The global synchronization of the Earth's ambient noises

Alexey Lyubushin

lyubushin@yandex.ru, http://alexeylyubushin.narod.ru/

Institute of Physics of the Earth, Russian Academy of Sciences, Moscow

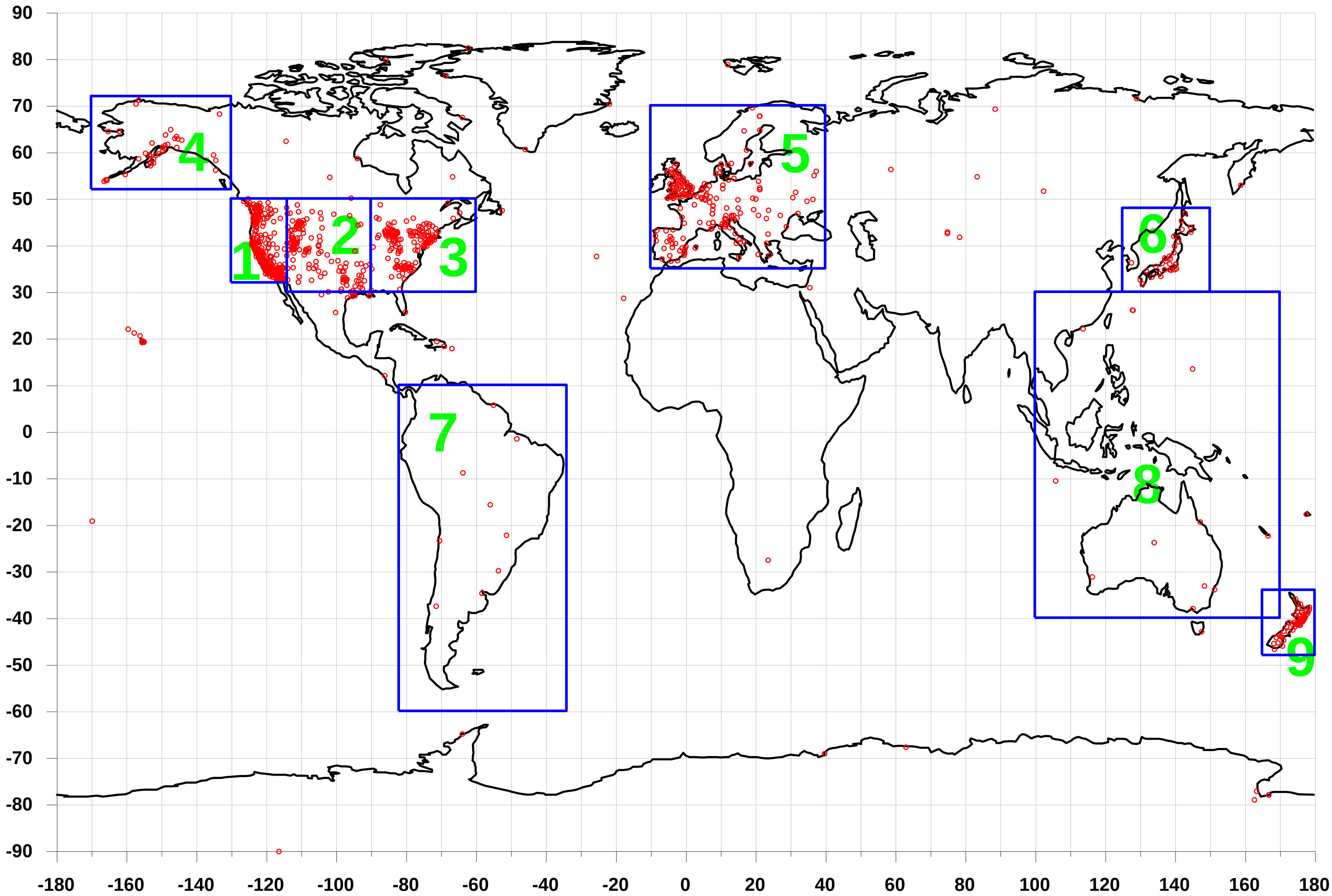
General Assembly 2018 of the European Geosciences Union
Vienna, Austria, 08-13 April 2018

Session E4.1/NP4.3/AS5.13/CL5.18/ESSI2.3/GD10.6/HS3.7/NH11.14/SM7.03
"Big data and machine learning in geosciences“
(on Monday, 09 Apr 2018, 11:45)

