# Prognostic properties of seismic noise at Japan Islands


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Data processing until Sep 30, 2024

# Relevant Publications


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Lyubushin A.A. Synchronization of multi-fractal parameters of regional and global low-frequency microseisms – European Geosciences Union General Assembly 2010, Vienna, 02-07 of May, 2010, Geophysical Research Abstracts, Vol. 12, EGU2010-696, 2010, http://meetingorganizer.copernicus.org/EGU2010/EGU2010-696.pdf

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Lyubushin A.A. (2018) Cyclic Properties of Seismic Noise and the Problem of Predictability of the Strongest Earthquakes in Japanese Islands // Izvestiya, Atmospheric and Oceanic Physics, December 2018, Volume 54, Issue 10, pp 1460-1469. https://doi.org/10.1134/S0001433818100067

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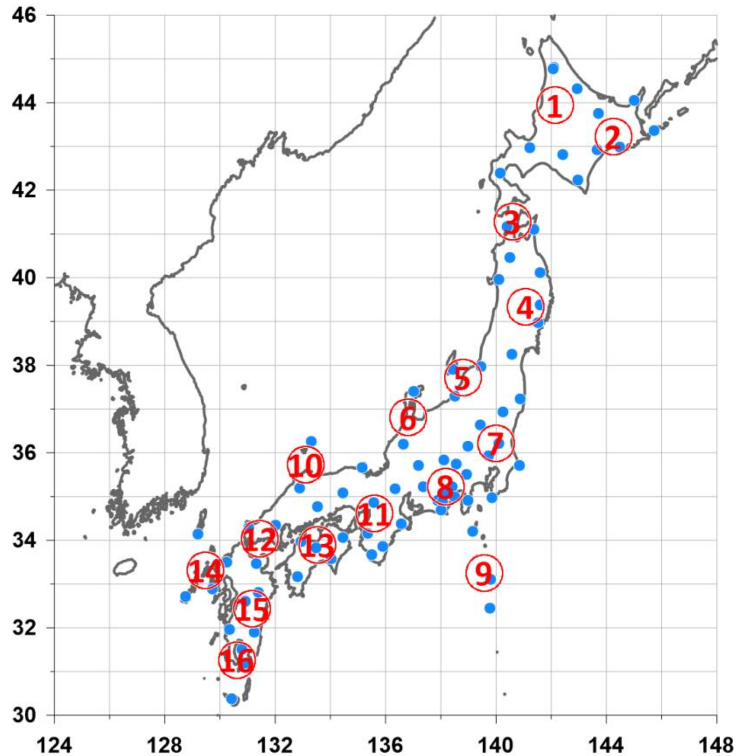
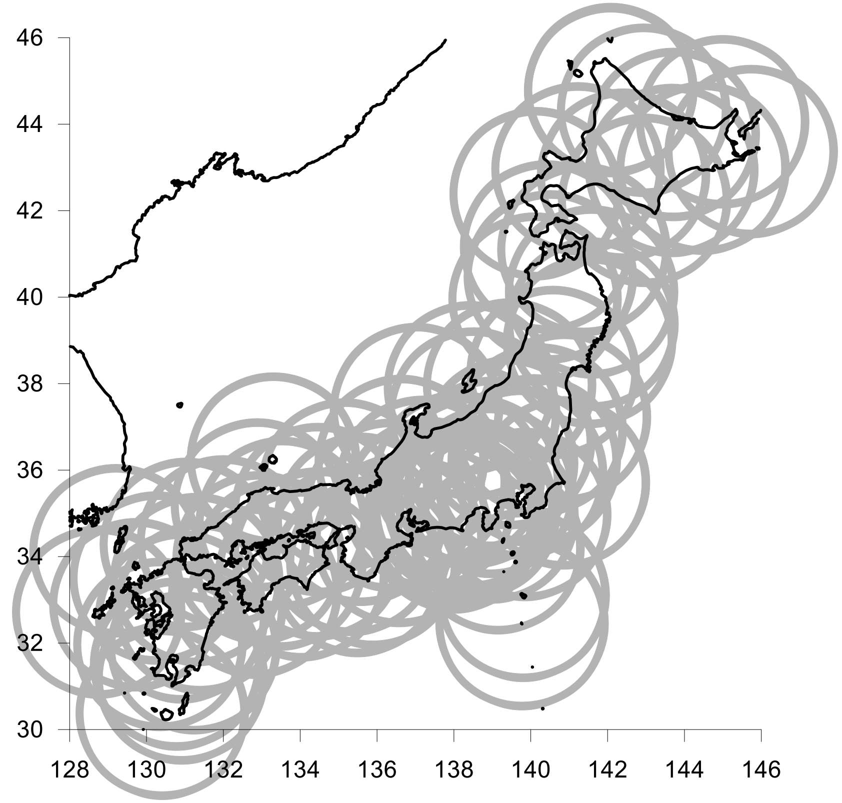
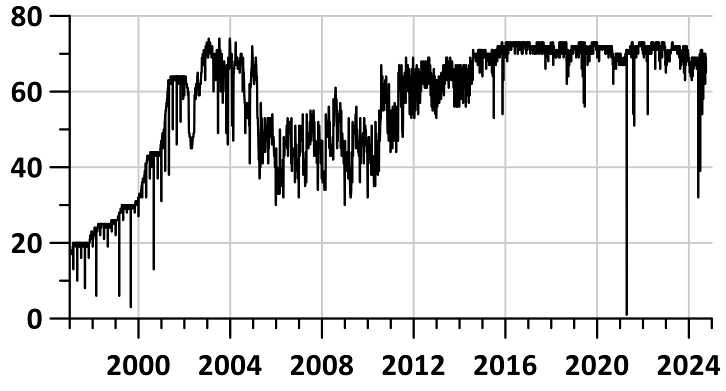
Positions of 78 seismic stations of broadband network F-net in Japan and 16 reference points.



Vicinity of Japanese Islands as the union of circles of radius 250 km around stations





**Daily numbers of working stations.**

https://www.fnet.bosai.go.jp/faq/?LANG=en

# Main seismic noise statistics

Information Minimum Normalized Entropy of the Distribution of Squares of Orthogonal Wavelet Coefficients :

$En = -\Sigma p_k \log(p_k) / \log(N)$, $p_k = (c_k)^2 / \Sigma(c_j)^2$, $c_j$ – wavelet coeff., $0 \le En \le 1$

An increase in seismic hazard is accompanied by a simplification of the noise structure and an increase in entropy : $En \uparrow$

*DJ* (Donoho-Johnstone) index - the ratio of the number of wavelet coefficients large in absolute value to their total number :

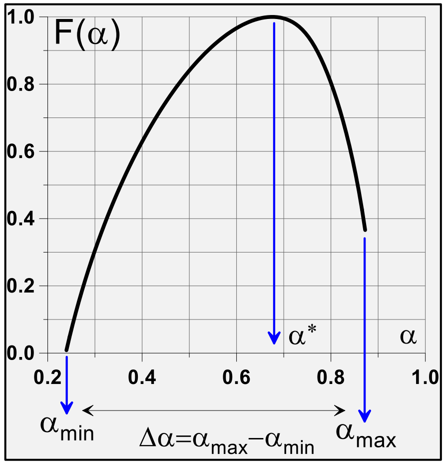
$\gamma = \#(|c_k|>T_{DJ}) / N$, $T_{DJ} = \sigma\sqrt{(2\log(N))}$, $\sigma$ – standard deviation of $c_k$ , $0 \le \gamma \le 1$

The increase in seismic hazard is accompanied by a simplification of the noise structure and a decrease in the DJ index : $\gamma \downarrow$

