The problem of predictability of the strongest earthquakes and perspectives of incorporating IoT into prognostic systems

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The problem of the forecast of earthquakes is one of the most complicated problems in modern natural science. This complexity is due to the multicomponent structure of the earth's crust, the nonlinear nature of the interaction of the elements of this structure, the presence of a large number of disturbances during geophysical observations, including those related to human industrial activities.

Over the past 50 years, significant progress has been made in understanding the causes and mechanisms leading to earthquakes. Many questions that begin with the words "how" and "why" have already been answered. The paradox is that the knowledge of earthquake physics does not automatically solve the problem of forecasting. If the places in which strong earthquakes can occur can be recognized using seismic zoning methods, then the forecast of the time moment of a strong seismic event in a given region is still unattainable.

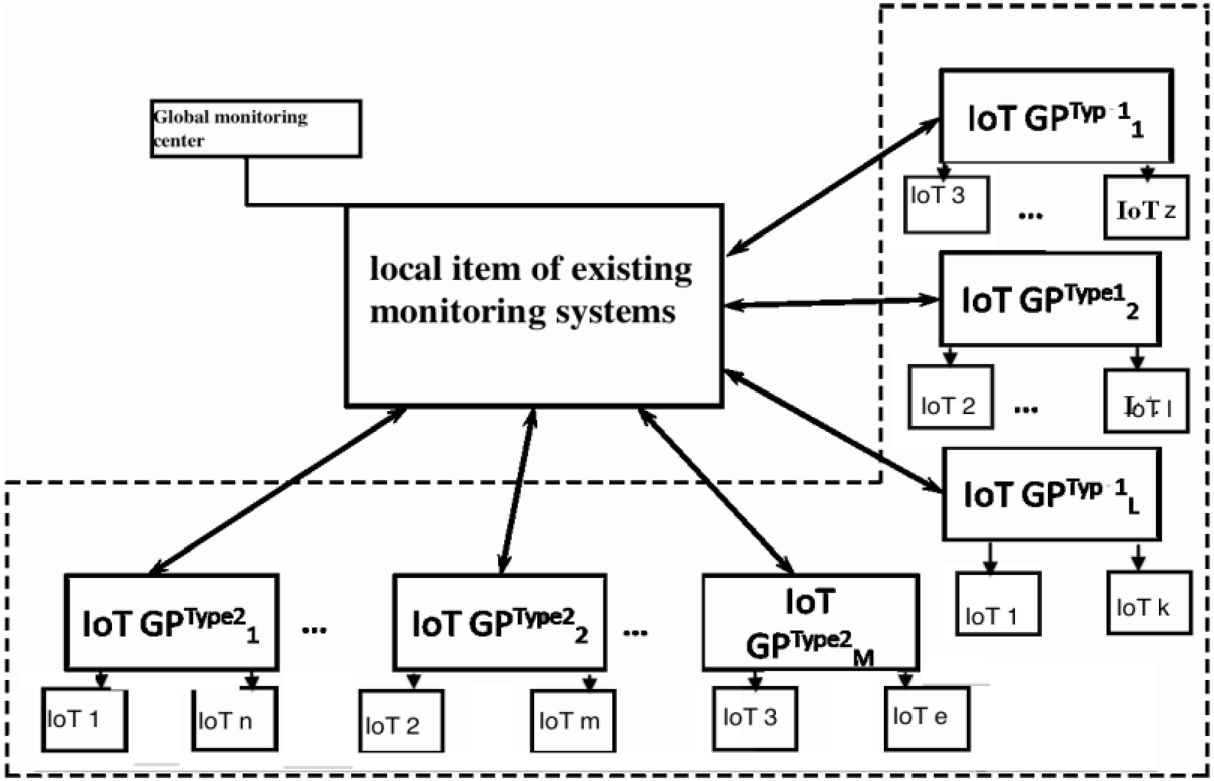
The behavior of complex natural systems, such as the Earth's crust, is reflected in the data stream from the monitoring system, the continuous development of which leads to a rapid increase in the number of simultaneously measured time series (the number of which currently goes up to several thousand) and sequences of events, collectively called "big data."

Examples of sources of such "big data," could be presented as a network of global observation of more than 11,000 GPS stations, network of broad-band seismic stations for continuous registration of seismic noise of the Earth. In order to highlight trends in the development of complex natural systems and for the detection of time intervals prior to natural disasters, it is necessary to create special methods for joint analysis of a large number of time series.

As a methodological framework for the development of specific methods of analysis of large data flow from current monitoring systems it is proposed to consider search for their synchronization effects, which further will also be called coherence. Coherence in the behavior of characteristics of a complex dynamic system is an important feature that allows to evaluate the approach of the system to the rapid changes in their condition, which are often referred to as a "catastrophe". The basis for finding the precursors of catastrophes as an occurrence of synchronization in various observations is the general idea of increasing the correlation of random fluctuations of the parameters of the system as it evolves.

We propose organizing multi-disciplinary centers which will allow to joint data analysis of traditional geophysical monitoring time series (seismic noise, GPS, geochemical observations) and IoT signals for increasing earthquake precursory potential. One of such centers is planning to establish at the Northern Caucasus under leadership of Prof. Vadim Ermakov from Institute of Geochemistry Russian Academy of Sciences

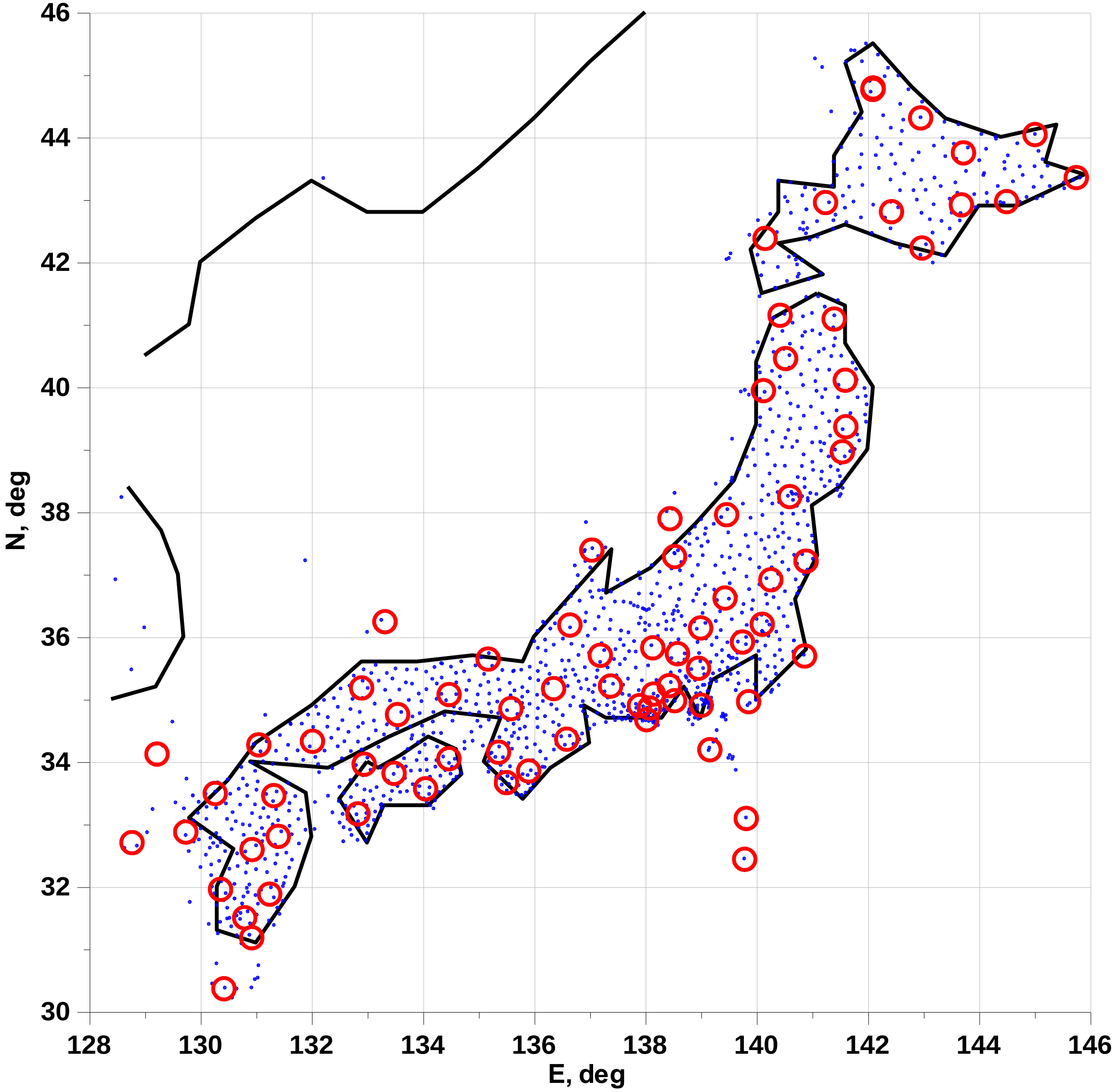
Perspectives: Incorporating IoT signals into existing geophysical monitoring time series analysis



