsed magnetic storms demonstrate "main phase" with repeated irregular *PC* and *SymH* fluctuations, which can last during many hours.** Fluctuations of *PC* can be of different period (from tens minutes to few hours) and different magnitude (either roughly constant, or decayed, or alternating). **To derive the relationship between the *PC* and *SymH* indices for pulsed storms, the *PC* and *SymH* characteristics averaged over main phase should be used.**

Time evolution of PC index and development of composite storms

(a) Storm intensity $SymH_{MIN} = -(30\text{-}60)$ nT

Growth phase 04-08 hours	Growth phase 08-12 hours	Growth phase 12-16 hours	Growth phase 16-24 hours

(b) Storm intensity $SymH_{MIN} = -(60\text{-}90)$ nT

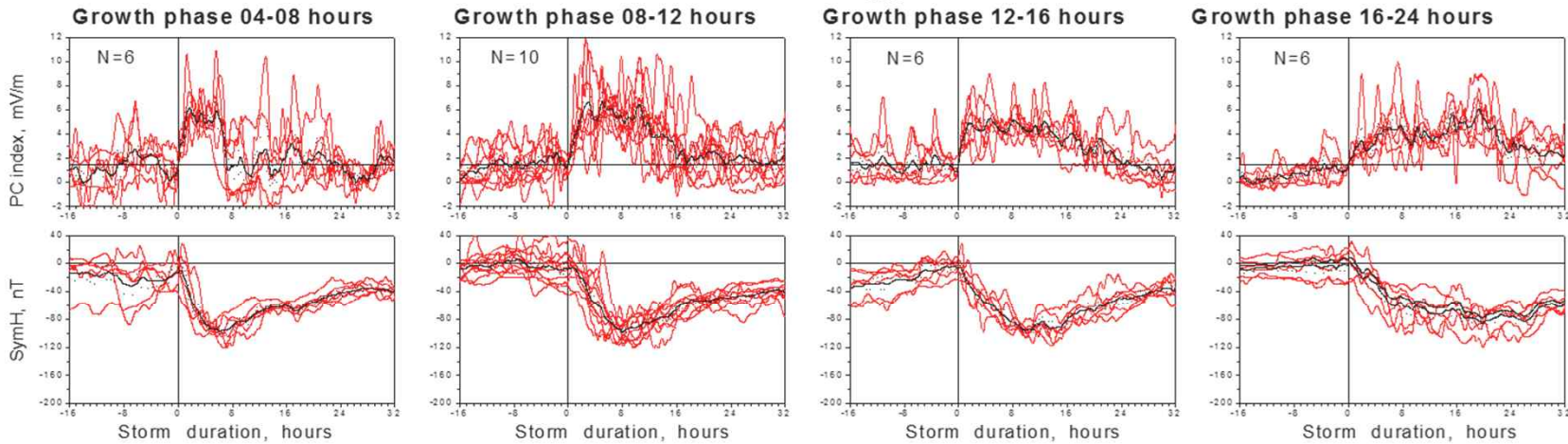| Growth phase 06-08 hours	Growth phase 08-12 hours	Growth phase 12-16 hours	Growth phase 16-24 hours

