

## ***Interactive comment on “Non-local deformation effects in shear flows” by A. V. Popova et al.***

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We are grateful to the referee for their interest to the article and attentive reading. Thank you for the advice on the style of the language and the found misprints.

Referee: “For example, the abstract starts with “The method for detection of clusters....generally accepted” as if there were only one method for doing this task. The Authors seem to ignore that Marsan and Lengline (Science, 2006) put recently forward a method based on the ETAS model, and that the paper by Zaliapin et al (last citation) is based on the method by Baiesi and Paczuski (Phys, Rev, E 2004). Moreover, before we had works by Frohlich and Davis, besides the mostly used box counting methods. I was thus pretty curious to find out which of the literature’s method was THE one, to finally not succeed in this.”

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The authors agree that there are plenty of methods for detection of clusters. In foreshock-main shock-aftershock sequences, event connectedness doesn’t cause doubts. It is just the idea the authors wanted report. Then the question arises if there is such a connection between events in a declustered catalogue, and can events located far from each other in time and space be connected. It is classically considered that events are distributed according to the Poisson law. (Kostrov, 1975, Marsan, 2008, Anderson & Nanjo, 2013)

Referee: “Then unexpectedly at page 72 there seem to be multiple methods: “In the present paper, the methods for timescale and space scale decomposition of foreshock and aftershock catalogues, filtered from events with small magnitudes, investigate the structure of the shear flow in the region and its deformation characteristics.”: what does it mean?”

We elaborate the translation: In the present paper, the catalogue cleared (filtered, declustered) from events with small magnitudes, foreshocks and aftershocks is used. Declustered catalogue is decomposed into sequences of related events in space-time scales with respect to the displacement direction. Using the obtained sequences, the structure of a shear flow in the region is investigated as well as its deformation characteristics.

Referee: “Also the results are not presented in a very lively way, there are some maps where it is not so clear what is going on, and many tables. Given that I did not understand much of the paper, I can just add that it is not clear whether the results are relevant. They might have been compared with different analyses where one or more ingredients of the method were changed, to have a reference (even better would be to

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compare them with other methods). For example, how would they change if the shear was not considered in the algorithm? Answering this point should be useful, to see if considering the shear is a crucial step in the presented methodology.”

In the introduction to the paper, there is a comparison with the articles of this direction (Shebalin, 2006, Shevtsov & Sagitova, 2009). In addition, in the paper (Shevtsov & Sagitova, 2009, 2012), carried out under the guidance of the Director of IKIR RAS, Shevtsov B.M., such investigation was realized not taking into the account the shift direction. This article is a continuation of that work and the direction criteria allows us to consider not only the characteristics of event connectedness in the catalogue, as it was done in (Shevtsov & Sagitova, 2012), but also to consider such sequence as clusters in a shear flow and to investigate deformation characteristics.

Referee: “page 70) “From the point of view of the specialists of the earth sciences, seismic events with the given energy concentrated in some volume form a Poisson flow of independent events”: I do not understand this sentence, how can be earthquakes considered as independent?”

In this case, the authors wanted to say that from the classical point of view seismic events are distributed according to the Poisson law (Kostrov, 1975). The papers (Marsan, 2008, Anderson & Nanjo, 2013) also state that the event distribution is closer to the Poisson one in a cleared catalogue.

Referee: “Page 71: “connectedness of seismic events” should be defined.”

If seismic events fall within the area of influence, they are considered to be associated with the initial event (initiating). We can only state the connectivity, since it possible to

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make the conclusion about the dependence or independence of events only on the basis of the statistical distribution of increments between the connected events.

Referee: “Page 71, L 24: “conditions close to critical ones”: what does it mean?”

According to the theory of critical phenomena, these are deviation from normal behavior. In the theory of critical phenomena deviations from the normal behavior of seismicity are referred to as sub- and supercritical regimes of earthquakes (Helmstetter, Sornette, 2002). In the framework of the plasticity theory, it is associated with intensification of viscous or brittle processes, but from the point of view of statistical theory it is the effect of abnormal delays or remote spatial correlations. In diffusion equations, components with fractional temporal and spatial derivatives play a significant role at that.