Here is a block-scheme of this interaction of IoT sensors with existing sensors, elaborated by Prof. William Sarian from Radio Research and Development Institute, Moscow.

Signals - the precursors of earthquakes - modulate synchronously existing sensors and periodic life (natural) processes that result from the IoT addition of these signals gives the synchronization effect and allows to detect the presence and power of signals - earthquake precursors, which will allow to determine with sufficient accuracy of the time of the earthquake, its strength and place of greatest shock.

Example of traditional geophysical data analysis: seismic and GPS networks in Japan

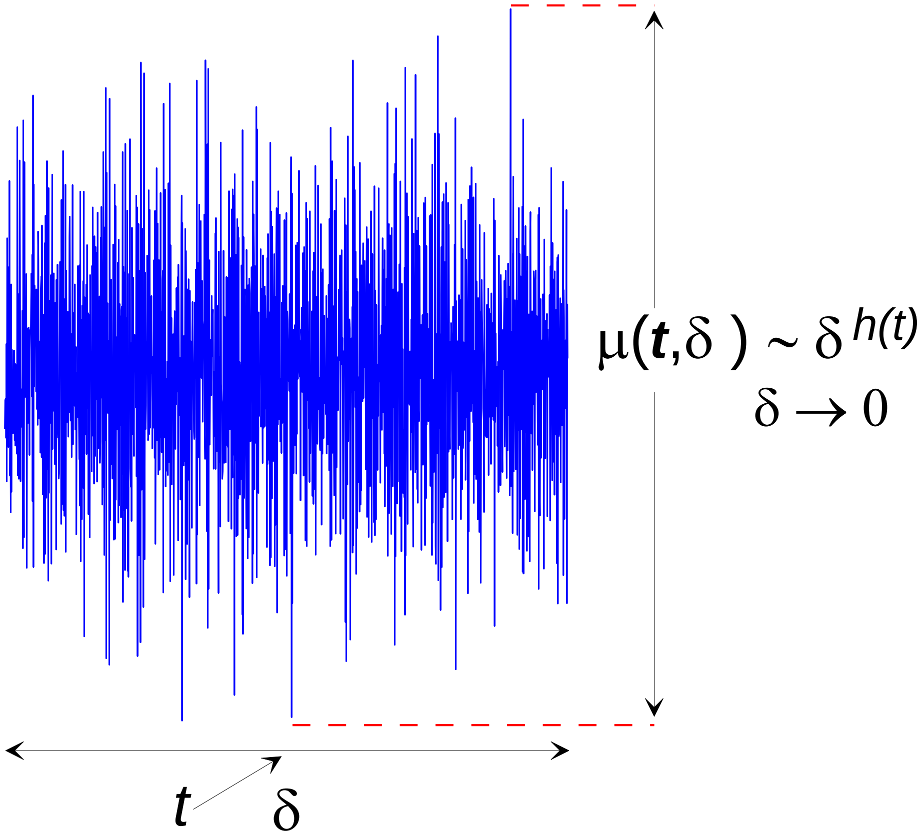


Red circles – positions of 78 broadband seismic stations, Observations 1997 – 31.07.2018, source:
http://www.fnet.bosai.go.jp/top.php

Blue points – positions of 1341 GPS stations, 03.03.2015 – 24.06.2018, Δt = 5 minutes, source:
ftp://gneiss.nbmg.unr.edu/rapids_5min/kenv/
(Nevada Geodetic Lab)

Multi-fractal properties of seismic noise waveforms

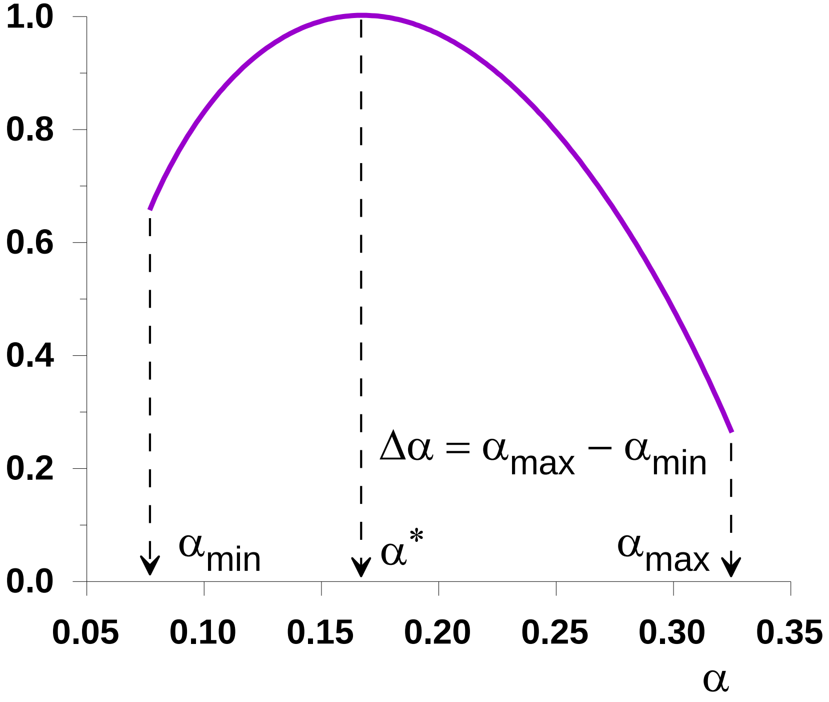
Measure of the random signal variability at the time interval [$t - \delta/2$, $t + \delta/2$]



$$\mu(t,\delta) \sim \delta^{h(t)}$$
$$\delta \to 0$$

Multi-fractal singularity spectrum $F(\alpha)$ and its parameters: $\Delta\alpha$ - support width and α^* - generalized Hurst exponent.

