RELATION between THE POLAR CAP MAGNETIC ACTIVITY (*PC* index) and MAGNETIC STORMS (*SymH* index) in course of *CIR* and *CME* induced magnetic storms.

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NINTH WORKSHOP

Solar influence on the Magnetosphere, Ionosphere and Atmosphere

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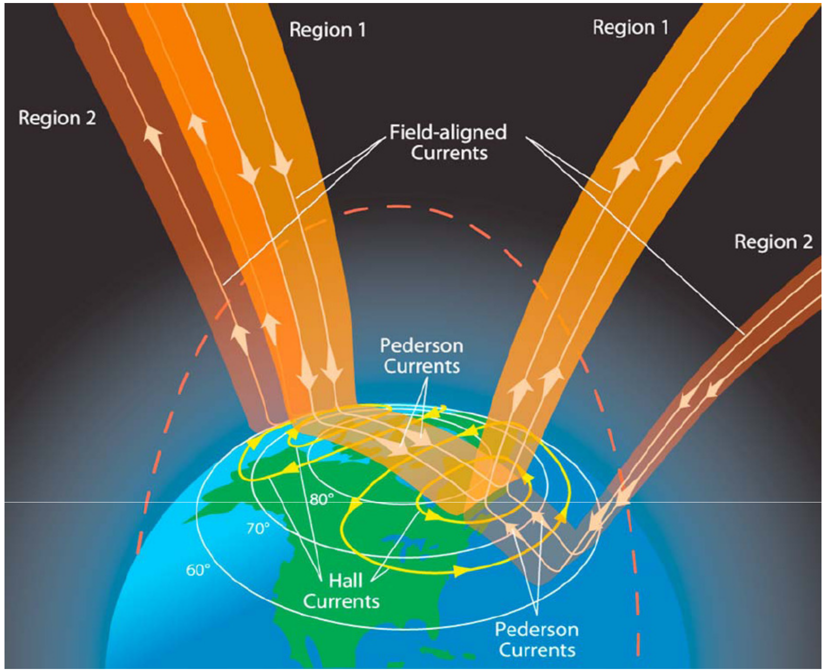
1. *Physical backgrounds for PC index: magnetic activity in the polar caps uniquely responds to the solar wind geoeffective variations*



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]

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

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.**

2. PC index as a proxy for energy that enters into the magnetosphere during solar wind-magnetosphere coupling

[*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 (*dEKL/dt*), not from **any one particular solar wind parameter (such as IMF Bz, Vsw, Psw)**
- Magnetic substorms start during gradually increasing ***PC*** index, the substorm sudden onsets (SO) are preceded by a distinct ***PC*** value leap observed 1-15 min ahead of SO;
- 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;
- The magnetic storms start when the ***E**KL* field and ***PC*** index steadily exceed the threshold > 1.5 mV/m and decay if ***E**KL* and ***PC*** firmly descent below this level.

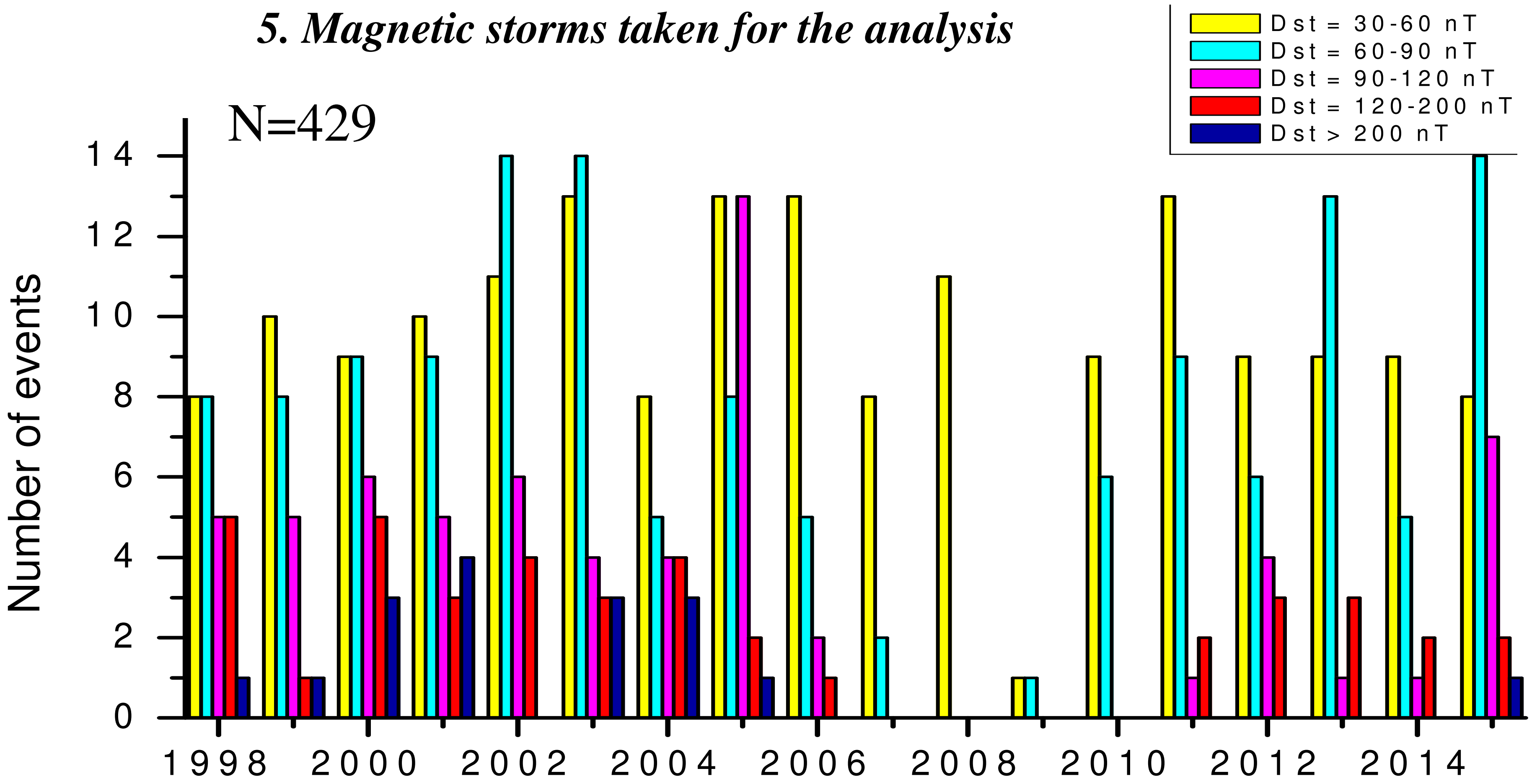
3. Resolutions of XXII Scientific Assembly of International Geomagnetism and Aeronomy Association (12th IAGA), Merida, Mexico, August 2013
No. 3: Polar Cap (PC) index

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).