Geophysical Research Abstracts, Vol. 20, EGU2018-2117-1, 2018,
EGU General Assembly 2018

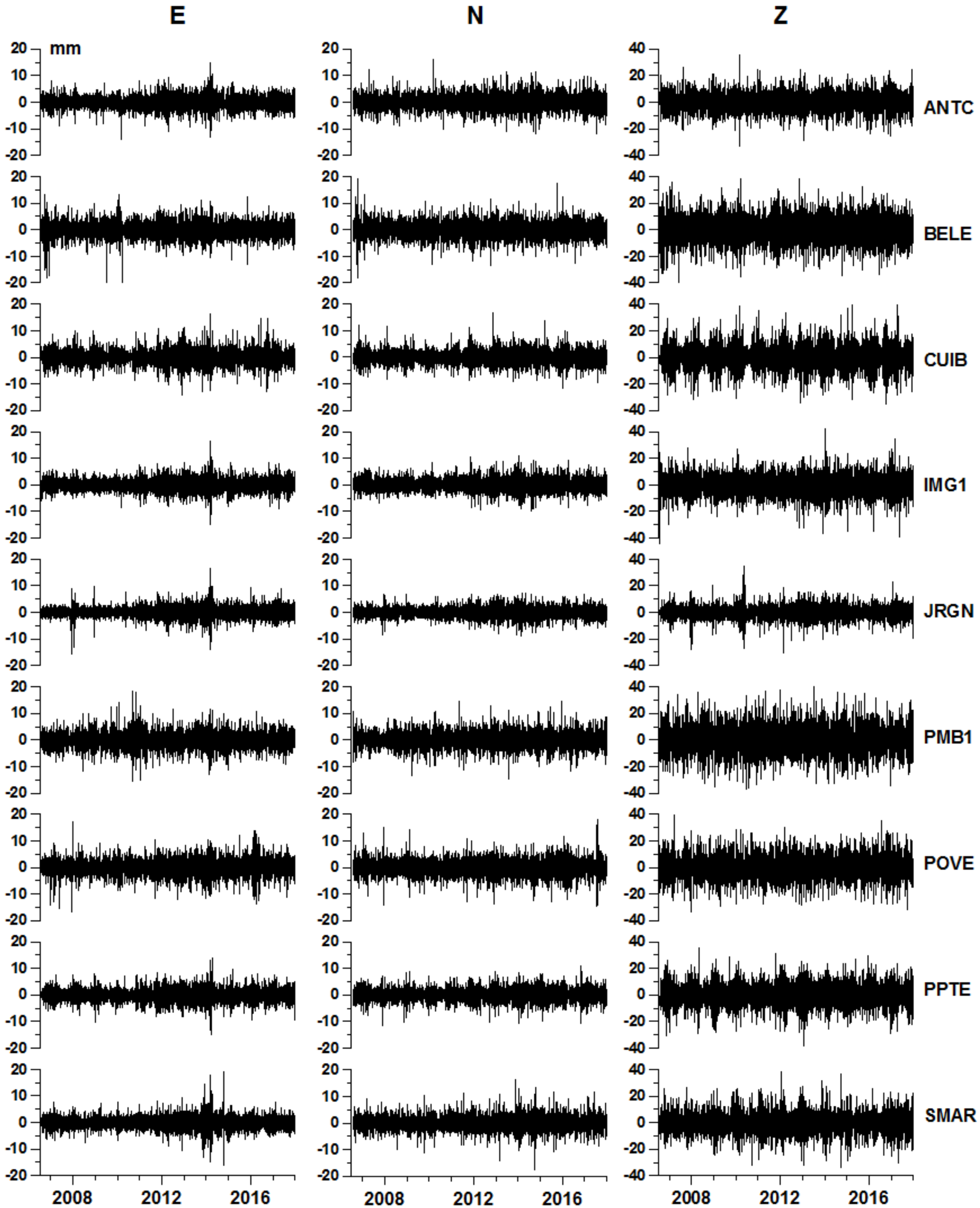
https://meetingorganizer.copernicus.org/EGU2018/EGU2018-2117-1.pdf

Positions of 1125 GPS stations which have daily records with length not less than 4200 samples with common end at January 31, 2017 with total number of gaps not more than 360 samples and longest gap not more than 120 samples. Before processing the gaps were filled up using information from right-hand and left-hand neighbor parts of the records of the same length as the length of the gap, blues lines indicate 9 rectangular domains which were extracted for joint processing. Three components daily GPS time series were downloaded from the site:
http://gf9.ucs.indiana.edu/daily_rdahmmexec/daily