$F(\alpha)$ - fractal dimensionality of the set of time moments t for which $h(t) = \alpha$



Entropy properties of seismic noise waveforms

Minimum normalized entropy :

$$En = -\sum_{k=1}^{N} p_k \cdot \log(p_k) / \log(N) \;\rightarrow\; \min$$

$$0 \le En \le 1, \qquad p_k = c_k^2 / \sum_{j=1}^{N} c_j^2 ,$$

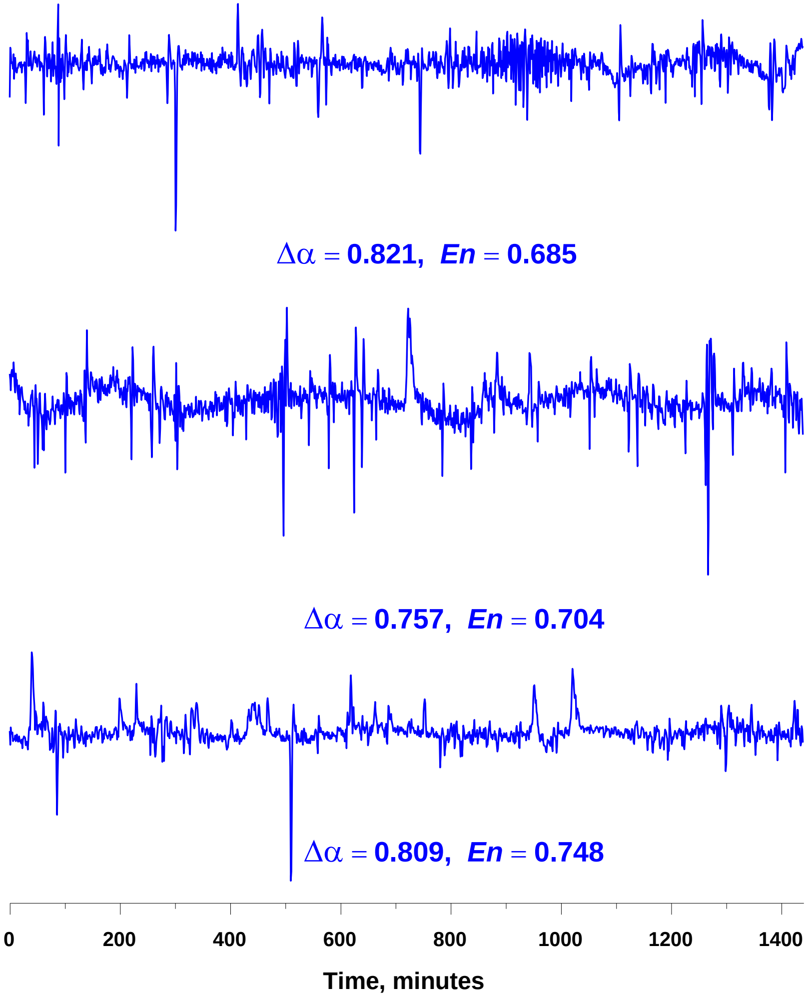
c_j - orthogonal wavelet coefficients,

minimum is taken by wavelets from Daubechies family.

Graphics of seismic noise of the length 1 day with sampling time step 1 minute after removing tidal trends

High Δα
Low normalized entropy *En*

Low danger,
high variability of stochastic behavior types, a lot of low-frequency spikes because of mutual movements of non-consolidated small blocks of the Earth's crust, energy is not accumulated.

