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Discrimination between Stochastic Dynamics Patterns of Ambient Noises (Case Study for Oni Seismic Station)

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Abstract

Investigation of complex dynamics of ambient seismic noise remains as an important scientific research challenge. In this work we investigated dynamical features of the ambient noises at Oni seismic station, Georgia. We used stochastic model reconstruction method from measured data sets. Seismic records for different time periods around Oni seismic station have been analysed.

It was shown that the dynamics of fluctuations of seismic noise vertical component undergoes essential changes for considered time period from 2005 to 2012. These changes are more noticeable for time periods of preparation and aftershock activity of strong *M*6.0 earthquake occurred in 2009 in the vicinity of Oni seismic station.

Key words: ambient noise, earthquake, complex dynamics, stochastic model reconstruction.

1. INTRODUCTION

It is well accepted that ambient noises are the Earth crust vibrations representing superposition of waves of different origin. They involve a number of factors, ranging from atmospheric pressure variation, seismic waveforms and ocean waves to human activity (Webb 1998, Yulmetyev *et al.* 2001, SESAME 2004, Correig *et al.* 2007). At present, features of complicated ambient noises remain the subject of active scientific interest. From dynamical point of view, several authors regard ambient noises as random-like high-dimensional dynamical process (Yulmetyev *et al.* 2001, Correig *et al.* 2007). Such processes are commonly characterized by uniform distributional features, the quantification of dynamical structure of which is a very difficult scientific task.

Among others, processes related to the earthquake generation and seismic wave propagation contribute to ambient noises. There are many researches devoted to the analysis of dynamics of seismic processes which are presently regarded as non-random processes having high-dimensional nonlinear dynamical structure (Lapenna *et al.* 1998, Rundle *et al.* 2000, Matcharashvili *et al.* 2000, 2012, Padhy 2004, Telesca 2010, Telesca *et al.* 2012). At the same time, an influence of earthquake preparation and seismic wave propagation on dynamics of local ambient noises remains poorly investigated. The problem is important both for understanding general features of ambient noises as well as for the prospective task of recognition of possible earthquake predictive markers. Posing such a research task is well grounded taking into consideration the well known facts about relation between processes of stress accumulation in Earth crust and the breakdown of a disordered solid together with concomitant stick-slip movement and propagation of elastic waves in the surrounding media (Kapiris *et al.* 2003, Telesca and Lapenna 2006, Karamanos *et al.* 2006, Chelidze *et al.* 2006, Telesca and Lovallo 2012).

In the present research we focus on the investigation of fluctuation features of the ambient seismic noise time series using recently developed method of reconstruction of stochastic model equation from measured data sets (Friedrich *et al.* 2000, Gottschall and Peinke 2008). This approach, which has been already successfully used for different real and model data sets (*e.g.*, Renner *et al.* 2001, Langner *et al.* 2010, Czechowski and Rozmarynowska 2008, Czechowski and Telesca 2011, Telesca and Czechowski 2012, Czechowski and Białecki 2012), is very helpful for targeted task because the complexity of the Earth crust structure and processes involved in ambient noises is such that its detailed modeling remains impossible.

Specifically, we have calculated drift and diffusion coefficients of the Earth ambient oscillations' velocity vertical component (in what follows – the Earth's vertical velocity) time series recorded at Oni seismic station, Georgia. The important advantage of the data sets used for targeted task was that the Oni seismic station is situated in the epicentral zone of the last strongest Caucasian earthquake, *M*6.0, occurred in September 2009. We selected data sets of seismograms recorded at nighttime to avoid or at least decrease effects of unwanted urban influences.

The main task of research was to focus on the problem of description of dynamical behavior of Earth surface vibration in the vicinity of seismic station in a region with essentially increased seismic activity. Thus, appropriate simplifications have to be introduced with the challenge that the "essential aspects" are grasped (Langner *et al.* 2010).

We would like to grasp such essential aspects of dynamics of targeted process by the assessment of their stochastic characteristics. By this, we aimed to find out whether discrimination between fluctuation features of ambient noises, during seismically quiet days in different time periods may be possible. Such analysis may provide important knowledge on features of dynamical behavior of ambient noises at different levels of local seismic activity.

2. USED DATA AND METHODS OF ANALYSIS

We investigated digital seismograms recorded by broad-band permanent station located in Great Caucasus mountains near town Oni (42.5905N, 43.4525E), Georgia (Fig. 1). Seismic station Oni, where analyzed wave-