In case of composite storms "Dst variation" is in progress as long as the *PC* index remains above the threshold level (*PC*=1.5 mV/m), the clear minimum *SymH* value being observed, like the classic storms.
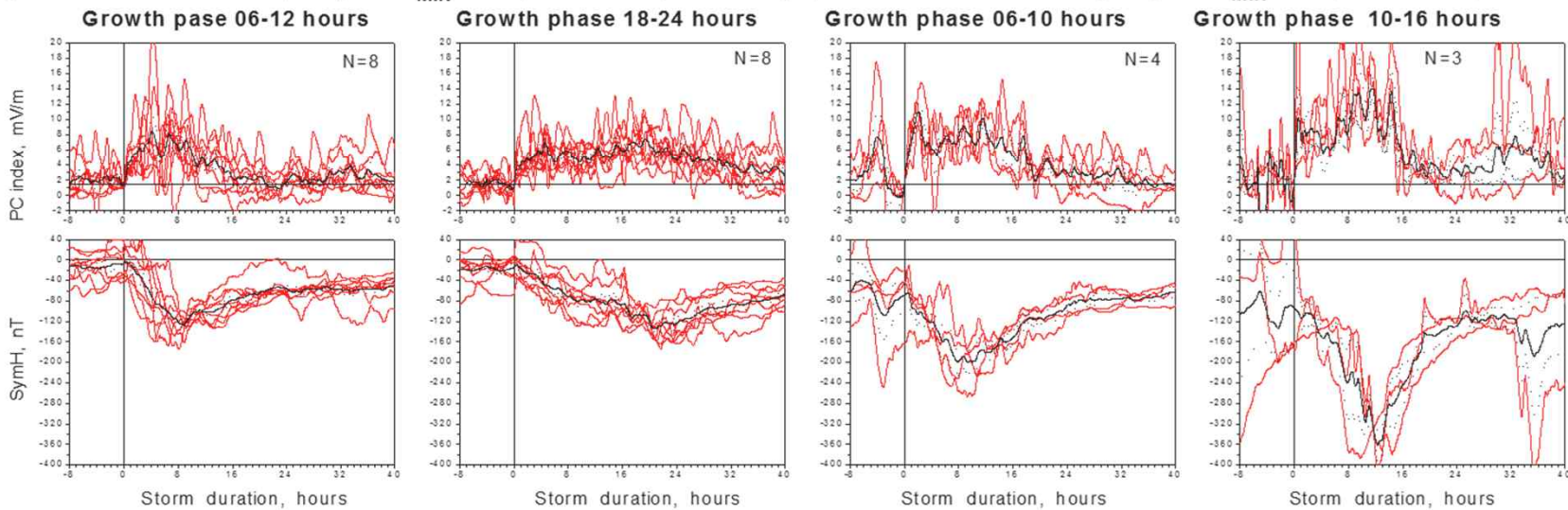
The mean *PC* and *SymH* values for each composed storm category demonstrate the clearly defined regularity: the maximum depression of geomagnetic field ($SymH_{MIN}$) is predetermined by the maximum *PC* value (PC_{MAX}).

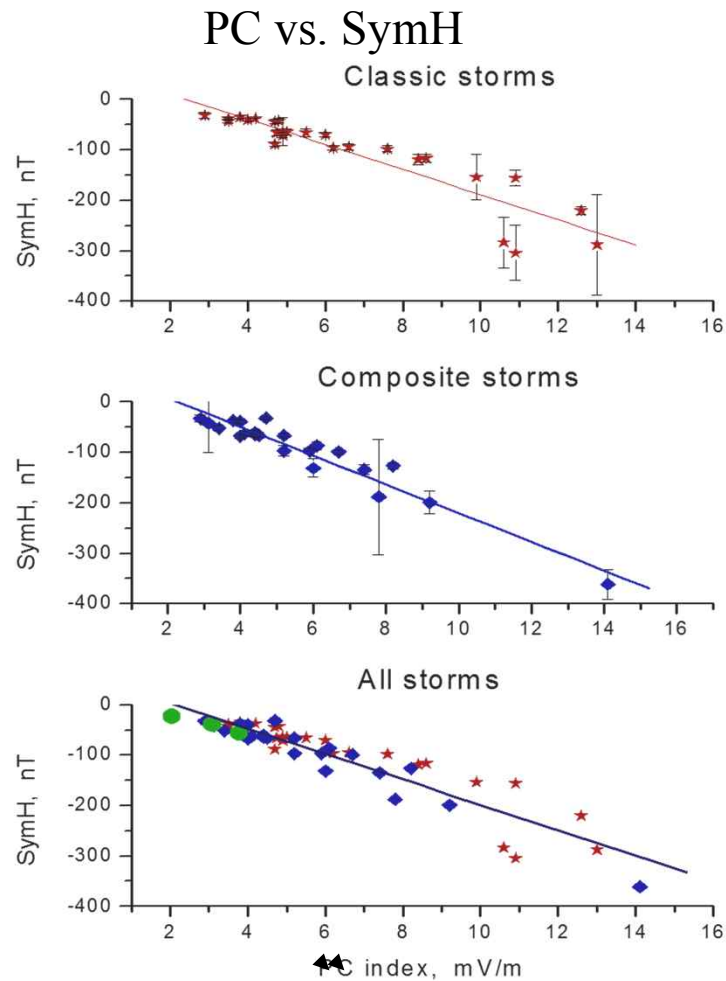# Time evolution of PC index and development of composite storms