Referee: “Page 71, L 25: “non-localness”: what does it mean? “and in statistical distribution” also not clear”

During the statistical description of the seismic process, the question arises: can we consider the increments between events in a sequence to be independent? The dependence can occur both in terms of time and space. The dependence of increments in time indicates that the process is of non-Markov type, when the memory effects take place. If there is a dependence of increments in space, the process is called nonlocal when long-range correlations appear (Shevtsov & Sagitova, 2009, 2012). We can say that in both cases there is a non-locality, in the first case it is time non-locality, and in the second case it is space non-locality.

Referee: “Page 72, L 10: “Poisson complicated process”: what is it?”

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complex Poisson process is the sum of a random number  $N(t)$  (where  $N(t)$  is a simple Poisson process) of summands  $Z_N$ , each of which is a random value independent of the others, and all the components are equally distributed (Tikhonov, Mironov, 1977).

Referee: "Page 72, L 20 : "The generalization of such kinds of discrete random processes is the process of random walks": I do not understand it, what are these random walks in the field of seismicity?"

A large number of papers are devoted to this issue, some of them are referenced in the article (Shebalin, 2006, Helmstetter & Sornette, 2002, Saichev & Zaslavsky, 1997, Sornette, 2006). In the case of small increments, description non-Markov and non-local processes is reduced to the approximation the mathematical apparatus of which is differential equation of the diffusion type with fractional derivatives (Uchaikin, 2003, Metzler & Klafter, 2000, Saichev & Zaslavsky, 1997). The diffusion approach is used for describing the geophysical processes (Lukk et al., 1996), including seismic ones (Golitsyn, 2001). It is possible to present diffusion processes with memory and nonlocality in the form of random walks on a fractal set (Zaslavsky, 2004). The properties of the medium determine the walk features and indicators of fractional diffusion equations, which describe the process.

If there are the effects of statistical dependence of increments, the process of walks is called the generalized Brownian motion, for which, along with the usual switch, tramples with returns and long spans called "flights of Levi" are typical (Zaslavsky, 2004, Lukk et al., 1996, Uchaikin, 2003, Metzler & Klafter, 2000). Trample is a subdiffusive mode associated with memory in the system, and flights are superdiffusive cases determined by nonlocality. The anomalous behavior of walks is the characteristic feature of their statistical connectedness. And walk mode change indicates the change of medium properties and stresses.

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Referee: "Page 74, L 2: "Thus, the events are almost simultaneous and the spatial correlation radius is estimated by the number of events in linear constructions, and goes to infinity in critical conditions": what does it mean?"

This question refers to the paper (Shebalin, 2006) which is referenced in the article. Events that fall within the defined time period are considered to be connected based on spatial criteria. If the sequence of events forms a linear structure, then under certain conditions a trunk gap is possible in this region, and in this case the radius of correlation will tend to infinity.

Referee: "Page 74, L 18: "This pair forms the simplest non-locality, the pair one.": what does it mean?"

Page 74: "...the cluster length of which may be interpreted as a measure of non-locality in a Markov sequence.": What is a non-locality of a Markov sequence?"

If some events in a sequence are dependent, this part can be considered as a random vector, then the rest of the sequence can be considered as Markovian, i.e. as a result a Markov chain of order  $k$  (Tikhonov & Mironov, 1977). In this case, the number of dependent events can be called a measure of non-locality in the Markov chain.

Referee: "Page 76, L 4: "Note that cluster formation should not be considered a manifestation of local effects.": not clear"

We elaborate the translation: "Note that cluster formation should not be considered **as** manifestation of local effects." That is the occurrence of a sequences connected

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events is not the manifestation of non-locality.

Referee: "Page 76: The time scale defined in (1) seems related to what appeared in Baiesi & Paczuski (2004). Where does this idea come from? Why is exactly  $T/n$  relevant and not, for example  $1/10$  or  $10$  times such value?"

This is the most simple equation, based on the frequency of event occurrence with a given energy in the catalogue, which can be determined from available statistics.

Referee: "Page 77: In the same spirit of the previous point, in the Dobrovolskiy model could one put a prefactor? Why is it exactly pure a power of 10?"

Page 77: After (3), there is the Mindlin model mentioned. From the description in the text it is not possible to understand what it is."