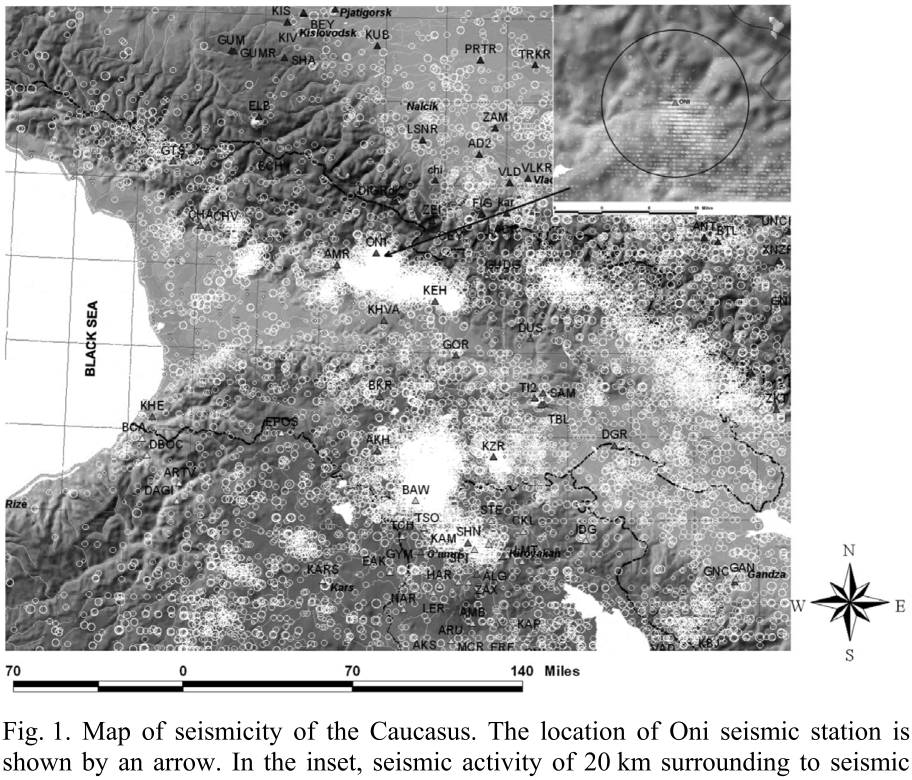


Fig. 1. Map of seismicity of the Caucasus. The location of Oni seismic station is shown by an arrow. In the inset, seismic activity of 20 km surrounding to seismic station area is documented.

forms were recorded, is part of seismic network operated by the Ilia State University, Seismic Monitoring Centre of Georgia. Station is situated on a sedimentary rock with limestone basement. It is equipped with broad-band Guralp CMG40T seismometer and has a flat velocity response from 0.01 to 100 Hz frequency band. The data were recorded at a sampling frequency of 100 Hz with a dynamic range over 140 dB.

Specifically, in this study we investigated data sets of the Earth's vertical velocity V_z. In order to trace temporal behavior of stochastic features of ambient noises, we analyzed 8 hour long seismograms recorded at nighttime (from 00:00 to 08:00, local time) in the area around Oni seismic station for seismically quiet days. It should be emphasized that in this area presently seismicity is activated and during observation period, from 2005 to 2012, two strong earthquakes have occurred in the vicinity of Oni seismic station; namely *M*5.2 earthquake in 2006 (04:08:1.3 UTC on 6 February 2006, Lat. 42.520, Long. 43.545) and *M*6.0 earthquake in 2009 (22:41:35 UTC on 7 September 2009, Lat. 42.5727, Long. 43.4825). Epicenters of these earthquakes were located 10 and 4 km from the Oni seismic station, accordingly.

Selection conditions for days which we regarded as seismically quiet were rather strong. We started from the supposition that the day will be regarded as a seismically quiet if no seismic waveform arrivals from local or remote earthquakes were registered by seismograph at station Oni. However, in practice to find such quiet days at selected location in the seismically active Caucasian mountains, appeared impossible (see Fig. 1). Moreover, for the last years, when several strong earthquakes occurred in Racha region, seismic activity in the Oni seismic station area increased significantly and small earthquakes occur almost permanently. Therefore, we regarded a day as quiet, in the sense of local seismic activity, if in 20 km area around Oni station no earthquakes larger than *M*0.9 has occurred even if no epicenter location was defined. We succeeded to find 12 such days from 2005 to 2012.

To investigate stochastic features of local ambient noises, time series of Earth's vertical velocity, V_z, recorded at these quiet days has been analyzed (typical view of normed data *versus n* of samples is shown in Fig. 2). It is important to mention that Oni town is located in a rural place with low urban and industrial noises. At the same time, in order to further decrease possible unwanted influences we, as it was said above, analyzed seismogram recorded in nighttime from 00:00 to 08:00.