(c) Storm intensity $SymH_{MIN} = -(90-120)$ nT

Growth phase 04-08 hours   Growth phase 08-12 hours   Growth phase 12-16 hours   Growth phase 16-24 hours

(d) Storm intensity $SymH_{MIN} = -(120-200)$ nT   (e) Storms intensity $SymH_{MIN} = -(200-450)$ nT

Growth pase 06-12 hours   Growth phase 18-24 hours   Growth phase 06-10 hours   Growth phase 10-16 hours

Storm intensity (SymH_MIN) as response to PC_MAX value

PC vs. SymH

Delay time ΔT in response of SymH_MIN to PC_MAX as a function PC_MAX (a), SymH_MIN (b), PC growth phase duration (c), and storm growth phase (d)
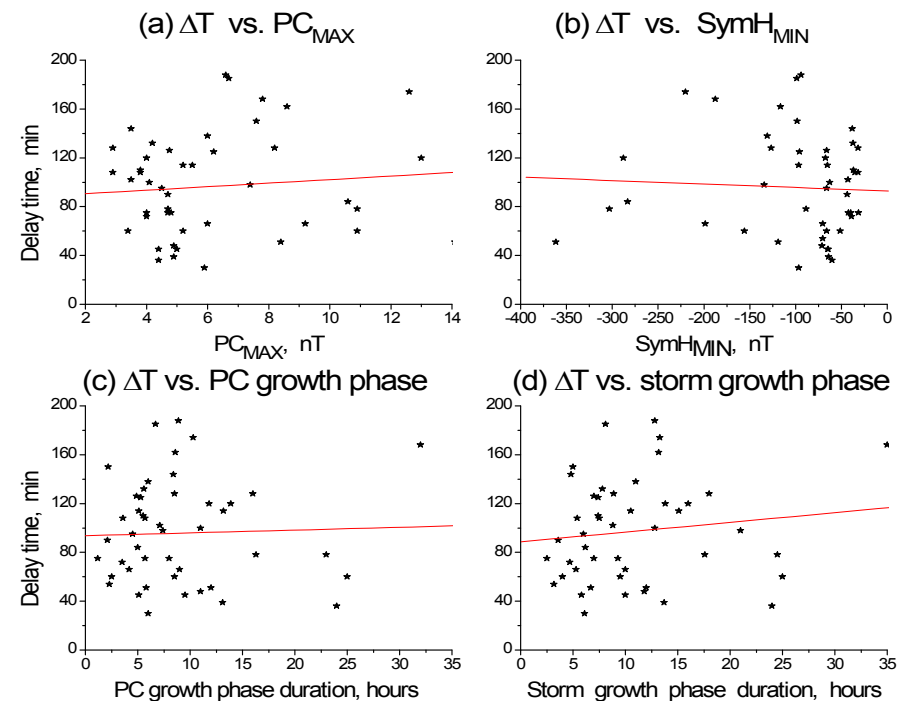

The maximal depression of magnetic field (storm intensity) follows to maximum value of the smoothed *PC* index. **Intensity of storm (Dst_{MIN}) is linearly related to preceding maximal PC value (PC_{MAX}): the higher the *PCmax* value, the larger is magnetic storm intensity (Dstmin).**

Delay times ΔT in response of *SymH_MIN* to the *PC_MAX* occurrence lie in the range from 30 to 180 minutes. Value of time ΔT seems to be slightly dependent on the storm growth phase duration (the longer the growth phase, the larger is delay time), however, this tendency is too slight to be the controlling factor. The mechanisms determining the actual ΔT values are not clear.