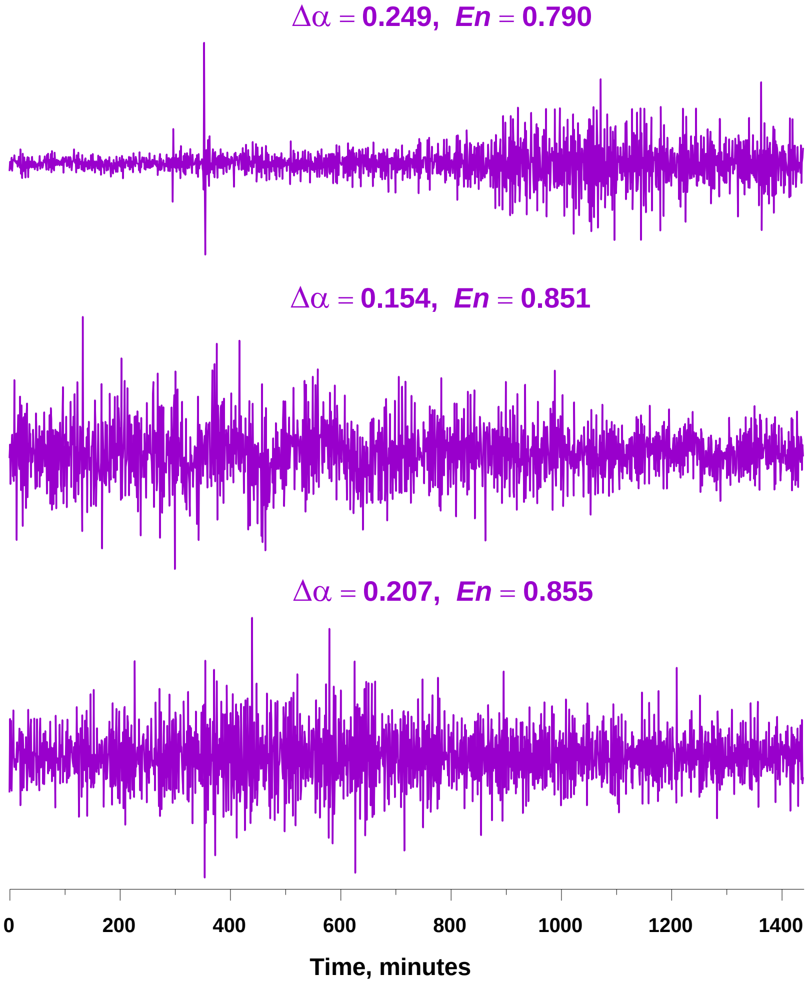

Δα = **0.821**, ***En*** = **0.685**

Δα = **0.757**, ***En*** = **0.704**

Δα = **0.809**, ***En*** = **0.748**

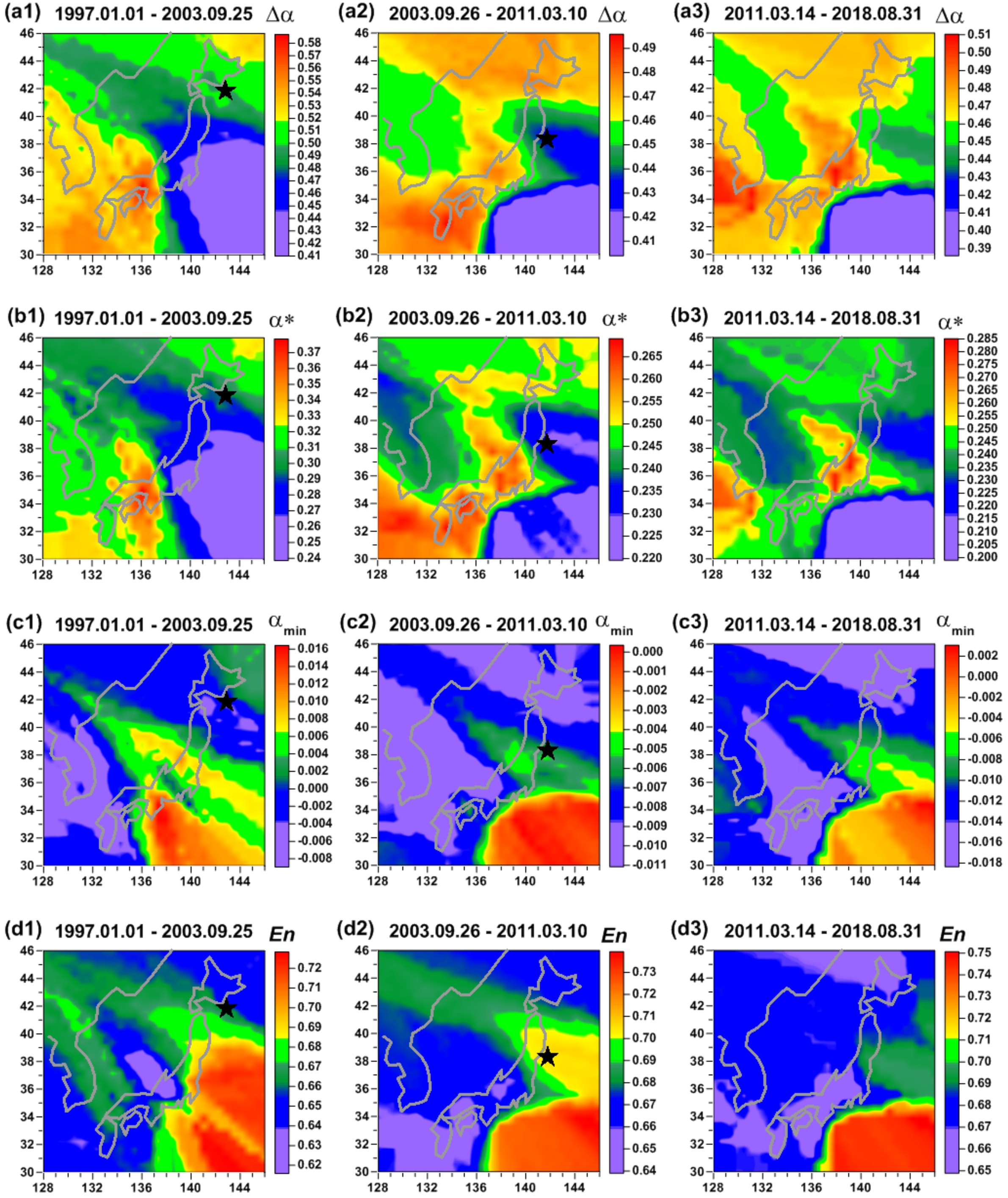
Low Δα
High normalized entropy *En*

High danger,
the behavior of the seismic noise is much more uniform, small blocks of the Earth's crust are consolidated, the energy could be accumulated.


Δα = **0.249**, ***En*** = **0.790**

Δα = **0.154**, ***En*** = **0.851**

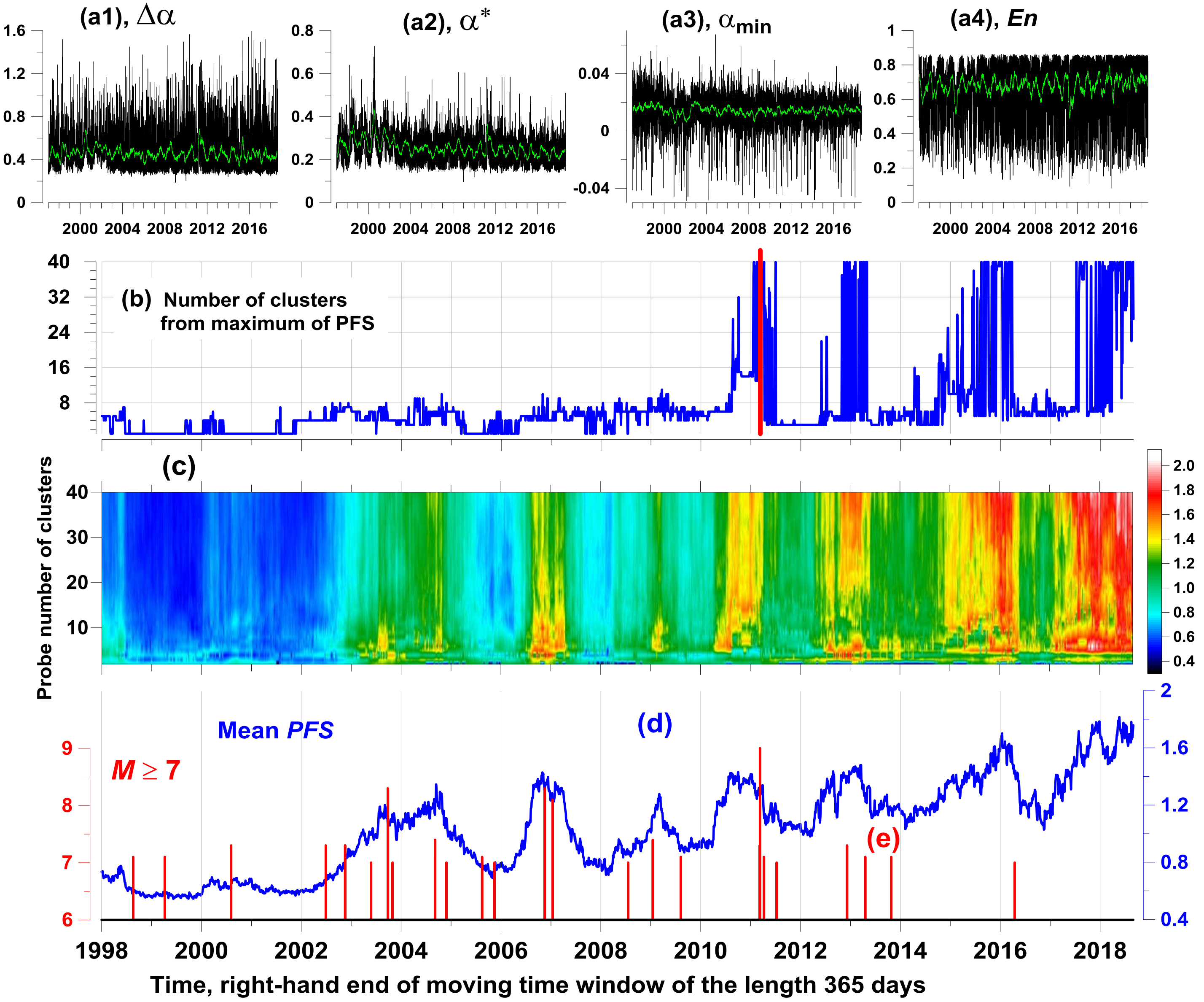
Δα = **0.207**, ***En*** = **0.855**



Averaged maps of multifractal singularity spectrums support width $\Delta\alpha$ ((a1)-(a3)), generalized Hurst exponent α^* (b1)-(b3)), minimum Hölder-Lipschitz exponent α_{min} ((c1)-(c3)) and minimum normalized entropy *En* of squared orthogonal wavelet coefficients ((d1)-(d3)) of seismic noise waveforms in Japan for 3 time intervals.

