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Search of Attractors in seismic time series of Caucasus

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Abstract

Last years appear controversial publications both on revealing attractors in seismic time series (which means that they can be represented by deterministic chaos model) as well as on theabsence of such ordered structures. So, it seems interesting to study, what methodology should be applied to earthquake time series (ETS) in order to reveal possible attractor structures. There are two main approaches to the problem: i. events in ETSare considered individually; ii. the number of events in ETS in some time window (a seismic rate) is calculated, which is widely used as a proxy of the strain rate in the Earth crust.

The study considers how the spatio-temporal parameters of seismic rate calculations affects the nonlinear structures (phase space plots) in low seismicity areas (Batumi region) as well as before, during main event aftershocks and after strongest Caucasian earthquakes Spitak (1988) and (Racha, 1991).The seismic phase portraits and recurrence plots are constructed for several time windows, different epicentral distances and different magnitude thresholds. The nonlinear structure of laboratory natural and synchronized stick-slip sequences are also considered. The phase space plots' analysis can reveal some fine details of seismic process dynamics.

Introduction

Earthquake time series (ETS) documented as seismic catalogs are objects of detailed statistical analysis, which show that catalogs contain both independent and correlated events (clusters), which means that mentioned data represent complex time series. In some earlier works (Goltz, 1997;Matcharashvili et al., 2000) it is shown that at least one component of catalogs considered as a point process, namely, interevent or waiting time series has a low fractal dimension, which means that catalogs contain some hidden nonlinear structures, which however cannot be considered as attractorsand are more similar to a pink noise pattern.

Last yearsappear publications on revealing attractors in seismic time series, which means that they can be represented by deterministic chaos model (Sobolev, 2011; Srivastava et al., 1996) as well as on absence of such ordered structures (Beltrami and Mareschal, 1993). So, it seems interesting to study, what methodology should be applied to earthquake time series (ETS) in order to reveal possible attractor structures. There are two main approaches to the problem: i. events in ETSare considered individually; ii. the number of events in ETS in some time window or a seismic rate (SR) is calculated, which is widely used as a proxy of the strain rate.

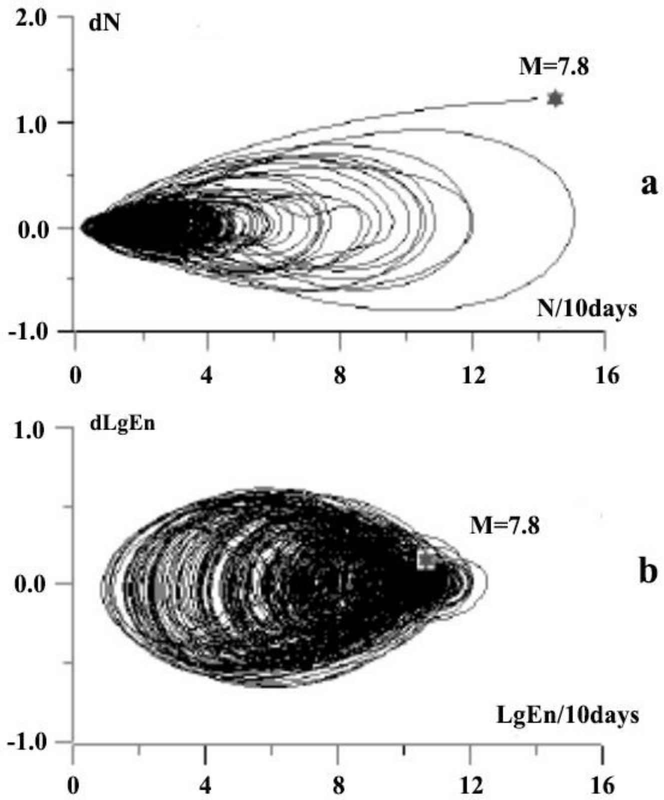


Fig.1. Phase portrait of seismicity within a radius of 100 km from the epicenter of the Kronotskoe earthquake for a 35-year period(1 January 1962–5 December 1997). The smoothed number N of earthquakes (a)or energy LgEn, Joules (b)for 10 consecutive days is marked on the X axis. Rates at which these parameters change (dN or $dLgEn$), i.e. the difference between the following and the preceding values are shown on the Y axis. The clockwise movement along the curve corresponds to an increase in time. The star marks the position of the main shock(Sobolev, 2011).

Recently many new methods of complex time series analysis, mainly due to intensive progress in nonlinear dynamics (complexity) theory (Abarbaneland Tsimring,1993;Anishchenko, 1995;Eckmann,1987;Goltz, 1997). The new tools developed in complexity theory reveal a lot of important information, contained in seismic catalogs, considered as discrete earthquake (EQ) time series (Chelidze and Matcharashvili, 2015). Methods, developed in complexity theory allow visualization and quantification of seismic rate patterns and their variation in time, what enriches significantly traditional statistical approach, presented in Marsan and Wyss (2011).

Data andMethods of ETS analysis

The statistical approach to seismic rate (SR) provides mainly tools for statistically reliable assessment of rate change using long enough earthquake (EQ) time series, e.g. for comparison of SR before and after strong earthquake (Marsan and Wyss, 2011). The same methods are applied to nonstationary time series (ETAS, Z-statistics). These methods are too crude to reveal fine anomalies in ETS, due, for example hidden non-linear structures.Presently for visualization and quantitative analysis of hidden non-linear structures are widely used such methods as phase space plots (PSP), Recurrence Plots (RP), Recurrence Quantification Analysis (RQA), see for example WebberandMarwan (2015). PSP and RP are two interconnected ways to reveal the recurrence in time series: for example, diagonal lines in PR appear when segments in PSP trajectory (attractor) run on close paralleltrajectories.The advantage of RP is that it enables qualitative visualization of highdimensional dynamics, while PSP is convenient for lowdimensional processes, where trajectories in the attractor run on close to parallel trajectories.

We analyze mainly seismic rates, which according to general statistics terminology correspond to a conditional rate (conditional intensity) models in point process theory. We used the rates, obtained either by simple averaging (Sobolev,2011) or by Savitsky-Golay (S-G)-filtering. Savitzky-Golay filter helps to resolve smoothing problem in the time domain. It approximates the data locally (corresponding to some user-chosen window) with an n^{th} degree polynomial preserving up to the n^{th} moments of the data. Hence it has the advantage over, for instance, moving average filter as the magnitude of the variations in the data, i.e., the value of the local extremes, is preserved to a large extent.The optimal lag for PSP reconstruction from daily series of EQ occurrences by Mutual Information (MI) test is close to 50 days.

The averaging/smoothing is widely used in the processing of real data though there are fierce opponents, who call down curses on the heads of "datasmoothers" such as: "Do not smooth times series, you hockey puck!" (http://wmbriggs.com/blog/?p=195). Still we consider the smoothing procedure is a quite lawful procedure (Simonoff,1998; Einicke, 2012), accepted in many signal processing packages (MATLAB, Matematica, etc). It isa very useful tool: the operation of smoothingperforms actually a low-pass filtering of the sequence, which in turn allow revealing long-range correlations in the data (here -in ETS).