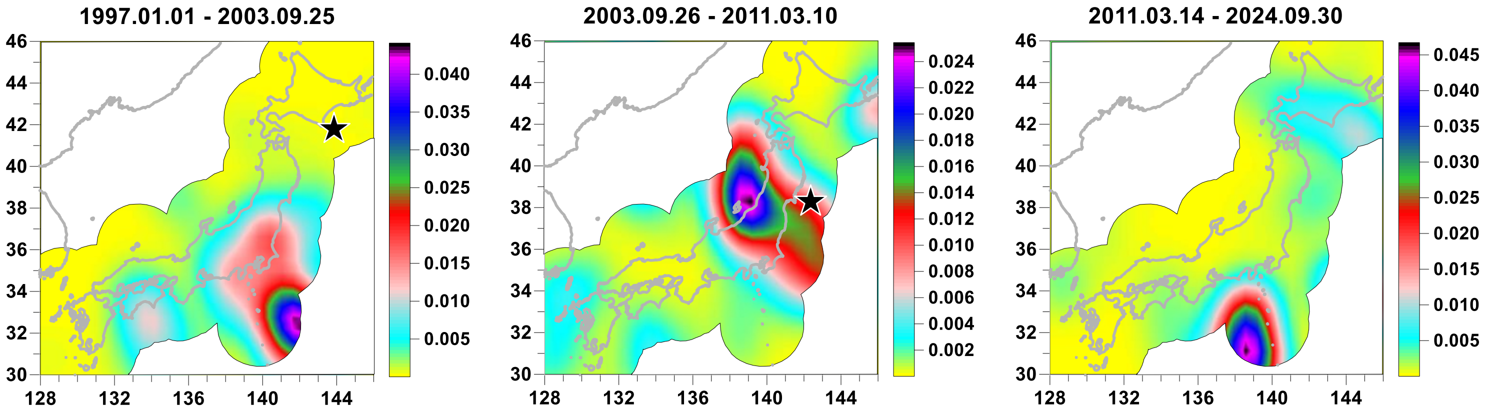
Hölder-Lipschitz exponent: $|x(t+\Delta t/2) - x(t-\Delta t/2)| \sim (\Delta t)^{H(t)}$, $\Delta t \to 0$

$F(\alpha)$ - fractal dimension of a set of points $t$, for which $H(t) = \alpha$

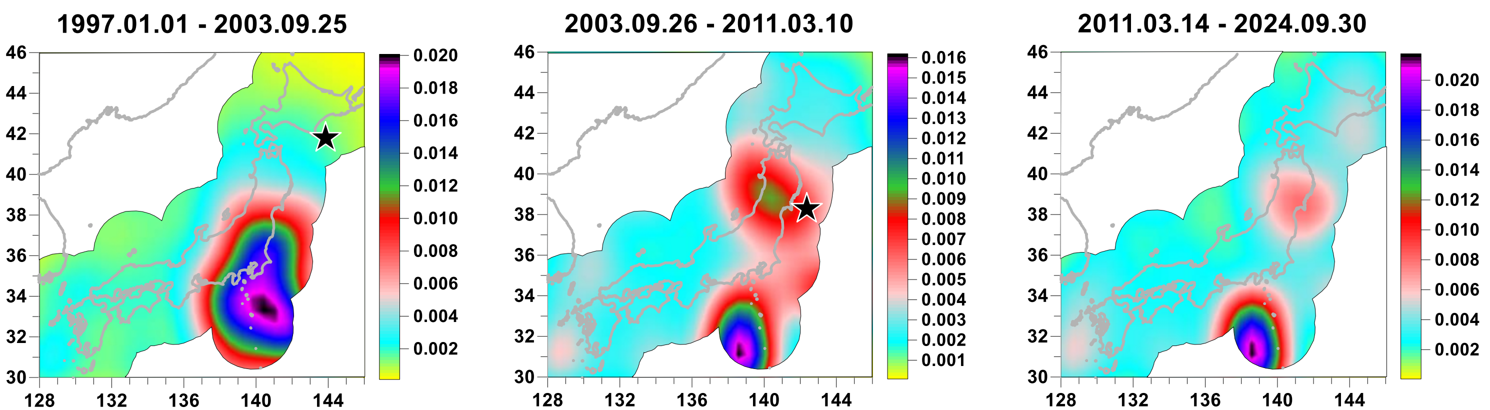
Support Width of Multifractal Singularity Spectrum $\Delta\alpha$.
The growth of seismic hazard is accompanied by a simplification of the noise structure and a decrease of $\Delta\alpha$ (“the loss of multifractality”): $\Delta\alpha \downarrow$



**Averaged maps of probability densities of maximum values of multiple correlation coefficient between increments of generalized Hurst exponent, DJ index, singularity spectrum support width, minimum entropy and kurosis for 3 time intervals.**

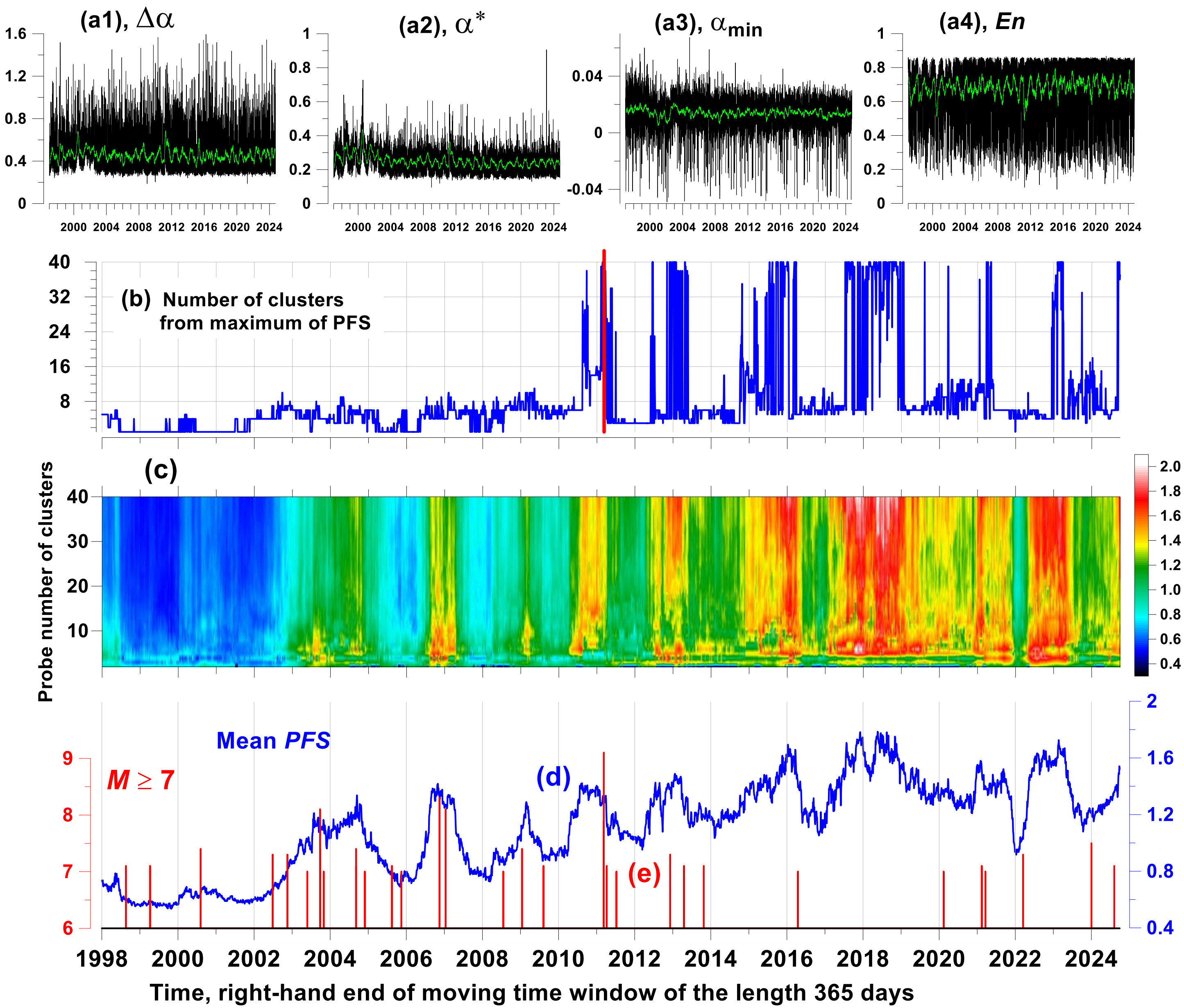



**Weighted means of probability densities of extreme values of 3 seismic noise properties (minima of singularity spectrum support width, minima of wavelet based DJ-index and maxima of wavelet based minimum entropy) for 3 time intervals**




**Black stars indicate hypocenters of 2 strong earthquakes: 2003.09.25, M=8.3 and 2011.03.11, M=9.1.**

**The maps are shown only in the vicinity of the Japanese Islands in the union of circles with a radius of 250 km, built around each seismic station.**