Stars indicates epicenters of earthquakes on September 25, 2003, *M*=8.3, (a1, b1, c1, d1) and on March 11, 2011, *M*=9.1, (a2, b2, c2, d2).

Pseudo-F-statistics map as an estimate of current seismic danger



(a1)-(a4) – plots of daily median values of multifractal singularity spectrum support width $\Delta\alpha$, generalized Hurst exponent α^*, minimum Hölder-Lipschitz exponent α_{min} and normalized entropy En from all 78 stations of broadband seismic network F-net in Japan;

(b) – plot of the best numbers of clusters for the sequence of clouds consisting of 365 daily 4D vectors $(\Delta\alpha, \alpha^*, \alpha_{min}, En)$ from moving time window of the length 365 days. The best number of clusters is defined from the maximum of pseudo-F-statistics.

Vertical red line indicates time moment of Tohoku mega-earthquake on March 11, 2011, $M = 9.1$.

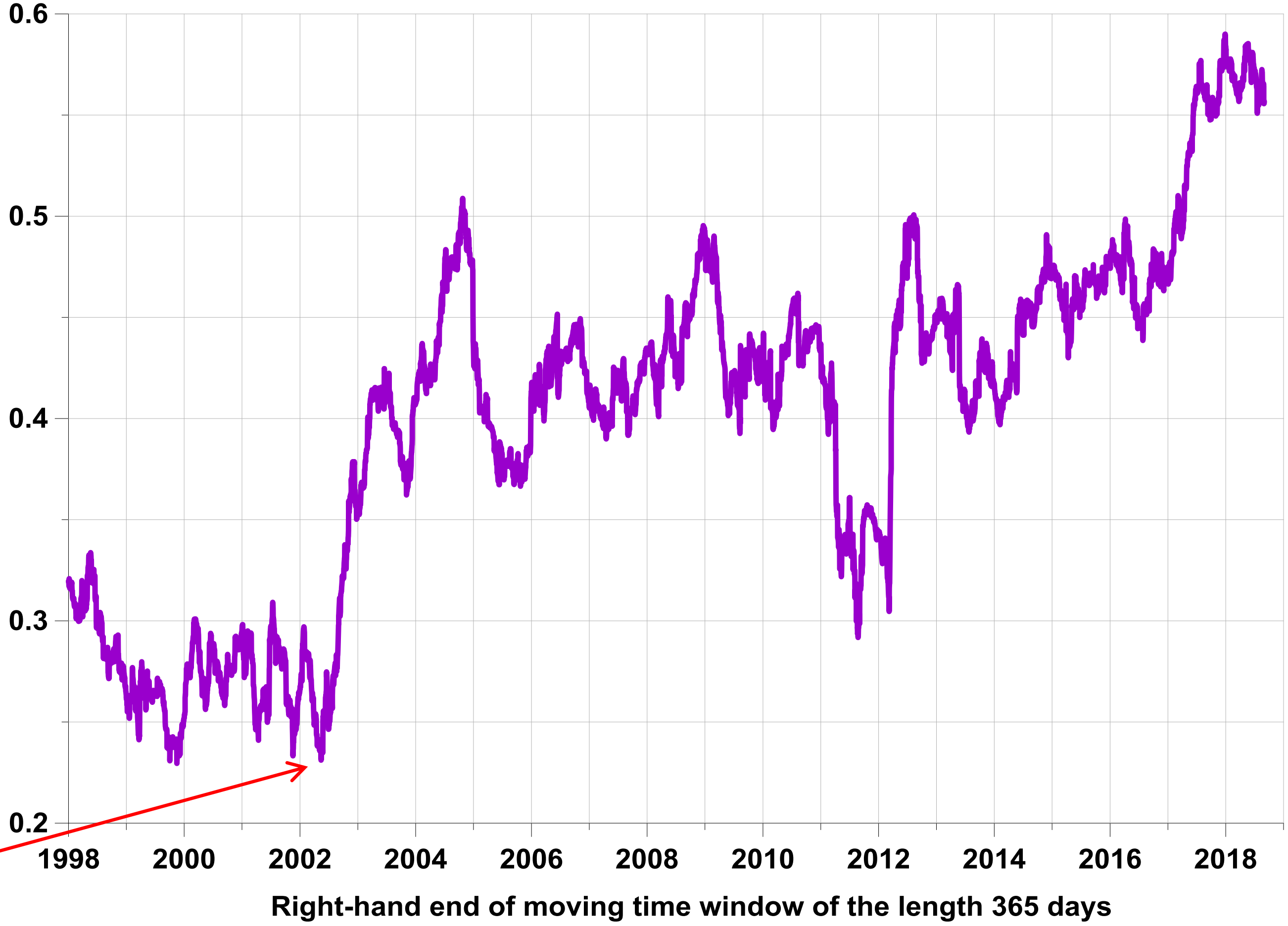
2D diagram (c) presents dependence of pseudo-F-statistics on the probe number of clusters, which is varying from 2 up to 40 within each time window.

Plot (d) presents mean value of pseudo-F-statistics averaged by all probe numbers of clusters in dependence on right-hand end of moving time window of the length 365 days.

Plot (e) presents the sequence of time moments of strong earthquakes $M \geq 7$ in the rectangular domain with coordinates $28^o\text{N} \leq \text{Lat} \leq 48^o\text{N}$; $128^o\text{E} \leq \text{Lon} \leq 156^o\text{E}$, which is a rather broad vicinity of Japan islands.

Multiple correlation for daily median values of 9 parameters of seismic noise from broadband network F-net:

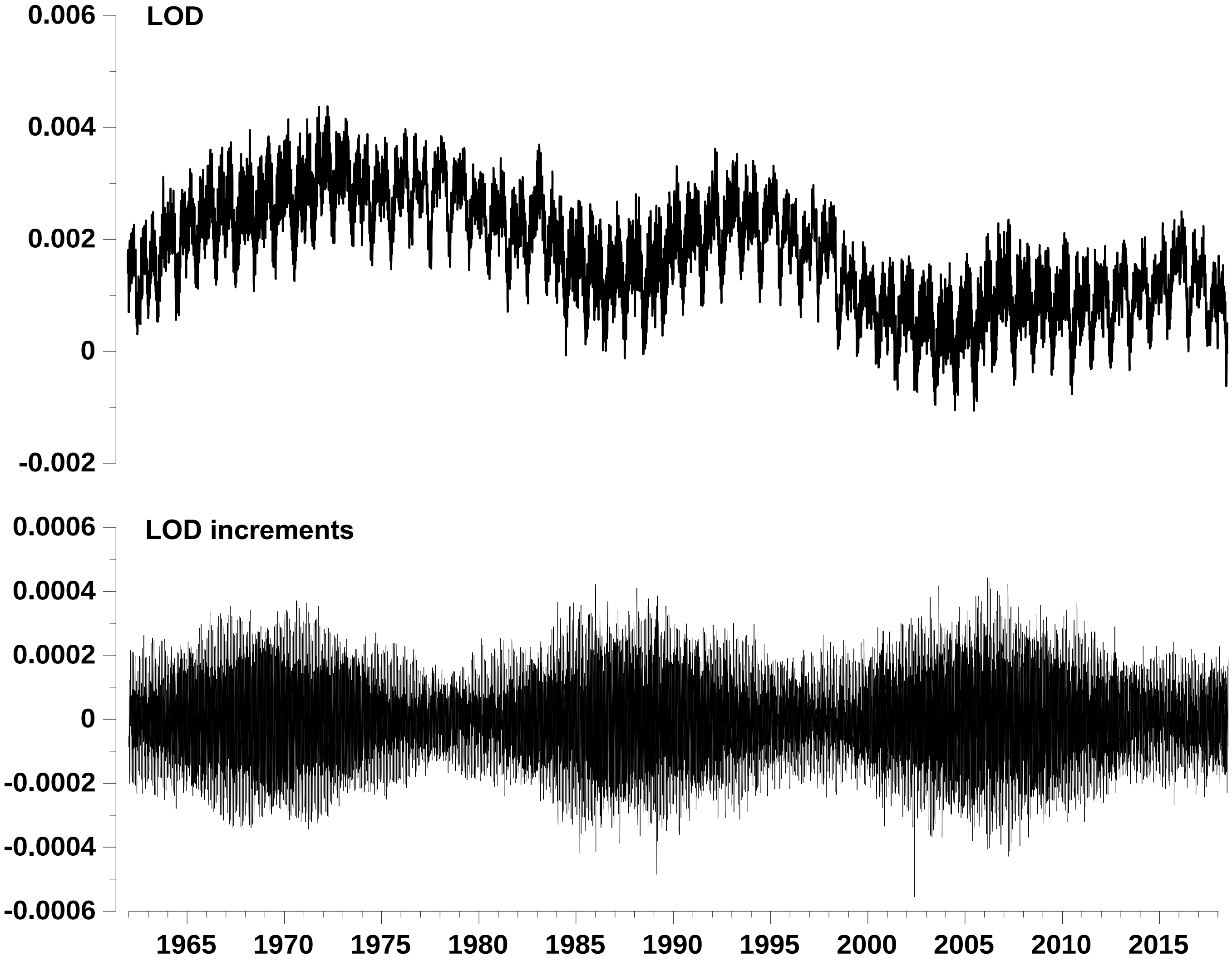
1. multi-fractal singularity spectrum support width;
2. generalized Hurst exponent;
3. minimum Holder-Lipschitz exponent;
4. wavelet-based spectral exponent;
5. logarithm of variance;
6. minimum entropy of squared orthogonal wavelet coefficients;
7. wavelet-based Donoho-Johnstone threshold;
8. index of linear predictability;
9. logarithm of kurtosis.



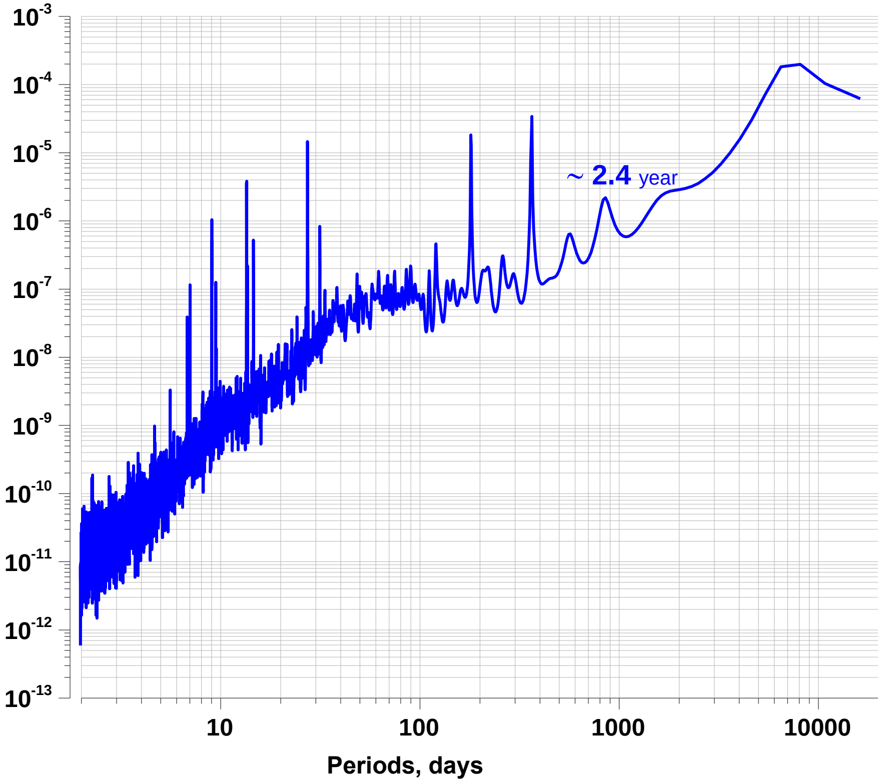
The change point corresponds to the first half of 2002

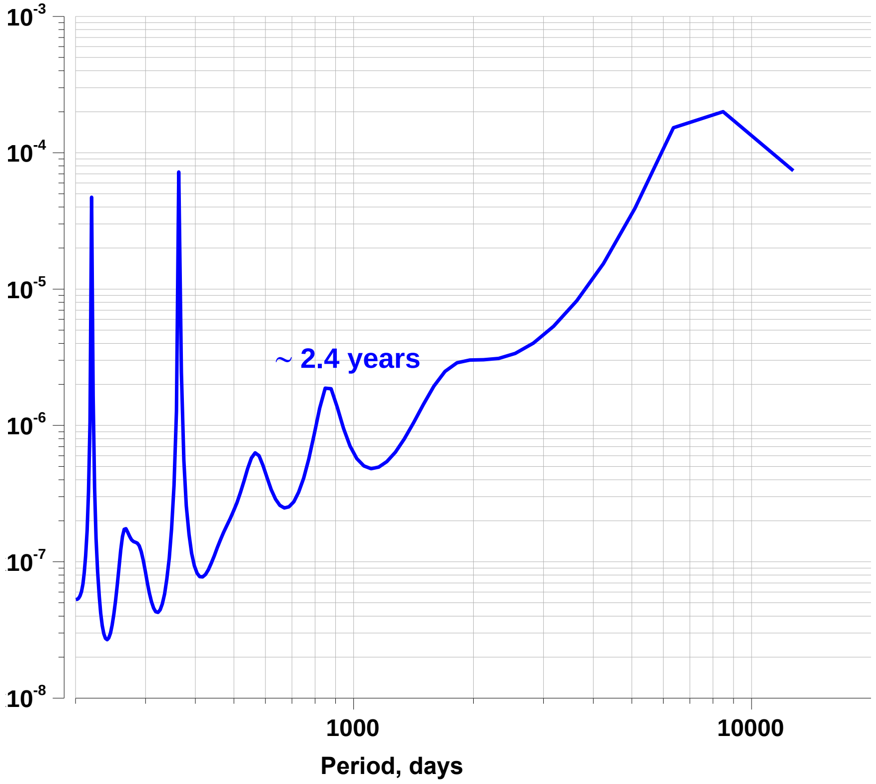
Anomalies of Earth's rotation as possible trigger for strongest earthquake