The area of influence of an event in space can be determined on the basis of different models to estimate the radius of influence, the authors used the Dobrovolskiy formula (Dobrovolskiy et al., 1979, Dobrovolskiy, 2009, Dobrovolskiy, Physics of the Solid Earth, 2003) and the model (Perezhogin et al., Math. Modeling, 2007, Perezhogin & Shevtsov, Computational Technologies, 2009, Perezhogin, Vestnik KRAUNTs, 2009), based on Mindlin model (Mindlin, 1950). The both models are developed on general basic equations, but Dobrovolskiy model introduces the coefficients which were determined according to the results of long-term experimental surveys. The authors made similar calculations by Sobolev model as well, the obtained results correlate well with the results of Mindlin model. That is value orders (influence scales), obtained by Mindlin and Sobolev models does not differ much.

In Dobrovolskiy model, the radius of influence of precursors is  $R = 10^{0.43 \cdot M}$ ,  $R$  is the radius,  $M$  is the earthquake magnitude. This formula was defined on the basis the

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model of homogeneous isotropic half-space with soft inclusion and experimental data.

In the second model, estimation of the region of the earthquake influence was carried out on the basis of the level of relative deformations  $10^{-8}$ . Dobrovolskiy also excepted such estimation of relative deformations. Within the Mindlin model, seismic moment was taken for each earthquake and the region of maximal shear deformations was estimated based on the level  $10^{-8}$  with concentrated sources in the form of double forces with a moment and without a moment.

Referee: "Page 77: the definition (4) is very technical and in general the whole consideration of shear properties (e.g. shear single vector sampling) sound for specialists and not clear at all for the average reader."

The volume of the paper does not allow us to consider many issues in detail, but there are references to the articles in this area (Riznichenko, 1965, Aki & Richards, 1983, Dobrovolskiy et al., 1979, Goldin, 2004). The paper defines the main characteristics of shear flow on the basis of available statistics and lists all formulas.

Referee: "Page 78: point 3 says "Among the set of events falling within the spatial-temporal region with regard to the shear direction, an event with a comparable energy (or magnitude  $M_{max}$ ) is chosen.". This sounds arbitrary. Let say we had another event with  $M_1 < M_{max}$ , yet very much closer in space and time to the  $j$  event we are considering: why should we still consider the one with  $M_{max}$ ?"

In this work, temporal and spatial regions of influence of events are detected, and if a subsequent event falls within this area, it is considered to be connected to the initiating event. Considering all the arising relations, one will receive a branching process.

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From the totality of such events, the authors selected an event with the highest or comparable energy, i.e. the main branch was distinguished.

Page 78: "As a rule, in three or four steps, the nodal state is achieved in the sequence of related events, after which the walks repeat their ways": what is the nodal state and what are the walks?

We elaborate the translation: "As a rule, in three or four steps, the nodal plane is achieved in the sequence of related events, after which the random walks repeat their ways in the cluster obtained from the initial sample which indicated the stability of the suggested algorithm to initial condition change."

Referee: "Page 79: the Authors say that "the Mindlin spatial radius values are 3.5 times less than the Dobrovolskiy radius.". Is there any way to assess which of the two radii is more meaningful?"

In this case, the authors do not assess which of the radii is more significant. Comparison of the two radii shows that during the reduction of the radius of influence, the length of the clusters decreases and in the limit, if the radius of influence continues to decrease, all the clusters fall apart. Then the catalogue can be considered as a set of independent events.

Referee: "Page 85: "the tendency to "jumps" appears in the process": I do not understand it. "Probably, approximation to critical condition changes the..": what are these critical conditions?"

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Answers to similar questions are given above (Shebalin, 2006, Helmstetter & Sornette, 2002, Saichev & Zaslavsky, 1997, Sornette, 2006, Zaslavsky, 2004; Lukk et al., 1996, Uchaikin, 2003, Metzler & Klafter, 2000).

Referee: "Summary energy" probably should be "total energy"

We agree with the comment.

Referee: Page 85: "between the vents in space"

We agree, it should be "event" instead "vent".

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Interactive comment on Nonlin. Processes Geophys. Discuss., 2, 69, 2015.

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