5. Magnetic storms taken for the analysis

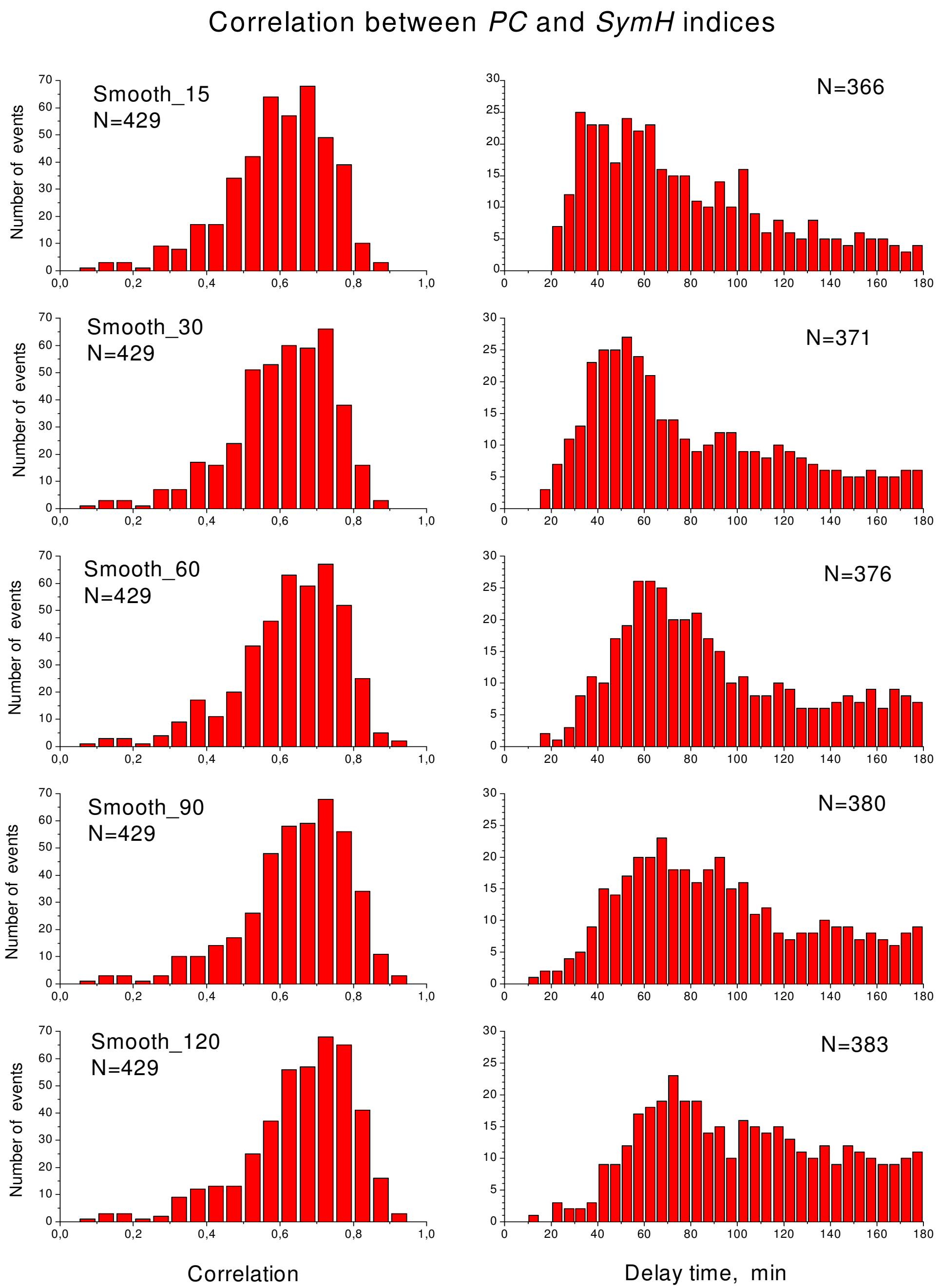


The following parameters were used to characterize magnetic storm: (1) beginning of the geomagnetic field depression is regarded as a magnetic storm beginning, (2) maximum of the geomagnetic field depression (*Dstmin*) is regarded as a magnetic storm intensity, (3) time interval between the moments of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

Magnetic storms with intensity *Dstmin* more than = -30nT, and duration longer than 12 hours, 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.

Figure shows distribution of storm of different intensity over period 1998-2015.

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



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).

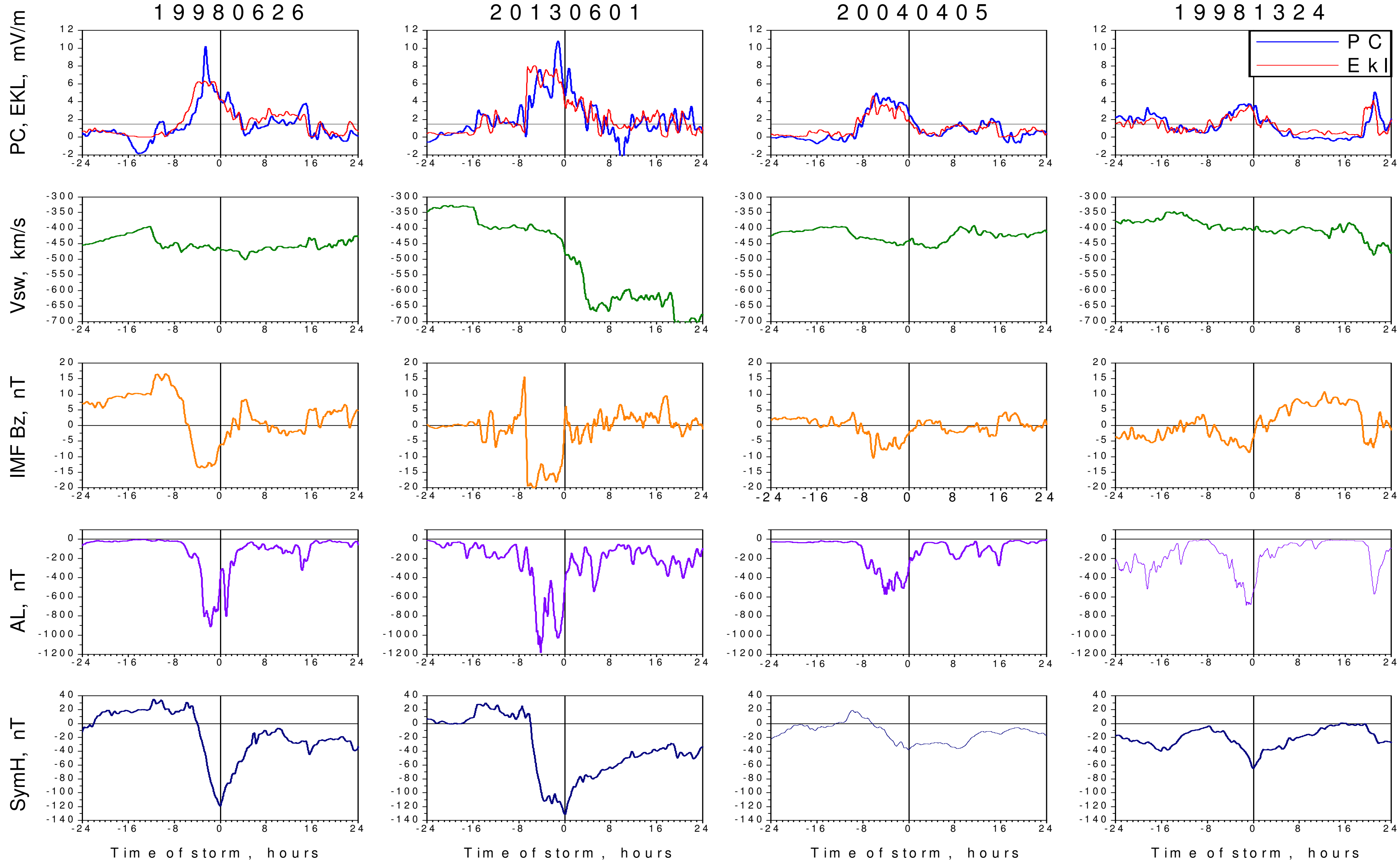
Results:

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.