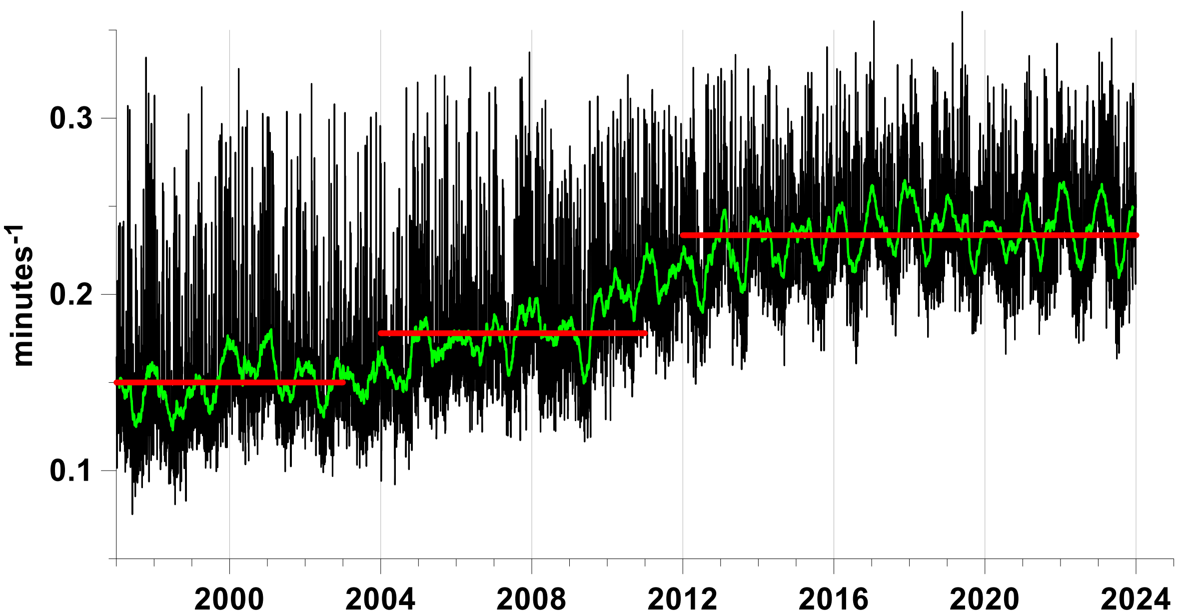

**(a1)-(a4) – plots of daily median values of seismic noise properties, green lines present running average within time windows of the length 57 days;**

**(b) – plot of the best numbers of clusters for the sequence of clouds consisting of 365 daily 4D vectors from moving time window of the length 365 days with mutual shift 3 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.**

**Two-dimensional 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.**

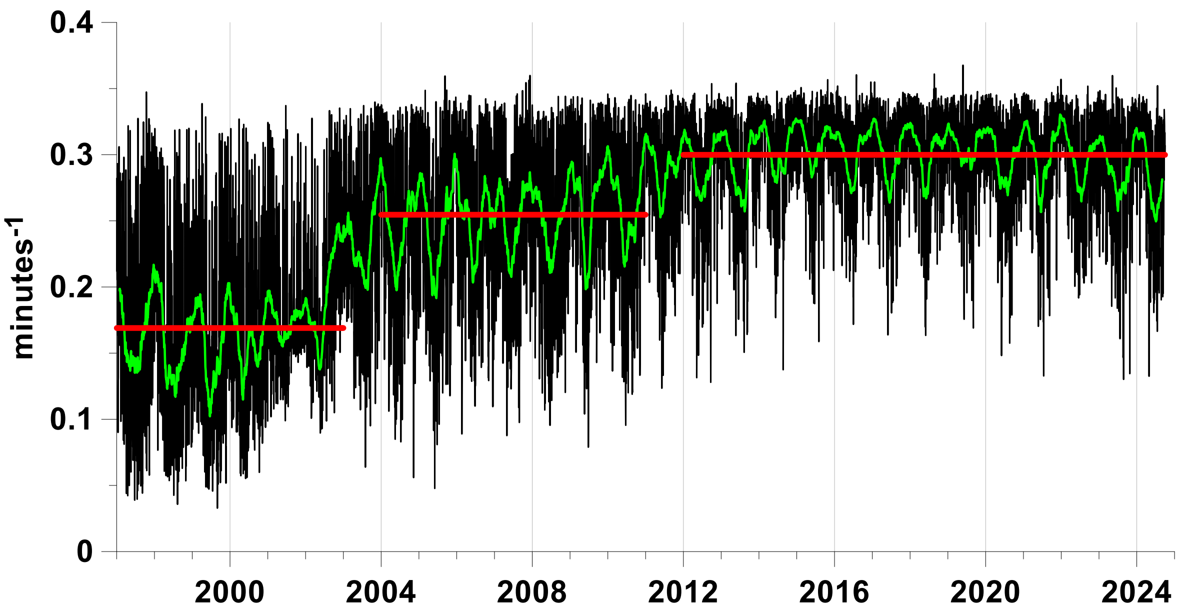
**Plot (d) presents mean value of pseudo-F-statistics averaged by all probe numbers of clusters in dependence on right-hand end of moving time window of the length 365 days.**

**Plot (e) presents the sequence of time moments of strong earthquakes in the rectangular domain with coordinates**
**$28^oN \leq Lat \leq 48^oN$;**
**$128^oE \leq Lon \leq 156^oE$**
**which is a rather broad vicinity of Japan islands.**



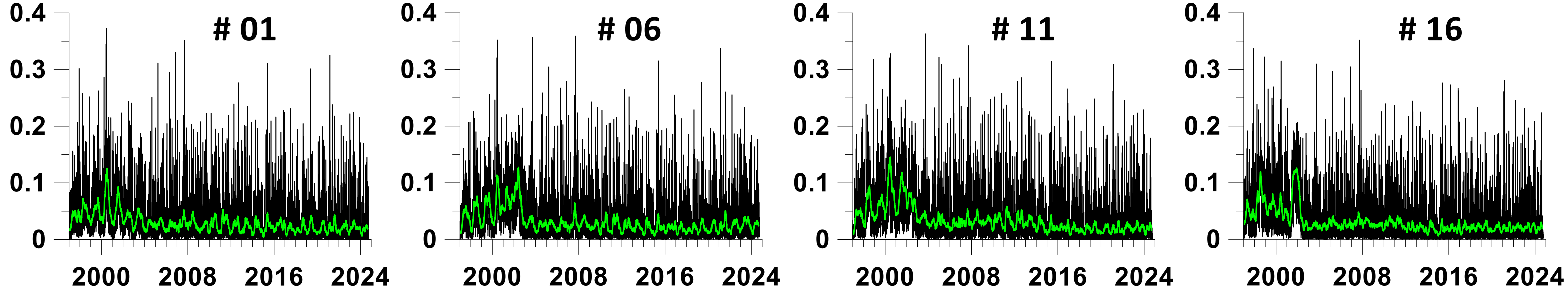

Daily median
values of
centroid frequency
of low-frequency
seismic noise,
global seismic network
229 stations
all over the world,

Three levels
of seismic danger.

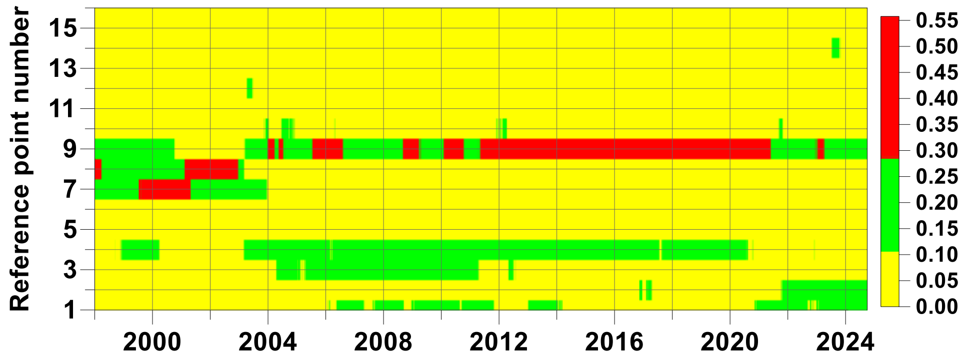



Daily median
values of
centroid frequency
of low-frequency
seismic noise,
84 stations
in Japan.