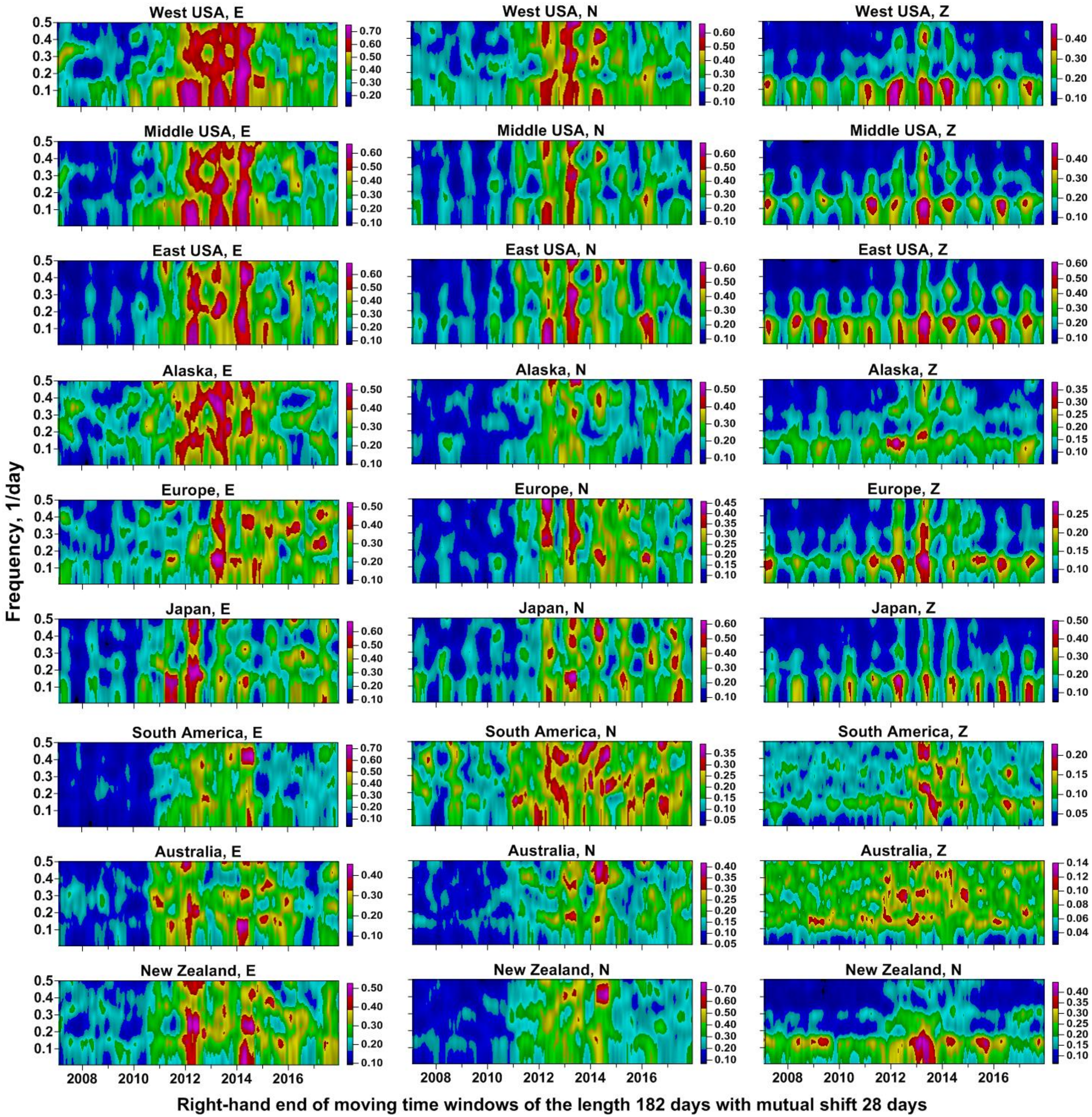


#	Domain	Minimum latitude, deg.	Maximum latitude, deg.	Minimum longitude, deg.	Maximum longitude, deg.	Number of stations
1	West USA	32	50	-130	-114	413
2	Middle USA	30	50	-114	-90	125
3	East USA	30	50	-90	-60	161
4	Alaska	52	72	-170	-130	41
5	Europe	35	70	-10	40	177
6	Japan	30	48	125	150	31
7	South America	-60	10	-82	-34	8
8	Australia	-40	30	100	170	13
9	New Zealand	-48	-34	165	180	60

Parameters of 9 extracted domains



Example of analyzed data: 8 records of increments of daily GPS time series for 3 components from domain “South America”



ω - frequency,

τ - right-hand end of moving window,

$k, j = 1, \dots, q$ - number of time series.

