The Abdus Salam International Centre for Theoretical Physics

2265-26

Advanced School on Understanding and Prediction of Earthquakes and other Extreme Events in Complex Systems

26 September - 8 October, 2011

Similarity and Difference of Impulsive Energy Release Processes

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Similarity and Difference of Impulsive Energy Release Processes

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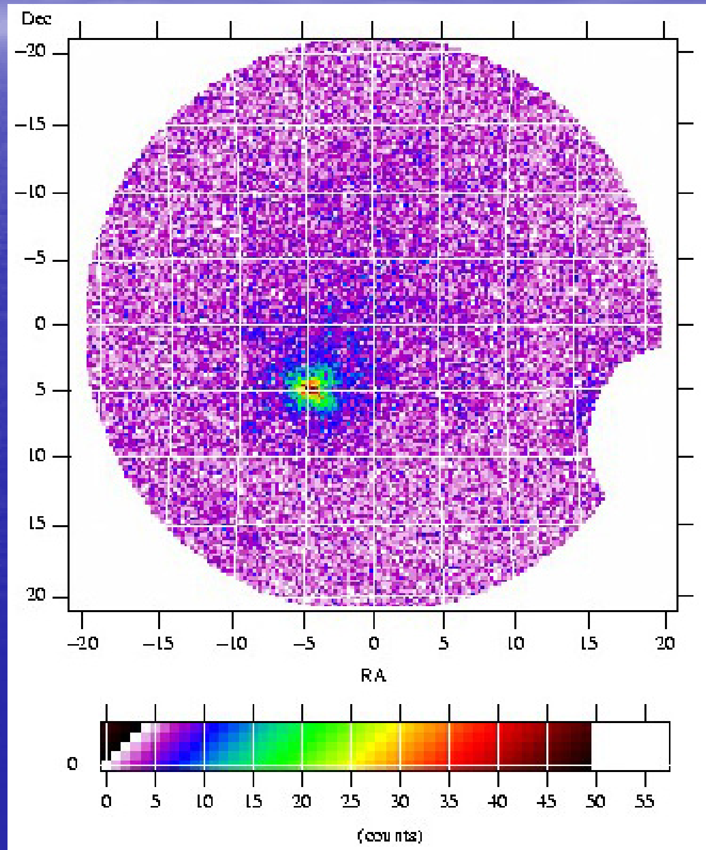
SGR1806-20 sequence

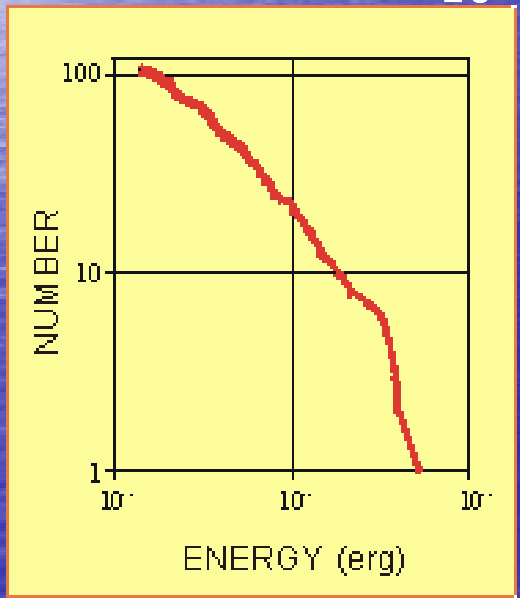
Soft-Gamma-Repeater 1806-20 is the source in Sagittarius, from which more than a hundred X-ray pulsations have been detected. Its location on the sky (1806-20 refer to celestial coordinates: 18 degrees 06 minutes right ascension, -20 degrees declination) is near the Galactic center, which is 25,000 light years away.

The energy of one burst varies from $1.4 \cdot 10^{40}$ erg to $5.3 \cdot 10^{41}$ erg (the largest earthquakes release about 10^{26} erg).



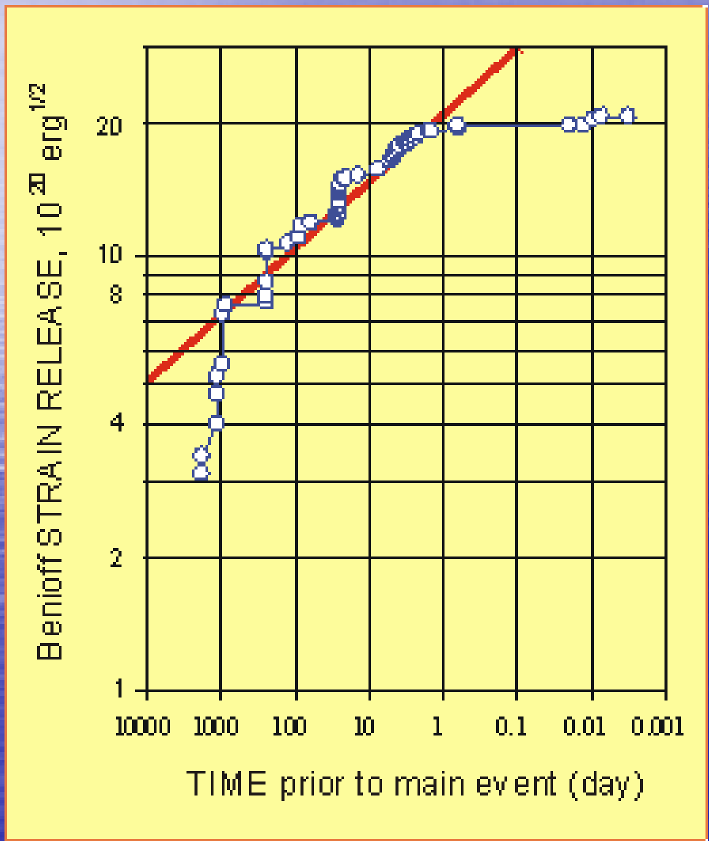
Common general features

A fundamental property of multiple fracturing is the power-law distribution of energy $\log_{10} N(E) = a + b \cdot \log_{10} E$



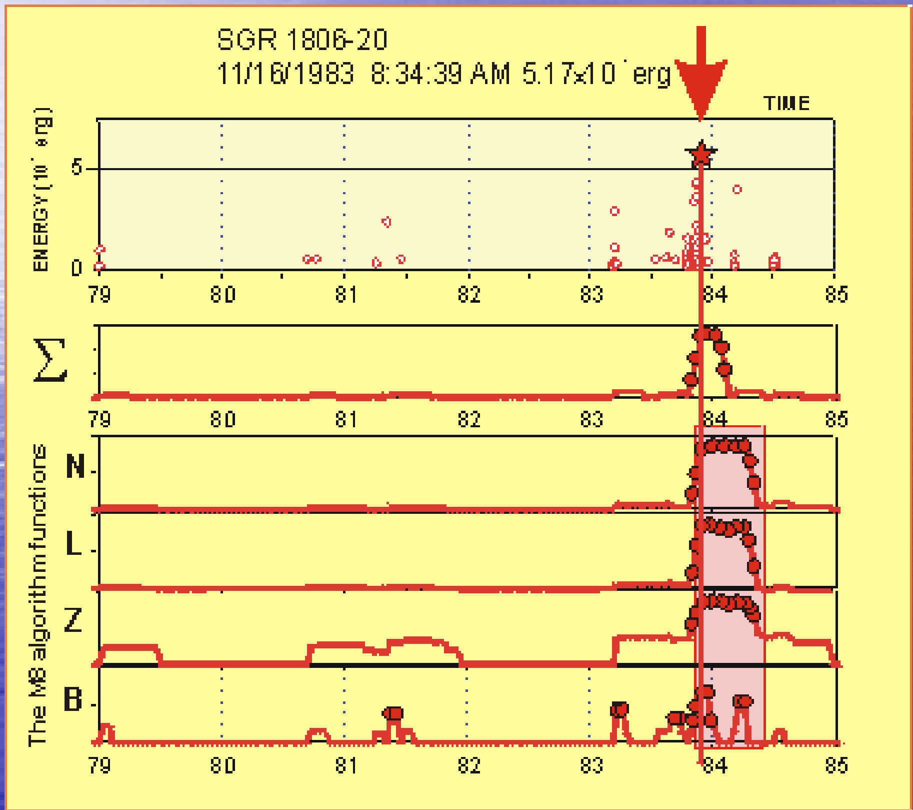
(Gutenberg-Richter relation)

Symptoms of transition to the main rupture



- Escalation of fracturing lasting nearly 1000 days and culminated with the largest starquake on November 16
- The power-law increase of activity, e.g. Benioff strain release ε(t), with a possible trace of the four log-periodic oscillations.

Seismic premonitory patterns



- Pattern $\Sigma \sim E^{2/3}$

  Keilis-Borok & Malinovskaya, 1964
- Pattern B

  Keilis-Borok, Knopoff & Rotwain, 1980
- M8 algorithm

  Keilis-Borok & Kossobokov, 1990

Similarity of starquakes and earthquakes

Qualitative so far

- Gutenberg-Richter relation
- Premonitory changes
- Decay of “aftershocks”
  - – Omori power-law

Starquakes evidence drastic expansion of the Realm of Multiple Fracturing previously observed from the lithosphere of the Earth to laboratory samples

Kossobokov, Keilis-Borok & Cheng, 2000

Introduction and motivation

- Impulsive energy release occurs in many natural systems. Some examples are earthquakes, solar and stellar flares, “neutron-star-quakes”, gamma-ray bursts, current disruptions in plasma devices, etc.
- Some similarities exist in the statistical properties of these phenomena, e.g. power law distributions of released energy and inter-event times

- Is there a common (“universal”) physical mechanism giving rise to these processes?
- This idea has been considered in particular for earthquakes and solar flares (e.g. the Self Organized Criticality paradigm proposed by Bak et al., 1987, 1988)
- The presence of universality in earthquake and solar flare occurrence has been more recently suggested on the basis of the analogies found in the statistical properties of the temporal sequences of the two phenomena (de Arcangelis et al. 2006)

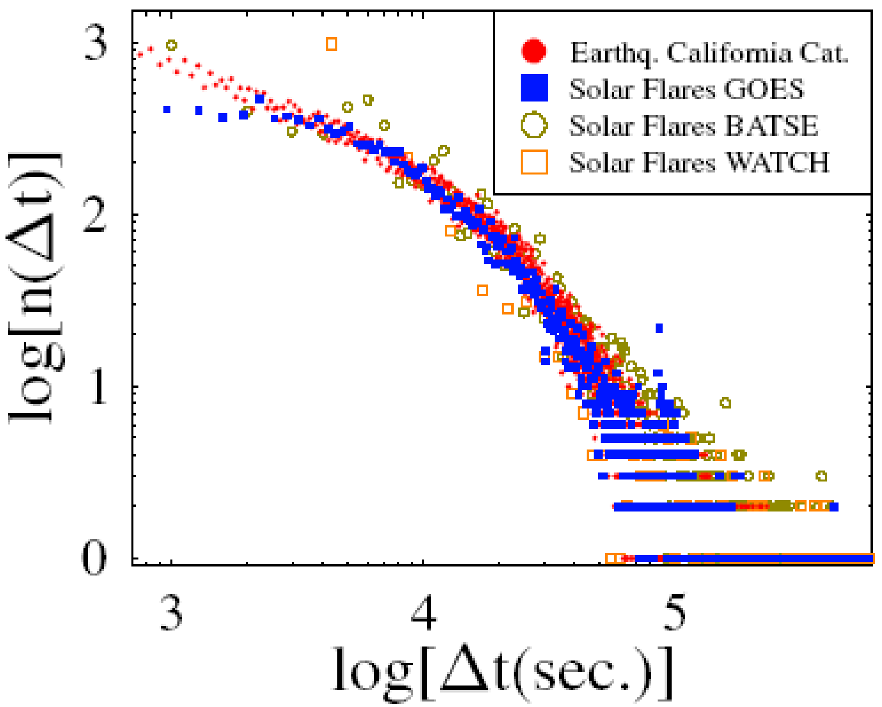


FIG. 1 (color online). The number distribution $n(\Delta t)$ of intertimes Δt between consecutive events in solar flare and earthquake catalogs. Solar data refer to x-ray observations in three different energy ranges covering different periods of the solar cycle: soft x-ray data in the 1.5–2.4 and 3.1–24.8 keV ranges from the GOES catalog (■); hard x-ray (>25 keV) from the BATSE catalog (○); intermediate x-ray (10–30 keV) from the WATCH catalog (□). Earthquake intertimes data are from the California catalog for events with magnitude $M \geq 2$ (●).

