Spatio-temporal clustering of successive earthquakes: analysis of a global CMT catalog.

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Abstract
Spatio-temporal clustering of seismicity features is an interesting phenomenon that is relevant for earthquake generation process and operational earthquake forecasting. We analyze successive earthquakes that closely occur in space and time in order to clarify how large earthquakes successively occur. We use the Global Centroid Moment Tensor catalog for the period from 1976 to 2016. Shallow earthquakes with a moment magnitude, Mw, of larger than or equal to 5.0 are analyzed. We first sort all of the earthquakes in time to select a master event from the beginning. Then, we group the earthquakes that occur within a horizontal distance (D) and a lapse time (Ta) from the master event into a cluster. Next master event is selected from the catalog in order, and the same procedure is repeated. We count the number of the clusters, which represent the successive earthquakes, for different D and Ta. To examine whether or not successive earthquakes randomly occur, we compare the results with simulations in which earthquakes are set to occur randomly in time but at the locations same with the estimated centroid. The results show that the cumulative numbers of clusters for the simulation more rapidly increase with the horizontal distance than those for real data at short distance ranges, and the former approach to the latter at long distance range. The triggering distance, at which the cumulative numbers of real and simulation data merge, increases with increasing the magnitude of master event. The triggering distance becomes smaller as the lapse time increases, which implies that the seismic activity turns to become the normal condition in which the occurrence time intervals of large earthquakes obey a Poisson distribution. The triggering distance increases with being almost proportional to the 1/3 of the seismic moment of master earthquake, and the number of earthquakes occurring in the region with positive Coulomb stress change (ΔCFF) are more than 60-80% of the total number of the successive earthquakes. These results suggest that static stress change introduced by a master event is one of the triggering mechanism of successive earthquakes.

Full Text
Due to technical limitations, full-text HTML conversion of this manuscript could not be completed. However, the manuscript can be downloaded and accessed as a PDF.

Tables
Table 1. Successive earthquakes within triggering distance.

| Magnitude   | Total number of earthquakes in the catalog | Number of successive earthquakes (%) |
|-------------|--------------------------------------------|-------------------------------------|
|             |                                            | days                  | days                  | days                  |
| 5.0 ≤ Mw <5.5 | 25299                                     | 37.9 %                | 44.2 %                | 37.5 %                |
| 5.5 ≤ Mw <6.0 | 9186                                      | 23.3 %                | 26.6 %                | 23.4 %                |
| 6.0 ≤ Mw <6.5 | 2753                                      | 18.2 %                | 18.9 %                | 16.3 %                |
| 6.5 ≤ Mw <7   | 931                                       | 9.6 %                 | 12.7 %                | 14.9 %                |
| Mw ≥ 7       | 419                                       | 4.1 %                 | 7.6 %                 | 5.5 %                 |

Figures
Figure 1

Schematic illustration of the selection method of master event and the removal of the aftershocks. We sort the earthquake catalog in time, and we select the first earthquake as a master event in a given magnitude range. We then find slave events and select a next master event from the catalog and repeat these process. $q_1$ is the first master event ($E_0^1$), and $q_2$ is its slave event. $q_3$ is out of the magnitude range so that this is not selected as a master event. $q_4$ is not selected as a master event, because it occurs within 2000 km distance and $t_b \leq 14$ days from a larger earthquake, $q_3$. $q_5$ is selected as master event ($E_0^2$) because it occurs at distance larger than 2000 km from a larger earthquake $q_3$ even though within $t_b \leq 14$ days (but without no slave event). $q_6$ is an earthquake out of target magnitude. $q_7$ is not selected as a master event because it is close to $q_6$. $q_8$ is selected as master event ($E_0^3$) because it is larger than $q_7$ even though occurs within 2000 km distance and $t_b \leq 14$ days from $q_7$. $q_9$ is also selected as master event ($E_0^4$) because it occurs at a distance larger than 2000km and $t_b > 14$ days from a larger earthquake, $q_6$, and $q_{10}$ is its slave event.
Schematic illustrations to show how different clusters of successive earthquakes are defined for different choices of D and T_a. Blue circles represent master events, gray circles slave events and each gray ellipse indicates a group of successive earthquakes (clusters). (a) A group of clusters obtained for initial D and T_a. To remove aftershock activity, we do not use the earthquakes (S_i) occurring within a distance of D_min that is determined from the magnitude of master event. (b) Green circle and green ellipse represent new slave events and a new cluster, respectively, obtained by increasing D. (c) Orange circle and orange ellipse represent a new slave event and a new cluster, respectively, obtained by increasing T_a. (d) New slave events and new clusters obtained by increasing both D and T_a.
Figure 3

Cumulative numbers of the observed (solid lines) and simulated (dotted lines) clusters versus horizontal distance for three lapse times (c=3 and $t_b=14$ day. Note that the ranges of vertical axis are different for (a) – (e). Arrows indicate the triggering distances where the cumulative numbers of the observed and simulated clusters merge (see text).
Relation between triggering distances and seismic moment. Triggering distances are measured for different parameters $t_b$ (a) and $c$ (b).
Figure 5

Spatial distributions of the successive earthquakes determined for (a) Mw≥7.0 (b) 6.5≤Mw<7.0, and (c) 6.0≤Mw<6.5. Blue, orange, maroon colors represent the successive earthquakes occurring within distances of 100, 500 and 1000 km, respectively, within a lapse time of 180 days.
Figure 6

Frequency distributions of the triggering distances calculated for 100 simulated data. The observed triggering distances measured from the average of the simulation are indicated by red dotted lines. Two lapse times (T_a) are examined: (a,b,c) for 365 days and (d,e,f) for 180 days.
Figure 7

Frequency distribution of Coulomb stress change calculated for the first fault plane (a,b,c) and the second one (d,e,f). Solid and dotted red lines indicate ΔCFF of 0 Pa and $10^3$ Pa,
respectively.

Supplementary Files
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