In this research we used method of retrieving features of a stochastic dynamical system from measured data (Friedrich *et al.* 2000, Renner *et al.* 2001). A basic assumption of this approach to the analysis of fluctuating data is the presence of a Markovian property, which for real systems can be valid above a certain time or length scale (Gottschall and Peinke 2008, Langner *et al.* 2010). For such systems, prediction of future evolution requires only the

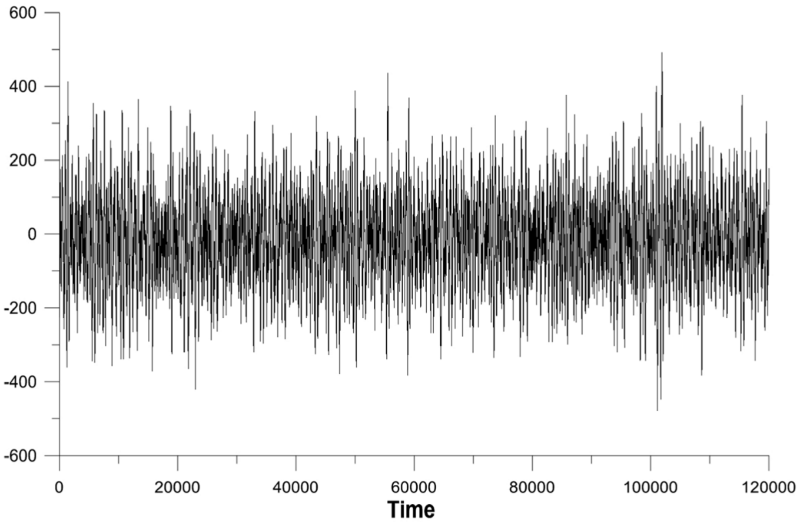


Fig. 2. Typical record of Earth's vertical velocity made during one of seismically quiet period at Oni seismic station.

knowledge of the actual situation and formally this requirement is given by the probability

$$p\left[x(t+\tau)\middle|x(t),x(t-\tau)\right]=p\left[x(t+\tau)\middle|x(t)\right] \ , \tag{1}$$

where t is the actual time and τ is the time increment.

For analysis of features of Earth surface fluctuations we applied stochastic differential equation (Langevin equation) reconstruction method. This method has been already successfully used for analysis of complex processes in different fields (see, *e.g.*, Renner *et al.* 2001, Langner *et al.* 2010, Czechowski and Telesca 2011, Czechowski and Rozmarynowska 2008). For a finite small time step τ, the Langevin equation is given as

$$x(t)=x(t-\tau)+\tau D_1(x)+\sqrt{\tau D_2(x)}\Gamma(t) \ . \tag{2}$$

Here $D_1(x)$, the so-called drift term, gives the deterministic contribution to the evolution; $D_2(x)$ is the diffusion term, which is related to the amplitude of the noise; $\Gamma(t)$ denotes the delta-correlated white noise (Friedrich *et al.* 2000, Langner *et al.* 2010). The methods developed in the last decade (Friedrich *et al.* 2000, Gottschall and Peinke 2008, Langner *et al.* 2010) enable to estimate drift and diffusion terms directly from the data:

$$D_n(x)=\frac{1}{n!}\lim_{\tau\to 0}\frac{1}{\tau}M_n(x,\tau) \ . \tag{3}$$

In Eq. (3), conditional moments $M_n(x,\tau)$ are given as:

$$M_n(x,\tau) = \left\langle \left[x(t+\tau) - x(t) \right]^n \right\rangle \Big|_{x(t)=x} \quad . \tag{4}$$

In practice, the first and second conditional moments ($n = 1$ and $n = 2$) can be calculated by binning of the data $x(t)$ and using different time steps, τ (Siegert *et al.* 1998, Siefert *et al.* 2003, Gottschall and Peinke 2008, Langner *et al.* 2010).

One of the often encountered problems in the stochastic analysis based drift and diffusion coefficients calculation is too few data in measured real time series. Therefore, to investigate dynamical features of fluctuations of the Earth's vertical velocity we decided to analyze windows of 120 000 data. This is quite enough to ensure appropriate population of every bin during moments calculation procedure. We moved 120 000 data length windows by the 60 000 data step, throughout considered Earth vertical velocity data. Analysis has been accomplished for data sets recorded in each seismically quiet day, as well as for a long data sets consisting of pooled recordings of all 12 seismically quiet days. For each window, D_1 (and the slope of central linear part of D_1 *versus* V_z), as well as D_2 terms have been calculated.

3. RESULTS AND DISCUSSIONS

As it was mentioned, we used data sets of Earth vertical velocity recorded at 8 night hours of selected seismically quiet days from 2005 to 2012. We analyzed the daily data sets (recordings of 8 night hours of each selected day) as well as long time series (pooled 8 night hours recordings of 12 selected days). In both cases, calculations were performed for consecutive windows of 120 000 data (20 min duration segments of seismogram) shifted by 60 000 data step.

Thus, for each selected quiet day, 48 windows and consequently 576 windows for the long 12-day time series have been considered. For each window drift and diffusion coefficients were calculated according to the method described in methods' section.

It should be emphasized here that in spite of enough data, in case of about 10-15% of windows, the proper calculation of M values and consequently D_1 and D_2 terms appeared impossible. Obviously, this mostly happened because of accidental influences on measurement system, other technical problems, or by the arrival of wavetrains from small local events, *et*c. All these effects could lead to missing of data or, untypical for the local seismic noise, surges influencing correctness of performed calculations.