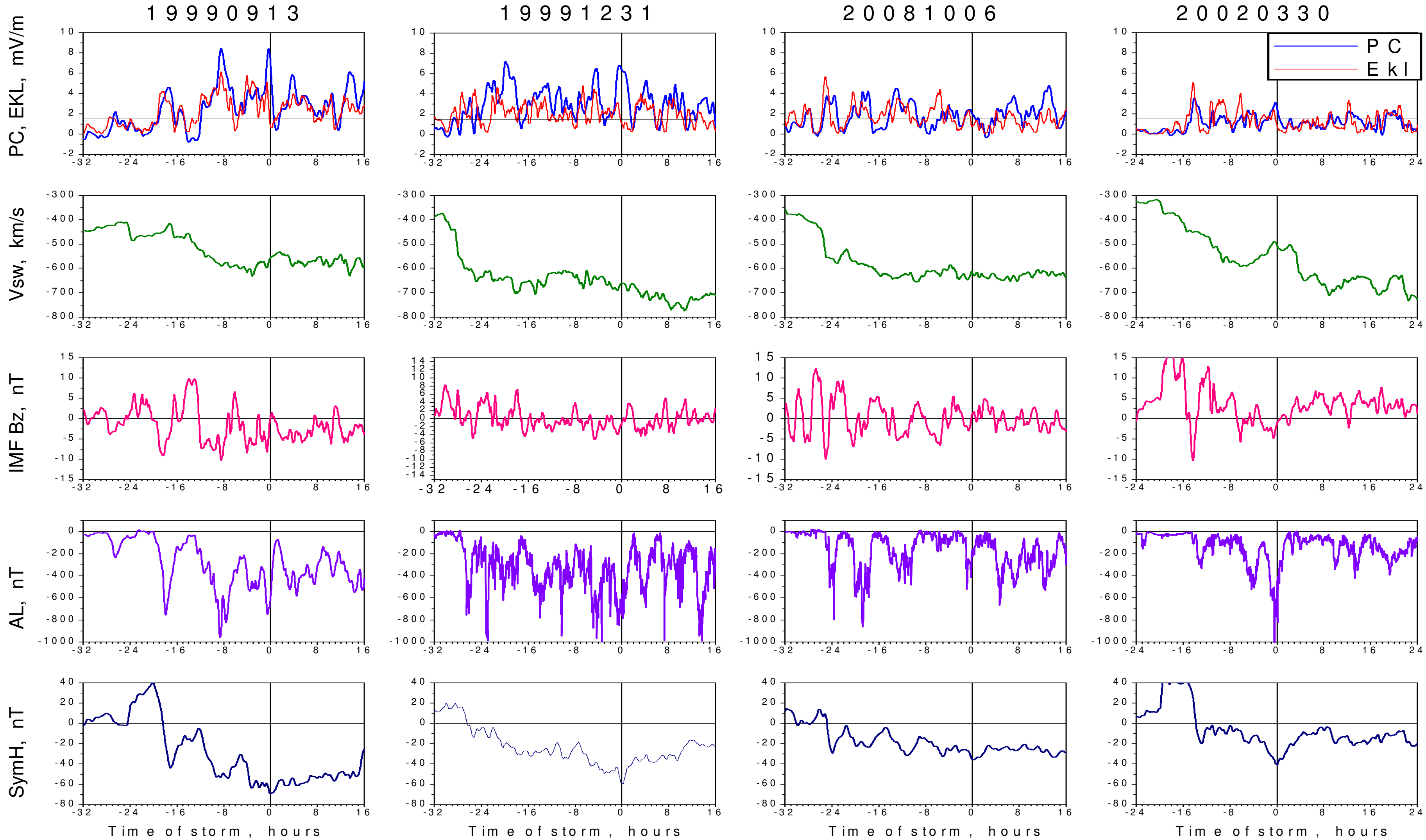
Taking into account these two oppositely acting tendencies, the running window width of 30 min was taken as optimal one.

PC index and development of magnetic storms: Classic storms



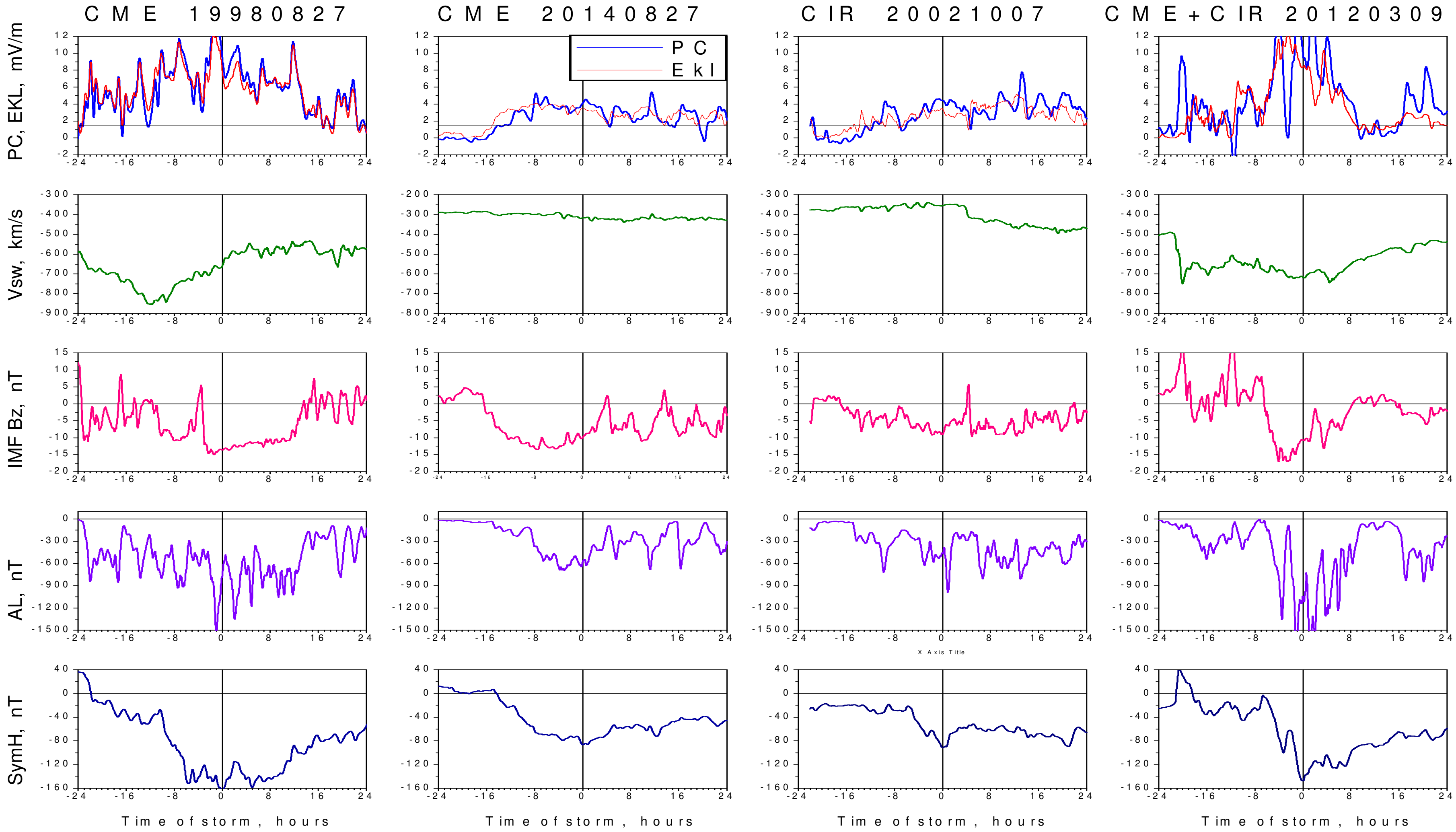
The *PC* index increases systematically after exceeding the threshold level (*PC*=1.5 mV/m) during few or many hours and does not drop below this level. The *PC* behavior is mainly controlled by the southward IMF turning, which determines, in combination with the solar wind velocity, the value of *EKL* 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 pulsations 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



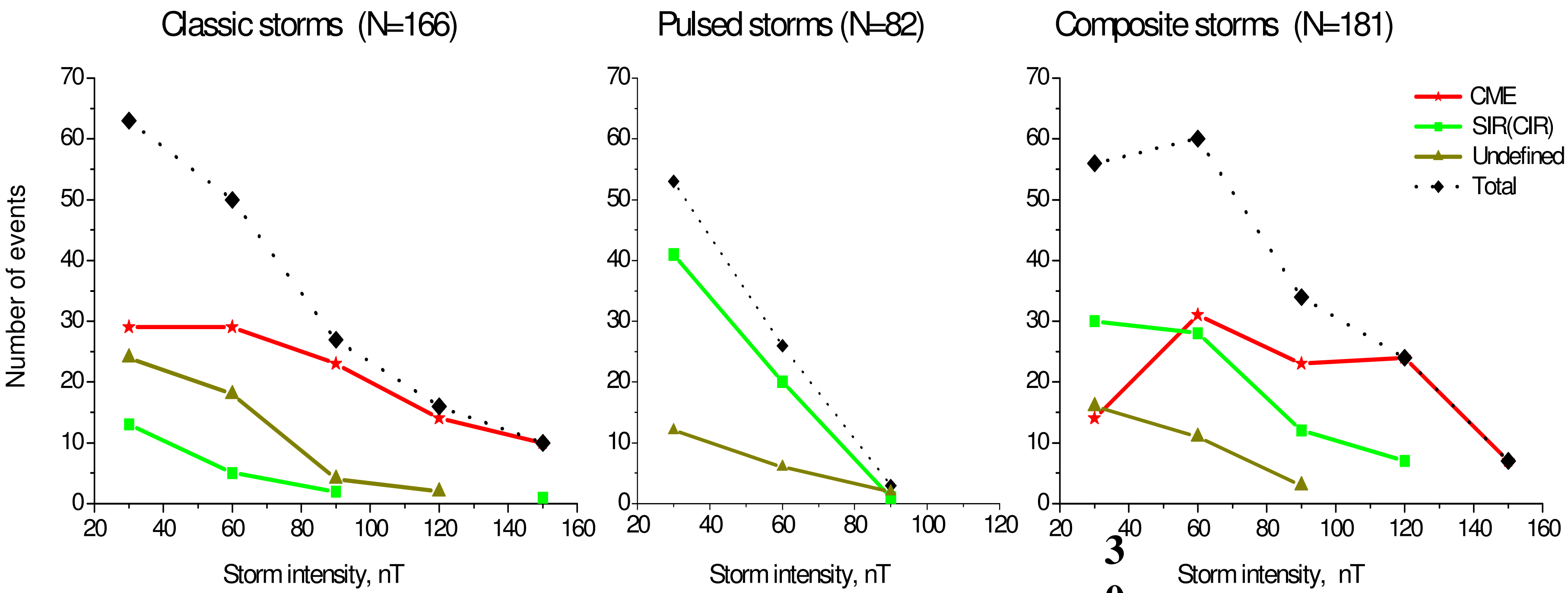
This type of storm events is intermediate between the classic and pulsed types, with the *PC* oscillations proceeding on the background of lifted or "humpbacked" *PC* index level. Composite storms are observed when the IMF Bz fluctuations occur against the background of pronounced southward IMF. The 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 SIR)

