Are foreshocks really mainshocks with larger aftershocks?

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Abstract: The question whether foreshocks behave like mainshocks that happen to have larger aftershocks is important for the understanding of earthquake nucleation and the modelling of earthquake clustering. A commonly used model for short-term earthquake occurrence combines empirical observations of aftershock occurrence and extends them to foreshocks assuming a single triggering mechanism for earthquake clusters. However, observed foreshock probabilities are significantly lower than predicted by this kind of model. We conclude that foreshocks differ in some way from mainshocks and look for statistical and physical causes in two earthquake catalogues.

1. Introduction

Earthquakes cluster in space and time. In retrospect, the largest earthquake in a cluster is called the mainshock. The earthquakes preceding a mainshock are named foreshocks, and the earthquakes following a mainshock aftershocks. Minor earthquakes of similar magnitude are referred to as swarms (e.g. Evison and Rhoades, 2004) and larger earthquakes of similar magnitude are sometime called multiplets (e.g. Felzer et al., 2004). The earthquakes that occur outside a cluster are referred to as background. As no physical differences between these earthquakes are known, some of this labelling is arbitrary. Careful considerations need to be given to potential biases introduced by arbitrary data selection.

In a different approach to earthquake modelling, complete earthquake catalogues are described as one family of earthquakes, which interact through an epidemic model (Console et al. 2003, Zhuang et al., 2004).

We briefly review the most common empirical laws for earthquake clustering. They can be used to derive the probability for a foreshock to occur. We review prospective foreshock probabilities and compare them with recalculated values from a homogeneous global catalogue. We find the observed values to be significantly smaller than the model predictions. We discuss reasons for the discrepancy between data and model.

2. Empirical laws for aftershock occurrence

Two empirical laws have been used successfully to model the short-term clustering of earthquakes. Omori’s law describes the decay of earthquake activity with time t.

$$\frac{dN}{dt} = K / (c + t)^p ,$$

where $dN$ is the number of earthquakes in the time interval $dt$; $K$ is a parameter that is proportional to the aftershock productivity; $p$ describes the decay and takes values around 1.0; and $c$ stands for a small time interval just after the mainshock (e.g. Utsu et al., 1995).

The Gutenberg-Richter relation describes the magnitude-frequency distribution

$$\log_{10} N(M) = a - bM ,$$

where $N(M)$ is the number of earthquakes of magnitude $M$ and $a$ and $b$ are parameters (e.g. Gutenberg and Richter, 1949).
Two less well explored empirical relations describe the increase of the average number $N$ of aftershocks (3) and the aftershock area $A$ (4) with mainshock magnitude $M$.

$$\log_{10} N(M) = cM - d, \text{ (e.g. Singh, and Suárez, 1988)} \quad (3)$$

$$\log_{10} A = 1.02M - 4.01, \text{ (Utsu and Seki, 1954)} \quad (4)$$

3. Predicting mainshocks from aftershock models

Reasenberg and Jones (1989, 1994) studied 62 Californian aftershock sequences and combined equations (1) and (2) to derive the probability for the occurrence of earthquakes in a given time and magnitude interval following an initiating earthquake. They extended the model for magnitudes larger than the initiating earthquakes, assuming that foreshocks trigger the mainshocks in the same way as the mainshocks trigger aftershocks. The Californian model predicts a probability of 10% that an earthquake outside an aftershock sequence is followed by one of equal or larger size.

Another model formulation combining equations (2) and (3) and assuming equal growths constants $b$ and $c$, also finds a probability of 10% that an initial earthquake is followed by one of equal size or larger (Vere-Jones et al., 2005).

4. The earthquake catalogues and defining earthquake sequences

We used a global catalogue based on the reports of the International Seismological Centre (2003). The catalogue includes more than 45,000 earthquakes of magnitude 5.0 and above in the period 1964 – 2001 and shallower than 70 km (Christophersen, 2000). We have also started to work with the ANSS (Advanced National Seismic System) catalogue for California covering the years 1984 – 2004 inclusive.

We used a simple window method in time and space to search for related earthquakes. In space we calculated a search radius of four times the radius of a circular area according to Utsu and Seki’s model (1954), resulting in a search radius of 8 km for $M = 5.0$ and 150 km for $M = 7.5$. In time we use a sliding time window of 30 days, extending the sequence each time a new event is found. We separated our global earthquake sequences into different tectonic regimes, following a method suggested by Kagan (1999).