Spectral matrix 2×2:

$$S^{(k,j)}(\tau,\omega) = \begin{pmatrix} S_k(\tau,\omega) & S_{kj}(\tau,\omega) \\ S_{jk}(\tau,\omega) & S_j(\tau,\omega) \end{pmatrix}$$

Squared by-pairs coherence spectrum:

$$\gamma_{kj}^2(\tau,\omega) = \frac{|S_{kj}(\tau,\omega)|^2}{S_k(\tau,\omega) \cdot S_j(\tau,\omega)}$$

Mean squared coherence:

$$\varphi(\tau,\omega) = \frac{\sum_{k=2}^{q} \sum_{j=1}^{k-1} \gamma_{kj}^2(\tau,\omega)}{q \cdot (q-1)/2}$$

Time-frequency diagrams of mean squared coherence for 9 domains and for each of GPS components within moving time windows of the length 182 days with mutual shift 28 days

Estimating of spectral matrix by using of vector AR-model:

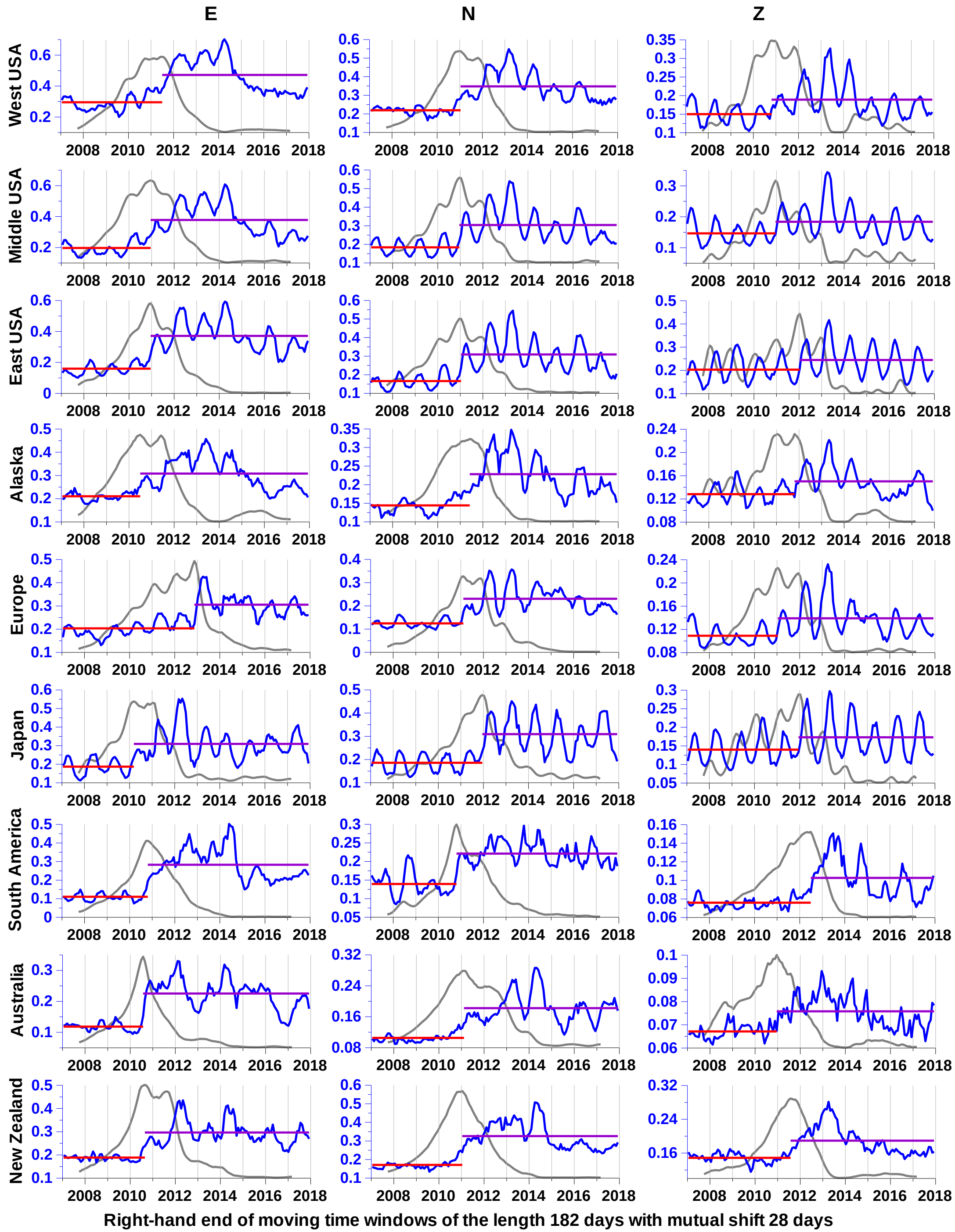
For estimating spectral matrix we used vector autoregression model for m-dimensional time series (in our case $m = 2$):