For nonlinear analysis the seismic catalogue of Caucasus (1960-2011) has been used; the representative magnitude for the period is M2 (Fig.2). The following parameters of ETSwere varied: i. the area, where ETS were obtained; ii. the length of time window for rate counting; iii. the years span (periods in catalog); iv. periods before and after strong events.

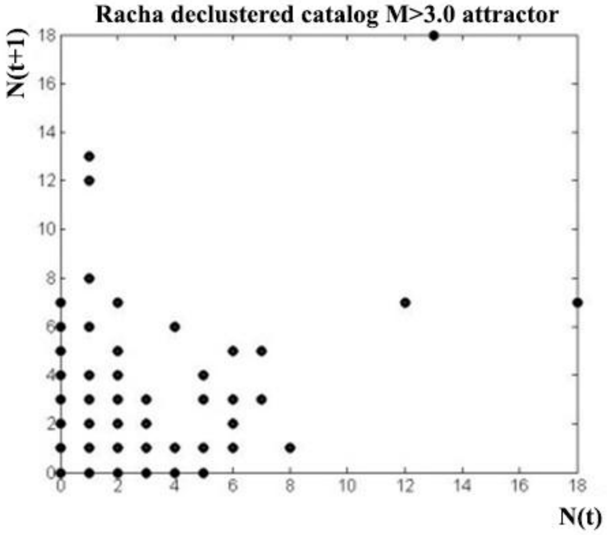
The PSP plots are compiled by two methods: i. The whole EQ data sets from the catalog were declusteredusing Reasenberg algorithm (Matthews and Riesenberg, 1988)and smoothed in the following way:on the *X* axis are plotted the mean values of number *N* of EQs per n days(n = 10,20,50) or N/n and on the *Y* axis is plotted just differential of *X*, i.e $(N_{i+1} - N_i)/n = dN$.This approach was used by Sobolev (2011).

ii. The whole EQ data sets from the catalog were declustered and smoothed by Savitzky-Golay (S-G) filter. Then on the *X* axis is plotted the smoothed by S-G filter value of number *N* of EQs for a given day N/day and on the *Y* axis - smoothed by S-G filter *N* value with some days delay $(N+lag)$, we plot smoothed by S-G filter lagged by 10,20, 50 days daily valuesof $(N+lag)$ versus daily value N/day.

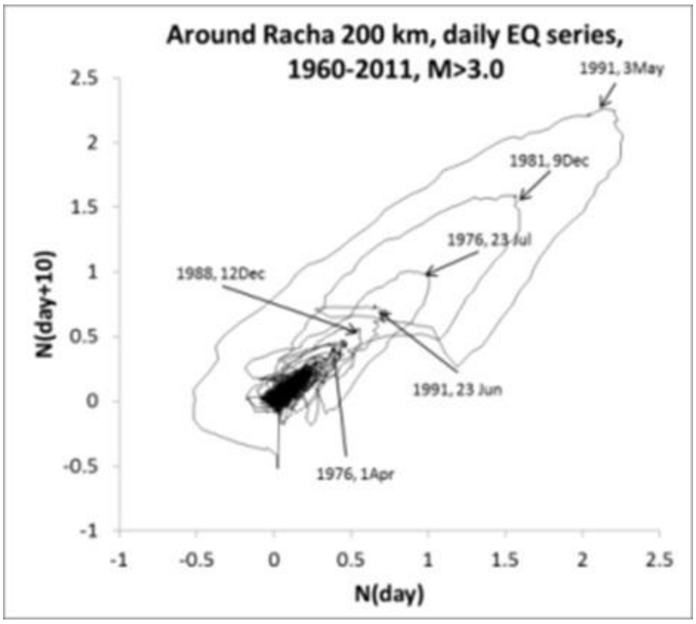
iii. Combined approach: PSP is compiled for one day step (like in Sobolev approach) as dN versus N/day for the data declustered and smoothed by S-G filter (in contrast to Sobolev approach, where just the mean value of *N* in the sliding window are used).

The trajectories on PSP plots are obtained by connecting the consecutive phase states. The consecutive phase spacepoints are plotted in clockwise direction, which corresponds to increase in time.For plotting phase plots were used either standard MATLAB scripts -seism_port and phase_portrait (in following - standard) or Sobolev (2011) approach (in following - Sobolev).

Both approaches sometimes produce negative values of phase states, which means that the smoothed lagged values are smaller than previous ones.As an example of processing, on the Fig.2are presented phase space plots of daily EQ occurrence sequence of EQs compiled for original non-smoothed data (a) and for the same data, smoothed by Savitzky-Golay filter (b). It is evident that the former is less informative and the latter one reveals some interesting structure in the phase space.



a.



b.

Fig. 2. Phase space plots of daily EQ occurrence sequence in Caucasian earthquake catalog(1961-1991) for the area in the radius 200 km around Racha EQ compiled by above mentioned standard scripts for original non-smoothed data (a) and for the same data, smoothed by Savitzky-Golay filter (b).

Results and Discussion

Nonlinear analysis of data sets obtained from the seismic catalogue of Caucasus for the period 1960-2011 has been performed; the representative magnitude for the period is M2.In the analyzed period 1960-2011 two largest Caucasian Spitak and Racha (M6.9-7) earthquakes (EQs) stroke the region in 1988 and 1991 correspondingly. Thus, three areas were selected: i. Batumi(in order to show the pattern of ETS in relatively quiet region; ii. Spitak and iii.Racha(Fig.3). We analyzed both original and declustered by Matthews and Riesenberg(1988) approach catalogs.