Three levels
of seismic danger.

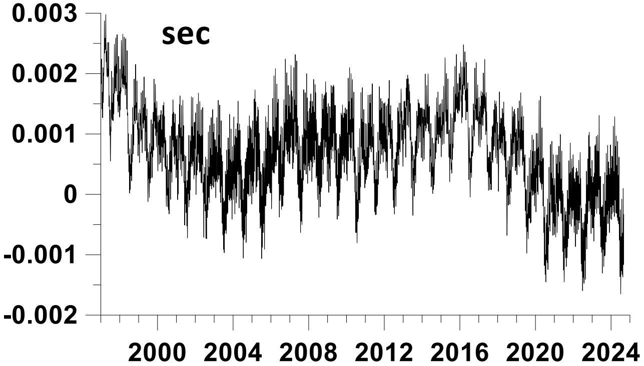



**Daily values of DJ-index in 4 reference points, green lines - running average within time window of the length 57 days.**

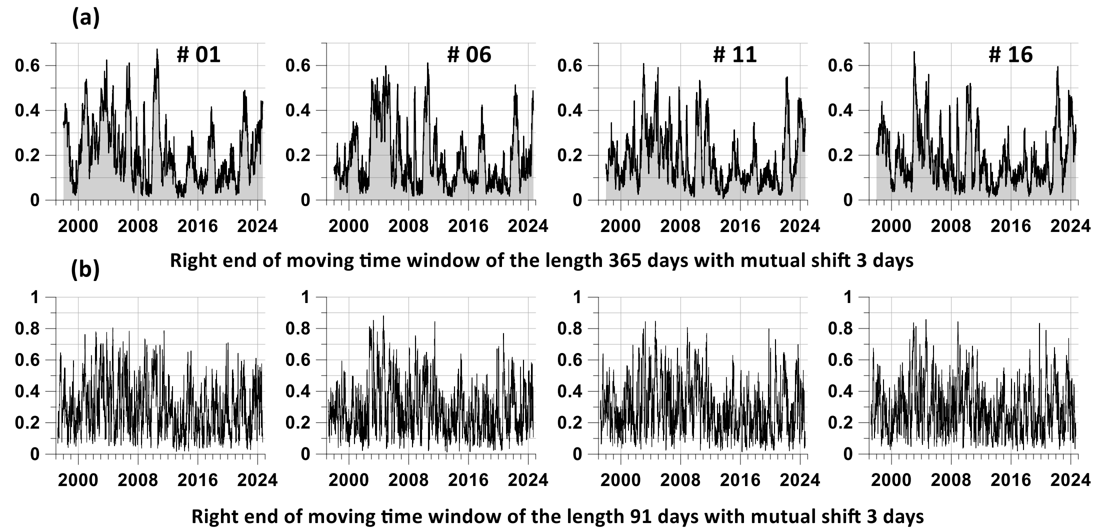



**Histogram of numbers of reference points, in which the minimum values of the DJ index were realized in a moving time window 365 days long.**

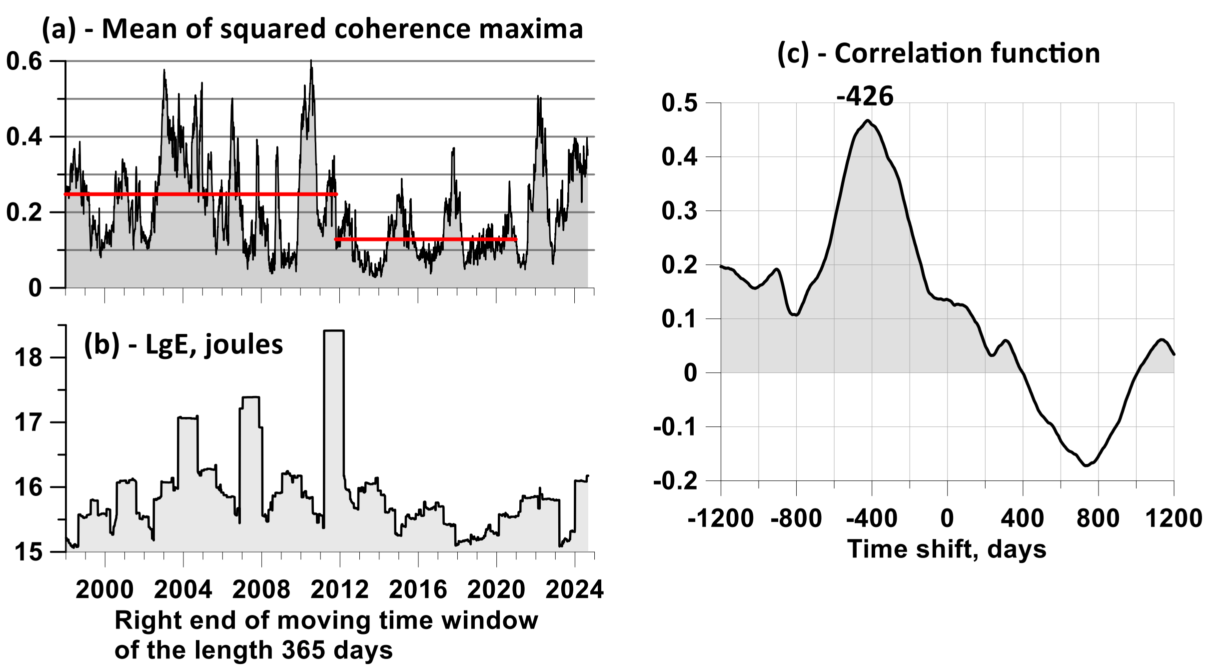
**The histogram shows strips of probability concentration for the minimum values of the DJ index for data from the vicinity of control points with numbers 7-9 and 3-4. The highest concentration of minimum values is observed for the reference point #9 starting from 2004 until the end of the considered time interval. This behavior of the minimum values of the DJ index is interpreted as the existence of a permanent source of seismic hazard with an increased probability of strong earthquakes in the vicinity of reference point #9. Another high risk area corresponds to point #4, which emerged in 2002-2003 (taking into account that the estimates are given for a 1-year time window) and ended in 2020. Note that the vicinity of reference point #4 is the area where the epicenter of the March 11, 2011 Tohoku mega-earthquake is located. The continuation of the line of increased probability of low values after 2011 for point #4 is associated with aftershock activity.**




Time series plot of the length of a day (LOD) for the time interval 1997-2024.

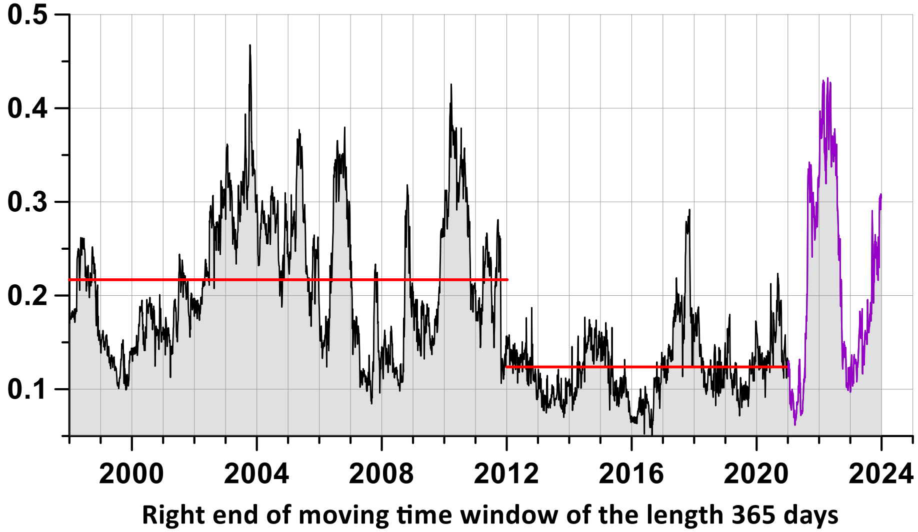



Plots of maximum coherence between index and LOD in a moving time window of 365 days (a) and 91 days (b) with mutual shift 3 days for 4 reference points.



