When Is the Probability of a Large Earthquake Too Small?

by Warner Marzocchi, Iunio Iervolino, Massimiliano Giorgio, and Giuseppe Falcone

INTRODUCTION

Classical probabilistic seismic-hazard models (Cornell, 1968), which typically refer to the homogeneous Poisson process for earthquake occurrence, are not able to model explicitly the space-time clustering of earthquakes. Clustering may be particularly evident in time windows of days and weeks (e.g., Kagan and Knopoff, 1987; Ogata, 1988), but it may be still appreciable in the medium term, because the time sequences to large earthquakes may last long (Kagan and Jackson, 1991; Parsons, 2002; Faenza *et al.*, 2003; Marzocchi and Lombardi, 2008). The modeling of such a space–time clustering is an important subject of seismological research (Jordan *et al.*, 2011). In fact, accounting for time–space clustering of earthquakes may provide additional information, not only to seismic-hazard assessment aimed at structural design (e.g., Iervolino *et al.*, 2014; Marzocchi and Taroni, 2014), but also to short-term seismic risk management. The latter issue has been explored by the International Commission for Earthquake Forecasting, established after the L'Aquila earthquake in 2009, which paves the way to the so-called operational earthquake forecasting (OEF). As defined by Jordan *et al.* (2011), OEF comprises procedures for gathering and disseminating authoritative information about the time dependence of seismic hazards to help communities prepare for potentially destructive earthquakes.

Notwithstanding some recent earthquake sequences showing the importance of tracking the time evolution of seismic hazard (e.g., as for the recent Canterbury sequence in New Zealand; Wein and Becker, 2013), currently OEF represents a controversial issue in seismology. Most critics are not focused on debating the scientific credibility of the models used to describe short-term earthquake clustering, but they dispute the usefulness (if not the potential danger) of the information they provide, in particular, the probability of a damaging event in a short time frame. According to OEF models available in the literature, the weekly probability of a large earthquake (e.g., of magnitude six or larger) is above a few percent only after another large event. During a seismic sequence of moderate events (e.g., of maximum magnitude less than five), the weekly probability of a large event may increase also by two to three orders of magnitude with respect to the background value, but almost always this probability remains below a few percent (Jordan *et al.*, 2011). These figures sparked a debate among seismologists about the usefulness and danger of releasing information on the time evolution of short-term earthquake probability. A comprehensive discussion of all these issues can be found in Jordan *et al.* (2014) and Wang and Rogers (2014).

In this article, we focus our attention on one particular aspect of this discussion. In particular, we put forward a different perspective that should replace the common practice of discussing when the probability of a large earthquake can be considered small. As a matter of fact, in a risk-informed decision framework, the variable of interest should be a probabilistically assessed loss (consequence) metric, for instance, the expected loss. A comparison of such a risk metric with some risk thresholds for individuals and/or for communities may help in understanding whether the risk is tolerable or not, and in choosing the optimal risk management decision. A step in this direction has been recently made by Iervolino *et al.* (2015), which introduces the operational earthquake loss forecasting (OELF) concept. Specifically, OELF translates short-term seismic hazard (OEF) into risk assessment (i.e., the weekly expected loss), using some specific metric, such as the expected number of collapsed buildings, displaced residents, injuries, and fatalities (see also van Stiphout *et al.*, 2010; Zechar *et al.*, 2014).

Along these lines, in this article we analyze the evolutions of seismicity forecasts and consequent seismic risk for a seismic sequence that occurred in southern Italy in 2012 and featuring an M_L 5.0 largest shock (the Pollino sequence hereafter). This sequence lasted for more than one year, and it was not associated with any destructive earthquake. In particular, the OEF seismicity rates and consequent OELF weekly estimates are evaluated as a function of time for a period spanning 2010–2013 to capture the full evolution of the sequence. Seismic risk metrics are compared with some reference risk values referring to other events from the literature.