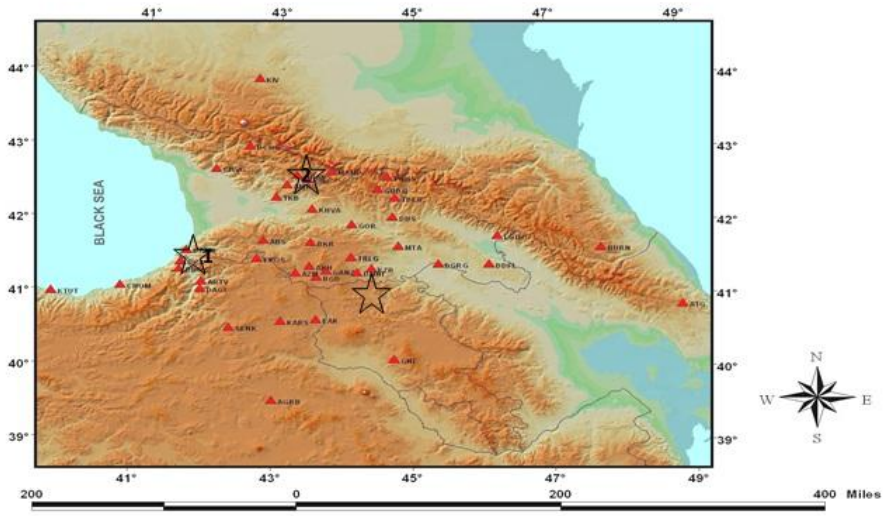
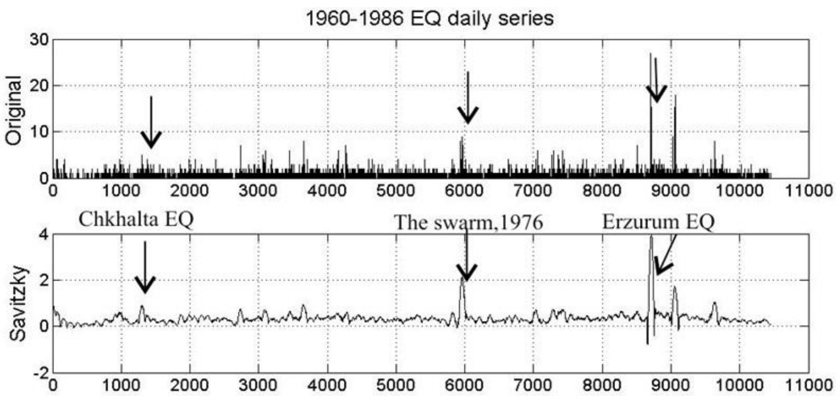


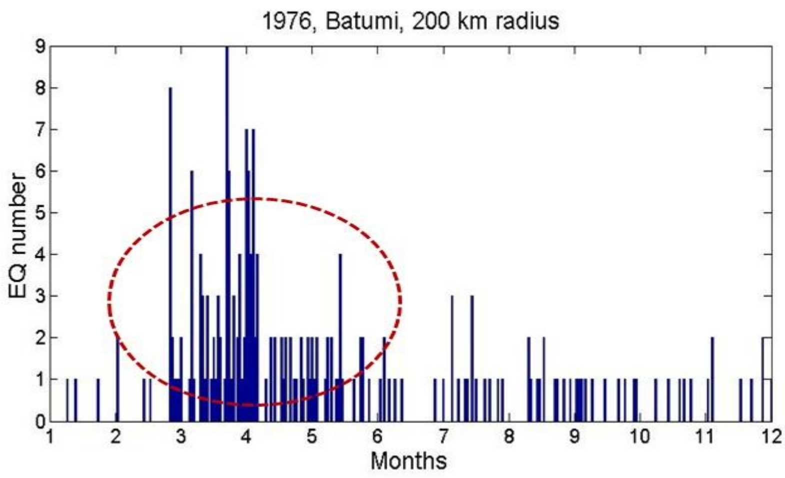
Fig.3. Areas in Caucasus where the analysis of seismic data sets was carried out for revealing possible attractors. Blue stars are centers of test areas: 1 – Batumi; 2 – Racha and 3 – Spitak. Triangles show seismic stations' locations.

Batumi area

Batumi area (Fig.2) was chosen as a (relatively) seismically quiet area:though there were nostrong EQs on the distance 100 km from Batumi, two EQs of M6.4-6.9 occur on the distance of the order 200 km in the considered period (Chkhalta, 16.07.1963 and Erzurum, 30.10.1983).Fig. 4presents original and Savitzky-Golay filtered daily series of EQ occurrences in Batumi area (R=200 km) in 1960-1986 declustered by Reasenberg algorithm. Fig. 5 a, b, c showsstandard phase space portraits of declustered daily series of EQ occurrences in Batumi area smoothed by the S-G filter for various Lags. On the *X*-axis is plotted the S-G filtered daily number of EQs and on the*Y*-axis the same value for *Lag*10, 20 and 50 days.These PSP plots demonstrate two main details: a highly populated area between 0 and 1, which can be considered as a relatively stable domain (or a source area) due to a background seismic activity(this area is shown by arrows for two successive enlargement scales) and strongly deviated trajectories (Fig. 5 a, b, c). These latter orbit-like figures, should reflect deviations from the background activity due to some extremes - swarms, foreshocks and aftershocks. This is a bit strange, as the declustering procedure should eliminate such effects. Still it seems that Reasenberg procedure does not eliminate all correlated events as it is shown in (Matcharashvili et al., 2015) and these orbits can be related to correlated events left after declustering.

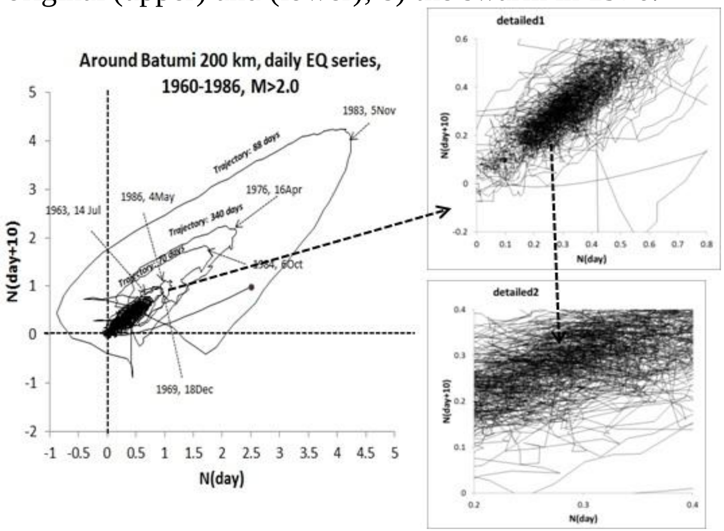


a.

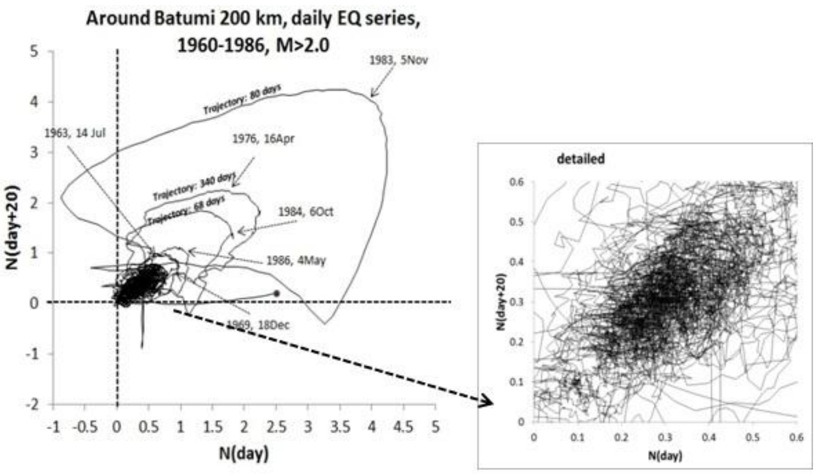


b.

Fig. 4. a) Daily series of EQ occurrences in Batumi area (R=200 km) in 1960-1986declustered by Reasenberg algorithm: original (upper) and (lower); b) the swarm in 1976.



a.