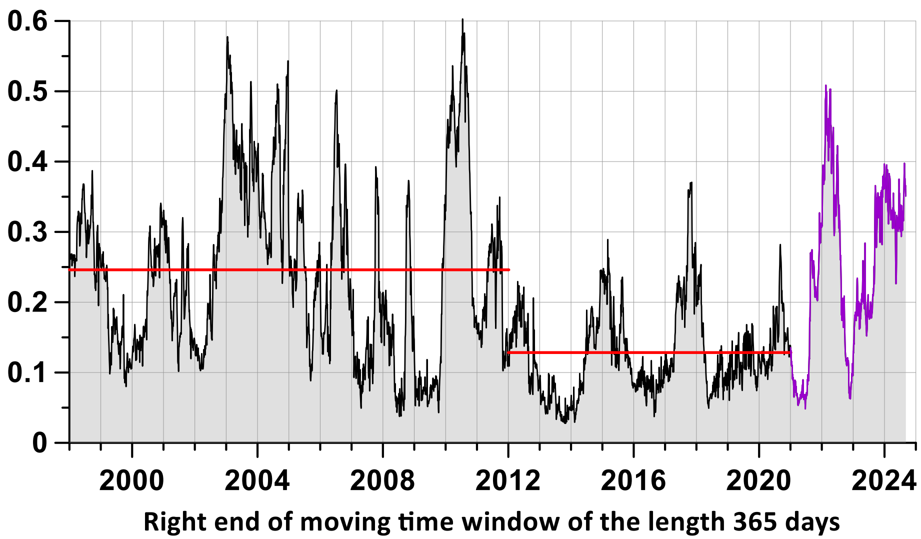

(a) is the logarithm of the released seismic energy (in joules) within moving time window of the length 365 days with mutual shift 3 days; (b) – average values DJ-index response to LOD; (c) is the correlation function between the released seismic energy and DJ-index response to LOD.

Global seismic noise response (229 stations, worldwide, networks GSN, GEOSCOPE, GEOFON) to irregulaty of Earth rotation, 1997-2023. Maximum quadratic coherence.

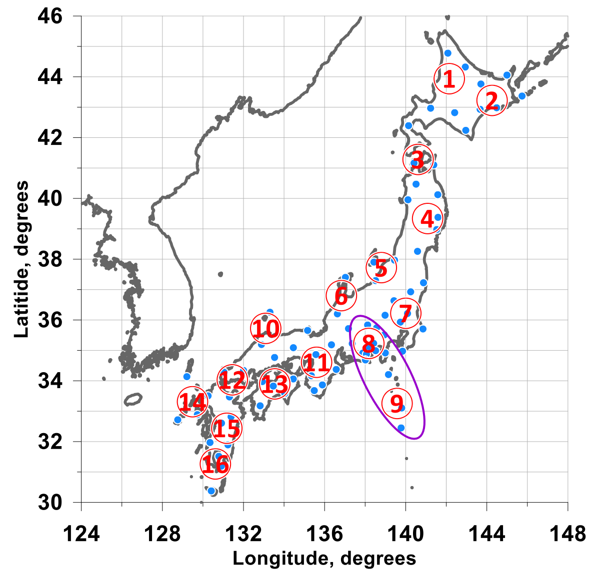


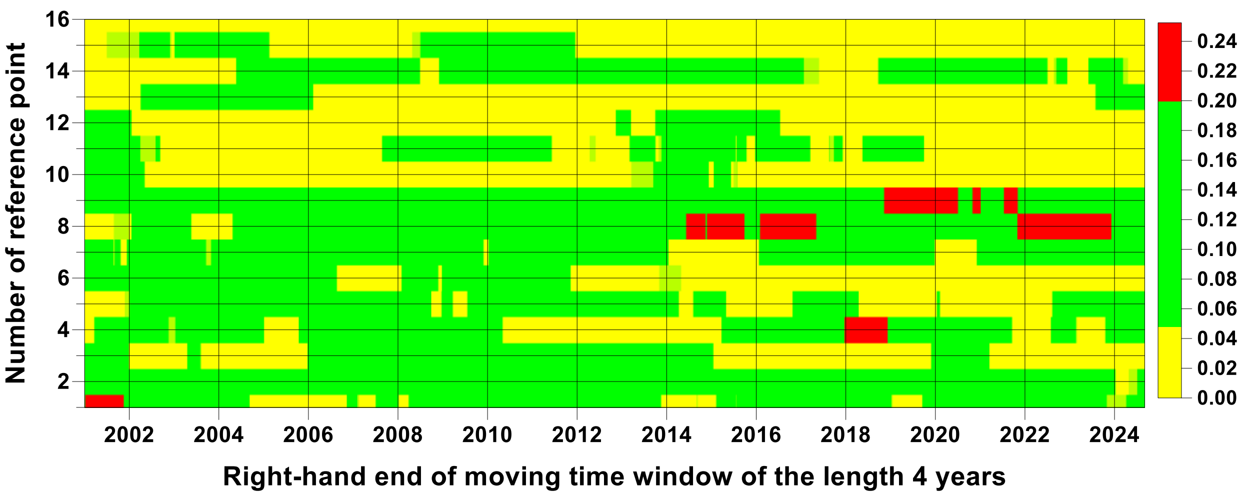

Seismic noise response in Japan (78 stations, F-net) to irregularity of Earth rotation, 1997 - Sep 04, 2024. Maximum quadratic coherence.

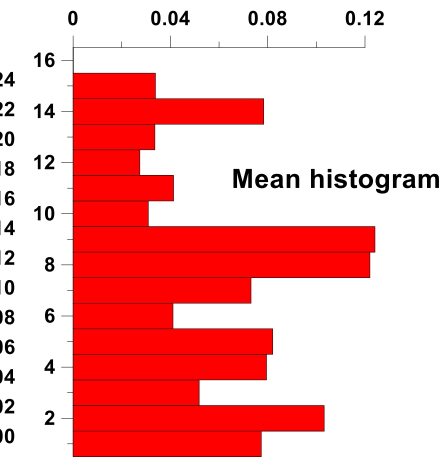
Correlation coefficient 0.85



**Distribution in space and time of <u>maximum</u> seismic noise DJ index responses to LOD in Japan**

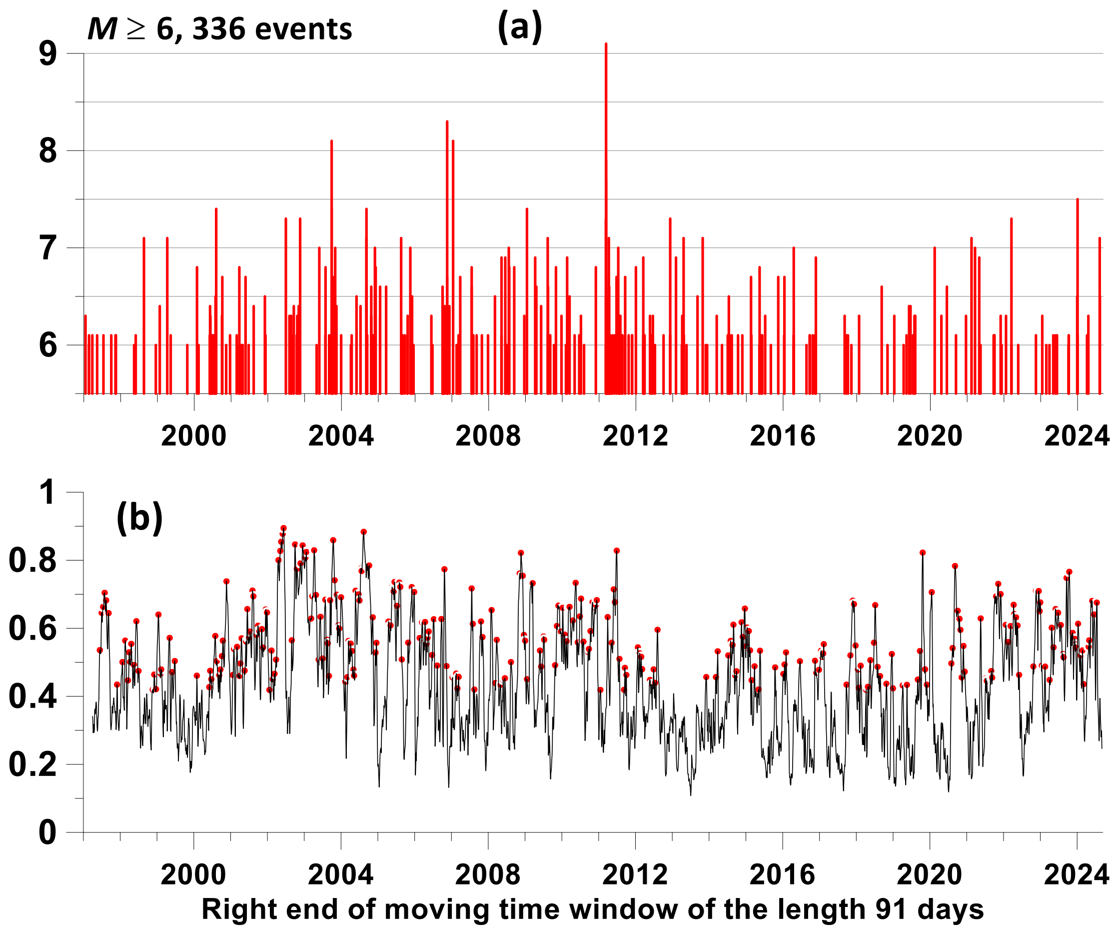



Changes in the histogram of the distribution of numbers of reference points in which the maximum response to LOD was realized in a moving time window of 4 years.