The above-mentioned values of D_1 and D_2 coefficients as well as slopes of D_1 have been calculated for several hundreds of windows (120 000 data length each). In order to avoid complication of resulting plots by enormous number of D_1 (or D_2) *versus* amplitude curves, we decide to average calculated values for consecutive 48 windows (*i.e.*, for 8 night hours of each quiet day). Such averaging helps to grasp the essence of changes in stochastic features of Earth vertical vibrations occurred during considered time period and is quite logical. Indeed, averaging was performed for nighttime measurements in seismically quiet days, when essential changes in the dynamical features of the Earth surface vibration look unlikely. Thus, we present below the original D_1 and D_2 *versus* amplitude relations (calculated for separate windows at the beginning, at the end and in the middle part of the considered long time series) as well as averaged ones for each day (*i.e.*, for 8 night hours). Such a combination of original and averaged curves helps to avoid possible mistakes and incorrect conclusions in the interpretation of obtained results.

We start from description of results of drift term calculation of Earth vertical velocity time series. In Fig. 3, coefficients D_1 of the Earth vertical velocity data calculated for different windows are presented. First, in Fig. 3a, we show original results of drift coefficients calculation obtained for several separate windows at the beginning, at the end and in the middle part of the considered time period (pooled long time series of nighttime recordings). From these figures we see that D_1 coefficients of Earth vertical velocity data, for certain amplitude ranges, generally show close to linear behavior. We mention that because of noticeable variation of amplitudes from window to

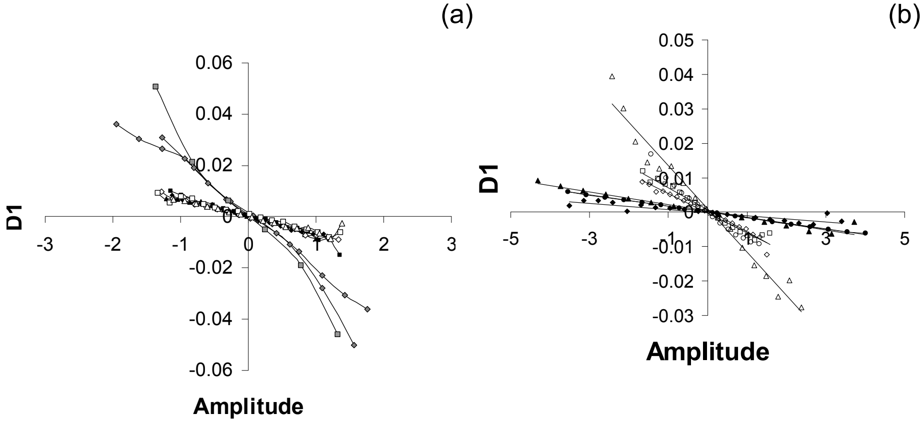


Fig. 3. Drift coefficients, D_1, calculated for Earth vertical velocity time series recorded in the nighttime: (a) Original data for three windows at the initial (black symbols), end (white symbols), and middle (grey symbols) part of observed time period; (b) Values of D_1 *versus* V_z amplitude, averaged for consecutive 48 windows of each seismically quiet day. Black symbols correspond to windows at the beginning and the end, white symbols to windows at the middle of observed time period. For better visibility, not all data are shown (further details in Fig. 4).

window; here, for clarity, we show not full amplitude range of Earth vertical velocity data, but just those where D_1 *versus* amplitude relation is closer to linearity (typical amplitude range of our data sets is shown in Fig. 2).

As we see from Fig. 3b, the D_1 *versus* amplitude relation, averaged for consecutive 48 windows, generally preserves features of original ones – shows a more-or-less linear part.

Results in Fig. 3 clearly show that there are differences in slopes of D_1 for different considered windows. To make these differences clear, in Fig. 4, we present slopes of D_1 *versus* V_z relation. Specifically, in order to grasp main features of changes in the drift term for different time periods of observation, here the slopes of averaged D_1 *versus* V_z relation are presented. As it was described above, the averaging was fulfilled for consecutive 48 windows of 20 min duration nighttime seismic records.

In previous section we pointed out that D_1 slope values have been calculated for pooled nighttime data of 12 seismically quiet days around Oni seismic station. These days were non-equidistantly distributed from 2005 to 2012 (see Fig. 4). We see that the D_1 slope decreases from 2005 and reaches minimum in 2008, point 7 in Fig. 4. Then we observe maximum (minimal negative slope) at points 9 and 10 in 2011.

Diffusion coefficient calculation also shows differences in dynamical features of Earth vertical velocity variation for different parts of the considered time series.