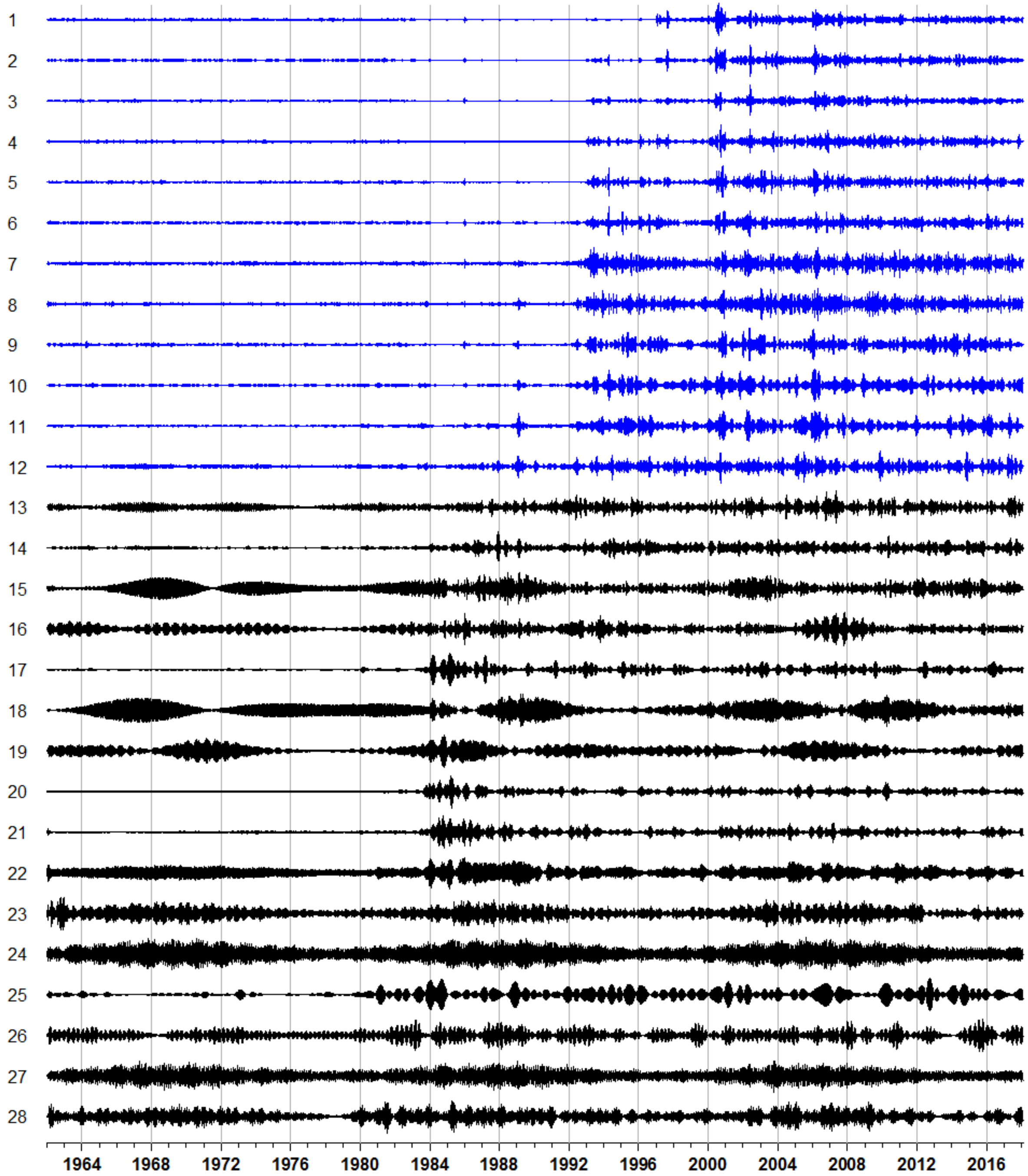
Daily LOD (Length of Day) time series, 1962 – 2018,
http://hpiers.obspm.fr/eop-pc/index.php?index=C04&lang=en



LOD power spectrum estimates, existence of 2.4 years periodicity


LOD power spectrum estimate





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Wavelet-packet
decomposition
of LOD increments.
Wavelet Daub20,
10 vanishing moments

 #    PeriodMin        PeriodMax
--------------------------------
 1    2.00000          2.13333
 2    2.13333          2.28571
 3    2.28571          2.46154
 4    2.46154          2.66667
 5    2.66667          2.90909
 6    2.90909          3.20000
 7    3.20000          3.55556
 8    3.55556          4.00000
 9    4.00000          4.26667
10    4.26667          4.57143
11    4.57143          4.92308
12    4.92308          5.33333
13    5.33333          5.81818
14    5.81818          6.40000
15    6.40000          7.11111
16    7.11111          8.00000
17    8.00000          8.53333
18    8.53333          9.14286
19    9.14286          9.84615
20    9.84615          10.6667
21    10.6667          11.6364
22    11.6364          12.8000
23    12.8000          14.2222
24    14.2222          16.0000
25    16.0000          17.0667
26    17.0667          18.2857
27    18.2857          19.6923
28    19.6923          21.3333
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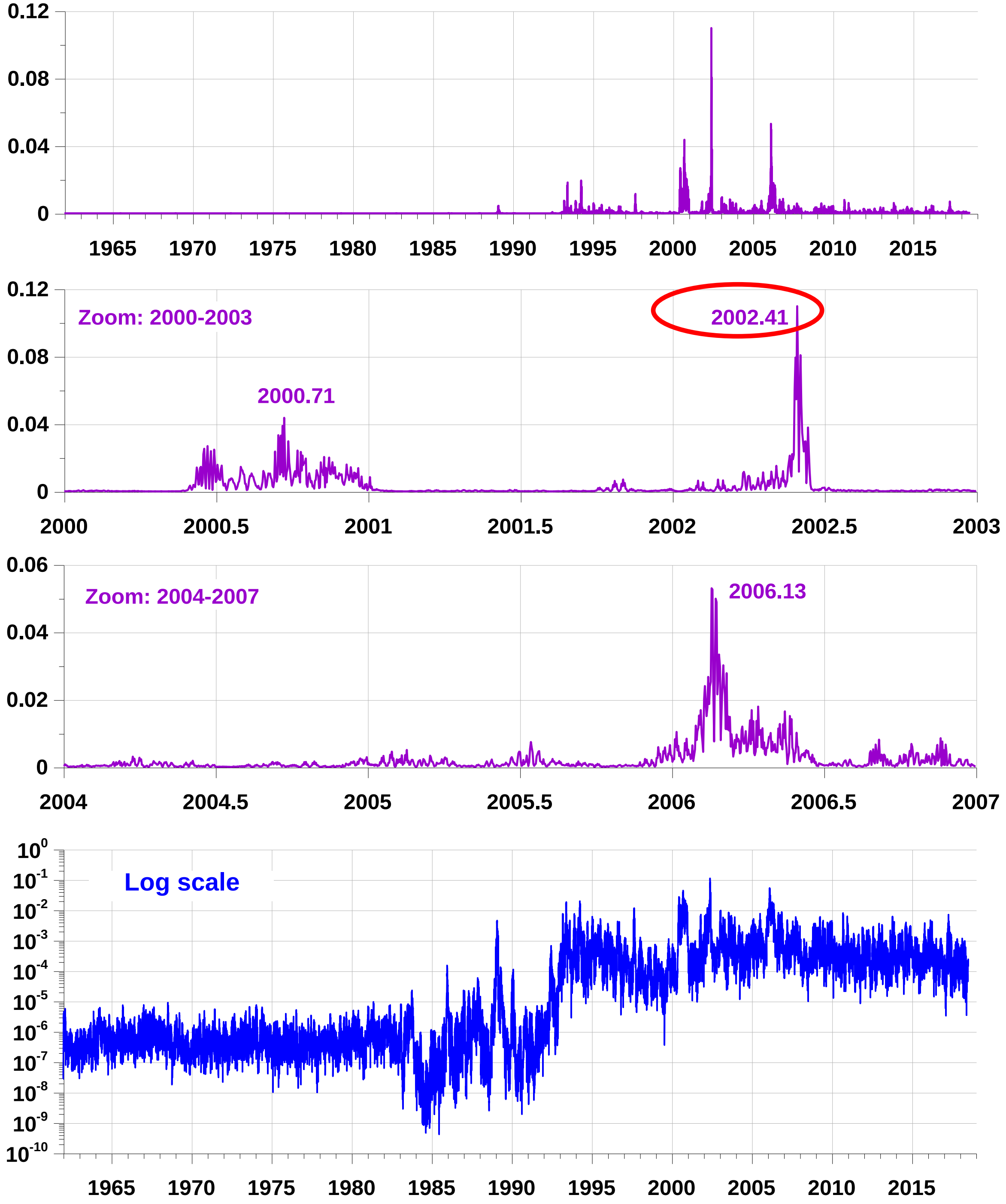
Starting from 1992 due to using modern methods of space geodesy high-frequency LOD variations became representative