Introduction and motivation

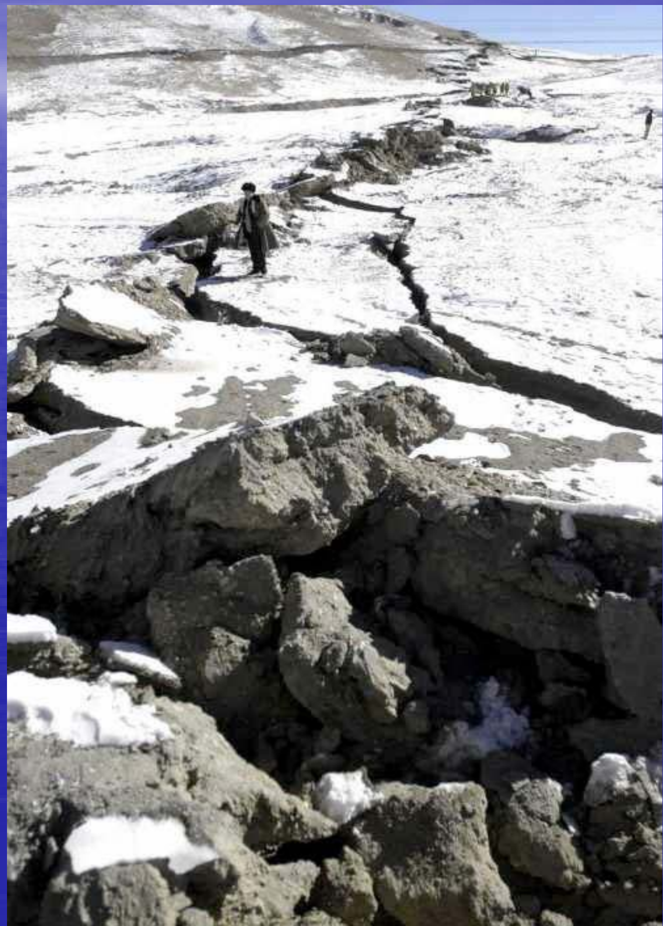
- In this work we reconsider the question of “universality” in earthquakes and solar flares analyzing the statistical properties of the sequences of events available from the SCSN earthquake catalog and in the GOES flare catalog

- An important technical issue in studies of probability distributions is the binning method. In order to reduce the ambiguities related to the choice of binning we decided to work with cumulative distributions

Earthquakes

- Sudden energy release events in the Earth crust.

  - A coherent phenomenology on seismic events, which we evidence from their consequences, is lacking. Apparently, earthquakes occur through frictional sliding along the boundaries of highly stressed hierarchies of blocks of different sizes (from grains of rock about 10^{-3} m to tectonic plates up to 10^{7} m in linear dimension) that form the lithosphere of the Earth (*Keilis-Borok 1990*).
  - $E = 10^{2} \div 10^{18}$ J (i.e., $M = -2 \div 9$)
  - Earthquakes occur prevalently in seismic regions, i.e. in fault zones.

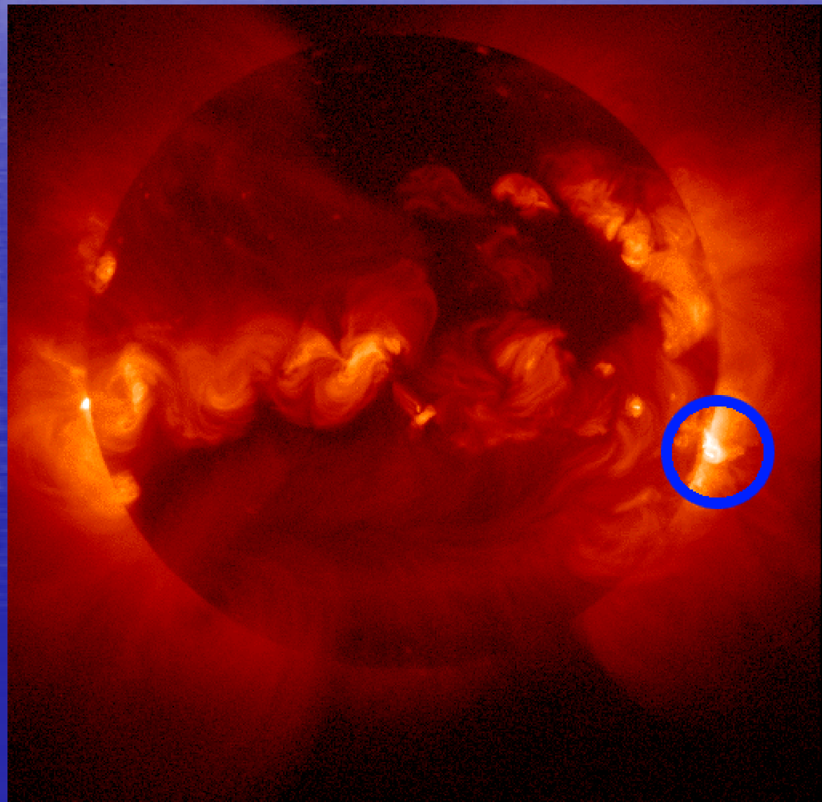


The Nov 14, 2001, Kokoxili Earthquake along the Kunlun fault in Tibet (Xinhua/China News Agency)

Solar flares

- Sudden energy release events in the solar atmosphere
- Emission observed in a wide frequency range of the E.M. spectrum, from radio waves up to X-rays and γ-rays

- Solar flares are due to the conversion of magnetic energy (accumulated in the solar atmosphere as a consequence of turbulent convective motions) into accelerated particles, heating, plasma flows.
  - $E = 10^{17} \div 10^{26}$ J
- Flares occur prevalently in magnetic activity regions



Soft X-ray image of the solar corona (Yohkoh spacecraft)

Data

Earthquake catalog

- Southern California Seismic Network (SCSN) catalog
- Period 1986-2005
- Over 350000 events. About 87000 with $M \geq 2$.

Solar flare catalog

- Compiled from observations of the Geostationary Operational Environmental Satellites (GOES) in the soft X-ray band 1.5-12.4 keV
- Period 1975-2006. Three solar cycles (1975-1986, 1986-1996, 1996-2006).
- Flares classified according to the peak burst intensity I_p in the above band

B class if $I_p < 10^{-3}$

C class if $10^{-3} < I_p < 10^{-2}$

M class if $10^{-2} < I_p < 10^{-1}$

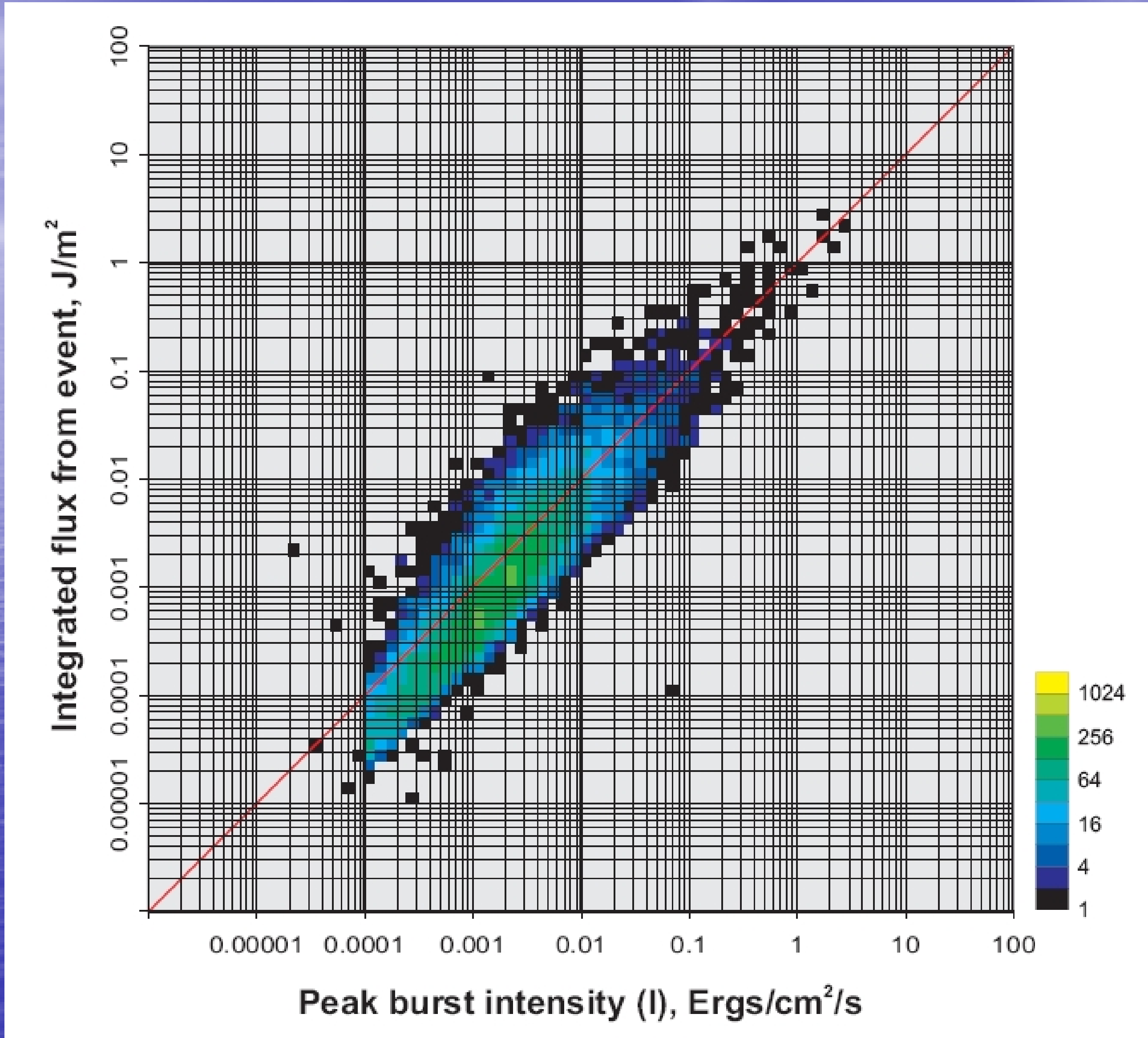
X class if $I_p > 10^{-1}$

For example a C4.6 class means that $I_p = 4.6 \times 10^{-3}$ erg s^{-1} cm^{-2}

(Values of I_p given in erg s^{-1} cm^{-2})

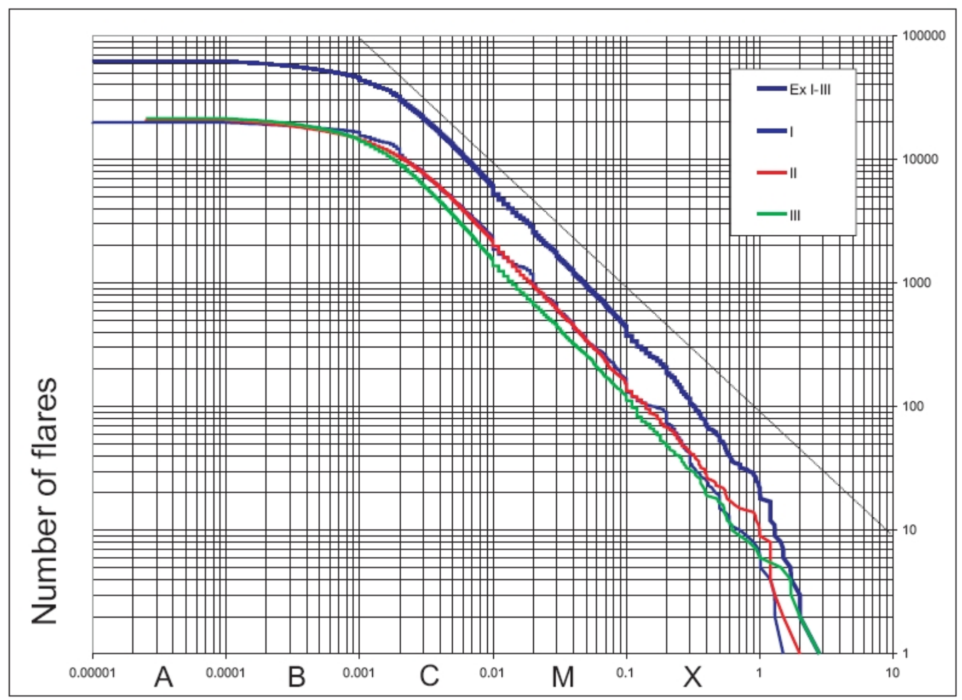
- Over 62000 events. About 32000 of class ≥ C2