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

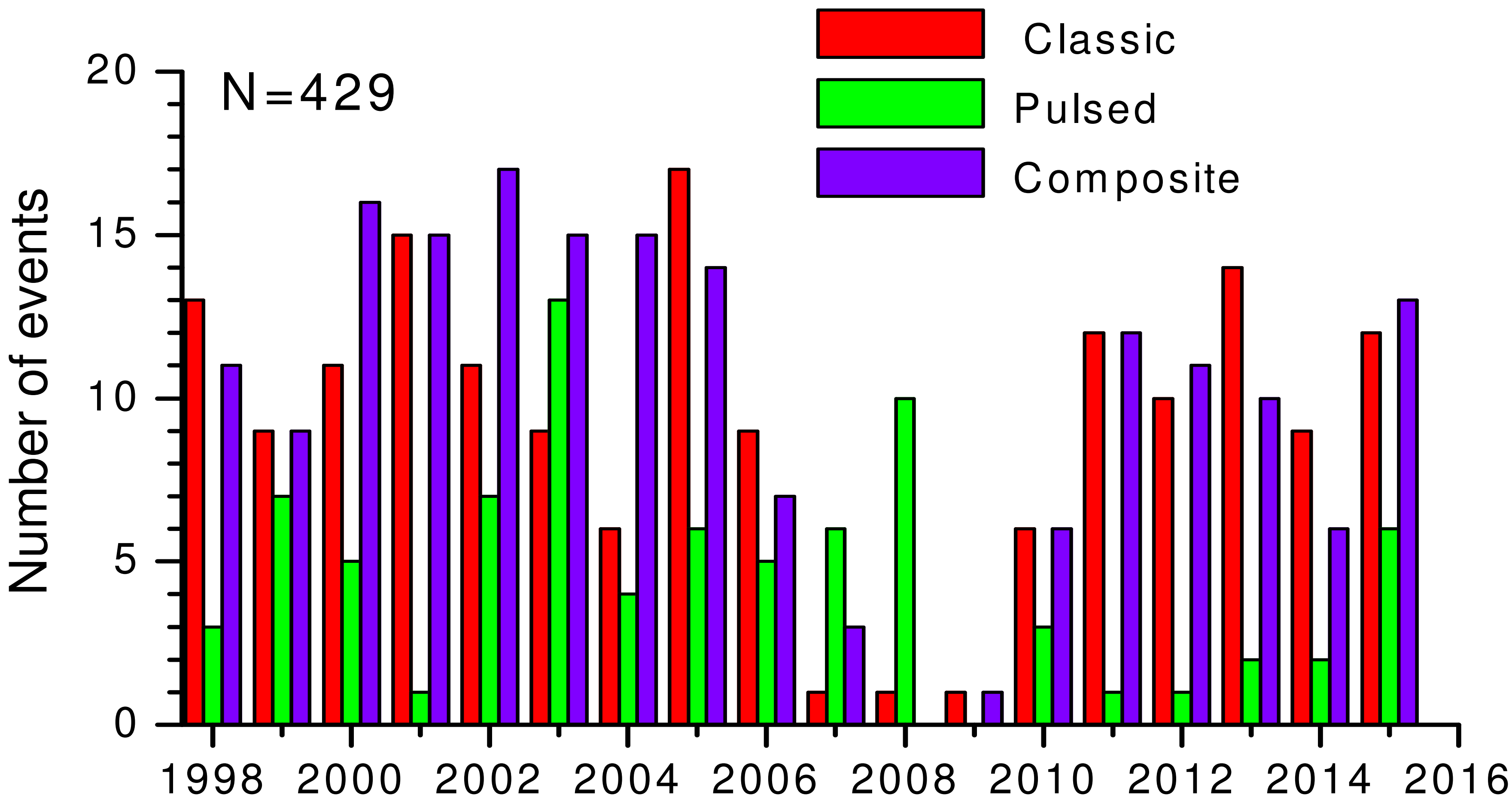
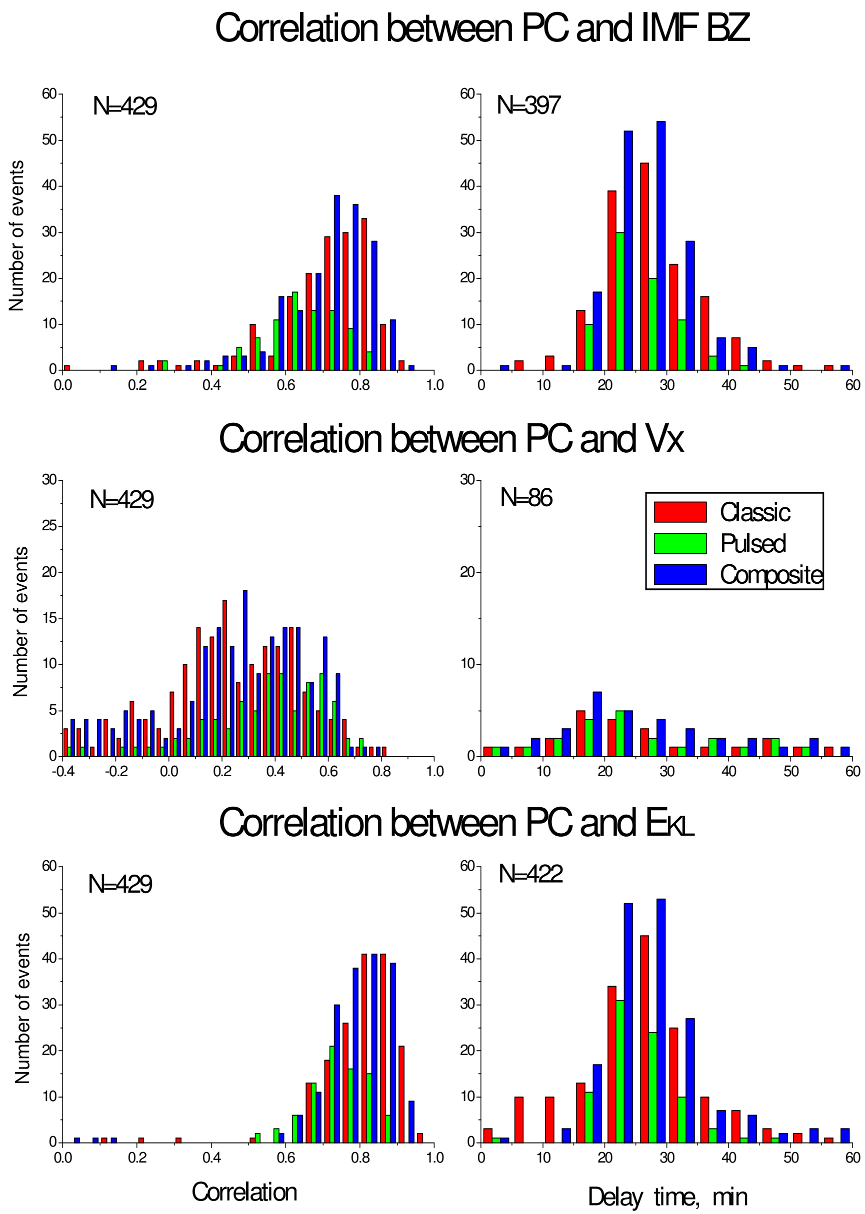


Figure shows distribution of storm of different intensity over period 1998-2015.