OPERATIONAL EARTHQUAKE FORECASTING AND OPERATIONAL EARTHQUAKE LOSS FORECASTING FOR A SEISMIC SEQUENCE IN ITALY

Figure 1 shows the seismic sequence that occurred in the Pollino area during the period 20 October 2011 to 15 July 2013. The largest earthquake of this sequence, M_L 5.0, occurred on 25 October 2012. This sequence did not cause significant damage, but it raised concern among the affected population because of the prolonged felt seismicity. This sequence is rather

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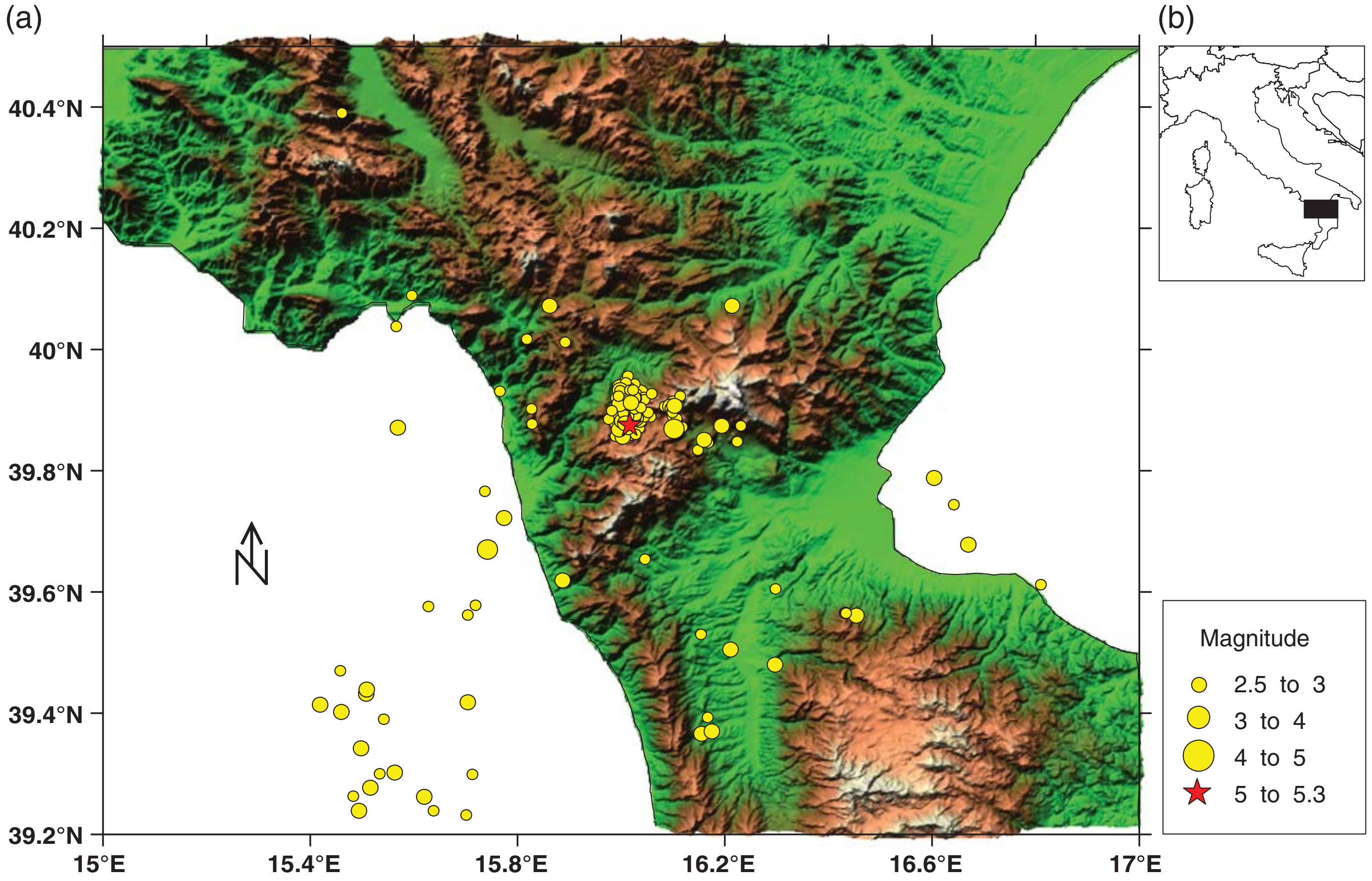