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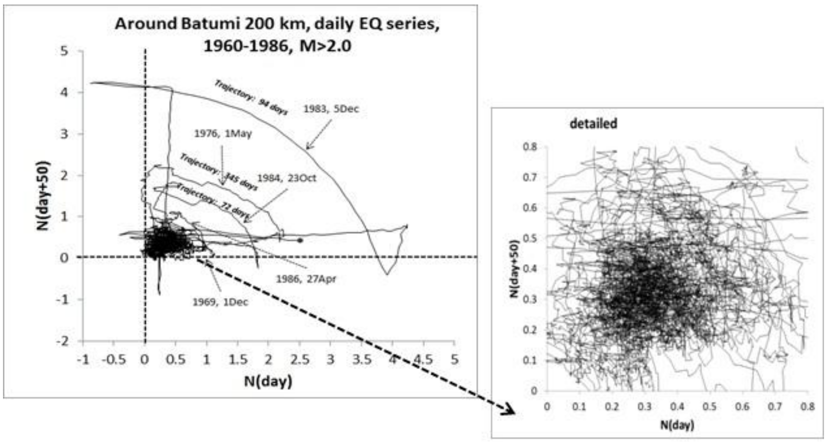

c.

Fig.5. a, b, c) Phase space portraits PSP (standard) of daily series of EQ occurrences in Batumi area for R=200 km, declustered and smoothed by the S-G filtered data sets from catalogs (data of Fig.4). PSPs of EQ occurrences daily value *N* (day) with: (a) *N* in 10; (b) *N* in 20 and (c) *N* in 50 days versus corresponding the lagged values ($N + lag$), where the *Lag* is 10, 20 and 50 days.

Some of extended (anomalous) orbits seem to be related to: i - in1968 - possibly to a swarm; ii - in 1983 - to Erzerum EQ 30.10.1983 Ms 6.9;iii. - 1984 - probably extended aftershocks of Erzerum EQ. Note – for the R=100 km around Batumi the Erzerum EQ 30.10.1983 Ms6.9 response (length of obit) is less significant than that of the 1968 swarm in contrast to data for R=200 km, due to lesser number of ErzerumEQ aftershocks in a more distant from the epicenter area (at R=100 km).The length of the whole trajectory (loop) corresponds to the summary period of foreshocks and aftershocks (Table 1).

Table 1. Duration of the most outlying trajectories on Fig. 5 a,b.

Trajectories on Fig. 5 a, b,c.	Duration of full trajectory, days	Half trajectory duration
Most outlying (1983)	80-94	40
Second distant (1976)	340-345	210
Third distant (1984)	68-72	40

Surprisingly, the strong 1963 ChkhaltaEQ (M6.4, distance from Batumi 175 km) caused relatively small deviations from the source area - see trajectories for Chkhalta in Fig. 5 a, b

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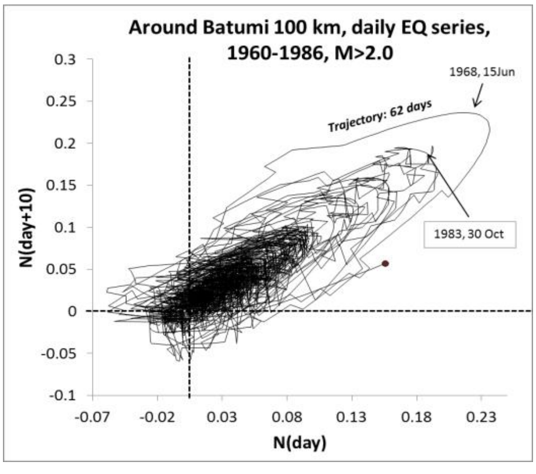
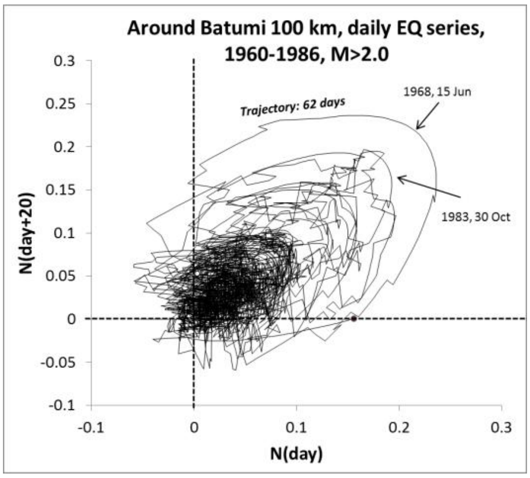


a.



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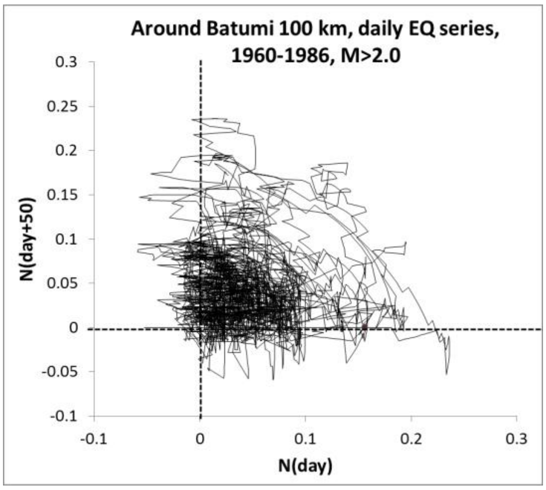
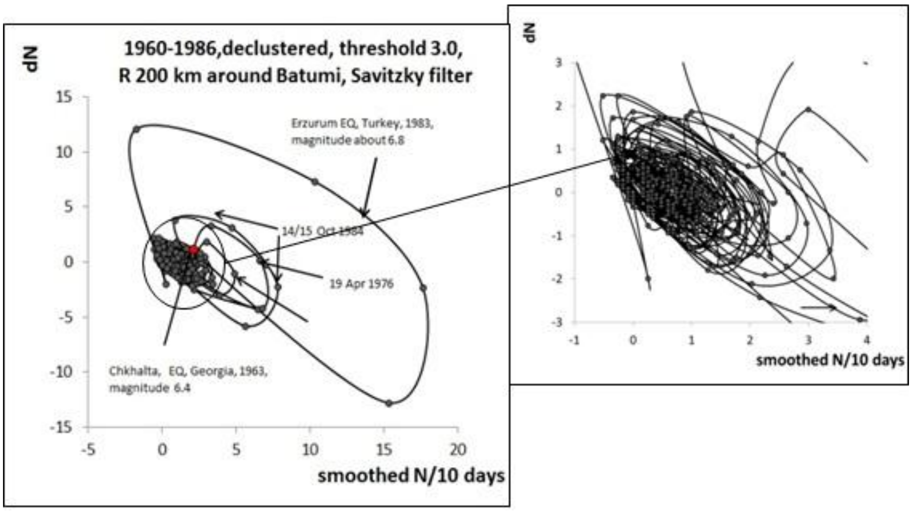


c.