The classic and composite storms were observed throughout the whole period, with maximum rate ($N \geq 10$ 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 ($N \geq 10$) in 2003 and 2008, being absent in 2009.

Correlation between PC and the solar wind parameters (B_Z, V_X, E_{KL})



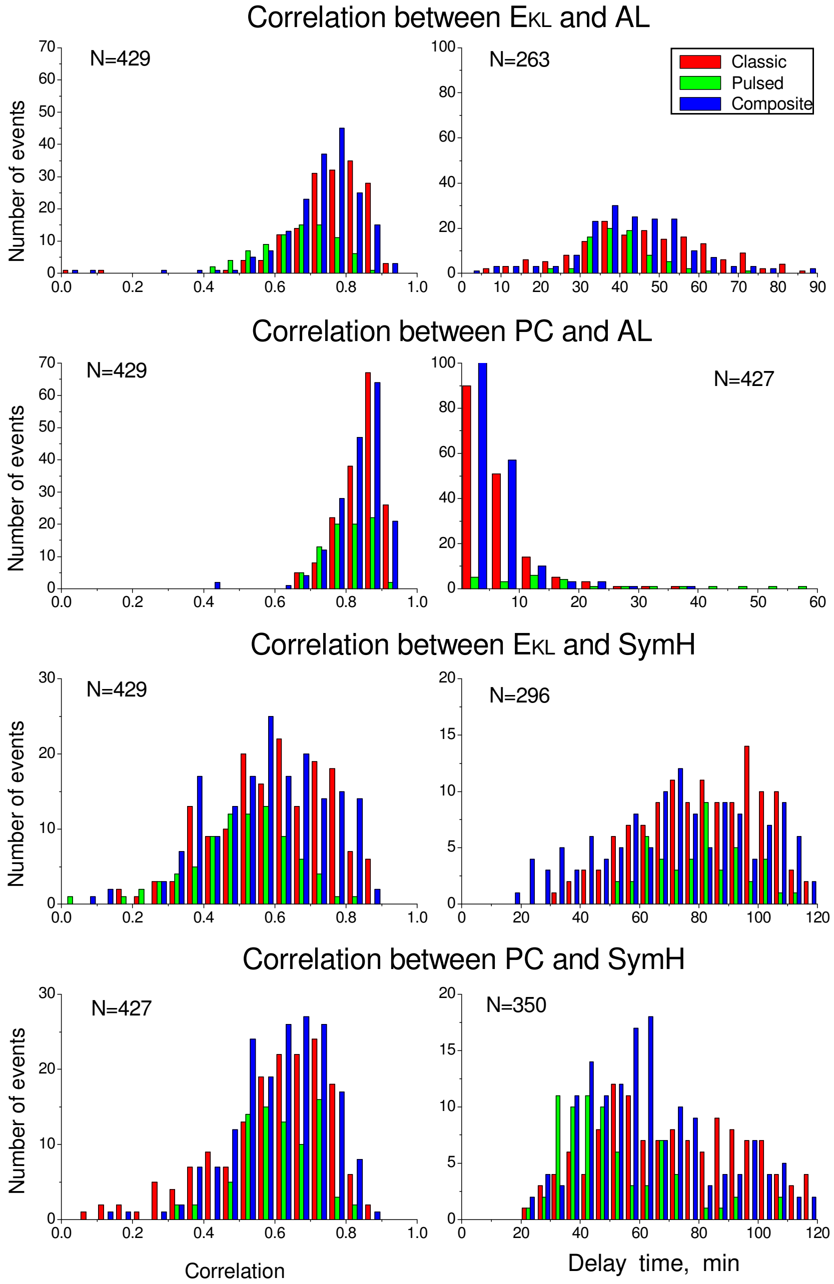
Correlation between the IMF Bz and *PC* (R>0.5) is observed in 397 storm events of 429 **(92.5%),** with typical delay time **ΔT=20-30 min** in response of *PC* to Bz changes.

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 *E_{KL}* 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 *E_{KL}* 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 the solar wind parameters (B_Z, V_x, E_{KL})

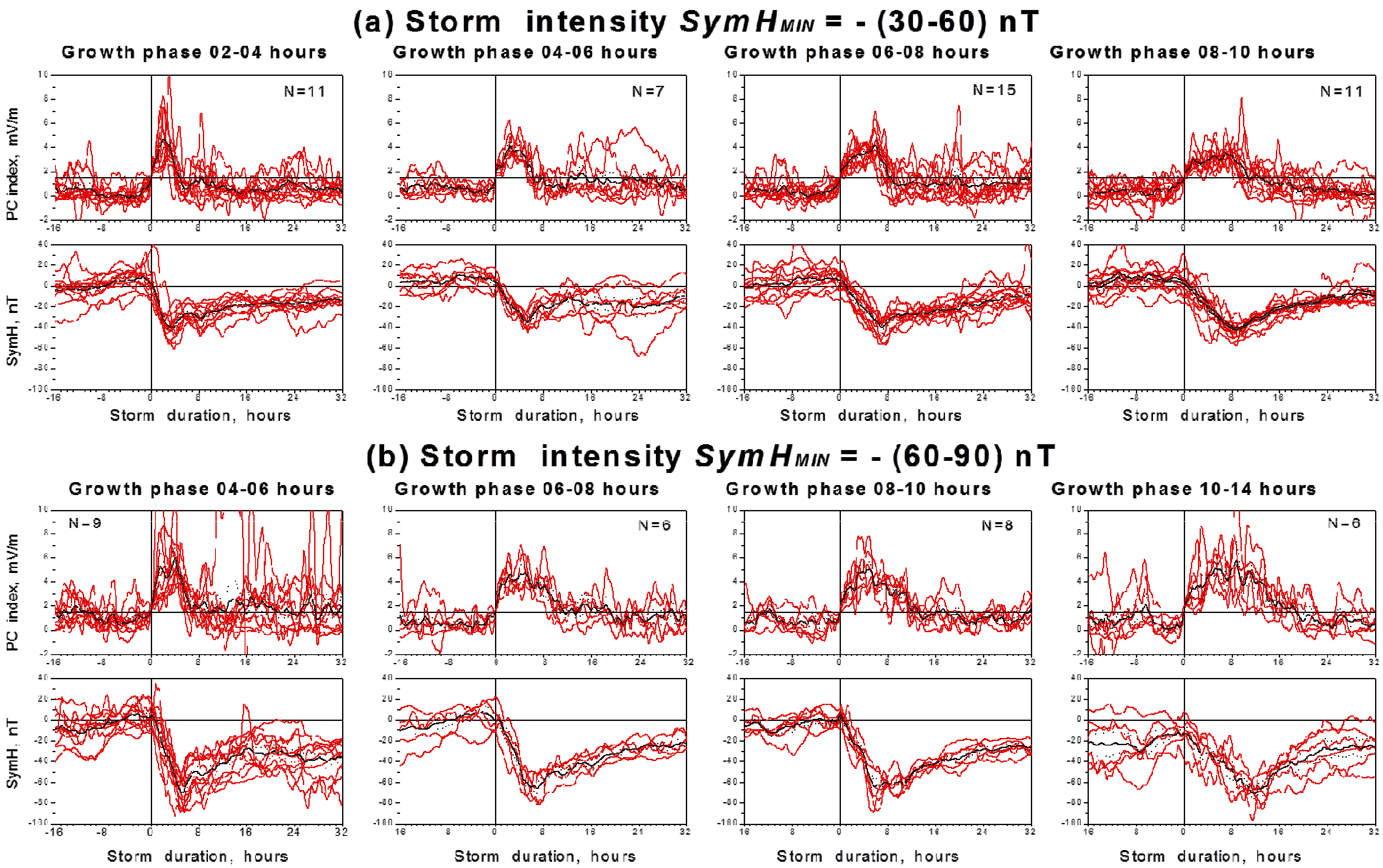


Correlation between the E_{KL} field and *AL* index (R>0.5) is observed in 411 storm events of 429 **(96%).** **Correlation between the *PC* and *AL* indices is always better than R=0.5**, in 72% of storms the correlation coefficients being higher than 0.75. **The *AL* index responds to the *PC* index changes with delay times ΔT=0÷10 min**; this value is in a good agreement with delay time ΔT=25÷55min in the *AL* response to the E_{KL} field evolution if the delay time between E_{KL} and *PC* (ΔT=15÷35 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 (ΔT=50÷110 min) is consistent with **delay time ΔT=30÷80 min in response of *SymH* to the *PC*** changes with allowance for ΔT=15÷35 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 (distribution of the storm occurrence over the coefficients of correlation is more smoothed) than in case of classic and combined storms.