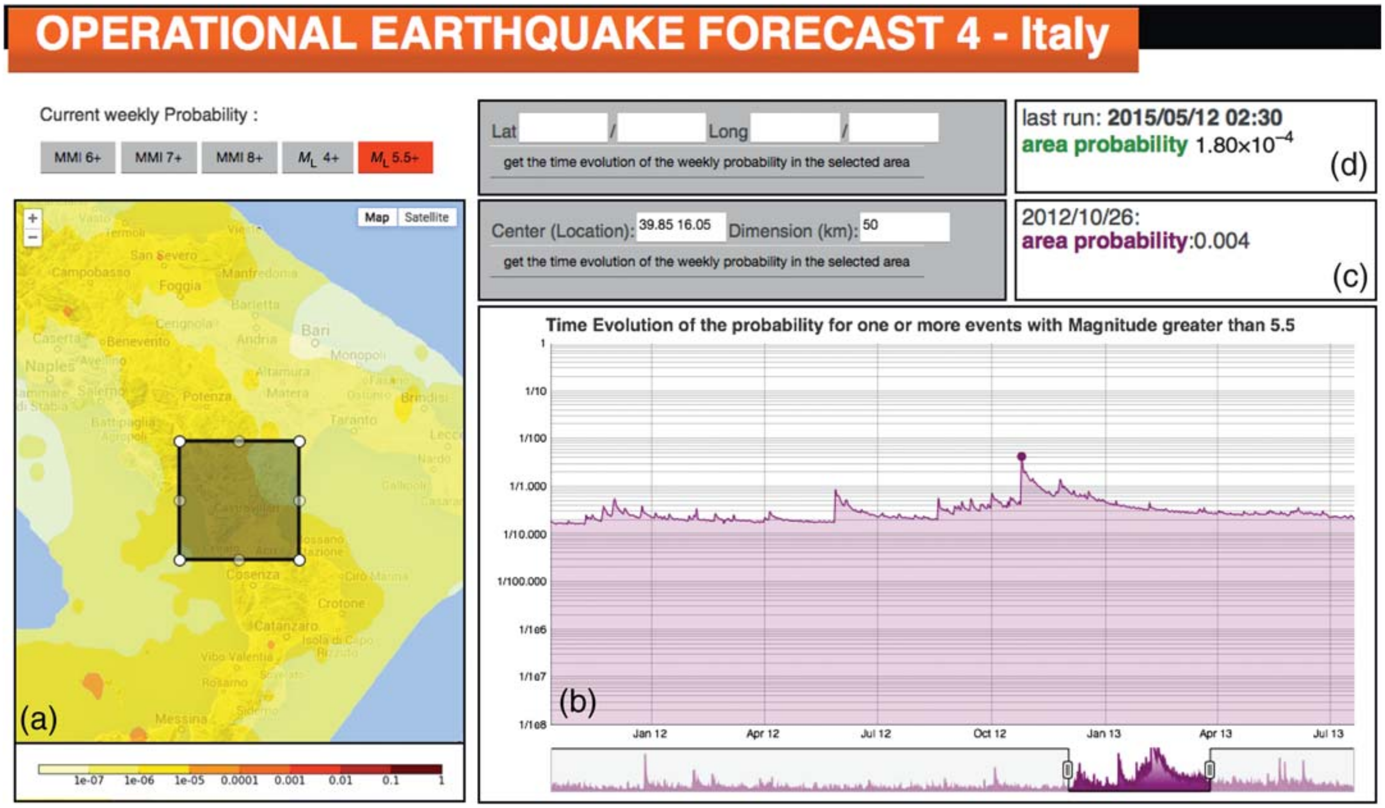
▲ **Figure 1.** (a) Seismicity above M_L 2.5 in the Pollino region during the period 20 October 2011 to 15 July 2013. The dimension of the circles is a function of the magnitude. The red star shows the epicenter of the largest earthquake (M_L 5.0), which occurred on 25 October 2012; (b) the black rectangle shows the location of the Pollino region in Italy.

typical in Italian territory where, on average, 10–15 seismic sequences like this one are observed per year.