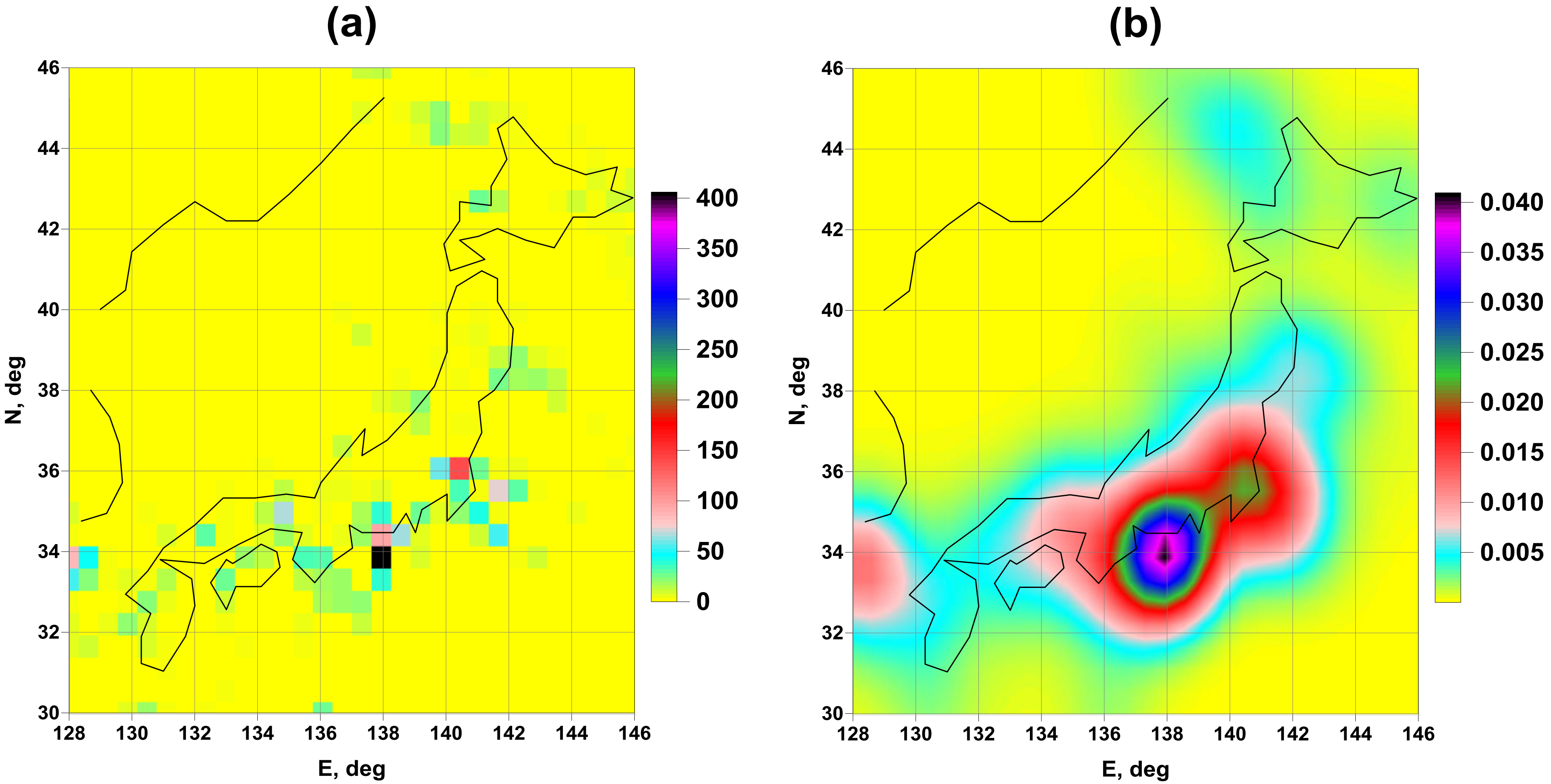
Measure of high-frequency LOD non-stationarity based on wavelet-packet decomposition with splitting each detail level into 8 sub-levels.

Daubechies orthogonal wavelet with 10 vanishing moments was used.

Measure was calculated for first 12 sub-levels with period range from 2 up to 5.33 days.

Radius of averaging vicinity = 5 days.

Series of 3 peaks of Earth’s rotation irregularity is observed within time interval 2000 – 2007.



(a) is a two-dimensional histogram of the maxima of the mean absolute by-pairs correlations of GPS time series in Japan from 10 nearest stations in sliding time windows of the length 5 days with mutual shift 1 day in nodes of a regular grid; (b) is the two-dimensional probability density of the positions of the maxima of the mean absolute by-pairs correlation, obtained by smoothing a two-dimensional histogram over the space.

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Conclusion

The mapping of various properties of low-frequency seismic noise (multi-fractal singularity spectrum support width and normalized entropy of wavelet coefficients) in sliding time windows represents a new method for estimating the dynamic seismic danger. This method makes it possible to trace the emergence and evolution of "spots of seismic danger".

Analysis of seismic noise on the islands of Japan on the broadband seismic network F-net made it possible to estimate in advance the approach of the region to the mega-earthquake on March 11, 2011. According to seismic noise analysis, after March 11, 2011, the next mega-earthquake in Japan in the Nankai Trough can occur.

To estimate the time interval for the occurrence of seismic event, a periodic structure of natural fluctuations of seismic danger with a period of about 2.5 years can be used. This periodicity could be caused by modulation by 2.4 periodicity of non-regularity of Earth's rotations. The change point of seismic process at the middle of 2002 could be a result of trigger action of high-frequency Earth's rotation anomaly at 2002.41.

Analysis of spatial high-frequency time series GPS allocates a spot of increased Earth's tremor noise correlation centered at the point (34N, 138E), which represents an independent assessment of the region of increased seismic hazard in the Nankai Trough.

The basic idea of using IoT sensors of another physical nature for seeking precursor synchronization is that the signals preceding the earthquake are a common modulating signal for sensors of different physical nature.