Maximum mean response at reference point number 9.



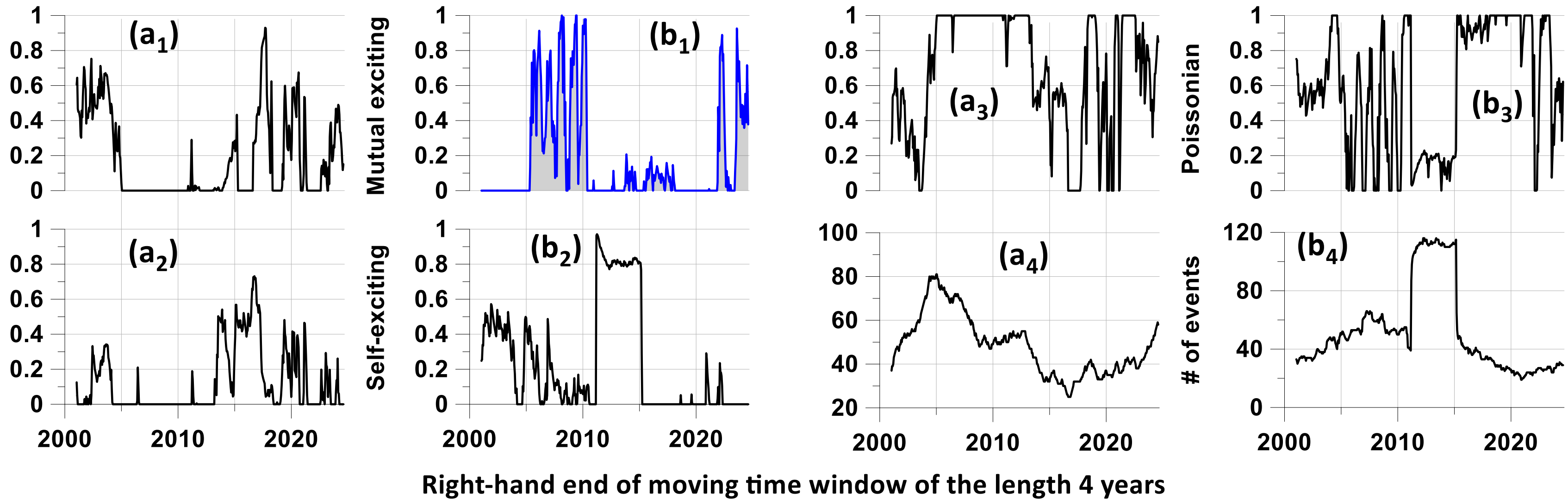

**(a) – sequence of 336 earthquakes with magnitudes in the vicinity of Japanese islands; (b) – maxima of maximum values of coherences between LOD and daily DJ-index values at 16 reference points within moving time window of the length 91 days with mutual shift 3 days, red points present the largest 336 local maxima values.**

# Influence matrix of 2 point processes

Let $t_j^{(\alpha)}, j=1,...,N_\alpha; \alpha=1,2$ be of time moments of 2 sequences of events. The intensities of these series are presented in the form: $\lambda^{(\alpha)}(t)=b_0^{(\alpha)}+\sum_{\beta=1}^{2} b_\beta^{(\alpha)}\cdot g^{(\beta)}(t)$ where $b_0^{(\alpha)}\ge 0, b_\beta^{(\alpha)}\ge 0$ are parameters, $g^{(\beta)}(t)$ is a function of influence of the events $t_j^{(\beta)}$ from the stream with number $\beta$: $g^{(\beta)}(t)=\sum_{t_j^{(\beta)}<t}\exp(-(t-t_j^{(\beta)})/\tau)$. This formula means that the weight of the event with the number $j$ is non-zero for times $t>t_j^{(\beta)}$ and decays with the relaxation time $\tau$. The parameter $b_\beta^{(\alpha)}$ determines the degree of influence of the flow $\beta$ on the flow $\alpha$. The parameter $b_\alpha^{(\alpha)}$ determines the self-exciting influence of the flow on itself, whereas $b_0^{(\alpha)}$ corresponds to a purely random (Poisson) intensity share. The relaxation time $\tau$ is a free parameter. Let's consider the problem of determining the values $b_0^{(\alpha)}, b_\beta^{(\alpha)}$. The logarithmic likelihood functions for a non-stationary Poisson process at the time interval $[0,T]$: $\ln(L_\alpha)=\sum_{j=1}^{N_\alpha}\ln(\lambda^{(\alpha)}(t_j^{(\alpha)}))-\int_0^T\lambda^{(\alpha)}(s)ds, \quad \alpha=1,2$. Let's consider the problem of seeking parameters $b_0^{(\alpha)}, b_\beta^{(\alpha)}$ from maximizing $\ln(L_\alpha)$. The next expression could easily be obtained: $b_0^{(\alpha)}\frac{\partial\ln(L_\alpha)}{\partial b_0^{(\alpha)}}+\sum_{\beta=1}^{2}b_\beta^{(\alpha)}\frac{\partial\ln(L_\alpha)}{\partial b_\beta^{(\alpha)}}=N_\alpha-\int_0^T\lambda^{(\alpha)}(s)ds$. At the maximum point of function $\ln(L_\alpha)$ each term on the left side of this formula is equal to zero. This follows from the conditions that parameters $b_0^{(\alpha)}, b_\beta^{(\alpha)}$ must be non-negative. Thus, if the parameters are positive at maximum point the partial derivatives equal zero from necessary extremum conditions or, if the maximum is reached at the boundary, then the parameters themselves are equal to zero. Therefore, at the maximum point of the likelihood function, the following equality holds: $\int_0^T\lambda^{(\alpha)}(s)ds=N_\alpha$. Another form of this formula: $b_0^{(\alpha)}+\sum_{\beta=1}^{m}b_\beta^{(\alpha)}\cdot\bar{g}^{(\beta)}=\lambda_0^{(\alpha)}\equiv N_\alpha/T$, $\bar{g}^{(\beta)}=\int_0^T g^{(\beta)}(s)ds/T$ - the average value of the influence function. Substituting expression of $b_0^{(\alpha)}$ into $\ln(L_\alpha)$, we obtain the following maximum problem: $\Phi^{(\alpha)}(b_1^{(\alpha)},b_2^{(\alpha)})=\sum_{j=1}^{N_\alpha}\ln(\lambda_0^{(\alpha)}+\sum_{\beta=1}^{2}b_\beta^{(\alpha)}\cdot\Delta g^{(\beta)}(t_j^{(\alpha)}))\to\max$, where $\Delta g^{(\beta)}(t)=g^{(\beta)}(t)-\bar{g}^{(\beta)}$, under the restrictions: $b_1^{(\alpha)}\ge 0, b_2^{(\alpha)}\ge 0, \sum_{\beta=1}^{2}b_\beta^{(\alpha)}\bar{g}^{(\beta)}\le\lambda_0^{(\alpha)}$. Function $\Phi^{(\alpha)}$ is convex with a negative definite Hessian and, therefore, problem of conditional maximization has a unique solution and is solving numerically for a given relaxation time $\tau$, The influence matrix elements $\kappa_\beta^{(\alpha)}, \alpha=1,2; \ \beta=0,1,2$ according to the formulas: $\kappa_0^{(\alpha)}=\frac{b_0^{(\alpha)}}{\lambda_0^{(\alpha)}}\ge 0, \quad \kappa_\beta^{(\alpha)}=\frac{b_\beta^{(\alpha)}\cdot\bar{g}^{(\beta)}}{\lambda_0^{(\alpha)}}\ge 0$. The value $\kappa_0^{(\alpha)}$ is the pure random share of the mean intensity $\lambda_0^{(\alpha)}$ of the process $\alpha$, the share $\kappa_\alpha^{(\alpha)}$ is the self-excitation part of intensity $\alpha\to\alpha$ and $\kappa_\beta^{(\alpha)}, \beta\ne\alpha$ is the share due to mutual exciting $\beta\to\alpha$. The normalization condition is satisfied: $\kappa_0^{(\alpha)}+\sum_{\beta=1}^{2}\kappa_\beta^{(\alpha)}=1, \quad \alpha=1,2$ The influence matrix of the size 3×2 could be defined:

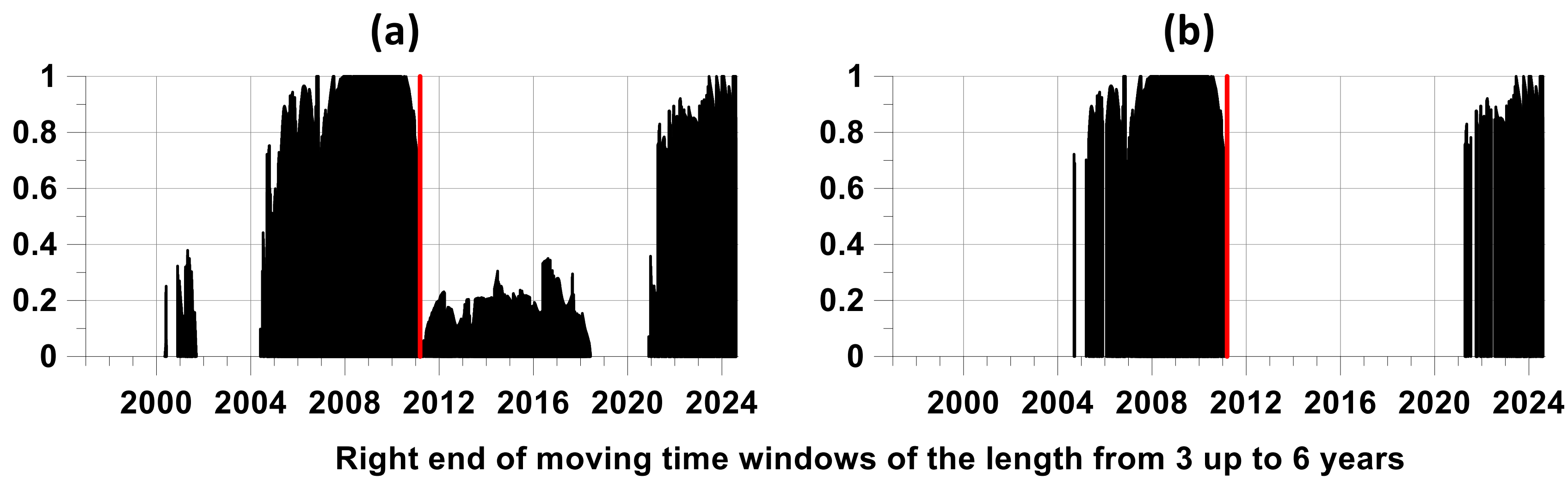
$$\begin{pmatrix} \left|\begin{matrix}\kappa_0^{(1)}\\ \kappa_0^{(2)}\end{matrix}\right| \left|\begin{matrix}\kappa_1^{(1)} & \kappa_2^{(1)}\\ \kappa_1^{(2)} & \kappa_2^{(2)}\end{matrix}\right| \end{pmatrix}$$

First column of this matrix is composed of Poisson shares of mean intensities. The diagonal elements of the right sub-matrix of the size 2×2 is composed of self-exciting shared of mean intensities whereas non-diagonal elements correspond to mutual-exciting. The sums of row components of influence matrix are equal to 1.



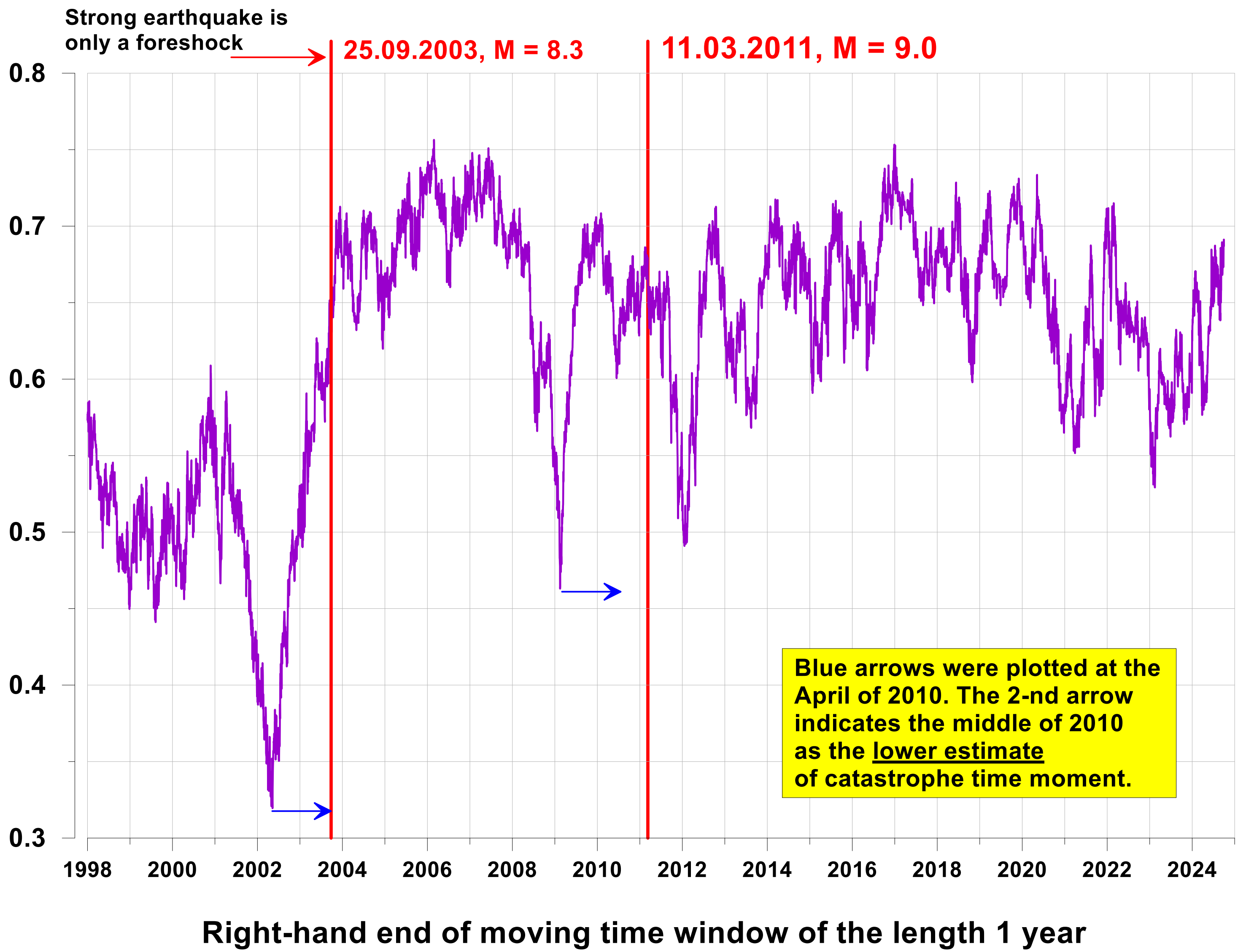

**Components of influence matrix for estimation of relations between the sequence of maxima seismic noise DJ index average response per LOD and the sequence of earthquakes within vicinity of Japan islands. Left panel of graphs corresponds to the influence of coherence maxima sequence from sequence of seismic events whereas right panel of graphs corresponds to vice versa influence of seismic events from coherence maxima. Intensity shares were estimated within moving time window of the length 4 years, relaxation time of the intensity model was taken 0.5 years. Graphs ($a_1$) and ($b_1$) present mutual exciting components of influence matrix; ($a_2$) and ($b_2$) – self-exciting components, ($a_3$) and ($b_3$) – Poisson shares of intensities; ($a_4$) and ($b_4$) – numbers of events within each time window.**