Flare peak burst intensity vs. integrated flux

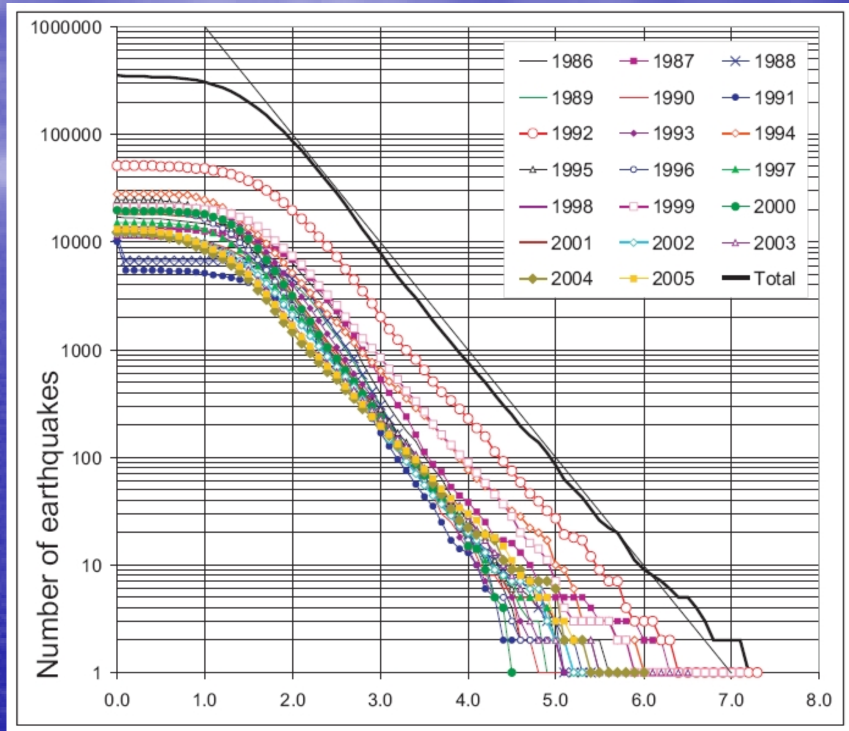


Gutenberg-Richter plots

Solar flares



Earthquakes

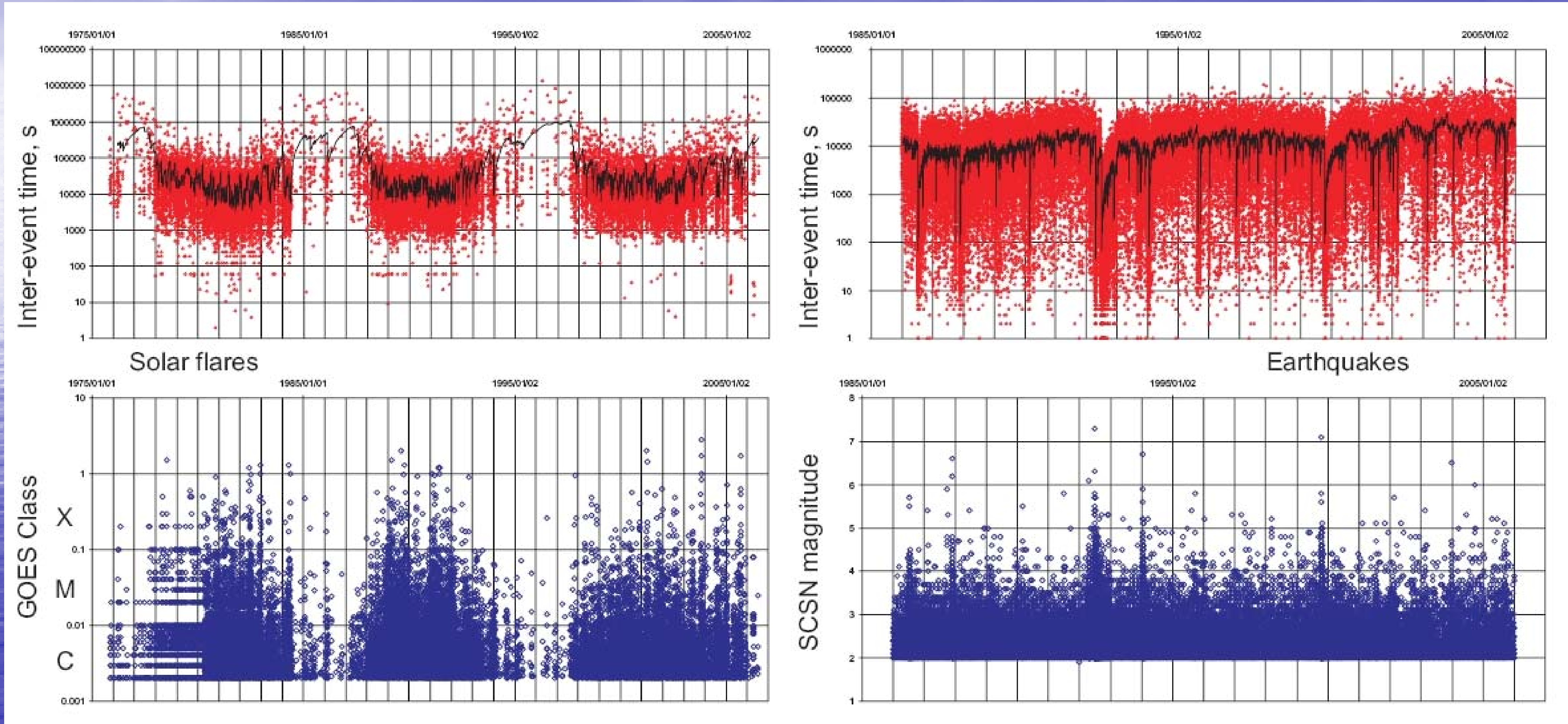


- Lower breakpoints of the power law linearity around C2 class for flares and M2 magnitude for earthquakes, suggest incompleteness of the catalogs below these values
- These cut-offs were considered in the rest of our analysis