Magnetic storm on 07-08 September 2017


2017-0907-0000-0909-0000
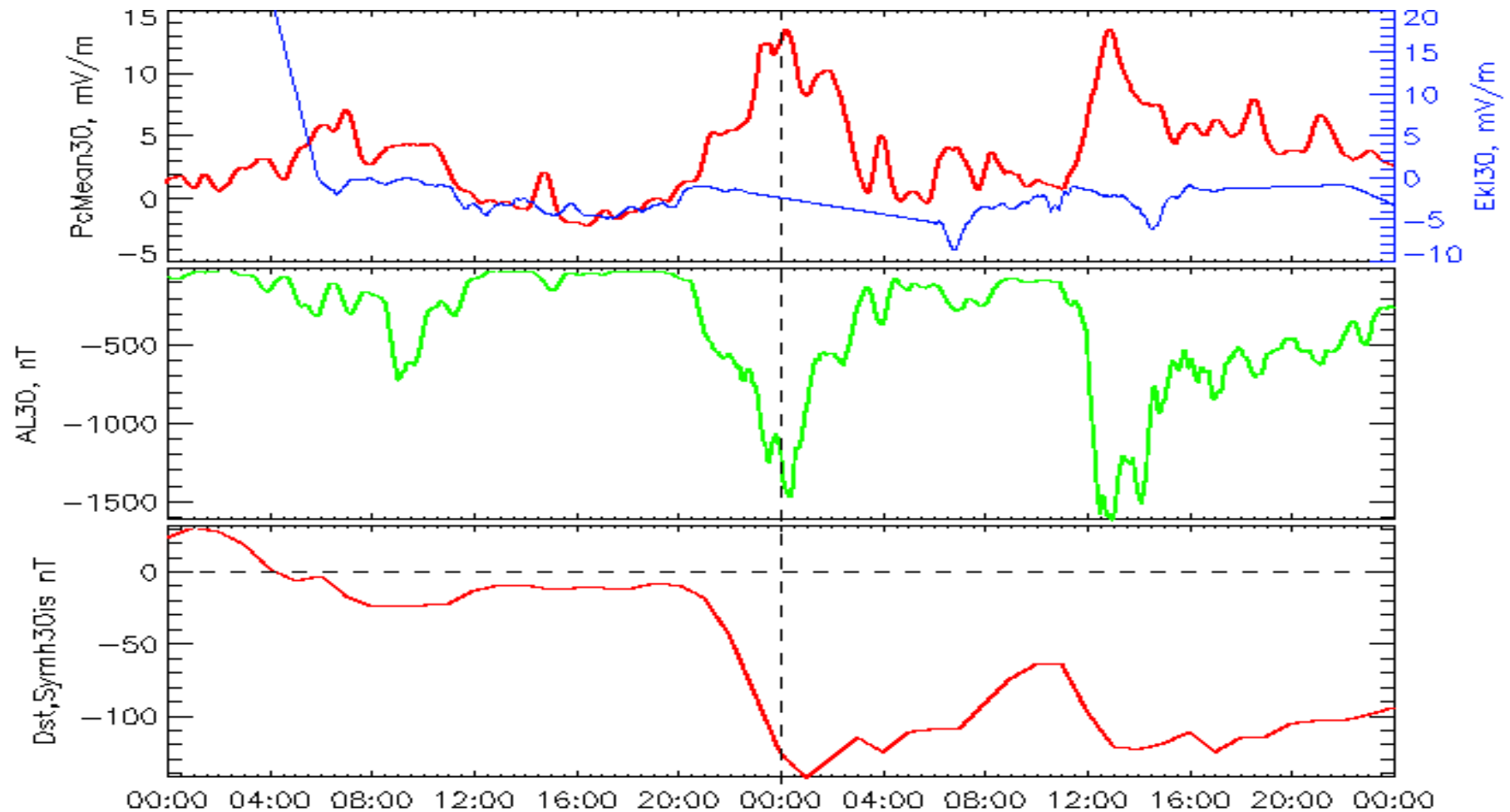
Upper panel: EKL field (blue) in L1 point, according to ACE data 30-min smoothed PC index,
Middle panel: 30-min smoothed AL index,   **Lower panel**: Dst index.
First "classic" storms with intensity Dst=150 nT started at 20:00 UT on 07.09 when PC index exceeded over 1.5 mV/m,
depression of geomagnetic field increased following the PC growth and reached maximum at 02:00 UT with delay ΔT~1.5 h
relative the PCmax=15mV/m. Second storm with intensity Dst=125 min started at 11:40 on 08.09 when PC index again
exceeded 1.5 mV/m, growth phase lasted 3.5 hours, Dstmin was preceded (ΔT~1.5 h) by PCmax, (Almax~1450 and 1600nT)