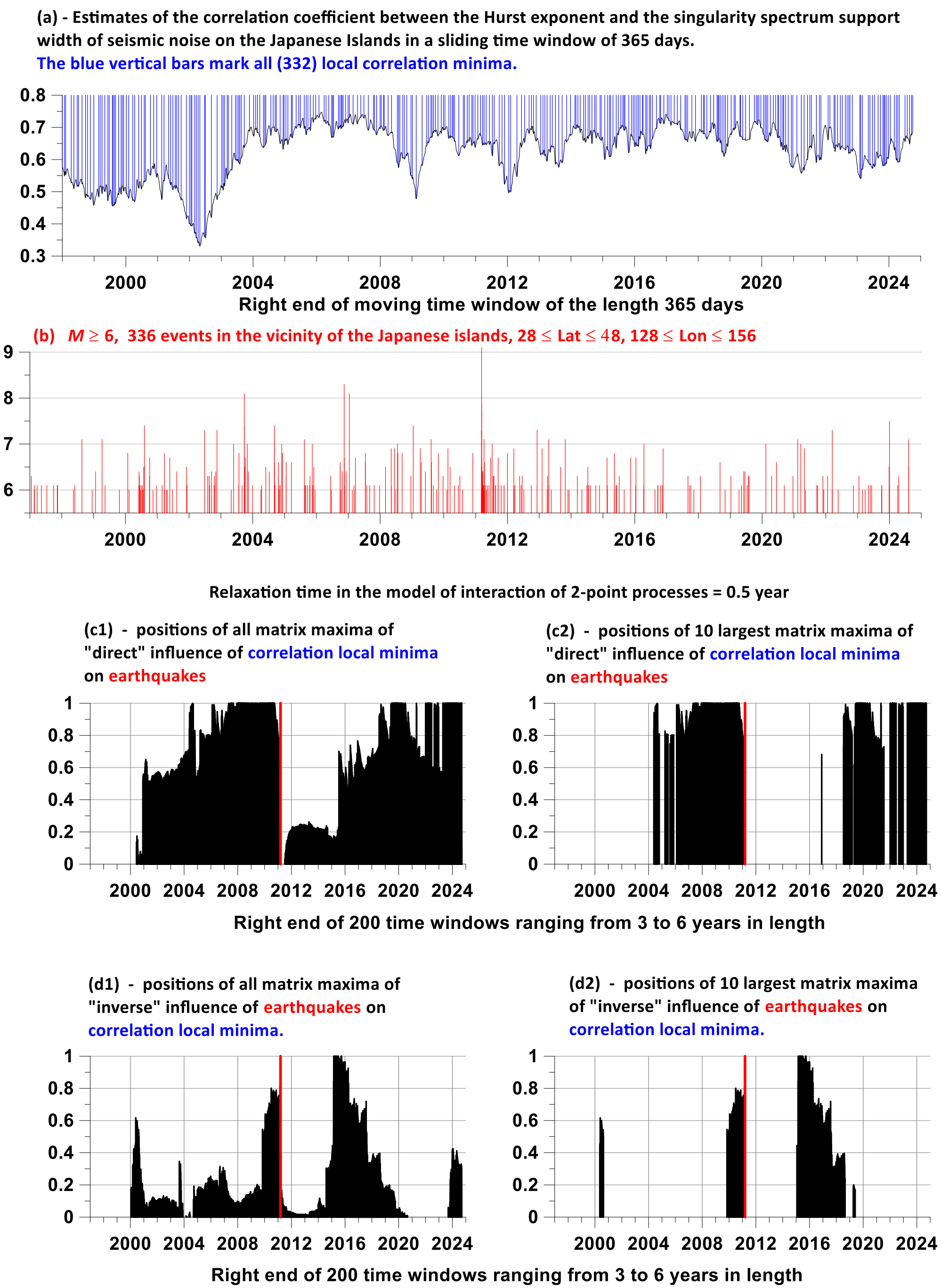

**Vertical lines - positions on the time axis and values of local maxima of elements of the matrix of influence corresponding to the "influence" of the sequence of maxima seismic noise DJ index average response per LOD on sequence earthquakes for evaluation in a sliding time window of 4 years with a shift of 0.05 years, the relaxation time parameter is 0.5 years.**




**The times and magnitudes of local maxima of the matrices of the influence of the seismic noise index DJ responses on the LOD on the sequence of earthquakes *M* ≥ 6 when estimating in moving time windows of lengths varying from 3 to 6 years with a shift of 0.05 years, the relaxation time in the model is 0.5 years. The vertical red line corresponds to the time of the March 11, 2011 mega-earthquake. Plot (a) corresponds to using all local maxima of influence matrix component whereas plot (b) corresponds to using of 10 maximum local maxima in each time window.**

**Time Prediction:** Squared correlation between mean values of multi-fractal parameters $\Delta\alpha$ and $\alpha^*$ of microseisms from all F-net stations estimated within 1 year moving time window.





(a) - Estimates of the correlation coefficient between the Hurst exponent and the singularity spectrum support width of seismic noise on the Japanese Islands in a sliding time window of 365 days.
The blue vertical bars mark all (332) local correlation minima.
0.8
0.7
0.6
0.5
0.4
0.3
2000
2004
2008
2012
2016
2020
2024
Right end of moving time window of the length 365 days
(b) M ≥ 6, 336 events in the vicinity of the Japanese islands, 28 ≤ Lat ≤ 48, 128 ≤ Lon ≤ 156
9
8
7
6
Relaxation time in the model of interaction of 2-point processes = 0.5 year
(c1) - positions of all matrix maxima of "direct" influence of correlation local minima on earthquakes
(c2) - positions of 10 largest matrix maxima of "direct" influence of correlation local minima on earthquakes
1
0.8
0.6
0.4
0.2
0
Right end of 200 time windows ranging from 3 to 6 years in length
(d1) - positions of all matrix maxima of "inverse" influence of earthquakes on correlation local minima.
(d2) - positions of 10 largest matrix maxima of "inverse" influence of earthquakes on correlation local minima.
Right end of 200 time windows ranging from 3 to 6 years in length

# Conclusions

**The experience of using various statistics of low-frequency seismic noise to search for features of noise behavior that can be preceded by strong earthquakes unexpectedly showed that a relatively simple quantity describing the ratio of the number of "large" wavelet coefficients to their total number surpasses such properties as entropy in its efficiency or the support width of the multi-fractal spectrum of the singularity. For this reason, in this article, we focused on studying only the properties of the DJ index, although earlier the first principal component of three properties was used for the seismic noise of Japan: the DJ index, the entropy of the distribution of the squares of the wavelet coefficients, and the singularity spectrum support width. At the same time, the previously used method for estimating spatial distribution maps of extreme properties of seismic noise using a kernel Gaussian estimate was also replaced by a simpler method for calculating the histogram of the distribution of reference points numbers, in which the minimum of the DJ index was realized in a sliding time window. This method of representing the variability of the distribution over space of the minimum values of the DJ index, in addition to its ease of implementation, makes it possible to present the temporal dynamics of this variability in a compact form. Inclusion in the analysis of new data 2 years in length compared to previous estimates led to the discovery of a significant spike in the response of the DJ index to LOD in 2022. This gives grounds to put forward a hypothesis about an increase in the current seismic hazard in the Japanese Islands, and the evaluation of the correlation function between the response to LOD and the release of seismic energy gives an approximate estimate of the time of a possible strong seismic shock. The use of a parametric model of two interacting point processes - a sequence of earthquakes with a magnitude of at least 6 and time points of the largest local maxima of the response to LOD, when assessed in a moving window of 91 days, also independently confirmed the hypothesis that the Japanese Islands would enter a dangerous time interval in 2023-2024. As for the place of a possible strong earthquake, according to the histogram of the change in the distribution over space of the minimum values of the DJ-index, the most probable place is the vicinity of reference point #9.**

**Monthly maps of seismic noise properties since 2012:**
**http://alexeylyubushin.narod.ru/Japan_Seismic_Noise_Properties_Monthly.pdf**