Inter-event times and event magnitude vs. time

Solar flares

Earthquakes



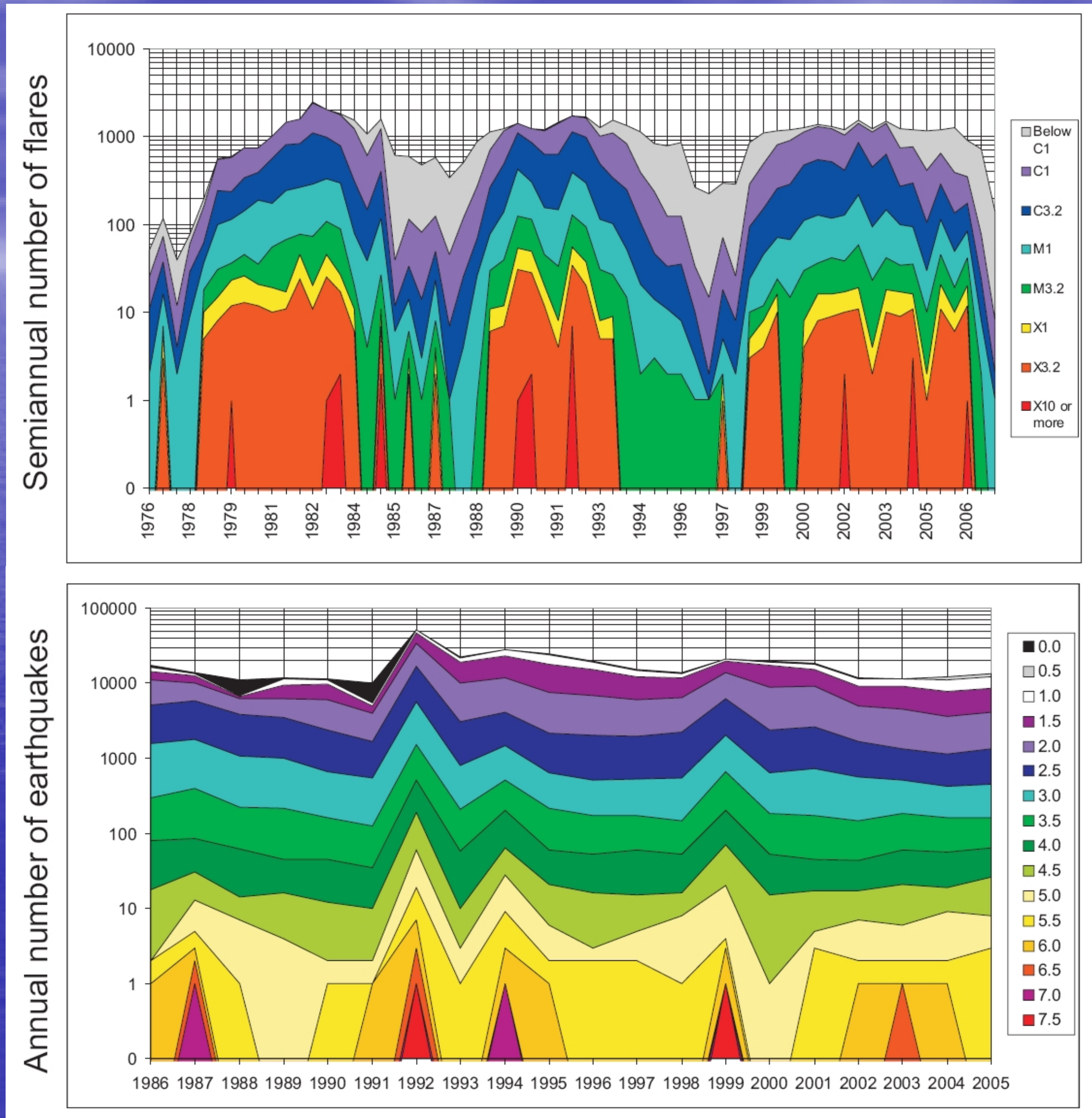
GOES class vs. time

Magnitude vs. time

Magnitude frequencies vs. time

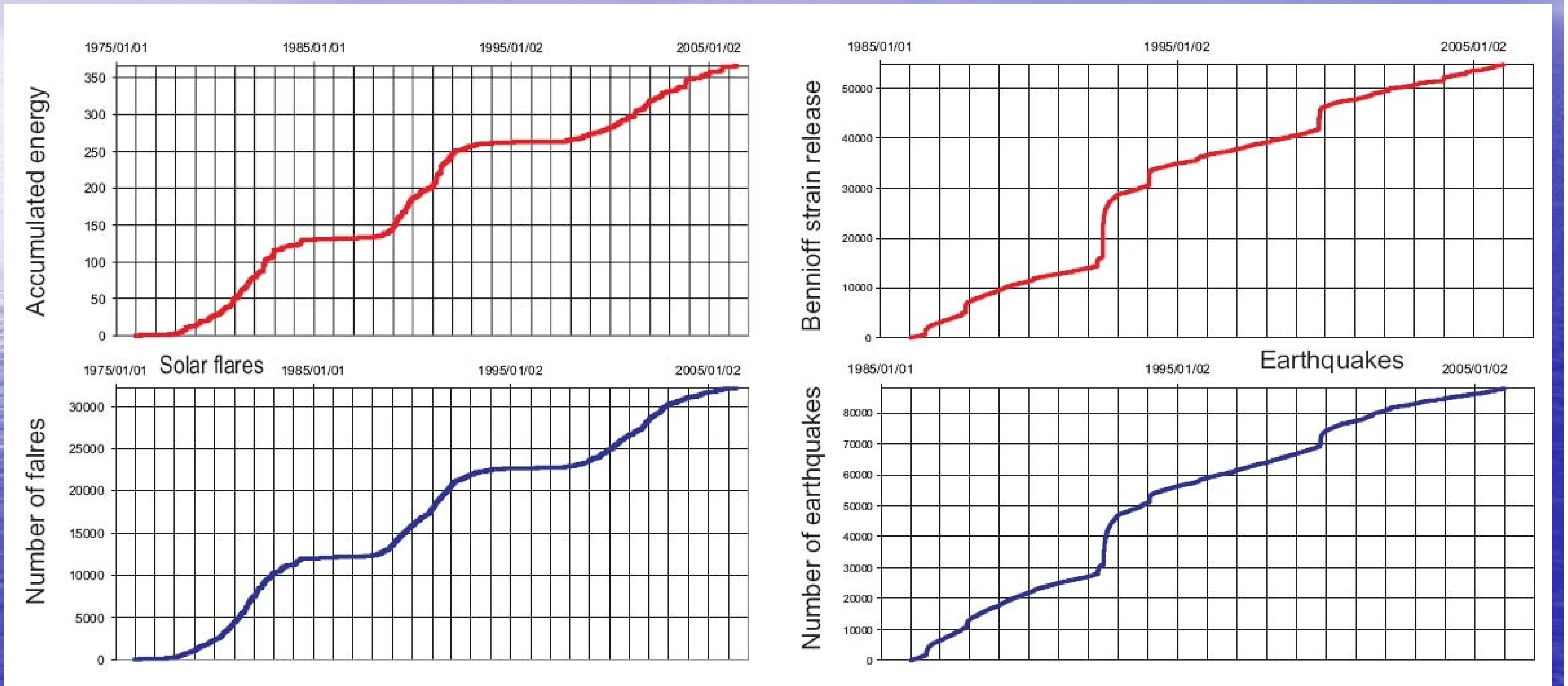
Solar flares

Earthquakes

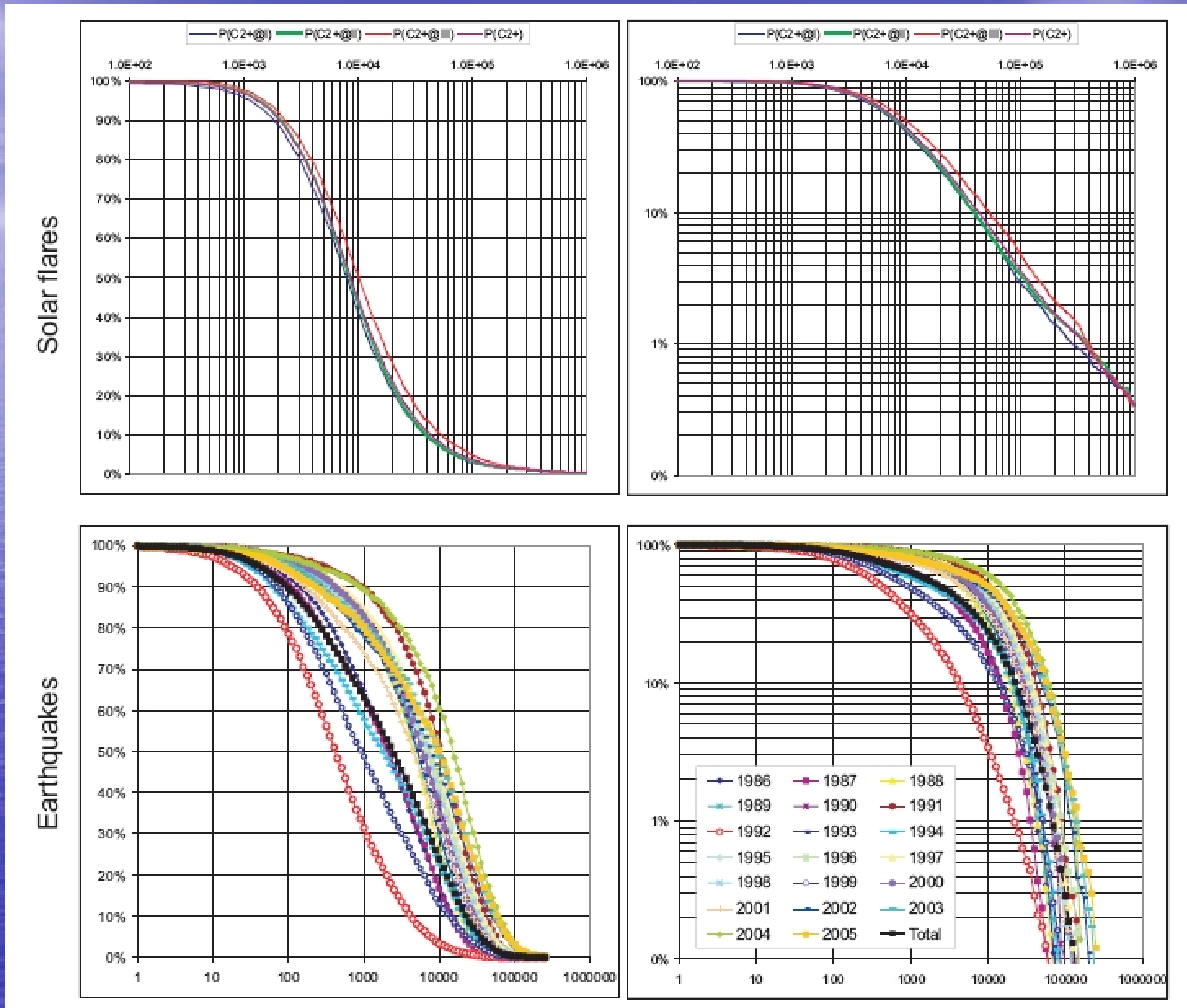


Accumulated number and energy vs. time

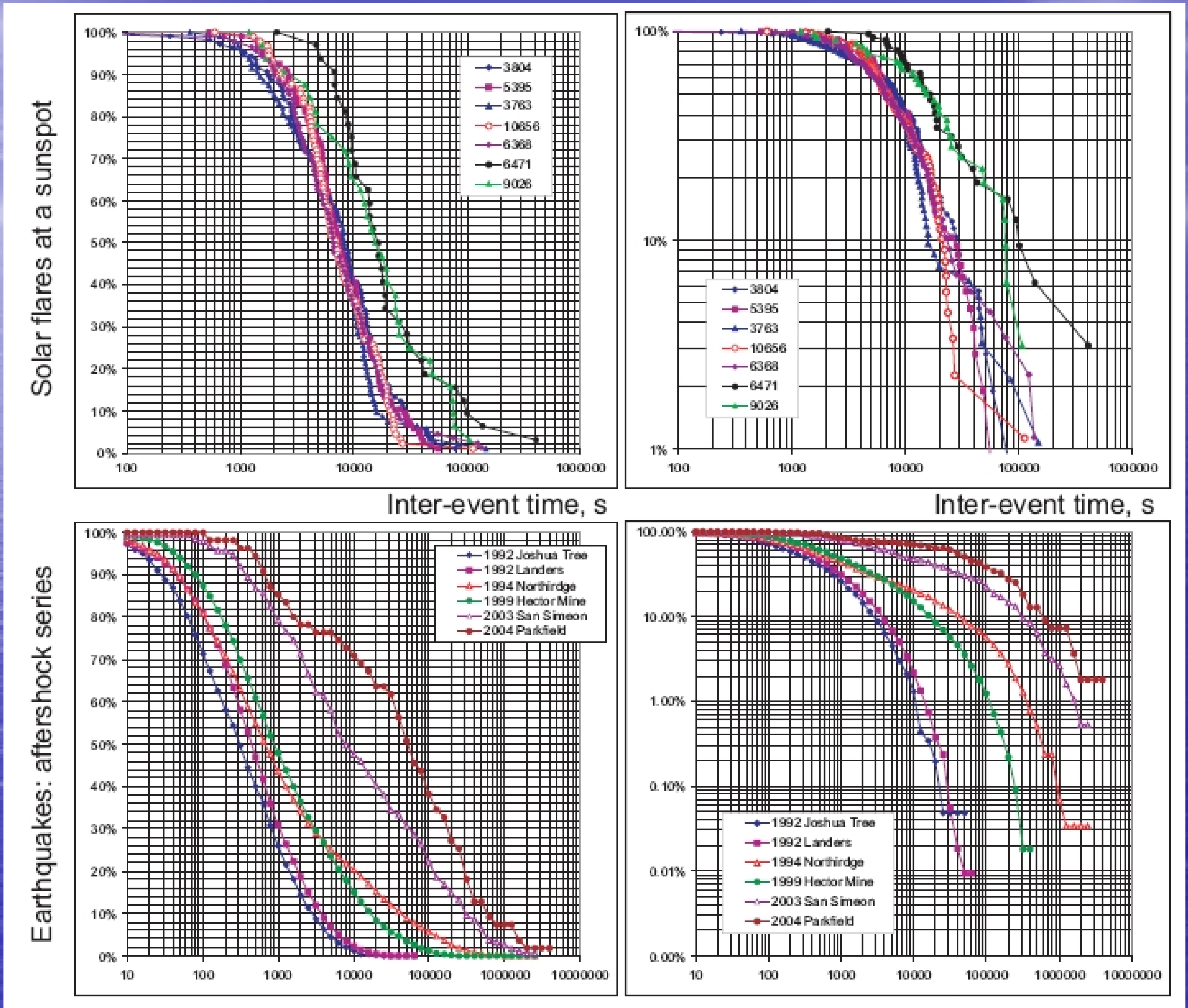
Solar flares | Earthquakes



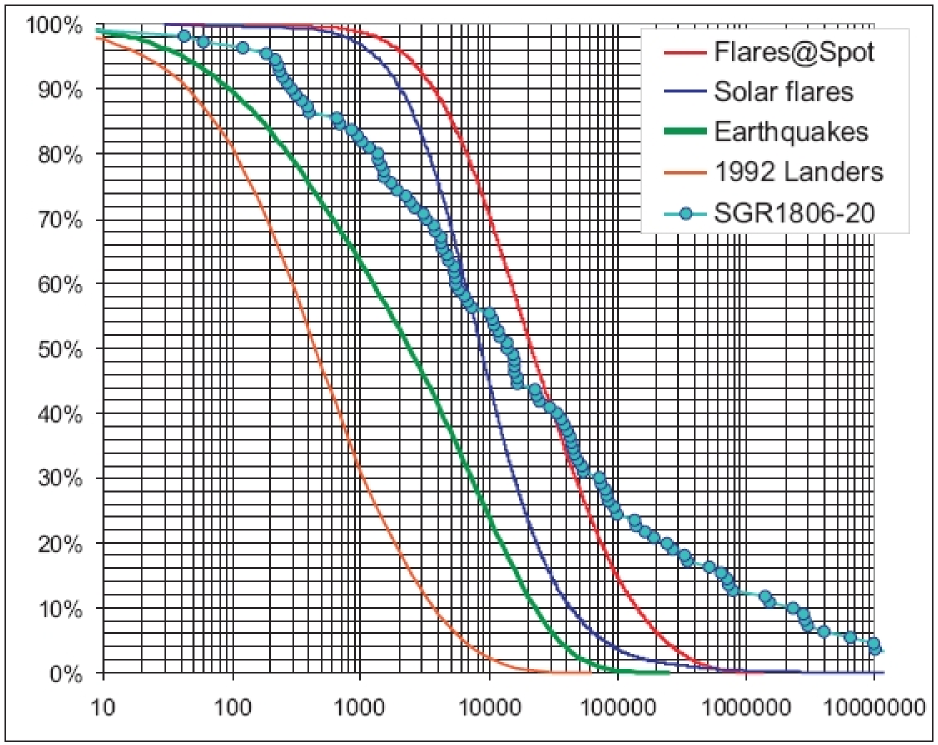
Inter-event time distributions

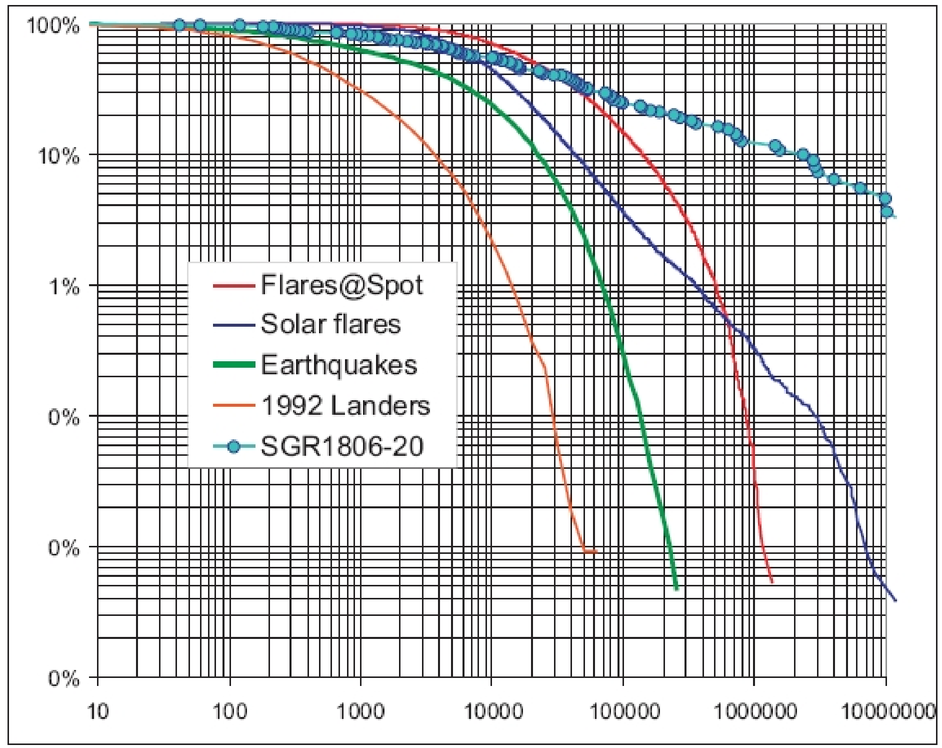


Inter-event time distributions in activity spots



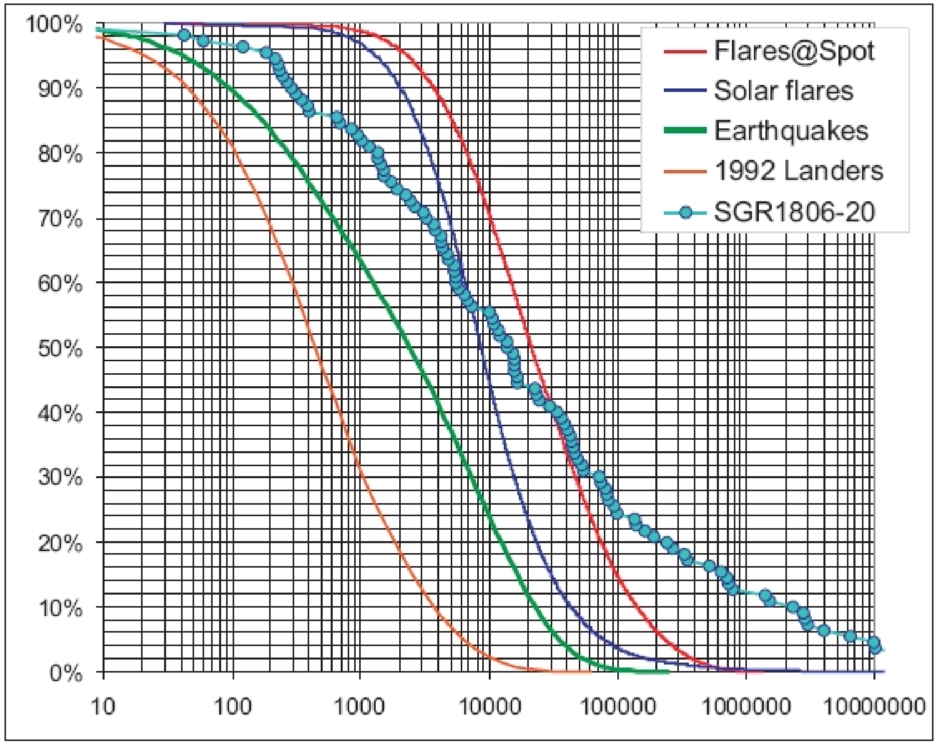
Inter-event time distributions

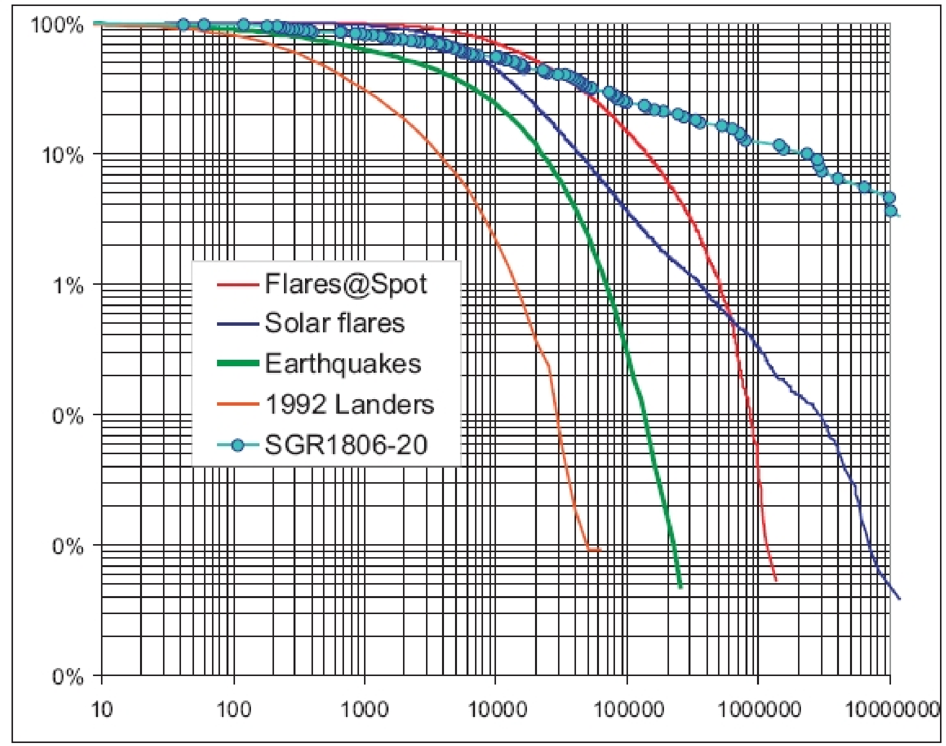




- The inter-event time distribution of soft γ-rays flashes produced by star-quakes on the neutron star 1806-20 is also shown (light blue circles). Energy released in a single event up to 10^{46} erg. (Kossobokov et al. 2000).

Inter-event time distributions





- The distributions show significant differences
- We calculated the minimum values of K-S statistic for all the couples of distributions over all rescaling fits of the type $P'(\Delta t)=P(C\,\Delta t^{\alpha})$, with C and α fitting constants

The K-S statistic

The two sample Kolmogoroff-Smirnoff statistic $\lambda_{K\text{-}S}$ is defined as

$$\lambda_{K\text{-}S}(D,n,m) = [nm/(n+m)]^{1/2} D$$

where $D = \max |P_{1,n}(\Delta t) - P_{2,m}(\Delta t)|$ is the maximum value of the absolute difference between the cumulative distributions $P_{1,n}(\Delta t)$ and $P_{2,m}(\Delta t)$ of the two samples, whose sizes are n and m respectively.

This test has the advantage of making no assumptions about the distribution of data. Moreover, it is widely accepted to be one of the most useful and general nonparametric methods for comparing two samples, as it is sensitive to differences in both location and shape of the empirical cumulative distribution functions of the two samples.

Inter-event time distributions:

The Kolmogoroff-Smirnoff two-sample criterion

	Flares	Flares at spot	SCSN	Landers	SGR1806-20
Flares	32076	3.435	8.648	2.071	0.636
Flares at spot	100 %	18878	5.898	1.669	0.434