$$Z(t \mid \tau) + \sum_{l=1}^{p} A_l(\tau) \cdot Z(t - l \mid \tau) = e(t \mid \tau)$$

where t is time index within current time window with time coordinate τ, $Z(t \mid \tau)$ is the piece of m-dimensional time series corresponding to the current time window, p is an autoregression order, $A_l(\tau)$ are matrices of autoregression coefficients of the size $m \times m$, $e(t \mid \tau)$ is m-dimensional residual signal with zero mean and covariance matrix $\Phi(\tau) = M\{e(t \mid \tau) e^T(t \mid \tau)\}$. Matrices $A_l(\tau)$ and $\Phi(\tau)$ are defined in each time window using Durbin-Levinson procedure and the spectral matrix is calculated using formula:

$$S(\tau, \omega) = F^{-1}(\tau, \omega) \cdot \Phi(\tau) \cdot F^{-H}(\tau, \omega), \quad F(\tau, \omega) = E + \sum_{l=1}^{p} A_l(\tau) \cdot \exp(-i\omega l)$$

where E is a unit matrix of the size $m \times m$, $"H"$ is the sign of Hermitian conjunctions.



Time-dependent mean squared coherence:

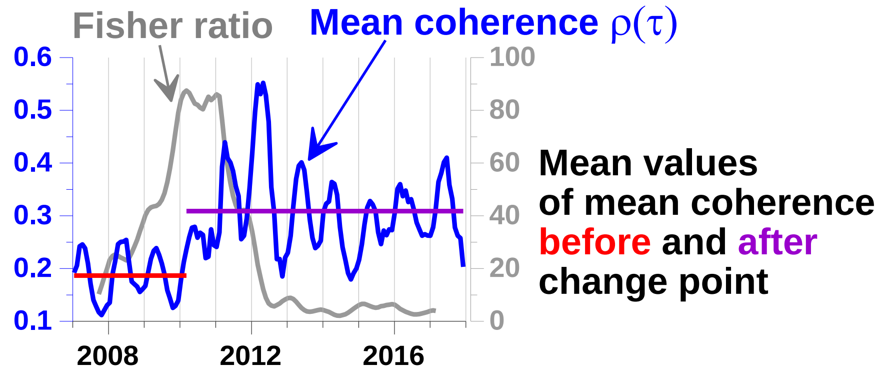
$$\rho(\tau) = \sum_{\omega} \varphi(\tau, \omega) / N_{\omega}$$

Blue lines – averaging over all frequency values within each time window of mean squared coherence for 9 domains and for all GPS components.

Red and purple horizontal lines – mean values before and after change points defined from maximum of Fisher ratio.

Grey lines – Fisher ratio in dependence on probe positions of time change point.