5. Review of prospective foreshock probabilities

Table 1 compares some previously reported foreshock probabilities with recalculated values from our global catalogue. We found good agreement with previous observations when matching our space, time and magnitude window. All observations are significantly lower than predicted by the aftershock models. The only exception is one observation in a volcanic area (Merrifield et al., 2003). We note that we found some significant variation in foreshock probabilities between different tectonic settings which we do not show here though. However, all these probabilities were still smaller than expected from the model.

6. The ETAS model

The ETAS (Epidemic Type Aftershock Sequence) model allows each earthquake to trigger its own offsprings (e.g. Ogata, 1988). The ETAS model separates between the background earthquakes and earthquake clusters. Interestingly, Zhuang et al. (2004) observed that the background in which the foreshocks occur have different triggering parameters than the clusters of aftershocks. This might be another indication that foreshocks require different modelling to aftershocks.
Table 1. Comparison of previously reported and recalculated foreshock probabilities in different magnitude, space and time windows.

<table>
<thead>
<tr>
<th>Previously reported foreshock probabilities</th>
<th>Recalculated foreshock probabilities</th>
<th>Comments</th>
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</thead>
<tbody>
<tr>
<td>Location, catalogue threshold, space and time window, author</td>
<td>Magnitude restriction</td>
<td>Foreshock probability</td>
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<tr>
<td>California, (Jones, 1985)</td>
<td>6%</td>
<td></td>
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<tr>
<td>Global catalogue, completeness M ~ 5.6, 75 km and 7 days (Reasenberg, 1999)</td>
<td>MS ≥ 5.0</td>
<td>7.5%</td>
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<td></td>
<td>MS ≥ 6.0</td>
<td>2.3%</td>
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<td></td>
<td>MS ≥ 7.0</td>
<td>0.4%</td>
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<tr>
<td>New Zealand, 30 km and 5 days (Savage and Rupp, 2000)</td>
<td>MS ≥ 5.0</td>
<td>4.5 ± 0.7%</td>
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<tr>
<td></td>
<td>MS – FS ≥ 1.0</td>
<td>0.8 ± 0.3%</td>
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<tr>
<td>Taupo Volcanic Zone (Merrifield et al., 2004)</td>
<td>9.6 ± 1.7%</td>
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7. Discussion

The probability of an earthquake to be a foreshock, i.e. to be followed by an earthquake of equal or larger size, within 75 km and 7 days, is about 4% in a global earthquake catalogue. The result confirms earlier observations and gives us some confidence that our clustering methodology to define earthquake sequences is consistent with commonly used methods of declustering earthquake catalogues.

The observed foreshock probability is significantly smaller than 10% as derived from models using aftershock parameters. Thus we conclude that there is some difference between foreshocks triggering mainshocks and mainshocks triggering the subsequent sequence.

One possible cause for this difference could be the ‘cumulative nature’ of the aftershock parameters. The parameters are derived from aftershock sequences in which some large aftershocks might have triggered their own sequence of events while the foreshock analysis does not extend past the largest earthquake in a sequence. To investigate possible differences in foreshock and aftershock parameters we have looked at the distribution of time and magnitude differences between foreshock and mainshock pairs.

The distribution of time differences between foreshocks and mainshocks is consistent with Omori’s law. The distribution of magnitude differences between foreshocks and mainshocks follows the Gutenberg-Richter relation. However, the $b$-value seems to be smaller than for aftershock sequences. We are still investigating in how far this is an artefact of the data selection.

Physical differences between foreshocks and aftershocks could be another possible cause for the difference between observed and model foreshock probabilities. For example, foreshocks could be triggered by the nucleation of the mainshock rather than trigger the up-coming mainshock (e.g. Dodge et al., 1995). In this case, the average foreshock size, the area of foreshock occurrence, and the average number of foreshocks per mainshock should all increase with mainshock size. Felzer et al. (2004) could not find any evidence for this. Instead they confirmed that a single triggering mechanism explains the occurrence of foreshocks, aftershocks and multiplicities. We will revisit this analysis in our global and Californian data sets and will report on our results in January.
8. Conclusion

Observed prospective foreshock probabilities are significantly lower than predicted by simple statistical models for aftershock occurrence. We conclude that foreshocks do not trigger mainshocks in the same manner as mainshocks trigger foreshocks. We consider two possible causes: Statistical bias in data selection and physical differences between foreshocks and mainshocks. We are still looking for evidence in two catalogues for both causes.

9. Acknowledgement

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10. References


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