Fig. 6. a) Phase space portraits (standard) of daily series of EQ occurrences in Batumi area for R=100 km, declustered and smoothed by the S-G filtered data sets from catalogs (data of Fig.4). PSPs of EQ occurrences daily value *N* (day) with: (a) *N* in 10; (b) *N* in 20 and (c) *N* in 50 days versus corresponding the lagged values ($N + lag$), where the *Lag* is 10, 20 and 50 days.

The PSPs of trajectories for R=100 km distance form Batumi (Fig. 6) differs from the PSPs for R= 200 km. Extended (anomalous) orbits are possibly related: i. - 1968 - to a swarm in 1968.The length of this most outlying trajectory for 1968 event is 62 days; ii. - 1983 - to Erzerum EQ 30.10.1983 Ms 6.9. Note – for the R=100 km around Batumi the Erzerum EQ 30.10.1983 Ms 6.9 the corresponding orbit is less significant than that for the local swarm in contrast to data for R=200 km, due to smaller number of aftershocks farther from the Erzerum epicenter area. According to the Table 1, the duration of the trajectory till Erzerum EQ is approximately 40 days - this can be considered as a precursory sign.

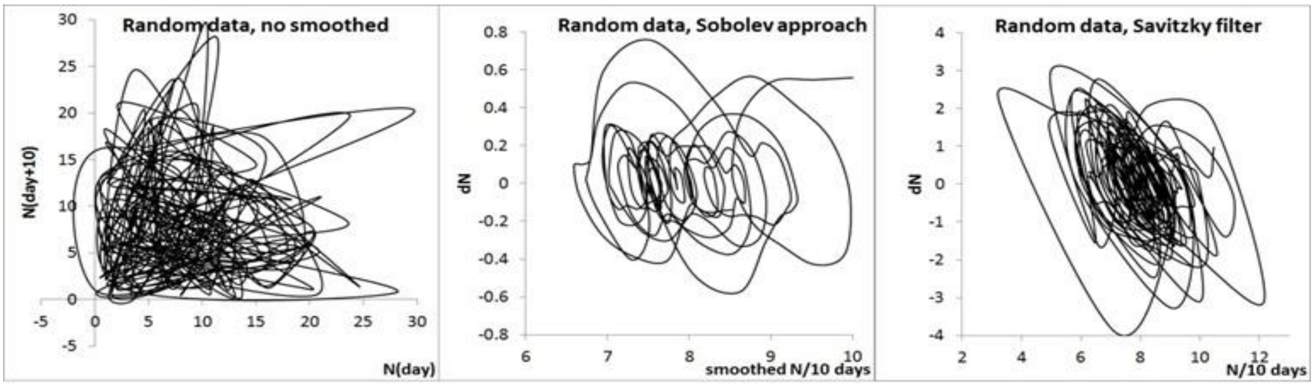
Finally, Fig. 7 illustrates the impact of processing methodology of EQ time series on the structure of PSP. Note that trajectories of orbits in PSPs plotted using differential of current and previous *N* (differential $N_{i+1} - N_i / n$) not versus smoothed *N*/10 days (Fig.7) are much more smooth and ordered compared to results obtained with larger stepsFigs. 4, 5)as the successive *N*/10 days input data sets plotted with 1 day step differ insignificantly, only by 2 days data; the rest of data in the sets are the same. In contrast, the data sets in Figs. 4 and 5 do not contain identical data (the successivedata sets are not overlapping), which results in more jogged trajectory. It is evident that for strongly overlapping data sets the PSP structure is close to that of attractor - we can see almost ordered orbits in the expanded source area (Fig.7 b)



a. b.

Fig.7.a) PSP of *dN* versus declustered and S-Gsmoothed for *N*/10 days data (catalog 1960-1986) in Batumi area (here we apply S-G smoothing and 1 day *Lag* in contrast to Figs 5, 6, i.e. we combine standard and Sobolev approaches), R=200 km; b) expanded view of the source area, limited by a circle in Fig. 7a.

In order to test whether the methodology used to obtain Fig.7 is really informativewe apply this procedure to the random sequence of numbers (Fig.8). It is evident that combination of smoothing with small successive steps (*Lags*) lead to appearance of smooth orbit-like trajectories even for random number sequences, so the similar ordered trajectories in EQ rate time series (Fig.7) appear just as result of a definite smoothing procedure and are not related to fundamental properties of the seismic rate dynamics. At the same time significant deviations from the source area in PSPs of earthquake time series, due to swarms and strong events are clearly revealed by both (standard and Sobolev) approaches - compare Fig.5 and 7.



a. **b.** **c.**

Fig.8. PSP compiled for a "rate" of random sequence of numbers considered as a proxy to number of EQ occurrences in 10 days; a) standard attractor, no smoothing applied; b) plot of *dN* versus *N/10* "days" for original (non-smoothed) data; c) plot of *dN* versus *N/10* "days" for S-G smoothed data; standard plot

Spitak earthquake area

Spitak earthquake (Fig.2) occurred in Armenia, December 7, 1988. The earthquake measured 6.9 on the surface wave magnitude scale. In following we calculated PSPs of EQ time series in Spitak EQ area– data for area of radius 100 km around Spitak EQ epicenter (catalogs1960-1988 and 1960-2011); both original and declustered ETS were analyzed. Fig. 9 shows the daily occurrence of

EQs in Spitak EQ epicenter area for R= 100 km.According to PSP in Fig. 10e, the deviating orbits are visible for 1967, 1971, 1978, 1986 and 1988. The last orbit is definitely related to Spitak EQ foreshock/aftershock activity. Note big difference in the structure of PSP for analyzed two catalogs, which can be explained by the strong influence of seismicity, caused by foreshocks/aftershocks activity of Spitak EQ included in the plots 10 d, e, f. It seems informative to divide the most outlying orbit in Figs. 10 d, e, f into pre- and post-Spitak parts in order to assess the "precursory" part of the trajectory. The full duration of the orbits is in Figs. 10 d, e, f is approximately 120-200 days and the duration of the "precursory" part is 30-50 days for various lags . Thus, a strong deviation of the orbit from the source area can be considered as the precursor of the strong event, due probably to foreshock activity (not excluded fully by Reasenberg declustering).