In Figure 2, we show the evolution of the weekly probability of an earthquake of magnitude 5.5 or larger for this period of time. In particular, each point of the graph is the weekly probability that an earthquake equal to or larger than 5.5 will occur in the selected area (the forecast starts at the time reported in the time axis). This plot was produced by the OEF_Italy system that is described in Marzocchi *et al.* (2014). In essence, earthquake forecasts are obtained through an ensemble modeling procedure (Marzocchi *et al.*, 2012), taking into account three different earthquake clustering models under testing in the Collaboratory for the Study of Earthquake Predictability experiments (see Marzocchi *et al.*, 2014, for more details). From the figure, it is possible to observe that the largest weekly probability is about 0.004 (1/250), just after the M_L 5.0 event.

In Figure 3, we show the correspondent OELF assessment from the MANTIS-K system (Iervolino *et al.*, 2015). In particular, the figure displays the weekly probability of death (for seismic causes) for an individual resident in an area of varying radius from the geometrical center of the sequence (arbitrarily defined as the location of the largest shock of the sequence, see Iervolino *et al.*, 2015, for details). In the following, this is referred to as the individual risk of death (IRD) caused by earthquakes. The IRD is not the same for each resident (depending on the different vulnerability of the buildings where the resident lives and works), but it is the value the risk assumes, on average, among members of the exposed community. Importantly, IRD allows the comparison of the seismic risk with the risk posed by other threats, like a disease, a car accident, and others. For this purpose, in the same figure we also plot a conventional acceptable weekly IRD threshold for developed countries (horizontal dashed line), which is taken from the literature.

The definition of the acceptable IRD threshold requires a cost–benefit framework in the widest sense, and it has to account for many factors such as weighing personal interest, national gain, economic affordability, feasibility of the mitigation actions, and also partially the widespread personal perception and aversion to risk (e.g., Iervolino *et al.*, 2007). For instance, it has been recognized that public tolerance may be a thousand times greater for risks taken voluntarily than for involuntary activities with the same benefit (Starr, 1969). In general, the definition of a common acceptable IRD across different kinds of threats is a key factor to prioritize funding for a balanced overall risk reduction strategy (e.g., Viscusi, 1992).