In Fig. 5, curves of averaged diffusion coefficients of Earth vertical velocity are presented. Calculation was performed for 120 000 data span consecutive 48 windows. We see that D_2 values and D_2 *versus* V_z amplitude curves calculated in the same way as D_1 show clear differences. Namely, at

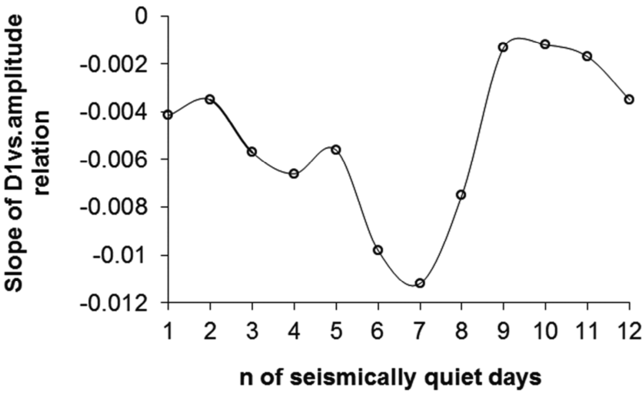


Fig. 4. Slopes of averaged D_1 *versus* amplitude relation calculated for nighttime data of 12 non-equidistant seismically quiet days around Oni seismic station from 2005 to 2012.

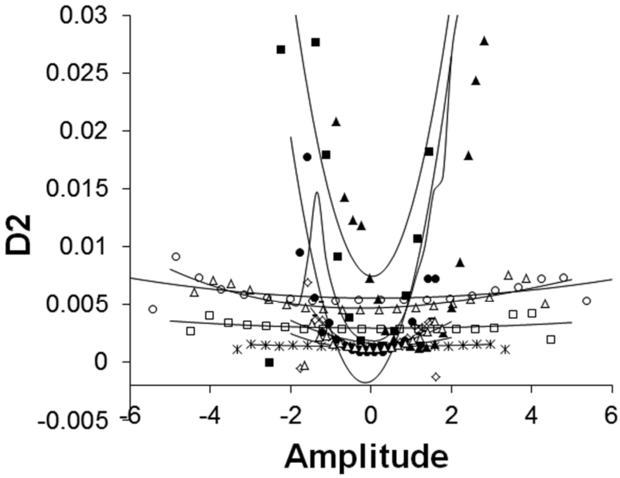


Fig. 5. Averaged diffusion coefficients, D_2, of V_z amplitude series, calculated for consecutive 48 windows containing 120 000 nighttime data for each seismically quiet day. Values are shown at the beginning and end (open symbols) as well as in the middle (black symbols) of the considered period. For better visibility, not all data are shown.

the beginning of observation period as well as at the end of this period, curves are essentially flattened comparing to narrow ones in the middle of the observation period.

Thus, the results shown in Figs. 4 and 5 indicate difference in dynamical features of ambient noise fluctuations for different periods of our analysis.

Next, we parameterized calculated drift and diffusion coefficients by linear and quadratic functions and reconstructed the Earth vertical velocity time series by Langevin Eq. (2). In Fig. 6, typical views of reconstructed series and histogram of the original and the reconstructed time series are shown for one of the considered windows. We see that in spite of unavoidable distortions due to averaging in calculation of drift and diffusion coefficients, the reconstruction was good enough.

Next we performed an analysis similar to that described above for original data on reconstructed Earth vertical velocity time series corresponding to seismically quiet days. Drift and diffusion coefficients calculated for reconstructed data also demonstrate differences for different considered time periods, similar to the original Earth vertical velocity time series variations found above and presented in Figs. 3 and 4. Indeed, in Fig. 7 are presented D_1 values for reconstructed data corresponding to different periods of obser-