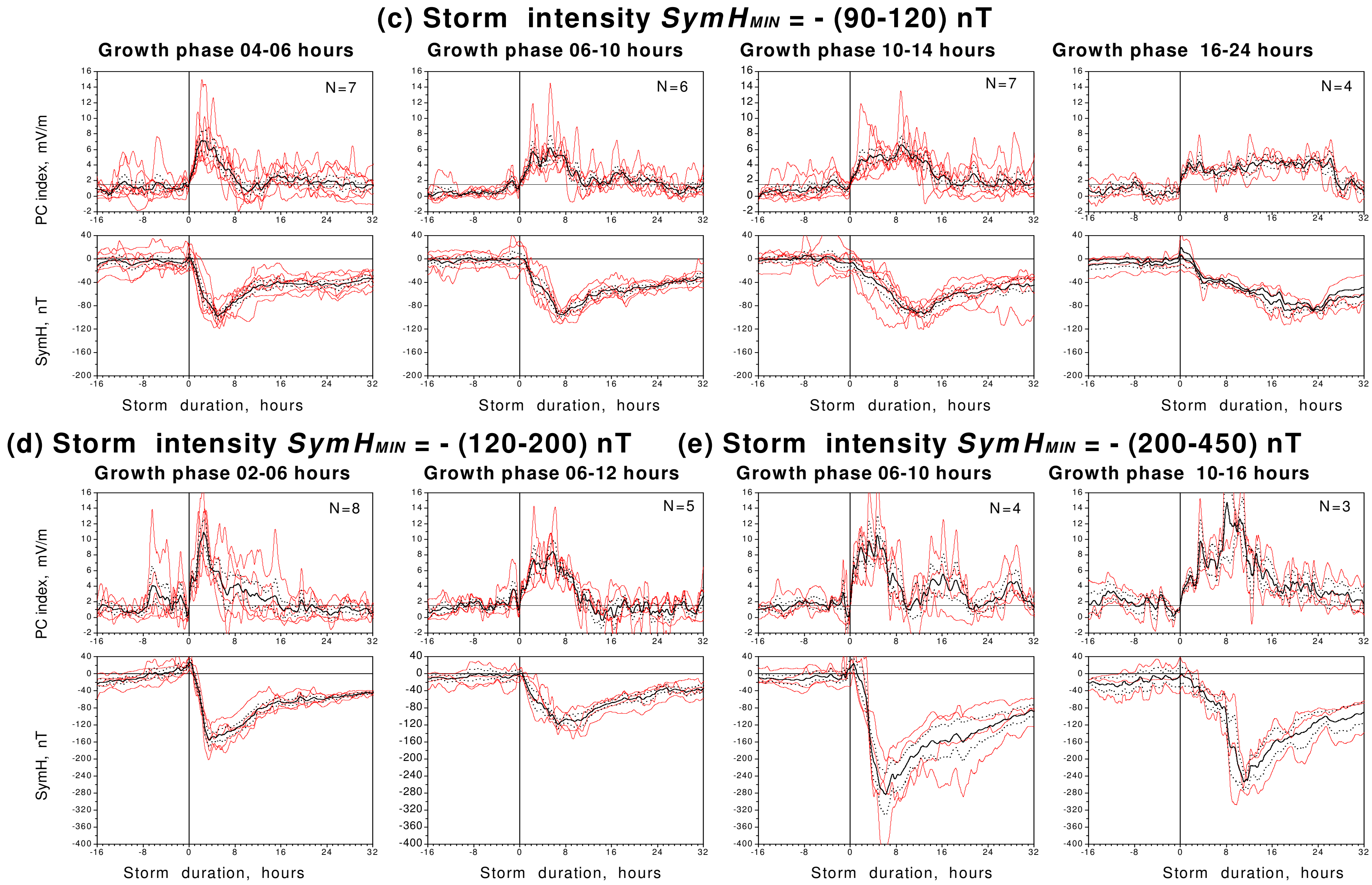
PC index evolution and development of classic storms



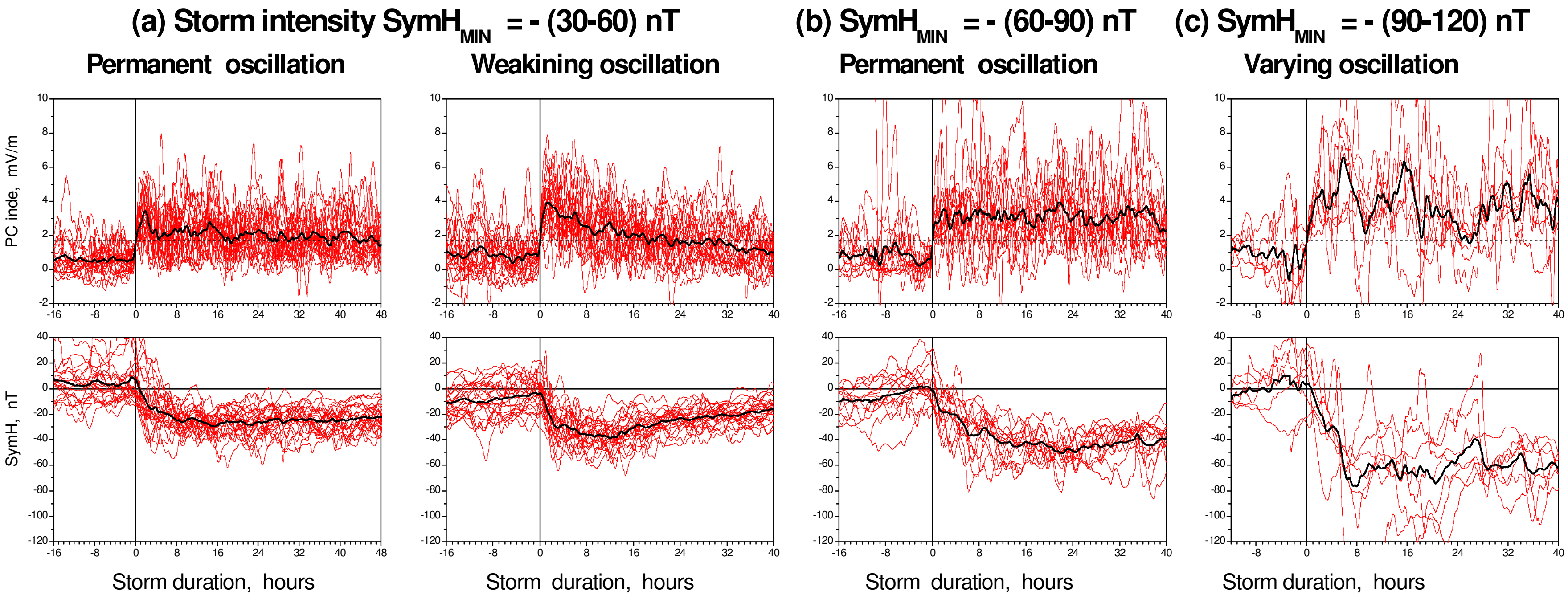
Development of classical magnetic storm is determined by time evolution of the PC index:

- **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.**

PC index evolution and development of classic storms



PC index evolution and development of pulsed storms

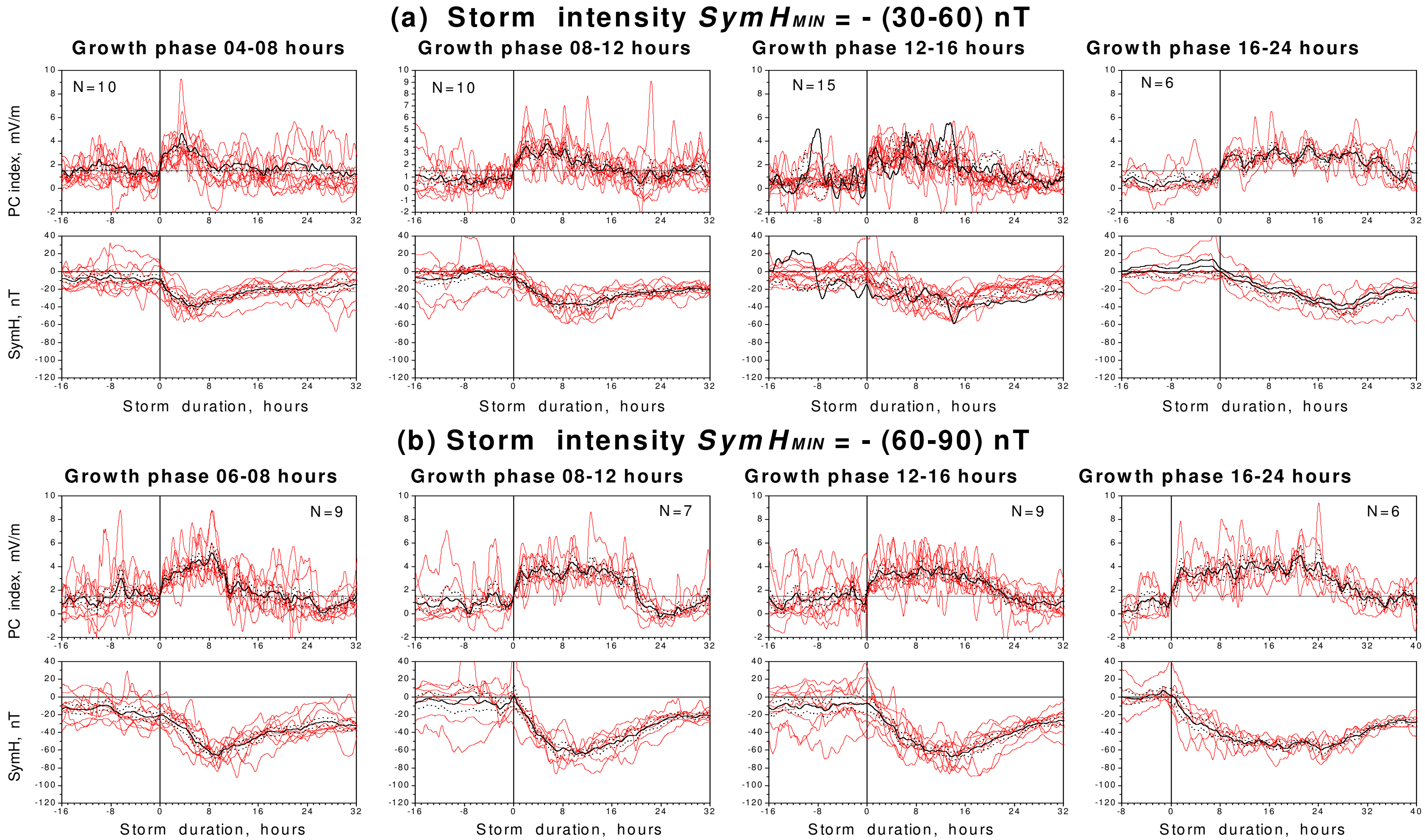


The beginning of the pulsed storms is determined, like to classic storms, by steady exceeding the *PC* index above the threshold level *PC* = 1.5 mV/m. However, the storm progressions turns out to be different. Instead of a prominent *PC* maximum and a single distinct *SymH* minimum, typical of the classic 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). The geomagnetic field depression presents succession of *SymH* fluctuations of modified periods and smoothed amplitudes that implyes the action of accumulating and smoothing processes.

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.

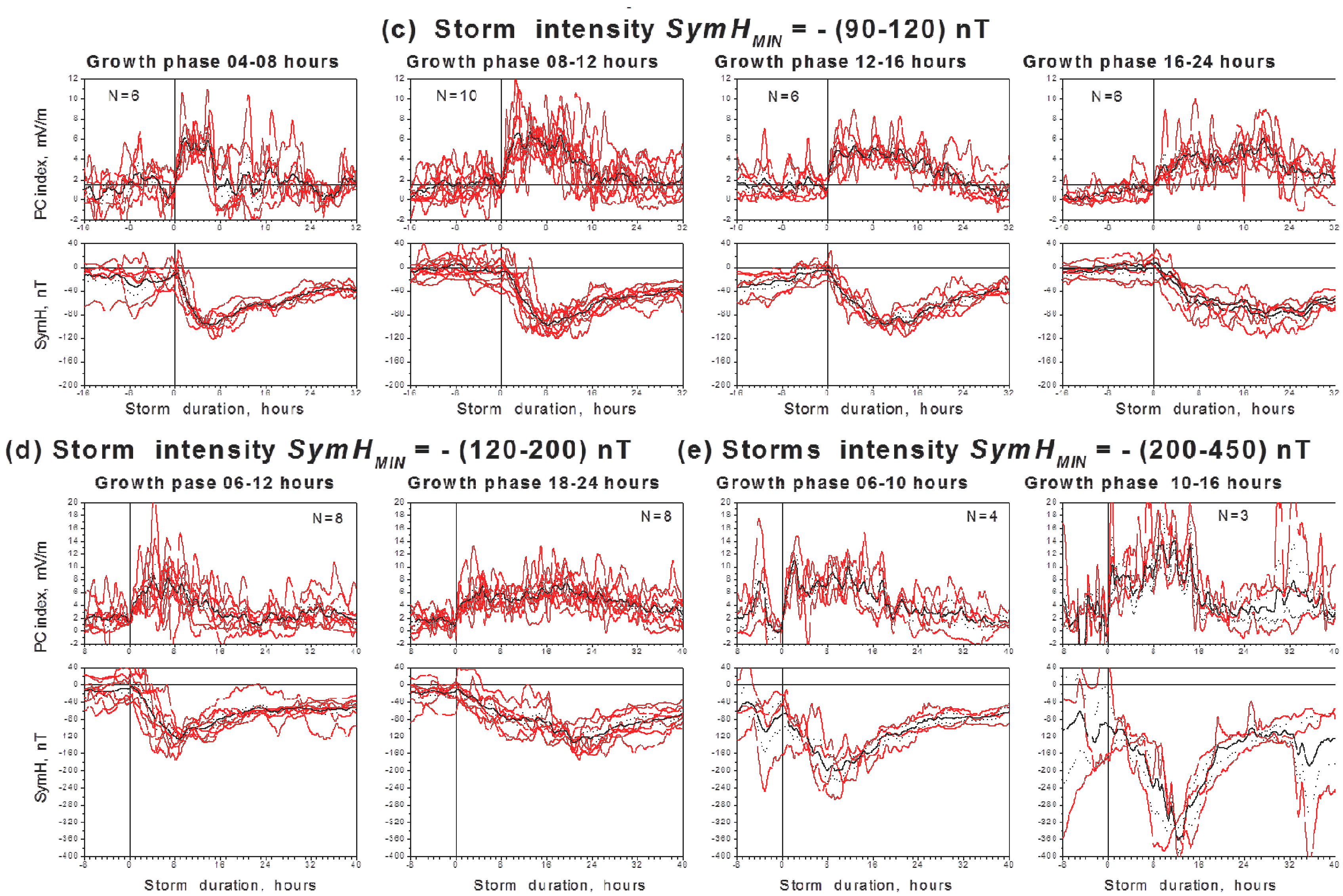
PC index evolution and development of composite storms



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.