SCSN	100 %	100 %	87688	3.726	1.435
Landers	99.96%	99.26%	100 %	10706	0.47
SGR1806-20	19.13%	0.92%	96.77%	2.24%	110

- The results indicate that the distributions cannot be rescaled onto the same curve (confidence level > 99%)
- Only the association of the starquake distribution (by far the smallest sample, 111 events) with all flares, flares at an activity spot, and Landers event cannot be rejected

Conclusions

(Kossobokov, V.G., Lepreti, F., Carbone, V., Complexity in sequences of solar flares and earthquakes, *Pure Appl. Geophys.*, 165, 761-775, 2008)

- The statistics of inter-event times between earthquakes and solar flares show different scaling.
- Even the same phenomenon when observed in different periods or at different spots of activity show different scaling. This difference were found in our analysis both for earthquakes and solar flares
- In particular, the observed inter-event time distributions of different phenomena show a wide spectrum of scaling and cannot be rescaled onto a single curve
- Even if some statistical analogies are present (e.g. power laws of different characteristics), which could be related to common characteristics of impulsive energy release processes in critical nonlinear systems, our results do not support the presence of "universality"

Can we predict the extreme geomagnetic events entirely from the knowledge of magnetic series?

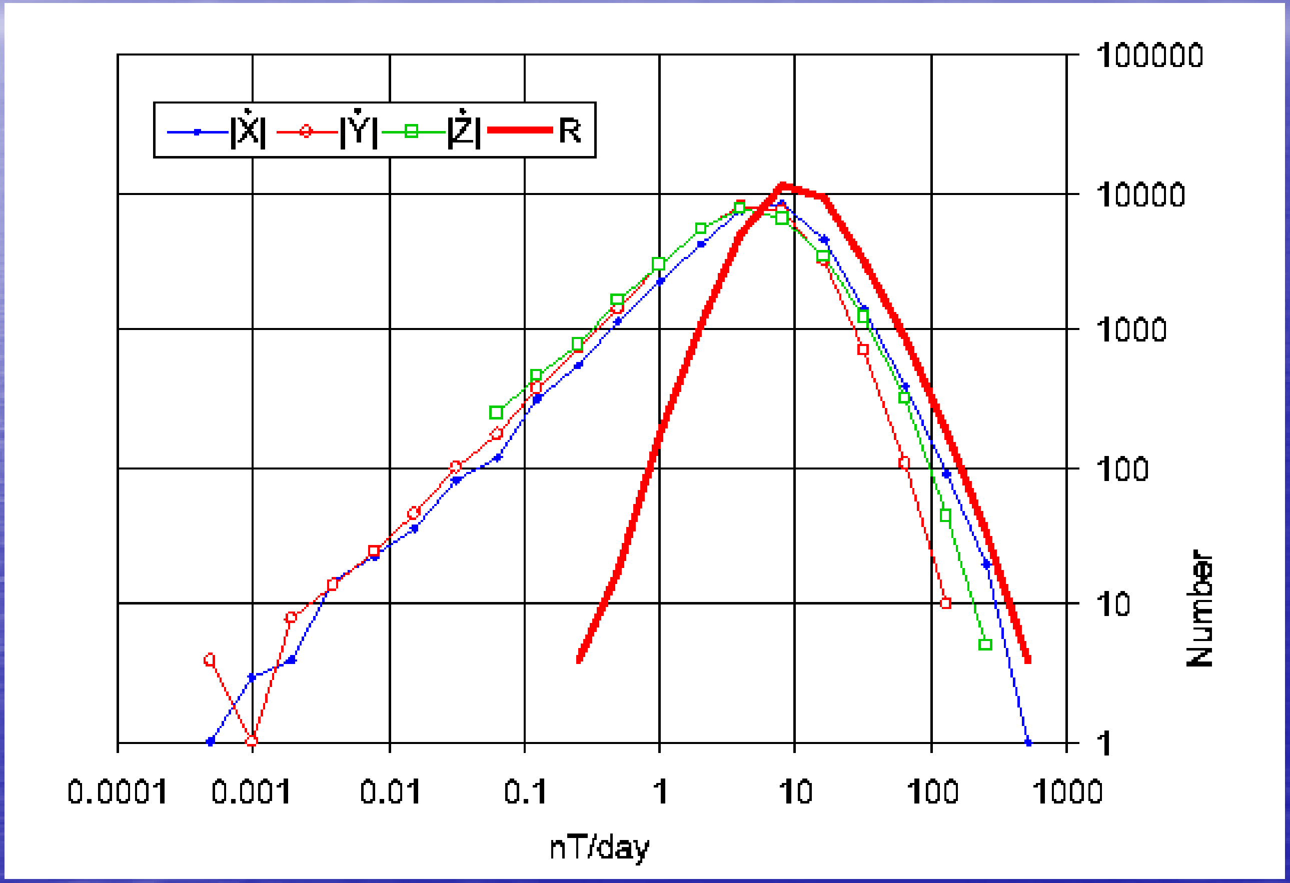
To investigate this problem we have compared unusually long series of the magnetic vector differential at different locations computed with different resolution, from daily to minute

(Bellanger, E., V. Kossobokov, and Le Mouël, J.-L.. Predictability of geomagnetic series. *Annales Geophysicae*, **21**: 1101-1109, 2003)

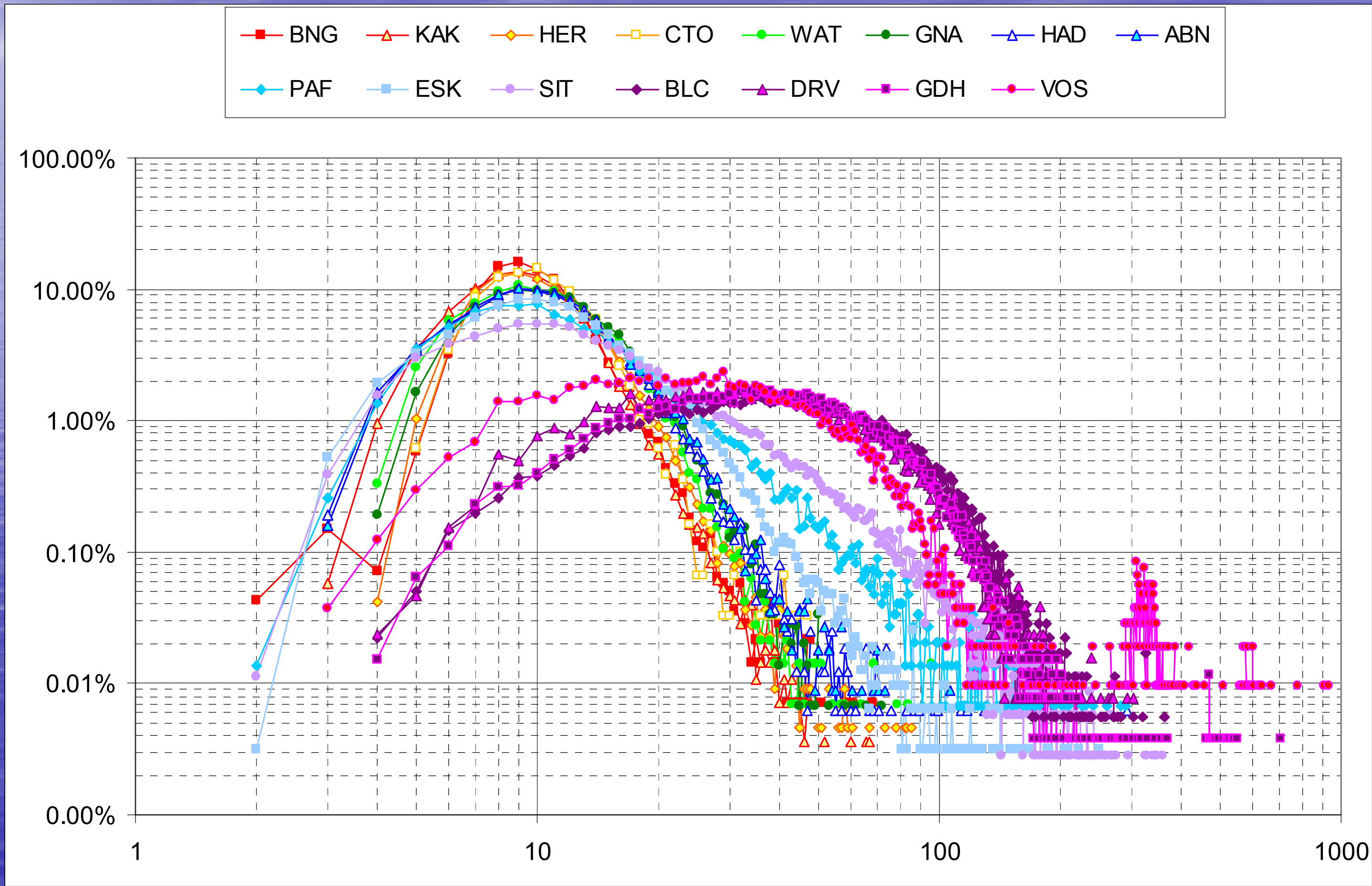
The analysis of $\mathrm{var}\,|\dot{B}| = R$ resulted firm statistical conclusions:

The observed variability of geomagnetic vector and specific distribution of its rate and variation suggests cascading nature of the underlining process characterized by power-law scaling, i.e., Self-Organized Criticality.

Histograms computed from daily means at Eskdalemuir.