Center (Location): 39.85 16.05 Dimension (km): 50

last run: **2015/05/12 02:30**
area probability 1.80×10^{-4}

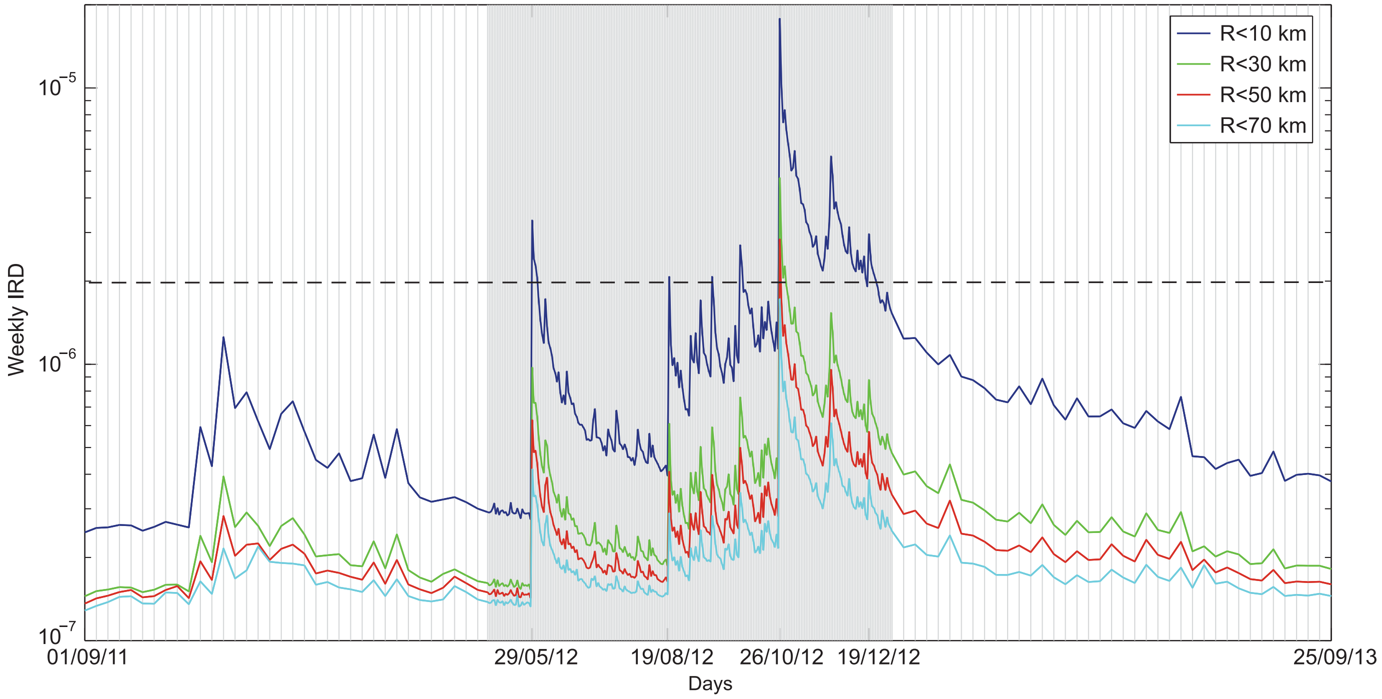
2012/10/26:
area probability:0.004

▲ **Figure 2.** The OEF_Italy output (Marzocchi *et al.*, 2014). (a) Spatial region for OEF calculations. (b) Evolution of the weekly probability of M_L 5.5+ from October 2011 to July 2013 for a circular area having the center at the coordinates 39.85° N and 16.05° E and radius of 50 km. (c) Probability of an earthquake with M_L 5.5+ on 26 October 2012 (the maximum value for the whole period investigated). (d) The same calculation relative to the last run of the system (12 May 2015).

Hence, accounting for consequences in risk assessment enables one to define reference values for nominally acceptable IRD that gathers consensus by all involved stakeholders. For instance, Vrijling *et al.* (1998) propose an equation to establish the acceptable IRD as a basis for design; according to their considerations, the acceptable annual IRD caused by structural engineering failures may be defined around 10^{-5}. A pragmatic approach is often used in the United Kingdom where risk management is based on the ALARP (as low as reasonably practicable) concept. Instead of using a single threshold to separate acceptable and nonacceptable risks, ALARP considers three zones separated by two thresholds: one broadly acceptable risk region, a tolerable region where the risk should be lowered if the mitigation actions are economically affordable and feasible, and an unacceptable risk region. The Health and Safety Executive (HSE, 2001) in the United Kingdom sets two annual IRD thresholds, 10^{-6} and 10^{-4}, to separate these three areas. This interval is symmetrically distributed around the value established by Vrijling *et al.* (1998), and it is in agreement with the definition of the acceptable annual IRD for different kinds of threats. For example, the World Health Organization sets the acceptable annual IRD for carcinogenic risk caused by potential sources to 2×10^{-5} (Hunter and Fewtrell, 2001); the Hong Kong Geotechnical Engineering Committee defines an acceptable annual IRD for new developments that is $< 10^{-5}$ and $< 10^{-4}$ for existing developments (Bell *et al.*, 2006); in Switzerland, the PLANAT national platform considers acceptable annual IRD for involuntary threats $< 3 \times 10^{-5}$ to 4×10^{-6} (Bell *et al.*, 2006); in western Australia, acceptable annual IRD for new installation is $< 10^{-6}$ and the annual IRD is unacceptable when $> 10^{-5}$ (Cornwell and Meyer, 1997); in the Netherlands, the annual IRD is considered acceptable when $< 10^{-8}$, and it is unacceptable when $> 10^{-5}$ for existing facilities and $> 10^{-6}$ for new facilities (Cornwell and Meyer, 1997); and in Iceland, the annual IRD for avalanches is considered acceptable when $< 2 \times 10^{-5}$ (Arnalds *et al.*, 2004).