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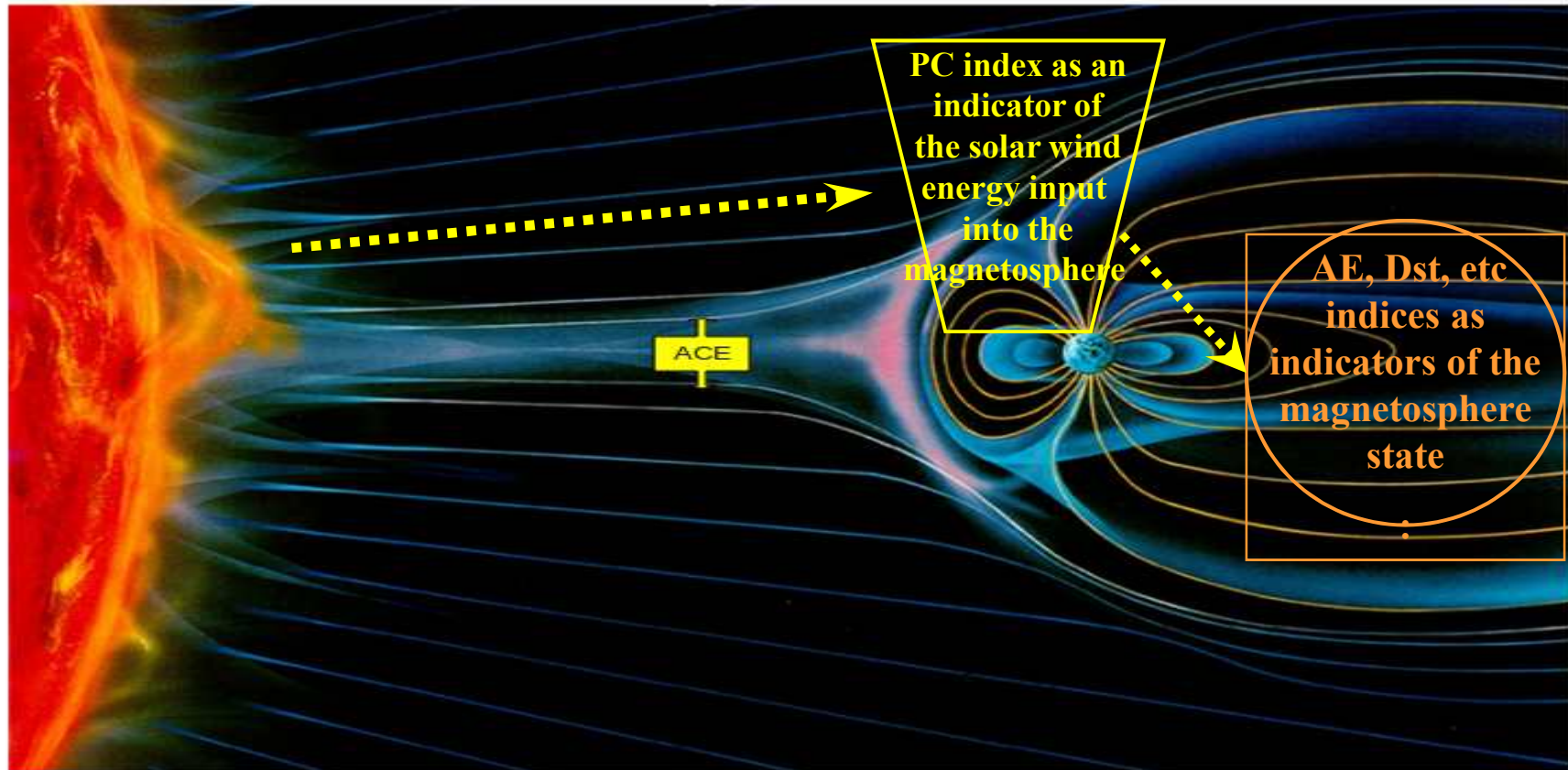
The experimental facts are strongly indicative of the *PC* index as an adequate indicator of the solar wind energy input into the magnetosphere.

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 sets of data on PC index for 1997-2015and 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!

PC web site: http://pcindex.org