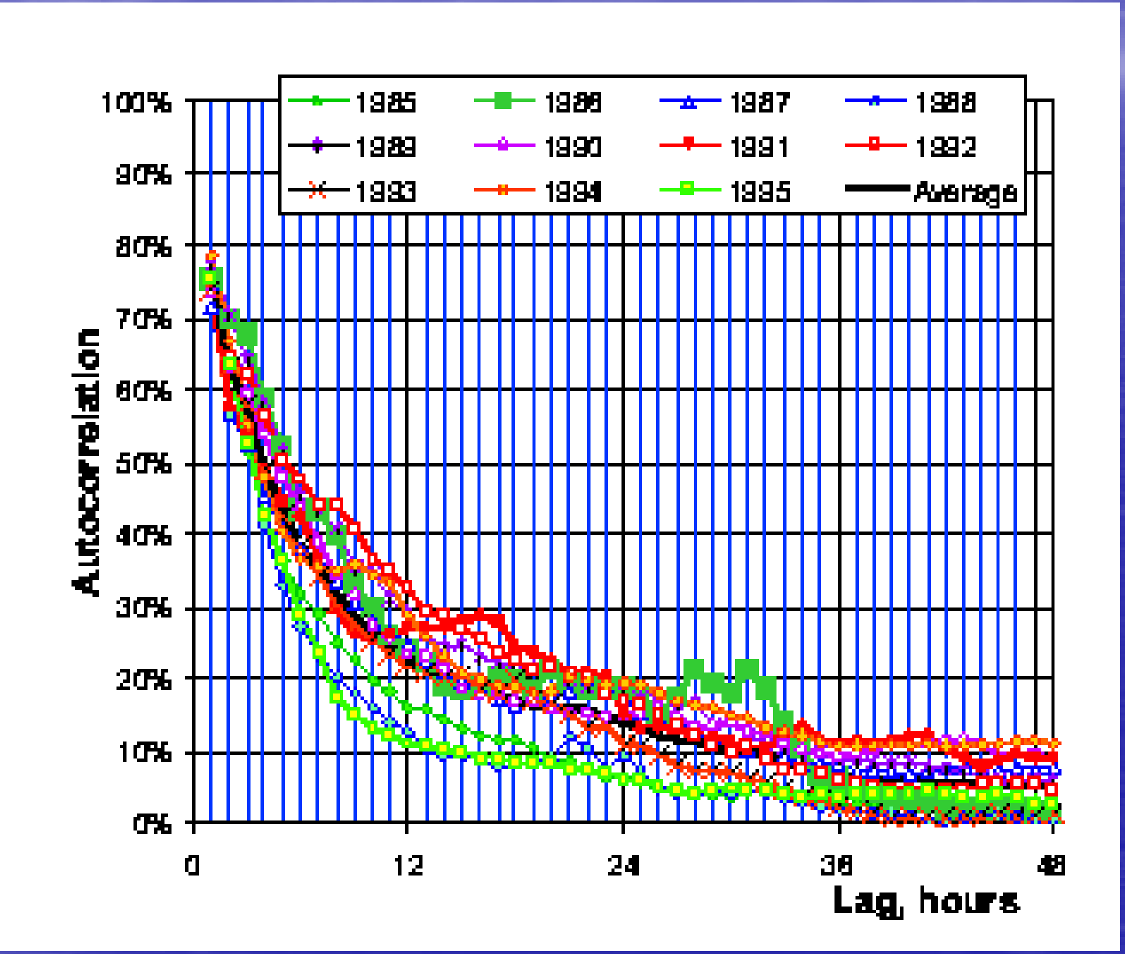
Comparison of the annual PDFs of the magnetic differential R computed from minute means.



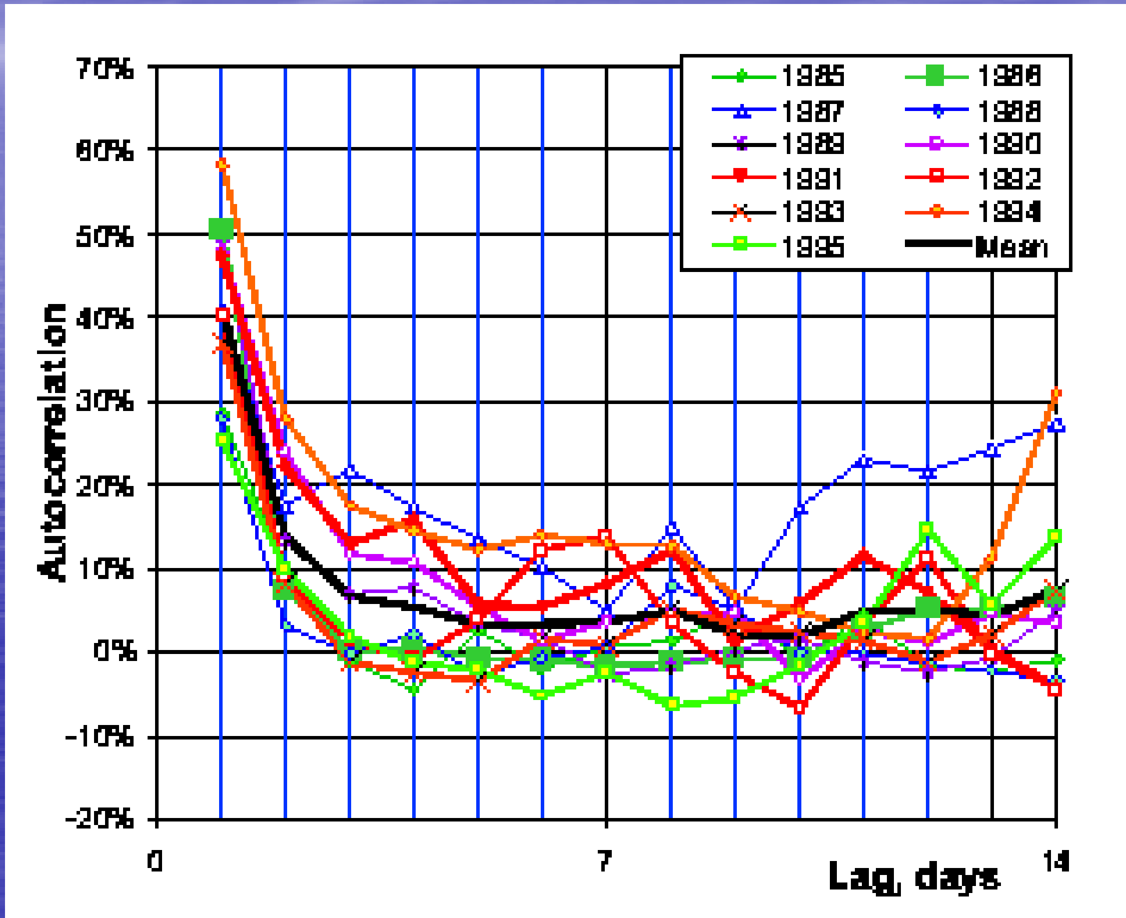
The magnetic vector differential distribution for each of the three components and its norm shows a systematic power-law increase of the density from the smallest values to the bulk distribution and power-law decay to the extreme events.

The series of magnetic differential has a high level of autocorrelation from about 40-50% for daily sampling to 60-75% for hourly averages of minute sampling. The autocorrelation depends on location and solar activity, i.e. phase of solar cycle.

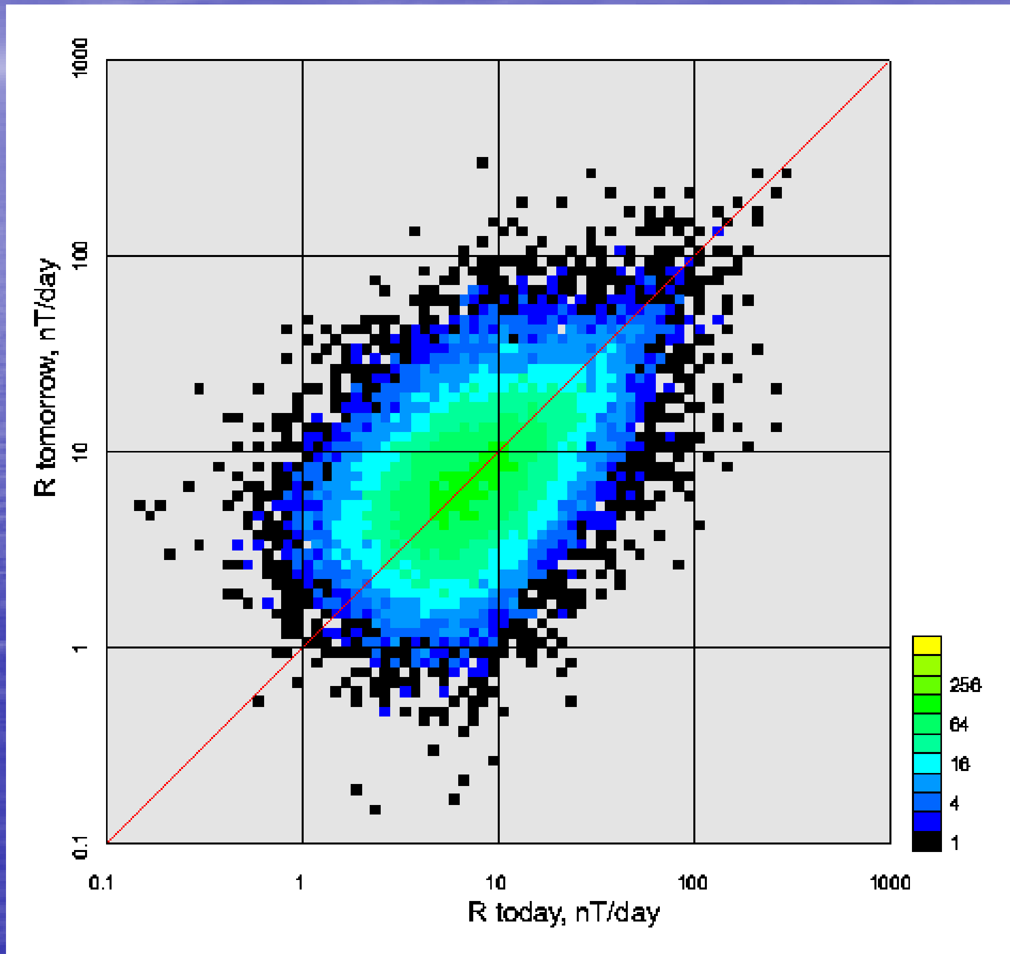
Hourly autocorrelation function of R (*computed from minute means*) at PAF.



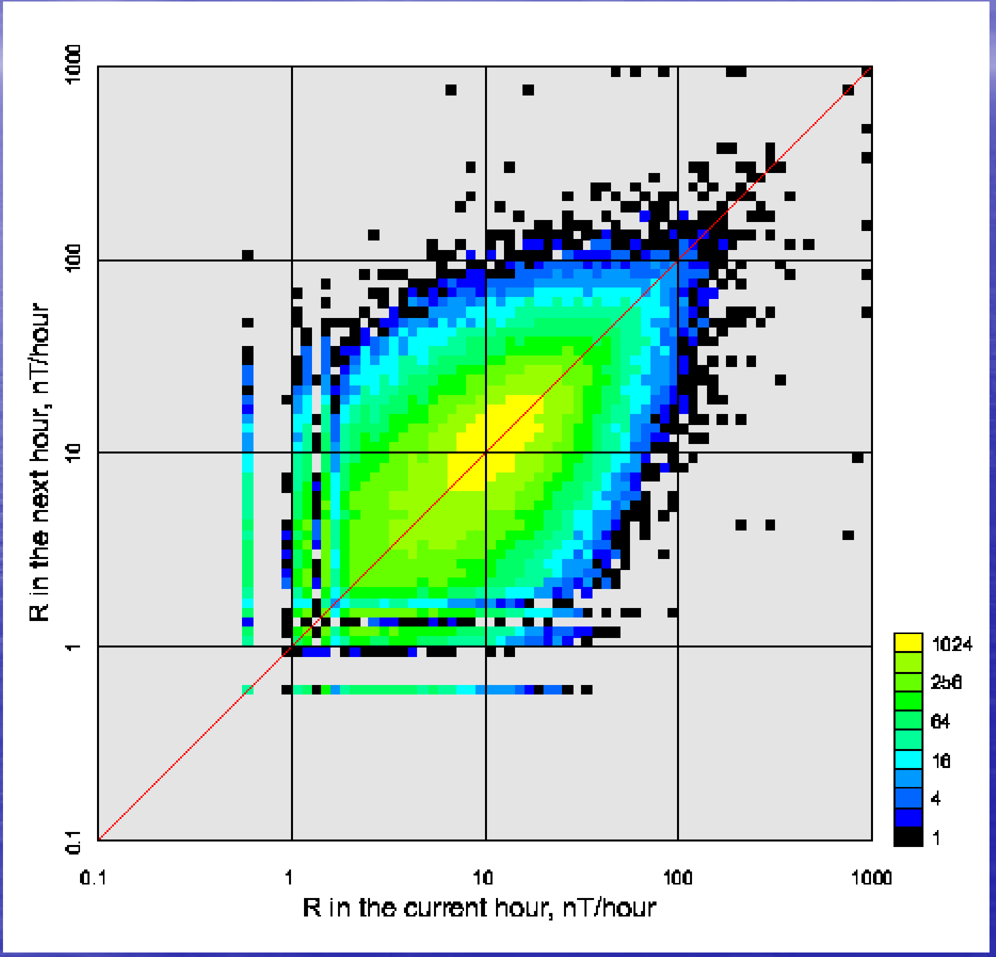
Daily autocorrelation function of R (*computed from minute means*) at PAF.