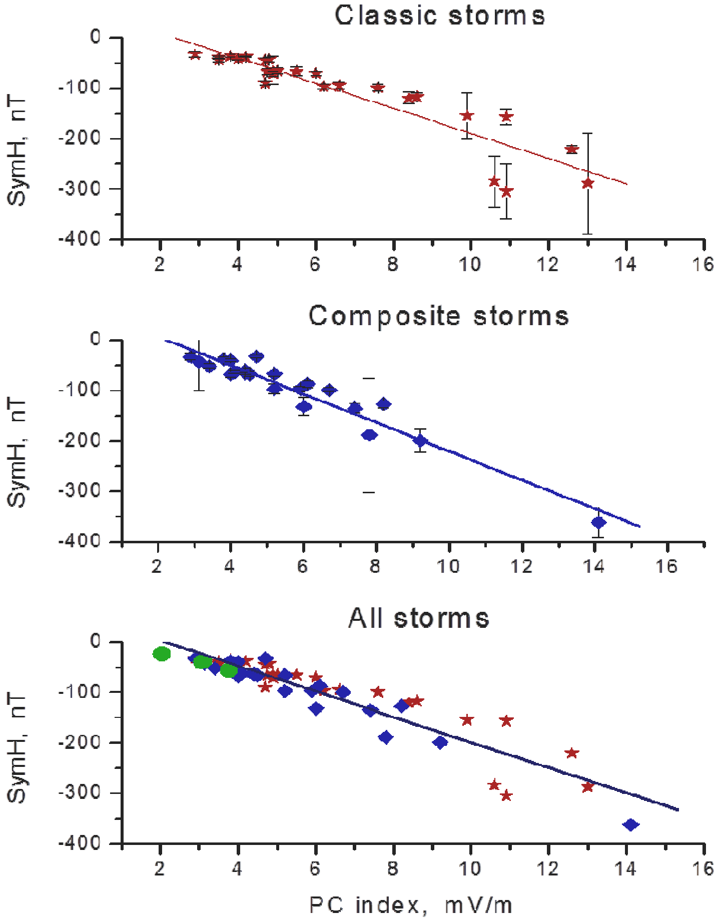
The mean *PC* and *SymH* values for each composed storm category (thick solid black lines in Figures 10) demonstrate the clearly defined regularity: **the maximum depression of geomagnetic field (*SymH*$_{MIN}$) is predetermined by the maximum *PC* value (*PC*$_{MAX}$).**

PC index evolution and development of composite storms

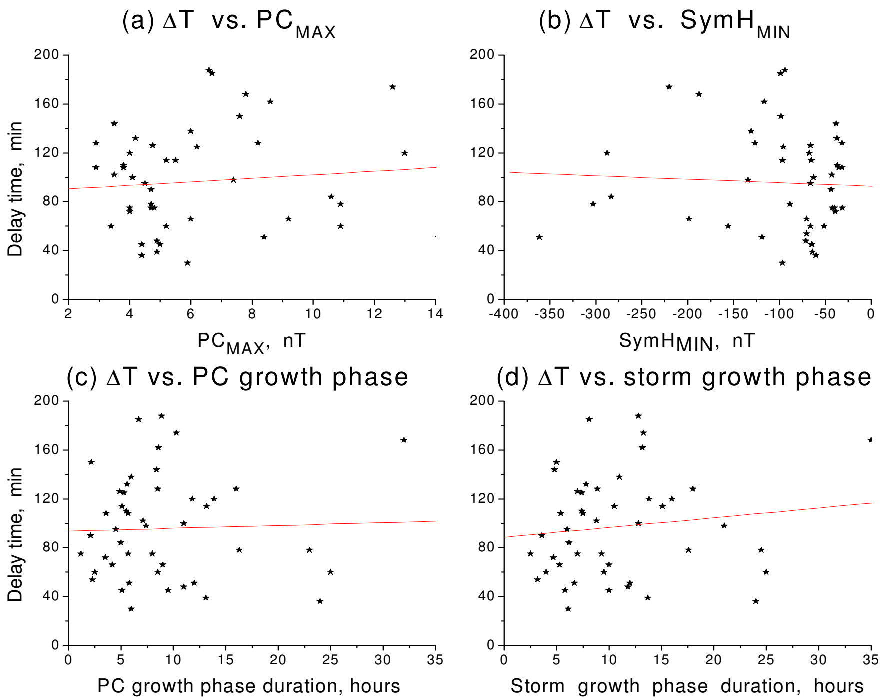


Relationship between the 30-min smoothed PCMAX and SymHMIN indices

PC vs. SymH



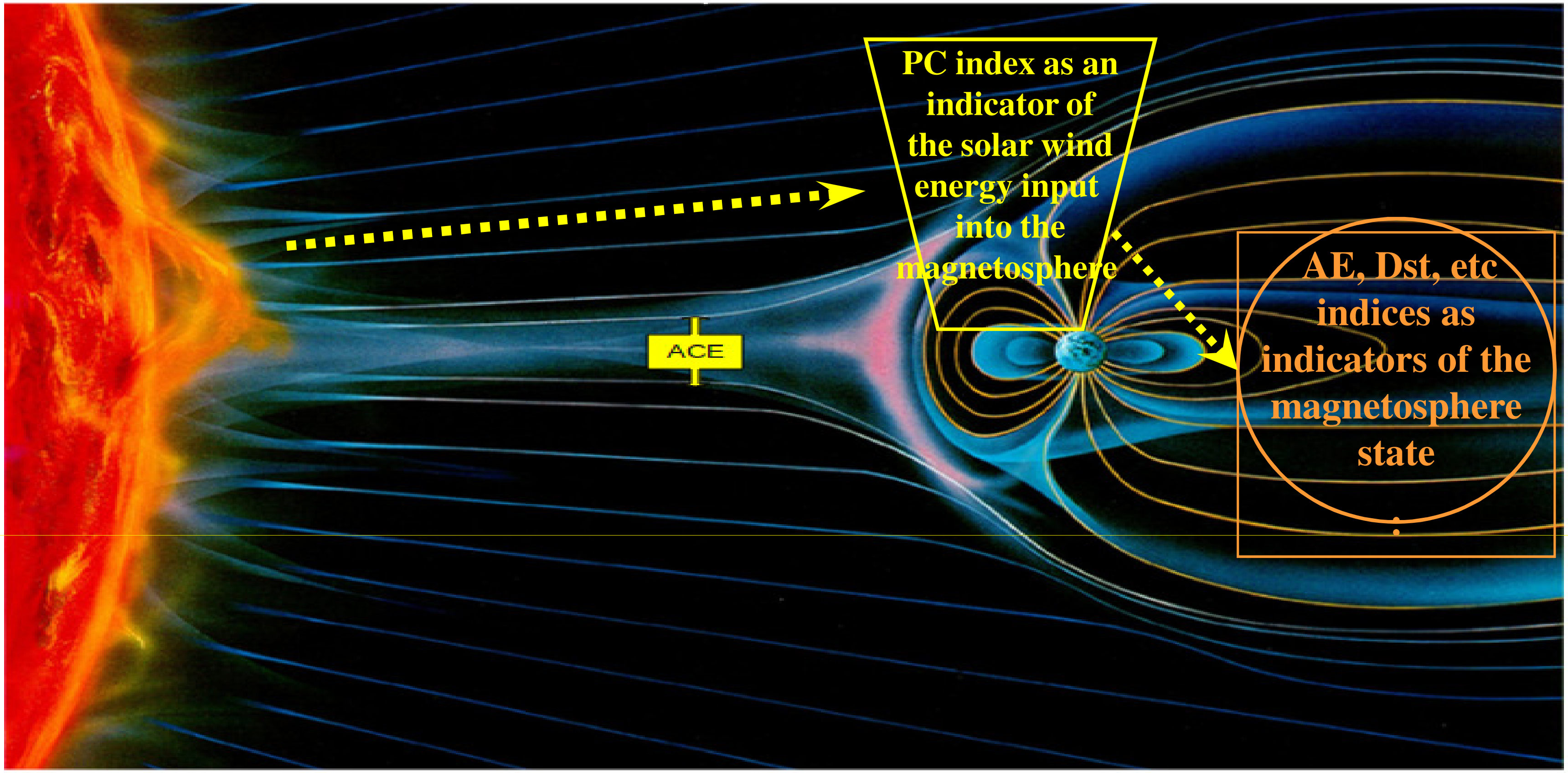
Delay time ΔT in response of SymHMIN to PCMAX as a function PCMAX (a), SymHMIN (b), PC growth phase duration (c), and storm growth phase (d)



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 *SymHMIN* to the *PCMAX* 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.

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 1997-2015) 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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