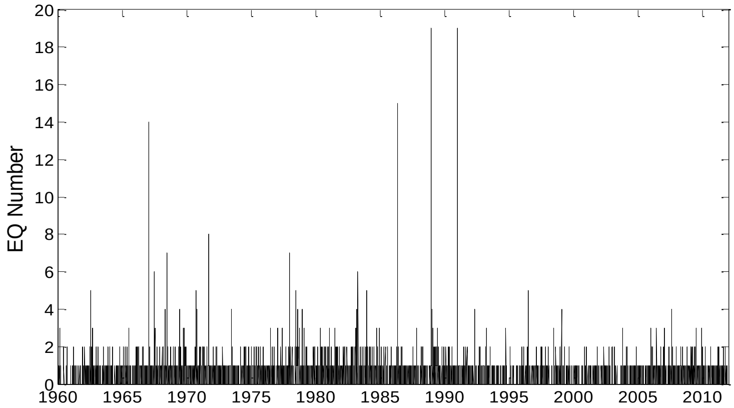
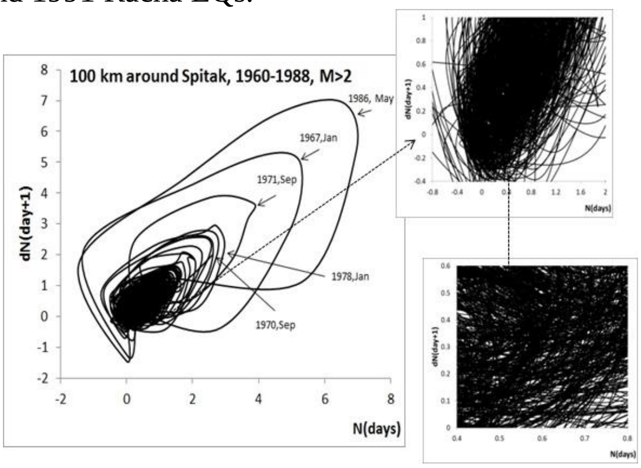


Fig.9. Daily occurrence of EQ in Spitak area in 1960-2011for R= 100 km; two largest spikes are related to 1988 Spitak and 1991 Racha EQs.



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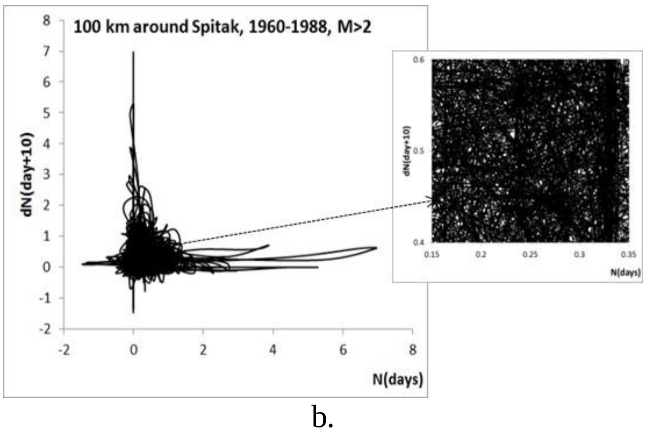

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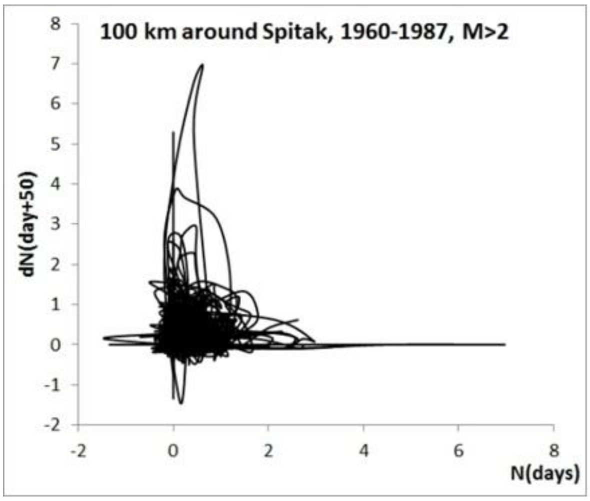

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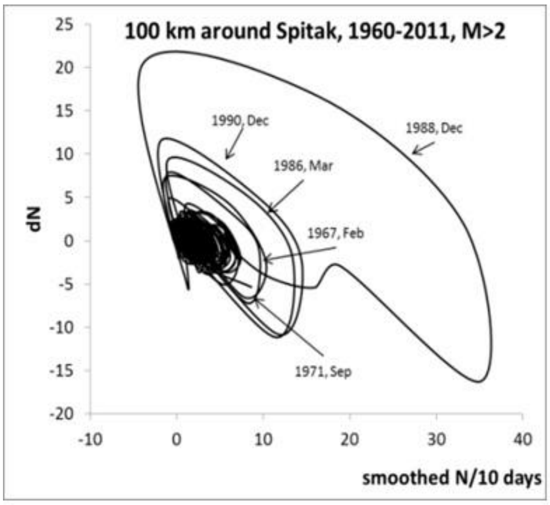
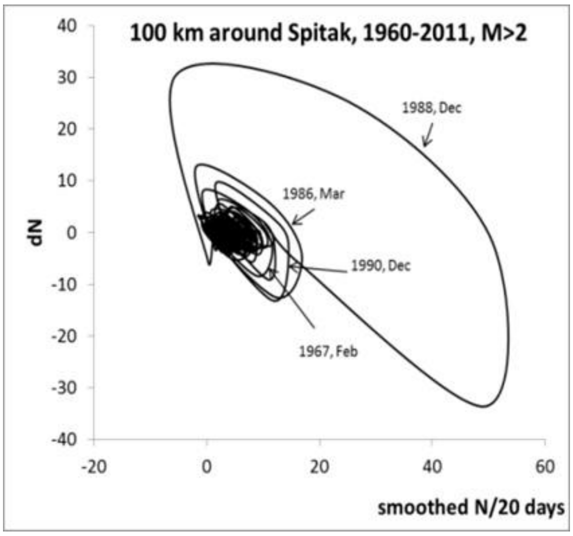
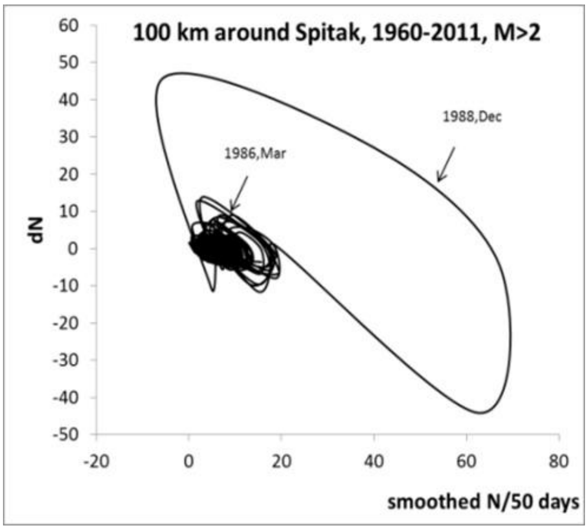


d.



e.