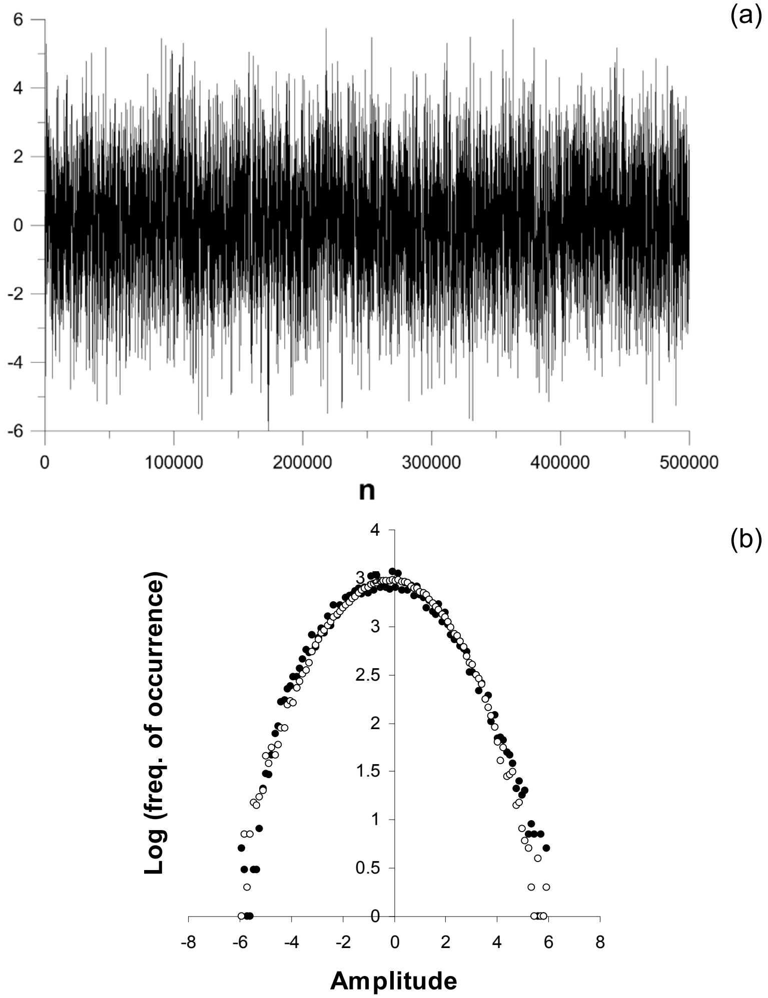


Fig. 6: (a) Typical view of reconstructed Earth vertical velocity amplitude time series; (b) Typical histograms of the Earth vertical velocity time series. Original time series – black circles, and the reconstructed ones –white circles.

vation: (a) calculated for several windows, and (b) averaged for consecutive 48 windows. In Fig. 8 results of D_2 calculation on reconstructed data are presented.

According to described results obtained from original as well as reconstructed for seismically quiet days' data, the dynamics of ambient noise fluctuations undergo changes for the analyzed time period: from 2005 to 2012. As has been said in methods' section, in this period two strong earthquakes occurred in close vicinity to Oni seismic station. Specifically, 10 and 4 km

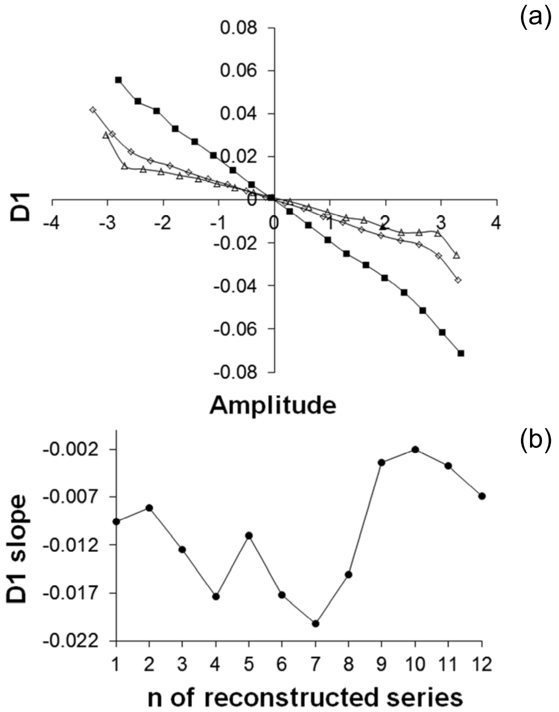


Fig. 7: (a) Drift coefficient values calculated for reconstructed data of nighttime Earth vertical velocity time series in seismically quiet days corresponding to the initial and end (open symbols) as well as to the middle part (black symbols) of considered period; (b) Slopes of drift coefficients averaged for consecutive 120 000 data windows of reconstructed time series.

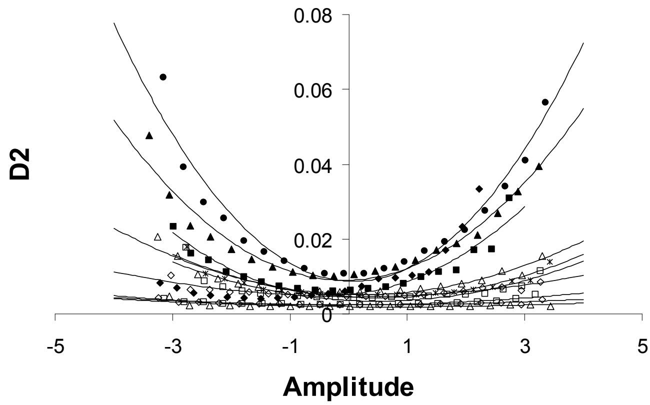
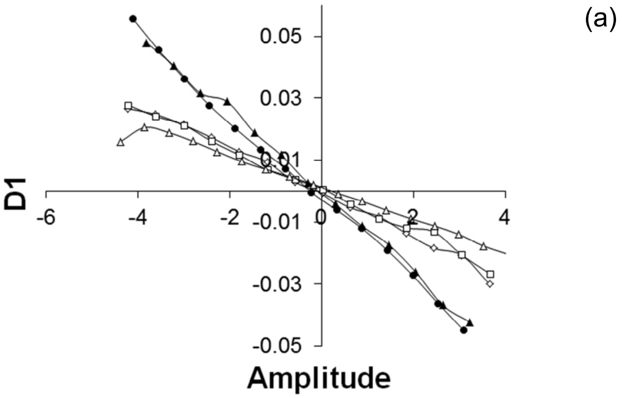