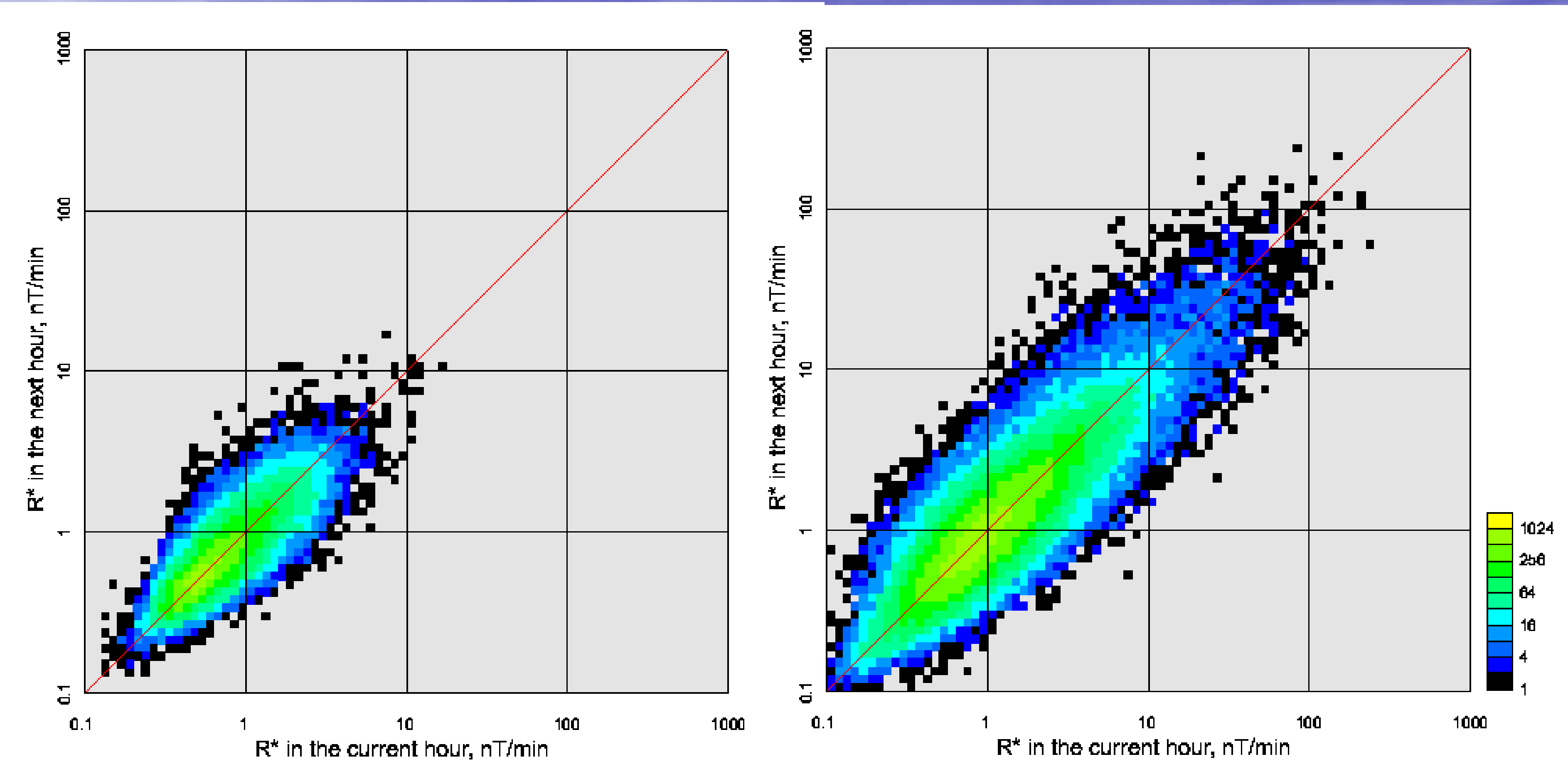
2D histogram computed from daily means at Eskdalemuir.



2D histogram computed from hourly means at Chambon-la-Forêt.



2D histograms computed from minute means at Chambon-la-Forêt and Port-aux-Français.

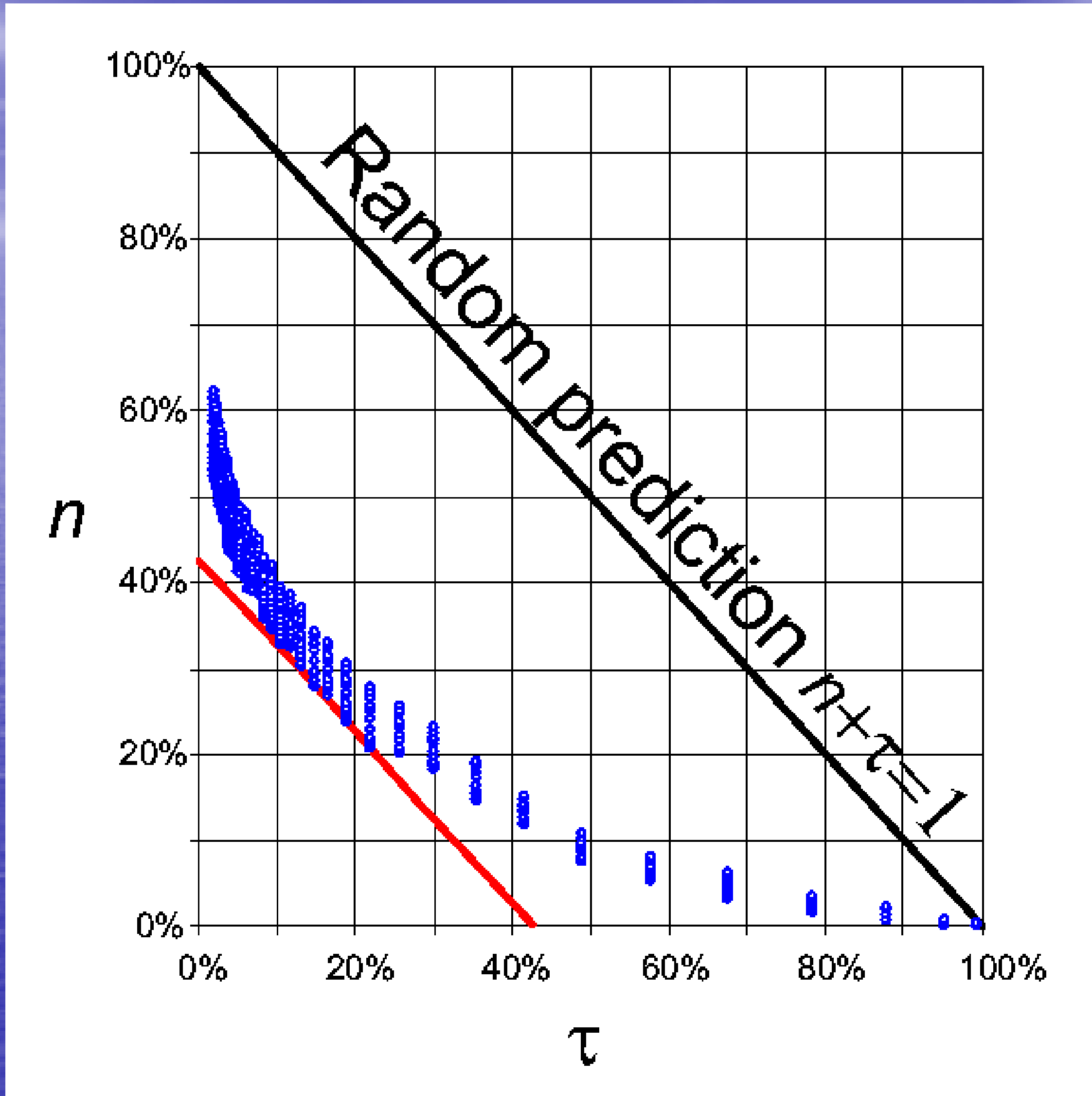


The magnetic differential can be used in a simple prediction scheme:

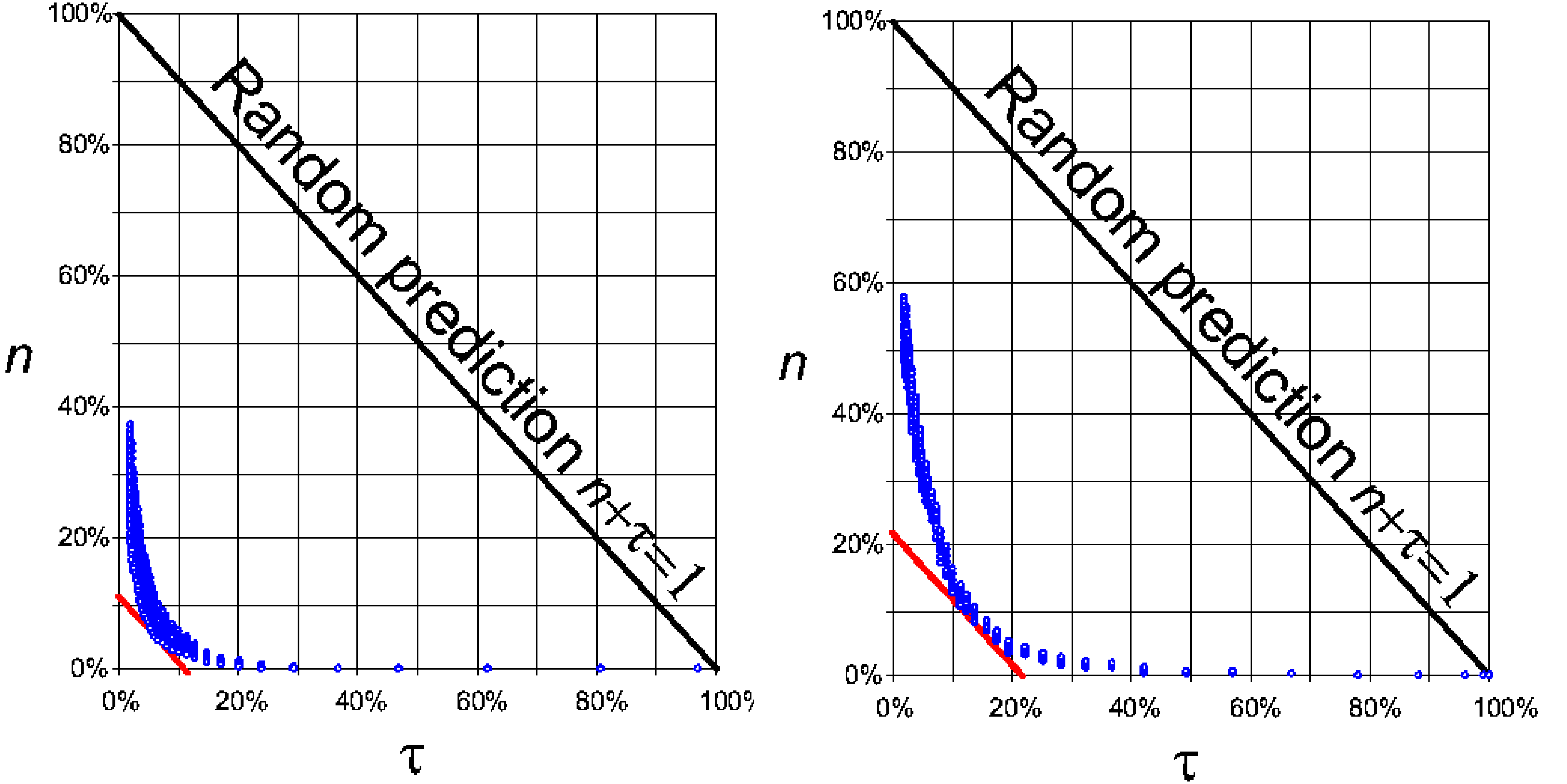
Suppose we are interested in predicting today the extreme events,defined by values of $R > R_0$, for tomorrow.

The simplest prediction scheme suggests to issue an alert for tomorrow if $R > r_0$ today; r_0 and R_0 are parameters.
We call the occurrence of a value of R larger than R_0 an extreme event.
We count a success, if it happens on the alert day, and a failure-to-predict otherwise.