Using Fisher ratio for seeking change point



Let us calculate general mean value of $\rho(\tau)$: $\bar{\rho}_0 = \sum_{\tau=1}^{N_\tau} \rho(\tau)/N_\tau$ where N_τ is the general number of time windows and mean values of $\rho(\tau)$ from left and right sides of probe time moment τ_C of change point: $\bar{\rho}_1 = \sum_{\tau=1}^{\tau_C} \rho(\tau)/\tau_C$ and $\bar{\rho}_2 = \sum_{\tau=\tau_C+1}^{N_\tau} \rho(\tau)/(N_\tau - \tau_C)$. Change point τ_C is found from the condition

$$F(\tau_C) = S_1^2(\tau_C) \big/ S_2^2(\tau_C) \to \max_{\tau_C}$$

where

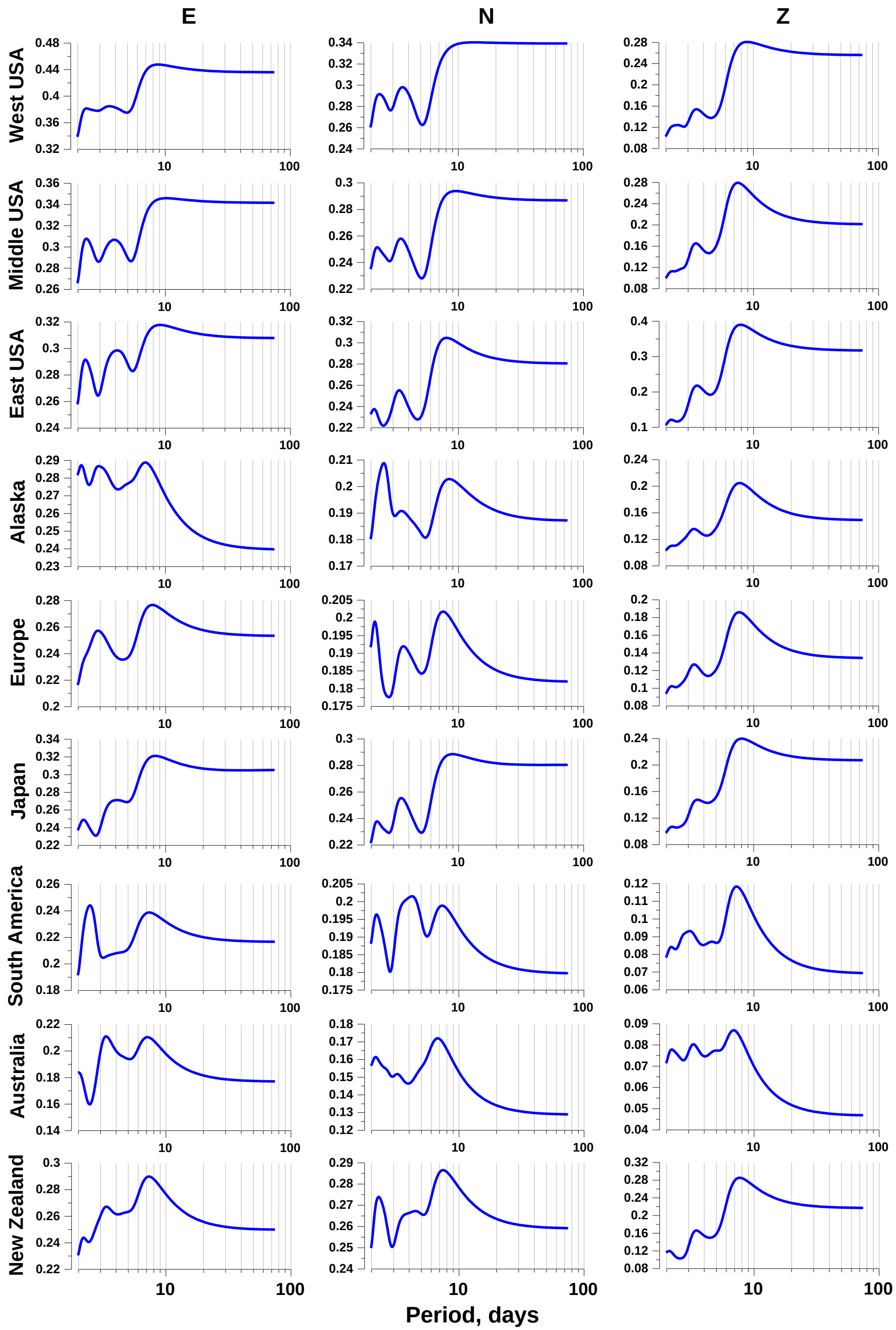
$$S_1^2(\tau_C) = \tau_C \cdot (\bar{\rho}_1 - \bar{\rho}_0)^2 + (N_\tau - \tau_C) \cdot (\bar{\rho}_2 - \bar{\rho}_0)^2,$$

$$S_2^2(\tau_C) = \left(\sum_{\tau=1}^{\tau_C} (\rho(\tau) - \bar{\rho}_1)^2 + \sum_{\tau=\tau_C+1}^{N_\tau} (\rho(\tau) - \bar{\rho}_2)^2 \right) / (N_\tau - 2)$$

are values of weighted square distance of mean values $\bar{\rho}_1$ and $\bar{\rho}_2$ of two groups of data from the general mean value $\bar{\rho}_0$ and of weighted sum of square distances of elements within each group from their mean values.