Fig. 8. Diffusion coefficients, D_2, calculated from reconstructed nighttime Earth vertical velocity time series in the seismically quiet days. White symbols correspond to windows at the beginning and the end, and black symbols correspond to the middle part of considered time period.

from the Oni seismic station, *M*5.2 earthquake occurred in 2006 (04:08:1.3 UTC on 6 February 2006, Lat. 42.520, Long. 43.545, Mag. *M*5.2) and *M*6.0 earthquake occurred in 2009 (22:41:35 UTC on 7 September 2009, Lat. 42.5727, Long. 43.4825), respectively. Taking into account that the Oni seismic station is located in the preparation area of these earthquakes and especially is close to the last strongest Caucasian *M*6.0 earthquake, it is possible to assume that the above mentioned differences in dynamical characteristics of local seismic noise may somehow be related to the earthquake preparation and aftershock activity of this earthquake.

At the same time, as it was said in methods section, selected seismically quiet days were distributed non-equidistantly and in different years different number of days were regarded as seismically quiet. Therefore, it is not ex-



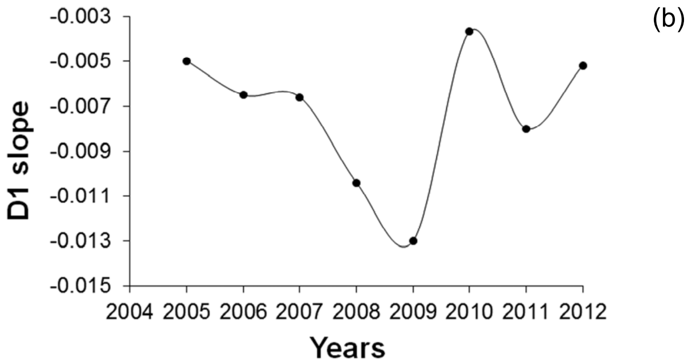


Fig. 9. Drift coefficients calculated for Earth vertical velocity data, recorded in nighttime on 5 July from 2005 to 2012: (a) Original data calculated for several windows, at the beginning and the end (white symbols) as well as in the middle part (black symbols) of the analyzed time period; (b) D_1 *versus* amplitude relation averaged for 48 windows of nighttime.

cluded that some kind of seasonal influences could affect results of our calculations. In order to reduce a possibility of incorrect conclusions, we decided to carry out an analysis, similar to the one described above, for one selected day throughout period from 2005 to 2012. Among 12 seismically quiet days, three were in July, and that is why we chose day of 5 July with no regard of seismic activity around Oni station. For these fixed eight days (5 July in the years 2005-2012), nighthour seismic recordings from 00:00 to 08:00 of local time were selected as target data sets.

In Fig. 9, we see values of drift coefficients calculated for Earth vertical velocity data, which have been recorded in nighttime on 5 July days from 2005 to 2012. As follows from Fig. 9a and b, both for separate windows as well as in case of averaging we see differences in D_1 values for different periods. Most important is that largest negative slopes were found for Earth vertical velocity time series recorded in 2008 and 2009. Note that in 2009 strong *M*6.0 earthquake occurred two months later, on 7 September.

Changes in the dynamics of fluctuation of Earth vertical velocity are visible also from D_2 calculation results (see Fig. 10).

Similar to the original data, results were obtained from reconstructed time series. Reconstruction was performed based on D_1 and D_2 values parametrization using Eq. (2). Results of drift and diffusion coefficients calculation for reconstructed data are presented in Fig. 11.

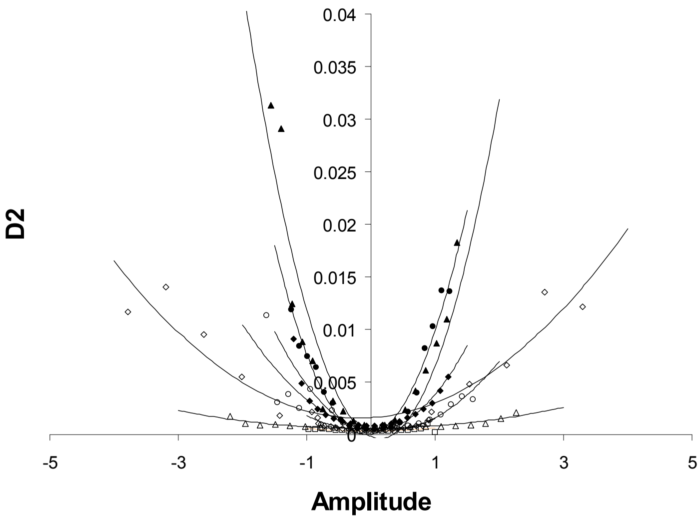


Fig. 10. Diffusion coefficients, D_2, averaged for consecutive 48 windows of Earth vertical velocity data, recorded in nighttime on 5 July from 2005 to 2012. White symbols correspond to the beginning and the end, and black symbols to the middle part of the analyzed time period.