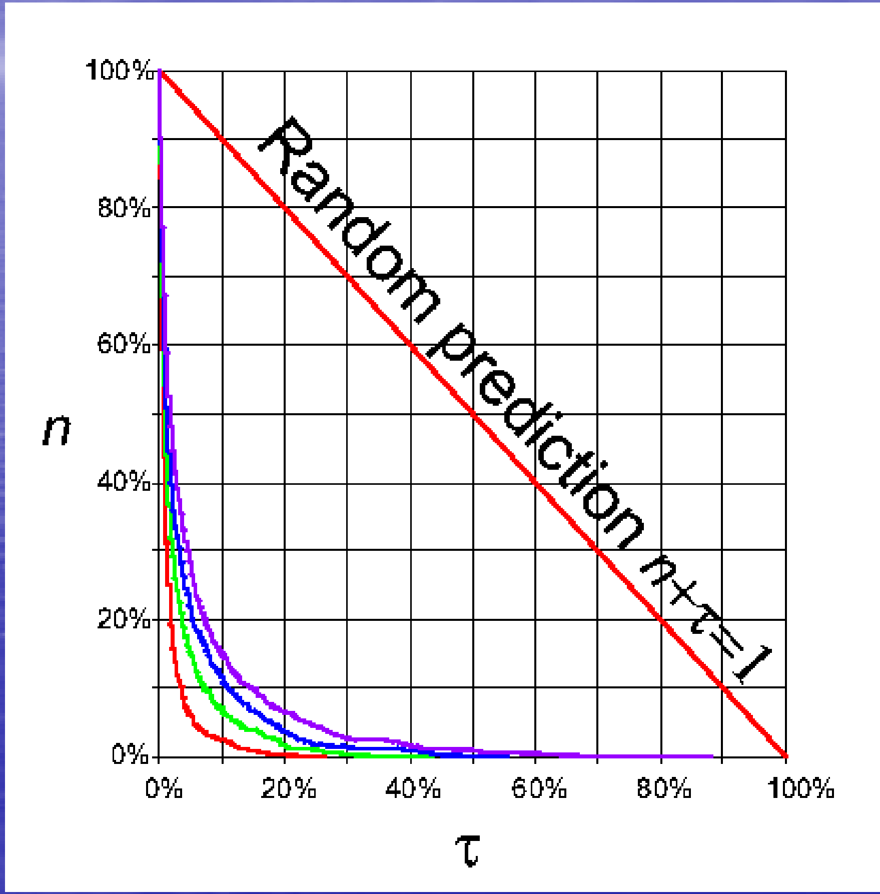
Prediction for tomorrow at ESK



Prediction for the next hour at PAF and CLF

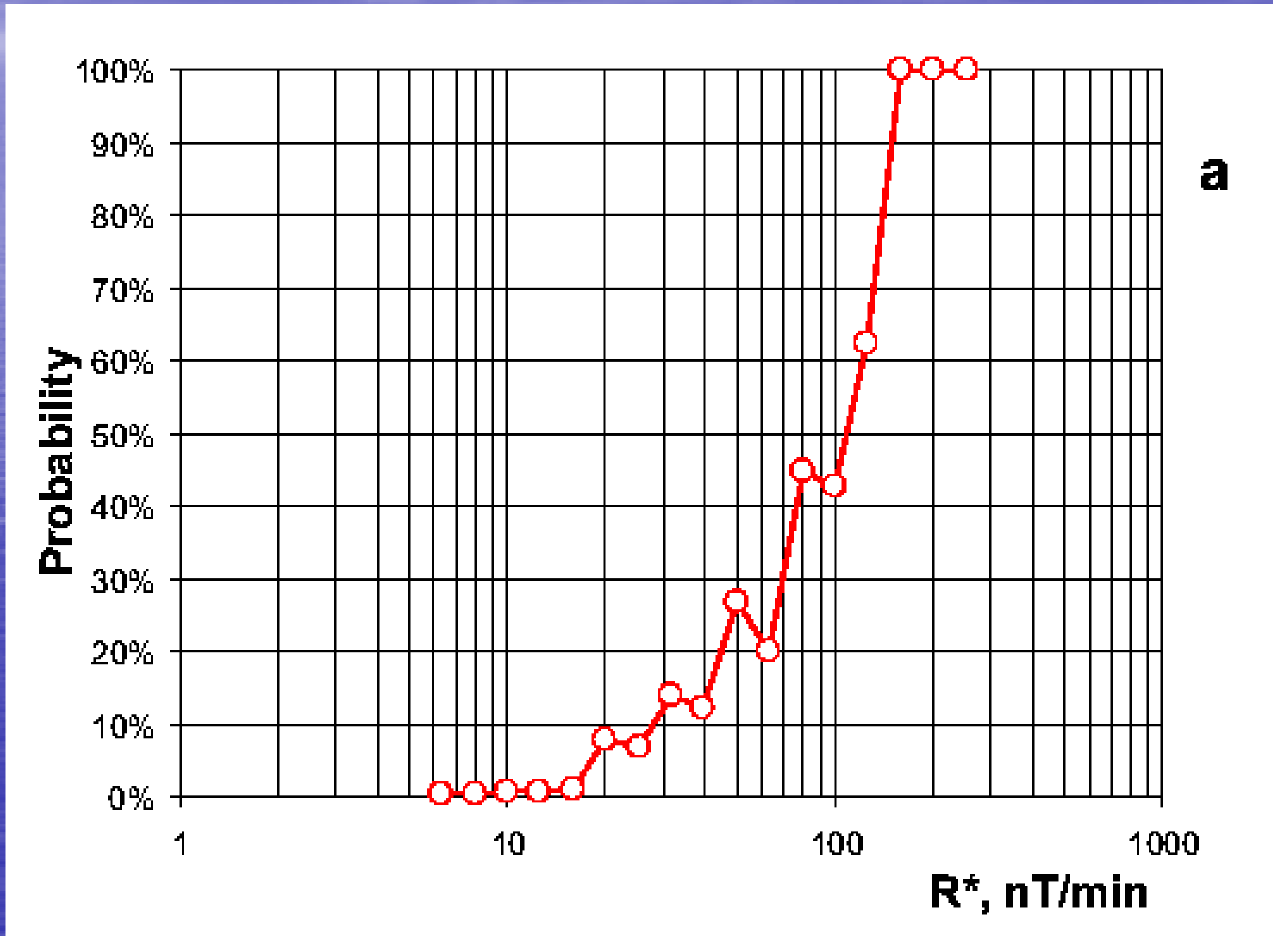


Prediction for the next few hours at PAF

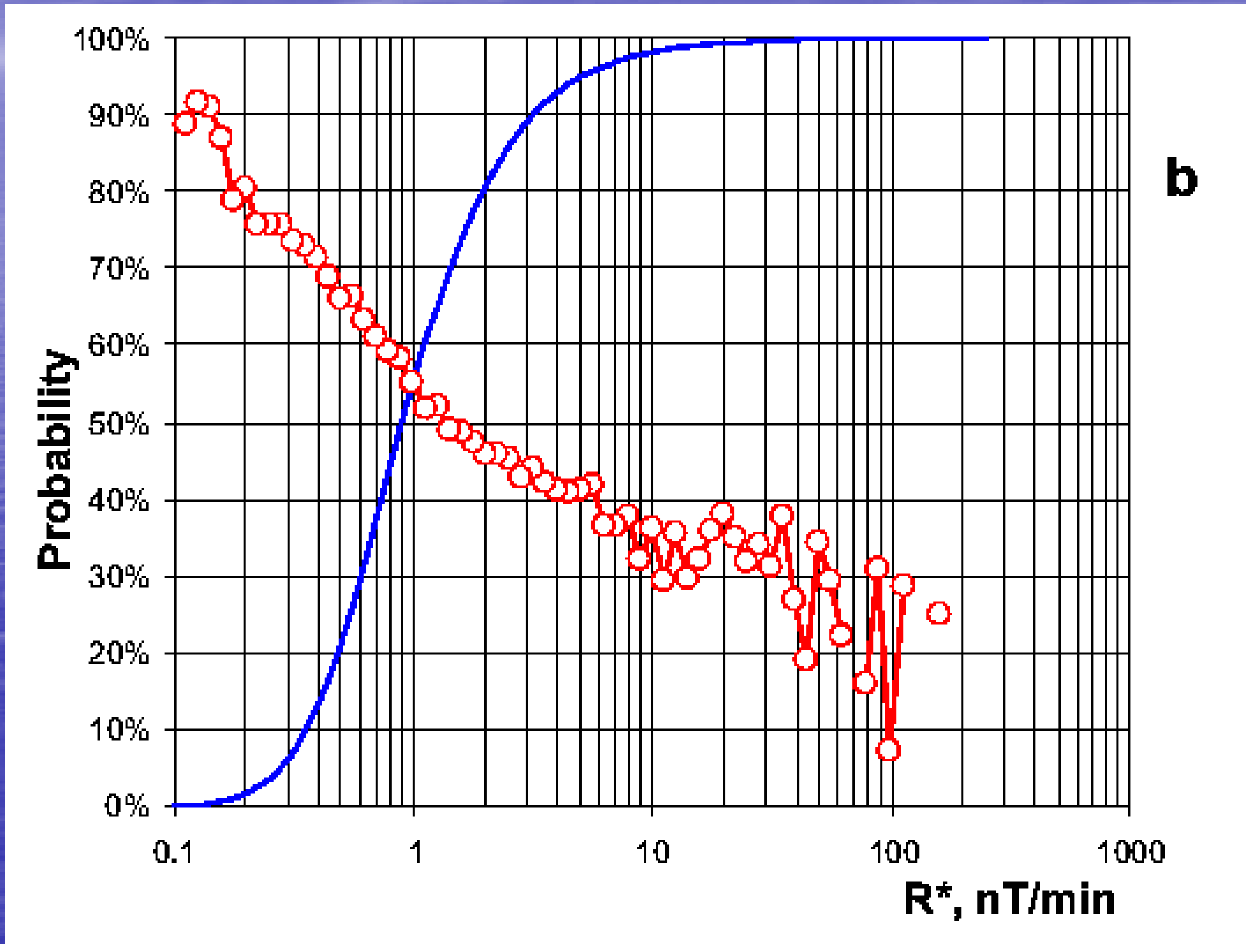


In a similar way, the 2-D empirical distribution of consecutive values of the magnetic differential norm permits computation of conditional probabilities of different type, which might be more appropriate in a specific risk assessment.

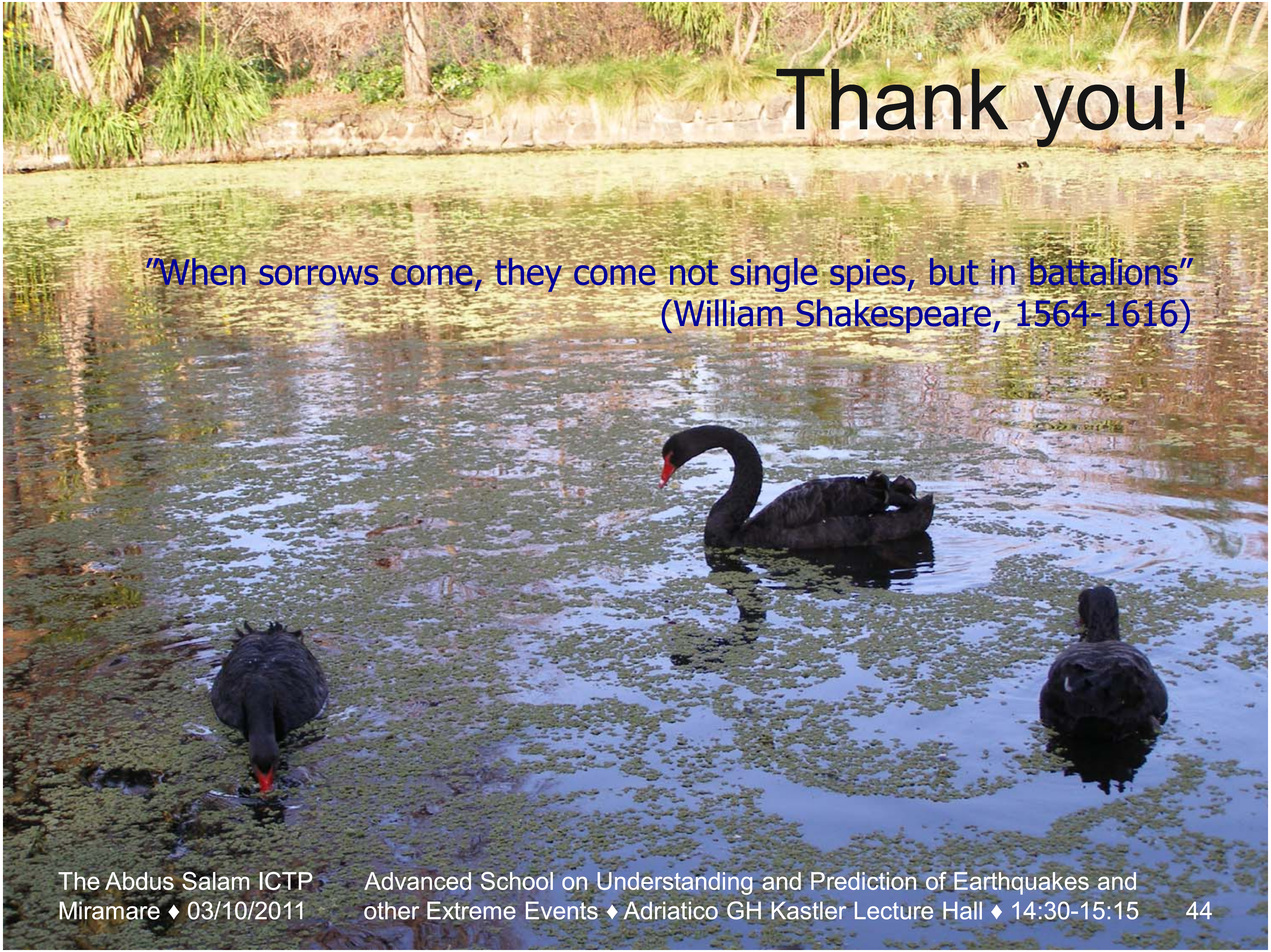
The empirical conditional probability of extreme R > 50 nT/min in the next hour at Port-aux-Français



The empirical conditional probability of larger R in the next hour at Port-aux-Français (red).



Our prediction results, although limited, **are established in a rigorous way, thus, allowing rigorous testing and adjustments for a specific risk assessment in a real-time experiment.**



Thank you!

"When sorrows come, they come not single spies, but in battalions"
(William Shakespeare, 1564-1616)