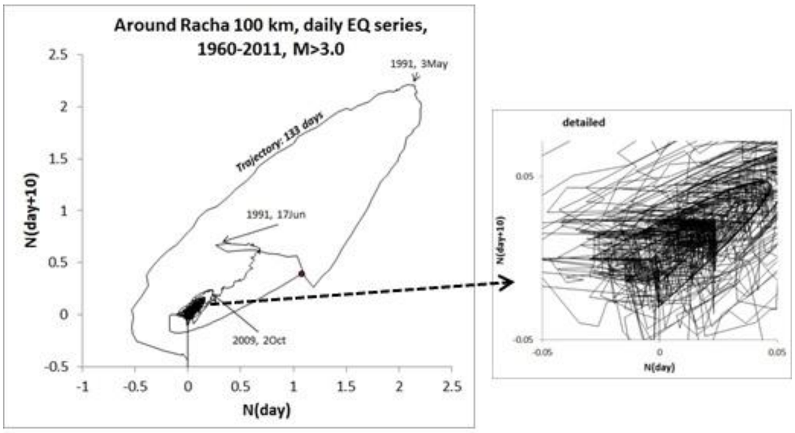


f.

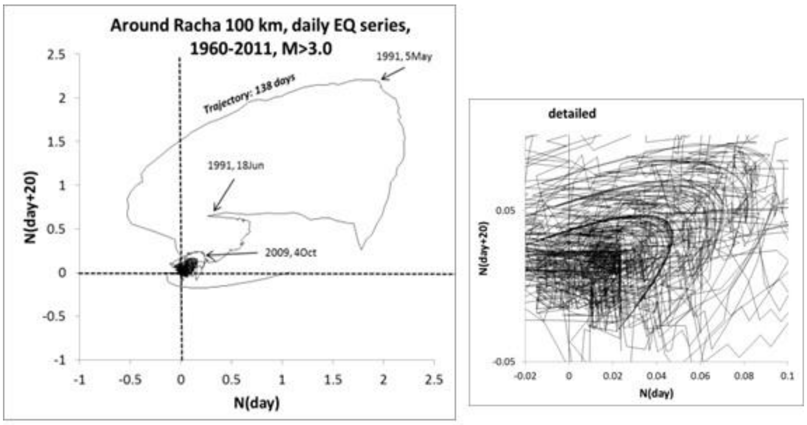
Fig. 10. Phase space portraits of daily series of EQ occurrences in Spitak area for R=100 km, declustered and smoothed by the S-G filtered data sets from catalogs; a, b, c - PSPs (standard) for catalog 1960-1988, of smoothed by S-G filter lagged value (*N+lag*) where the *Lag* is 1, 10, 20 and 50 daysversus daily value *N*(day) with *N* 10; 20 50 days not including Spitak EQ; d, e, f - PSPs of *dN* versus declustered and smoothed for *N*/10 days data in the same area for catalog 1960-2011, R=100 km. Note a big difference in the structure of PSP for two catalogs caused by inclusion of foreshocks/aftershocks activity of Spitak EQ in the plots 10 d, e, f.

Racha EQ area

The Racha earthquake occurred in the Racha province of Georgia at 9:12 UTC on 29 April 1991 on the southern foothills of the Greater Caucasus mountains. It had a magnitude of 7.0 and was the most powerful earthquake recorded in the Caucasus.



a.



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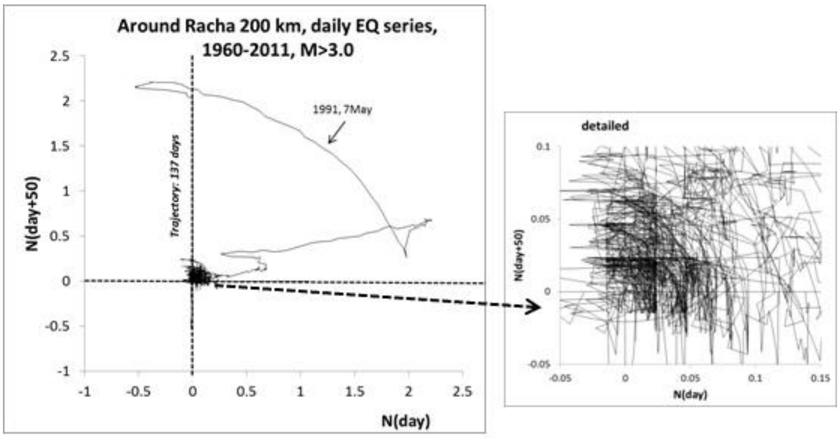


c.

Fig.11. a, b, c. Phase space portraits of data set for Racha test area for declustered S-G filtered catalog 1960-2011 (R= 100 km), for lags 10,20,50 days; note ordered structures in the source area.

Table 2. Duration of the most outlying trajectories on Fig. 11 a, b,c.

Trajectories on Fig. 11 a, b,c.	Duration of a full trajectory, days	Trajectory duration till Racha EQ, days
Most outlying (1991)	133-138	64

The most extended orbits reach the following maximal deviations at lags 10 and 20: i. the point on the orbit for 1991, 3 May is close to the mainshock moment of Racha EQ, which occur 29

April; ii. - the point 1991, June corresponds to Java strong aftershock of Racha EQ, 15 June, 1991, M6.2; iii. - 2009, Oct is related to Racha EQ, 8 Sep 2009, M6.

The length of the most extended trajectory with a label 1991, 3 May is 133 days (beginning from the central cluster). If we assume that the time to a label 1991, 3 May is a half of the full duration (133 days) than the significant deviation from the background seismicity (central cluster) begin before the Racha mainshock. Possibly, this time, needed for forming the half-orbit - approximately 60 days (Table 2) - can be considered as a precursor of the mainshock.

The phase space portraits of Fig.11a,b seems to be the most interesting ones: here in the radius R=100 km in the detailed (expanded) plots of the central cluster of trajectories some clear recurrent orbits are visible with strange configurations – parabolas, right angles. We cannot see such recurrent configurations at PSP for the larger test area, namely, for R=200 km.

PSP of waiting time series

Besides seismic rates the phase space plots of EQ waiting times were investigated (Fig. 11); earlier studies reveal low values of correlation dimension of EQ time series (Matcharashvili et al., 2000). The results do not confirm existence of any clear ordered structure in PSPs of EQ waiting time series.