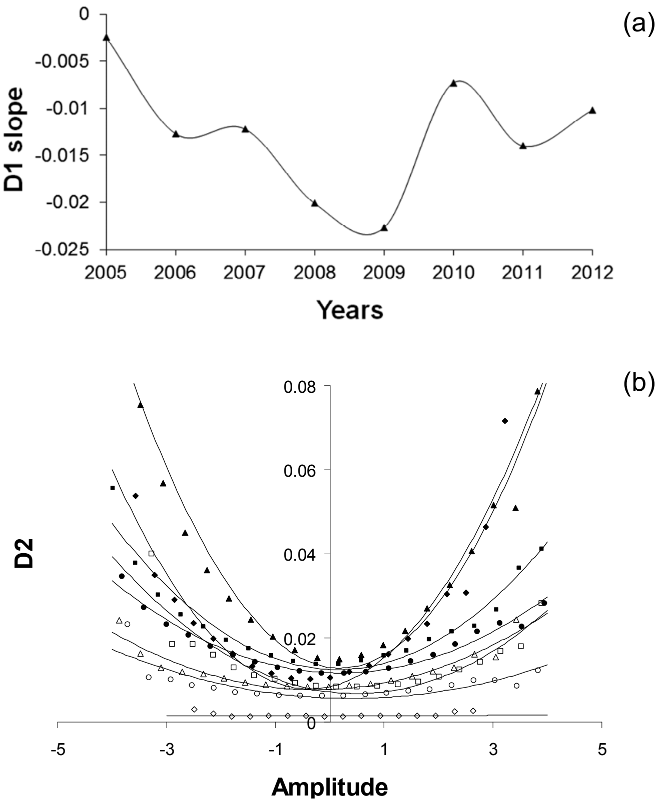


Fig. 11. Averaged for consecutive windows of Earth vertical velocity data reconstructed for 5 July, values of: (a) drift, D_1, and (b) diffusion, D_2, coefficients (windows at the beginning and at the end of analyzed period are shown by white symbols, windows at the middle part – by black symbols).

The results presented above give important new knowledge about features of ambient noise fluctuations. Changes found in the Earth vertical velocity time series both for seismically quiet as well as for selected days in July, show that the dynamics of ambient noise undergoes noticeable changes for the analyzed period. These changes can be regarded as related to the local seismic activity process, because they coincide in time with the period prior and after the last strongest Caucasian earthquake, epicenter of which was located in 4 km from the Oni seismic station. In the above results we see also some changes in the behavior of D_1 slope values occurred in 2006 and 2011. At the same time, we cannot confirm similar differences in calculated D_2 values for these time periods. In this respect, it can be speculated that the dynamics of ambient noise fluctuations is sensitive to processes related to the preparation of strong local events. Changes in the dynamical structure of ambient noise which are caused by smaller earthquakes (*e.g.*, $M5.3$ occurred in 2006 within 10 km from Oni station as well as series of small earthquakes with magnitudes $M < 3.5$ in 2011 and 2012) should be much weaker and seem hard to be detected in the frame of the approach used in this research.

On the other hand, changes found in this research before the strong $M6.0$ earthquake are quite explainable from dynamical point of view. Specifically, an increased extent of correlations in the tectonic system during strong earthquake preparation could change physical, chemical, *etc.* features of the medium, which should affect dynamical and distributional features of ambient noises in the epicentral area of an impending earthquake. In our previous research it was indeed shown that at the Oni seismic station, in seismically calm periods preceeding periods of essentially increased local seismic activity, ambient noises revealed more long-range correlated behavior comparing to periods of strong earthquake's and aftershocks occurrence (Matcharashvili *et al.* 2012). This explains the observed in this research increase of D_1 slope and narrowing of the shape of D_2 *versus* amplitude curve for seismically quiet periods, when collective behavior increases and the system approaches critical point of strong earthquake occurrence. When seismic processes leading to more correlated behavior in the Earth surface vibration become weaker, distributional and dynamical features of ambient noises should return to initial condition, which was observed in our analysis.

4. CONCLUSION

We investigated fluctuation features of Earth vertical velocity time series. For this purpose, seismograms recorded at nighttime in seismically quiet periods at Oni seismic station were used. Stochastic features of fluctuation of Earth vertical velocity were investigated by the method of stochastic model reconstruction using real data sets. It was shown that dynamical features of ambient noise undergo essential changes for the analyzed time period. It was assumed that the changes found may be related to peculiarities of local seismic noise patterns during preparation and aftershock activity of strong local $M6.0$ earthquake. From these preliminary investigations we can conclude that the technique of stochastic model reconstruction from real time series is a useful method for discrimination of subtle dynamic changes in the local seismic noise patterns.

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