Usually, IRD thresholds are continuously under discussion and negotiation. Nonetheless, an annual IRD of 10^{-4} is an upper bound among those quoted in this article. Assuming that this threshold has to be constant in time, we can rescale this value for one week, dividing it by 52 to get upper bound weekly IRD $\sim 2 \times 10^{-6}$ (the value reported in Fig. 3).

Coming back to the example, Figure 3 shows that although the probability of observing an event above a magnitude threshold remains always below 0.01 (see Fig. 2), the corresponding risk during the seismic sequence may be intolerable. In fact, it may be noted that during a seismically quiet period, the weekly IRD due to earthquakes is under the upper



▲ **Figure 3.** The OELF outcome (Iervolino *et al.*, 2015). The continuous lines of different colors show the evolution of the weekly individual risk of death (IRD) caused by earthquakes for circular areas of different radius from the center of the seismic sequence located at latitude 39.85° N and longitude 16.05° E. The IRD is computed as the expected number of fatalities per radius bins divided by the total number of residents in the area. The horizontal dashed line marks the commonly used threshold for acceptable weekly IRD in developed countries (see text for more details). The vertical gray lines mark the times in which the IRD has been calculated (updating is more frequent during the rapidly evolving seismic sequence).

bound of tolerable IRD, whereas during the most intense phases of the seismic sequence, it overcomes the acceptable threshold for several weeks.

DISCUSSION AND CONCLUSIONS

Seismologists can provide information about the variation of seismic hazard in time windows that span from days to decades. In particular, it is possible to capture orders of magnitude variations in the weekly probability of earthquakes exceeding specific magnitude thresholds. On the other hand, because the weekly probability of a damaging earthquake typically remains lower than a few percent, it is debated whether it is actually information useful for risk management. In this study, analyzing a seismic sequence in Italy, we have shown that the probabilities of a large earthquake, as derived from short-term clustering models, may lead to IRD that is comparable or above a threshold taken from the literature, beyond which the risk may be considered intolerable. This result reiterates a basic concept of seismic risk assessment; that is, the risk metric is the loss and associated probability (e.g., IRD), whereas information about earthquake probability (i.e., the hazard) alone is more limited, mostly because it does not allow (1) direct comparisons with other risks and (2) any kind of cost–benefit analyses.

How to manage such an unacceptable seismic risk is challenging (e.g., Woo and Marzocchi, 2013) and beyond the scope of this article. In general, although enforcing the building code is often considered the main defense against earthquakes, risk mitigation is hardly a zero-sum game (Jordan *et al.*, 2014), and short-term hazard and risk assessment may provide additional and useful information for stakeholders. As a matter of fact, the stakeholders are the only ones entitled to evaluate whether such information is useful or not, and to define proper acceptable risk thresholds (e.g., Marzocchi, 2013).

In this framework, seismologists and engineers should cooperate to customize comprehensible and unambiguous risk-information messages for each potential stakeholder, so they can be eventually used for planning possible effective risk-mitigation actions. This task can be particularly challenging when the public is the stakeholder, because of the diffuse probabilistic illiteracy. However, this difficulty should not prevent us from disseminating scientifically sound risk information, and a significant involvement of experts in risk communication can help to reach this goal.

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Warner Marzocchi
Giuseppe Falcone
Istituto Nazionale di Geofisica e Vulcanologia
Via di Vigna Murata 605
00143 Rome, Italy
warner.marzocchi@ingv.it

Iunio Iervolino
Dipartimento di Strutture per l'Ingegneria e l'Architettura
Università degli Studi di Napoli Federico II
via Claudio 21
80125 Naples, Italy

Massimiliano Giorgio
Dipartimento di Ingegneria Industriale e dell'Informazione
Seconda Università degli Studi di Napoli
via Roma 29
81031 Aversa (CE), Italy