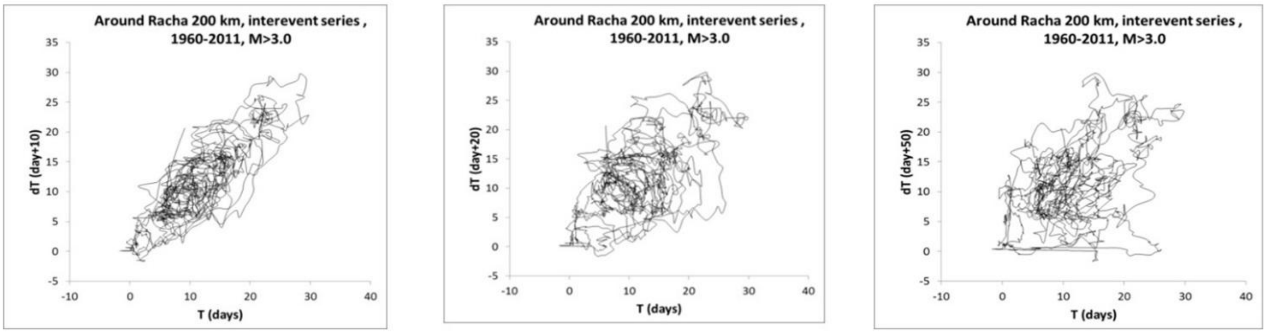
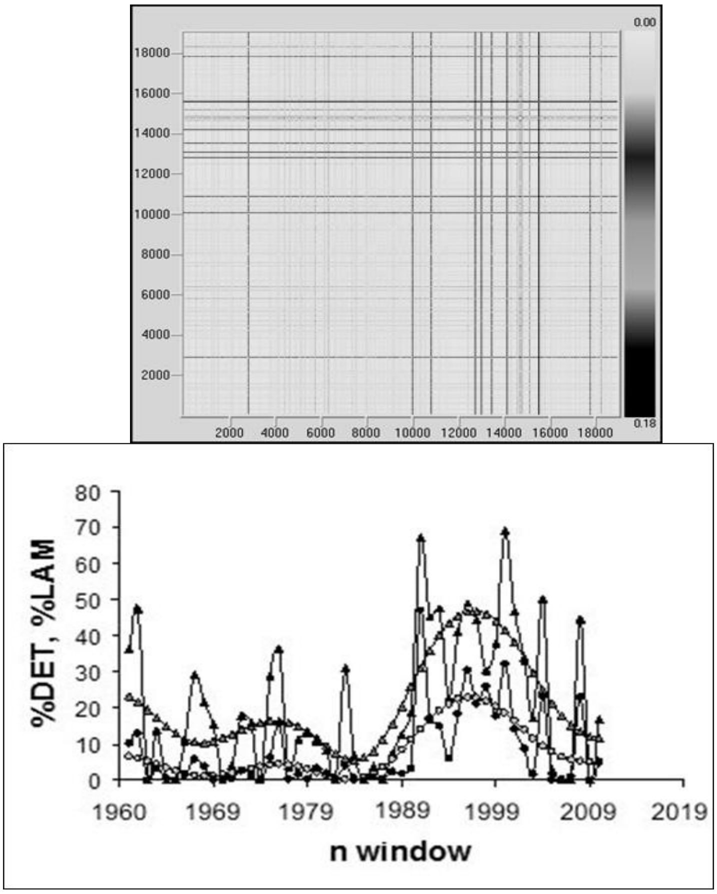


Fig. 12. PSPs of waiting time series were obtained from declustered 1960-2011 catalogs of Racha EQ area (R=200 km) using standard approach.

Recurrence Quantification Analysis of EQ time series

Last years for visualization and quantitative analysis of hidden non-linear structures are widely used Recurrence Plots (RP) and Recurrence Quantification Analysis (RQA) - see for example (Webber and Marwan, 2015). As mentioned earlier, PSP and RP are two interconnected ways to reveal the recurrence in time series. RQA is preferable at quantitative assessment of high-dimensional dynamics. In Chelidze and Matcharashvili (2015) RQA method is usedfor investigation of earthquakes catalogues' complexity. Exactly, earthquakes' daily and monthly occurrences data sets have been derived both from the original as well as from the declustered (according to Matthews and Reasenberg, 1988) catalogues with a magnitude threshold $M \geq 3.0$.



a b.

Fig. 13.a) RP and b) RQA %DET (black circles) and %LAM (triangles) of daily frequency of earthquake occurrence time series, 365 days length sliding window and 365 days step. Grey circles - Savitzky-Golay smoothing(Chelidze and Matcharashvili, 2015).

In Fig. 12 results of RP and RQA calculations for consecutive one year length daily frequency of earthquake occurrencesets at one year step are shown. Because of essential variation of RQA measures calculated for short (365 data) segments, results for data smoothed according to Savitzky-Golay filtering method are also presented (filled triangles and circles). Indeed we see that the EQ timeseries contain component with significant % of determinism (%DET) and laminarity (%LAM), which varies in time: large values of %DET and %LAM are fixed approximately from 1990 to 2005.

Thus, it is evident that Recurrence Quantification Analysis is more effective in revealing hidden nonlinear structures in the EQ timeseries than PSP or RPapproach.

Conclusions

1. The structures in phase pace portraits of 10 days smoothed earthquake rate time series at volcanic area (Kronotskoe EQ) obtained by Sobolev seem to be very similar to attractors: this can be related to the processing methodology (using 1 day step and overlapping 10 days windows) as well as to a specific seismic regime in such areas. Investigations in volcano seismology show that seismic events near volcanic centers reveal some regularities due to weak external periodic forcings (e.g.tides), which is explained by high sensitivity of such areas to small perturbations.
2. The possibility of existence of seismic attractors and correspondingly, of deterministic chaos regime in non-volcanic areas, which are less sensitive to weak forcings remain obscure: analysis of nonlinear dynamics of earthquake time series (namely, Recurrence Quantitative

Analysis) shows that there are nonlinear structures of relatively low fractal dimension, especially intime and space domains; at the same time trajectories in the phase space are not very regular.

3. Phase Space Portraits (PSP) and Recurrence Plots can be considered as interesting visualization tools for analysis of seismicity dynamics. On phase space plots of smoothed (for 10,20,50 days) seismic rate sequences in Racha area there are some attractor-like clusters generated by background seismicity. It seems that before/after strong earthquake there are some anomalies in PSPs even using declustered (by Riesenberg approach) catalogs, presumably well expressed in case of significant foreshock/aftershock activity or presence of clusters. In principle this can be used in strong earthquake precursors' search.
4. More detail studies in various tectonic regions should be performed in order to make definite conclusions on the dynamic structure of seismic rate time series and on potential of the used methods (PSP, RQA) for analysis of seismic process.

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ატრაქტორების ძიება კავკასიის სეისმურ დროით სერიებში

თამაზ ჭელიძე, ნატალია ჟუკოვა, თეიმურაზ მაჭარაშვილი, ეკატერინე მეფარიძე

რეზიუმე

ბოლო წლებში, გამოჩნდა სადავო პუბლიკაციები სეისმურ დროით სერიებში ატრაქტორების როგორც არსებობის (რაც ნიშნავს, რომ შეიძლება წარმოადგენდეს დეტერმინირებული ქაოსის მოდელს), ასევე ასეთი მოწესრიგებული სტრუქტურების არარსებობის შესახებ. აქედან გამომდინარე საინტერესოა მეთოლოგიის შესწავლა, რომელიც შეიძლება გამოყენებულ იქნას მიწისძვრის დროით სერიების (ETS) დამუშავებისას შესაძლო ატრაქტორების გამოსავლენად. ასეთი პრობლემის გადასაწყვეტად შემუშავდა 2 მიდგომა: 1. მოვლენები ETS განიხილებიან ინდივიდუალურად; 2. მოვლენების რაოდენობა ETS- ში გამოითვლება რამდენიმე დროის ფანჯარაში (სეისმურობის დონე). ეს უკანასკნელი სიდიდე ფართოდ გამოიყენება მიწის ქერქის დეფორმაციის სიჩქარის დასახასიათებლად.

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