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Short-term foreshocks in Southern California and Italy revisited: Observed deviations from the Epidemic-Type Aftershock Sequence (ETAS) Model

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Numerous studies have suggested that short-term foreshocks observed prior to large earthquakes are undistinguishable from the normal behaviour of seismicity, which is well described for example by the Epidemic-Type Aftershock Sequence (ETAS) model. Here we show that these studies fail to extract abnormal foreshock behaviour due to the much more frequent occurrence of aftershocks in comparison to potential foreshocks, which results in undervaluing the role of foreshocks.

We first define mainshocks as earthquakes of magnitude M6+ and use a space-time-magnitude window method with a maximum distance of 10 km to the mainshock, a maximum time range of 3 days before the mainshock and a minimum magnitude M4+ to define foreshocks in Southern California and in Italy. We then compare the observed rate of foreshock-mainshock pairs to the rate expected by ETAS simulations. Similar to previous studies, these results indicate that the foreshock activity observed in real catalogues is compatible with the ETAS model. Definition of foreshocks with a window method is, however, simplistic, since any individual event may be considered a foreshock although it is impossible to distinguish a foreshock from background or aftershock activity at a one-to-one event basis. We extend our foreshock analysis based on the predictions of the Non-Critical Precursory Accelerating Seismicity Theory (NC PAST), which are: (1) foreshocks are due to overloading on the main fault and occur in clusters, the activity of which is significantly higher than background activity, (2) microseismicity (M<3) must be included for the emergence of a reliable signal and (3) foreshocks are not systematic before large earthquakes due to aleatoric uncertainty on the rupture process. Following these guidelines, we systematically investigate foreshock sequences before large earthquakes (M6+) in Southern California and Italy. Using different approaches, we finally show that significant anomalies are observed before some mainshocks (e.g., 1992 Landers, 2009 L'Aquila earthquakes), which are not explained by the ETAS process. Anomalies are defined as any deviation from a Poissonian distribution (which describes the stationary background seismicity) with a Poisson probability lower than 10-̃4. We use approaches such as heuristic (what if a large cluster of events is not preceded by any event large enough to produce such a cluster?), ETAS stochastic declustering and a nearest-neighbour cluster technique that differentiates between foreshocks, mainshocks and aftershocks.

Our results highlight the shortcomings of current systematic precursory seismicity analyses: First, in order to consider a sufficient number of mainshocks, a large region is usually considered, which requires the use of a relatively high completeness magnitude. This considerably limits the significance of potential anomalies, which are mostly defined from microseismicity (according to the NC PAST). Second, it is commonly assumed that all mainshocks behave the same (in agreement with the ETAS process), which would validate stacking/averaging over multiple sequences. This approach however fails if mainshocks behave differently from one to another (according to the NC PAST). To conclude, microseismicity and non-systematic presence of anomalies are key conditions to better understand potential foreshocks before large earthquakes, their physical origin and their potential role in time-dependent hazard assessment and earthquake prediction.