Table of time moments of change points of averaging with respect to frequencies of mean squared coherence spectra, right-hand end of time windows of the length 182 days

Domain	E	N	Z
West USA	2011.517	2011.057	2010.827
Middle USA	2010.981	2010.981	2010.981
East USA	2010.981	2011.057	2012.054
Alaska	2010.521	2011.441	2011.824
Europe	2012.897	2011.134	2011.057
Japan	2010.214	2011.977	2011.977
South America	2010.827	2010.827	2012.514
Australia	2010.597	2011.134	2010.981
New Zealand	2010.674	2011.057	2011.594



Frequency-dependent mean squared coherence:

$$\psi(\omega) = \sum_{\tau} \varphi(\tau,\omega) / N_{\tau}$$

Graphs of frequency-dependent mean coherence after averaging over all time windows for all 9 domains and for all 3 components of GPS time series.

Time-frequency principal components

Let us try to extract the most common peculiarities in the behavior of 2-dimensional functions $\varphi(\tau,\omega)$ by applying principal components approach. Let $\varphi_\alpha(\tau,\omega)$ be averaged by-pairs squared coherence spectra for domains with numbers $\alpha=1,\dots,m_D=9$ from the Table 1. The first step in applying principal components method is preliminary normalizing:

$$\varphi'_\alpha(\tau,\omega)=(\varphi_\alpha(\tau,\omega)-\mu_\alpha)/\sigma_\alpha$$

where $\mu_\alpha=\sum_{\tau,\omega}\varphi_\alpha(\tau,\omega)/(N_\tau\cdot N_\omega)$, $\sigma_\alpha^2=\sum_{\tau,\omega}(\varphi_\alpha(\tau,\omega)-\mu_\alpha)^2/(N_\tau\cdot N_\omega)$ are sample estimates of mean and variance of $\varphi_\alpha(\tau,\omega)$. Elements of covariance matrix of normalized functions $\varphi'_\alpha(\tau,\omega)$ are defined by the formula:

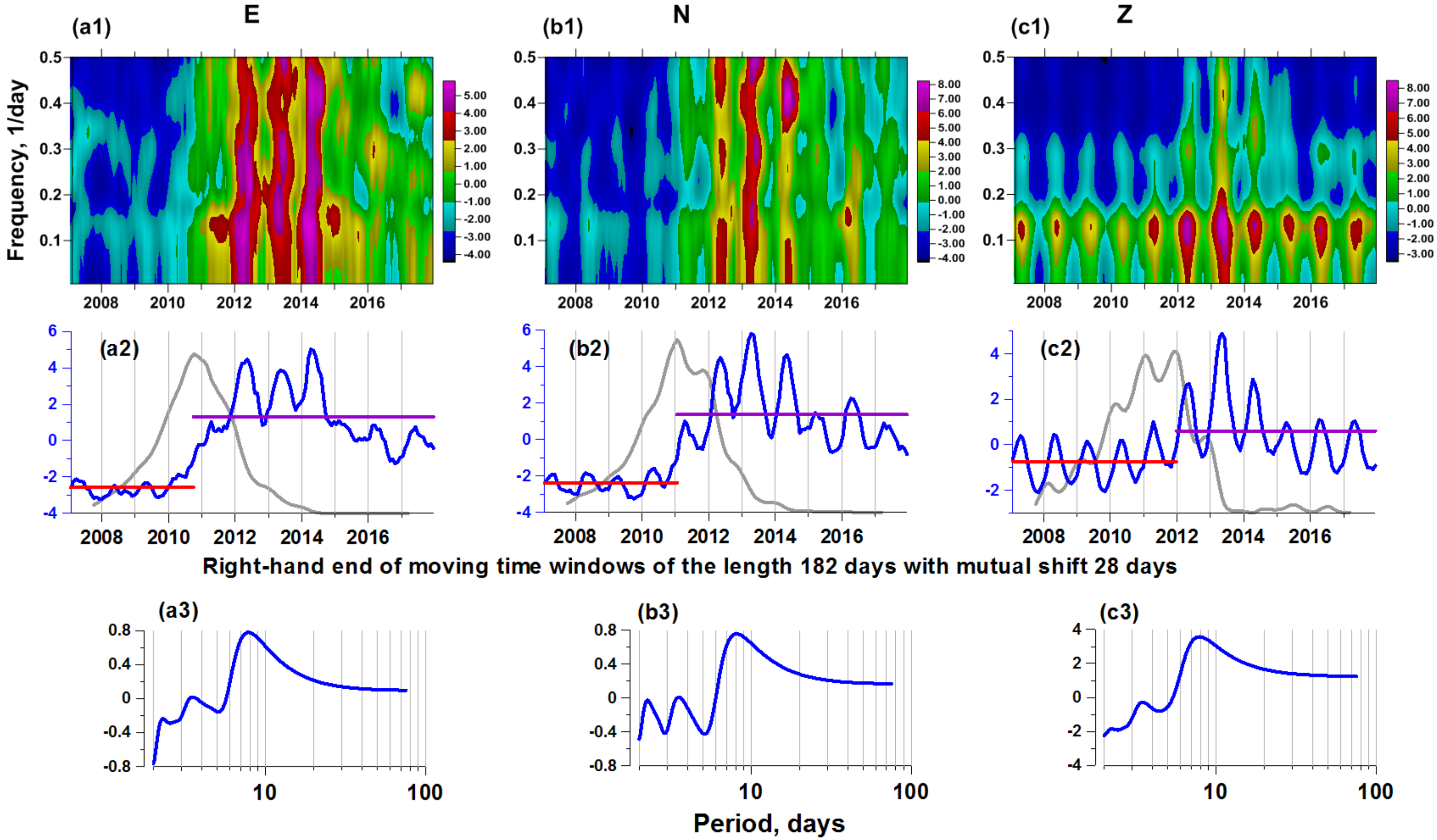
$$C_{\alpha\beta}=\sum_{\tau,\omega}\varphi'_\alpha(\tau,\omega)\cdot\varphi'_\beta(\tau,\omega)/(N_\tau\cdot N_\omega),\quad \alpha,\beta=1,\dots,m_D$$

and first principal component of functions $\varphi_\alpha(\tau,\omega)$ is calculated by the following formula:

$$p(\tau,\omega)=\sum_{\alpha=1}^{m_D}c_\alpha\cdot\varphi'_\alpha(\tau,\omega)$$

where c_α are components of eigenvector of the matrix $(C_{\alpha\beta})$ corresponding to its maximum eigenvalue. We can define values which are obtained by averaging $p(\tau,\omega)$ over all frequency values and positions of time windows separately:

$$r(\tau)=\sum_{\omega}p(\tau,\omega)/N_\omega,\quad g(\omega)=\sum_{\tau}p(\tau,\omega)/N_\tau$$



(a1), (b1) and (c1) – first principal component time-frequency diagrams computed from mean squared coherence time-frequency diagrams from all 9 domains for 3 components of GPS time series.

(a2), (b2) and (c2), blues lines – graphs of first principal components after averaging over all frequency values; grey lines – graphs of Fisher ratio; red and purple horizontal lines – mean values from left and right sides of change points defined from maximum of Fisher ratio. Change points: for (a2) – 2010.751; for (b2) – 2011.057; for (c2) – two points could be extracted which have slight difference between values of Fisher ratio local maxima: 2011.057 and 2011.977.

(a3), (b3) and (c3) – graphs of frequency-dependent first principal components after averaging over all time windows. Periods corresponding to maximal values – 7-9 days.

Conclusion

Global coherence of daily GPS noise estimated within half-year moving time windows (182 days) for 9 different parts of the Earth demonstrates rapid increasing in 2010-2012 which could be the consequense of 2 mega-earthquakes:

Maule EQ, Chili: M=8.8, 27.02.2010, t = 2010.1589

Tohoku EQ, Japan: M=9.1, 11.03.2011, t = 2011.1918

The Maule EQ initiated this change of global coherence but the main increasing began slightly before Tohoku EQ and corresponds to 2nd half of 2010.

It is important to notice that for some of investigated domains the mean levels of GPS noise coherence have not returned to the initial values before 2010 and remain high till end of 2017.

Thus, a hypothesis could be proposed that Maule EQ was a trigger for Tohoku EQ.