When is the probability of a large earthquake too small?

Warner Marzocchi[a], Iunio Iervolino[b], Massimiliano Giorgio[c], Giuseppe Falcone[a]

[a] Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Rome, Italy.

[b] Dipartimento di Strutture per l'Ingegneria e l'Architettura, Università degli Studi di Napoli Federico II, via Claudio 21, 80125, Naples, Italy.

[c] Dipartimento di ingegneria Industriale e dell'Informazione, Seconda Università degli Studi di Napoli, via Roma 29, 81031, Aversa (CE), Italy.

Submitted to *Seismological Research Letters*

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 (Parsons, 2002; Faenza et al., 2003; Kagan and Jackson, 1991; 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 if 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 (ICEF), established after 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 show the importance of tracking the time evolution of seismic hazard (e.g., as for the recent Canterbury sequence in New Zealand; e.g. Wein and Becker, 2013), presently OEF represents a controversial issue in seismology. Most of the critics are not focused on debating the scientific credibility of the models presently 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 literature, the weekly probability of a large earthquake (say, of magnitude six or larger) is above a few percent only after another large event. During a seismic sequence of moderate events (say, of maximum magnitude less than five), the weekly probability of a large event may increase also two-three orders of magnitude with respect to the background seismicity, but almost always this probability remains below a few percent (Jordan et al., 2011). These figures sparkled a debate among seismologists about the usefulness and danger of releasing information on the time evolution of short-term earthquake probability. A comprehensive discussion on all these issues can be found in Wang and Rogers (2014) and Jordan et al. (2014).

In this paper 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) that introduce 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 this line, in this letter we analyze the evolutions of seismicity forecasts and consequent seismic risk, for a seismic sequence that occurred in Southern Italy in 2012 and featuring a M_l 5 largest shock (the Pollino sequence hereafter). This sequence lasted for more than one year, and it was not associated to any destructive earthquake. In particular, the OEF seismicity rates and consequent OELF weekly estimates are evaluated as a function of time for a period of time spanning 2010 to 2013 to capture the full evolution of the sequence. Seismic risk metrics are compared to some reference risk values referring to other events from literature.

Operational Earthquake Forecasting and Operational Earthquake Loss Forecasting for a seismic sequence in Italy

Figure 1 pictures the seismic sequence that occurred in the Pollino area during the period October 20, 2011, until July 15, 2013. The largest earthquake of this sequence, M_l 5.0, occurred on October 25, 2012. This sequence did not cause significant damage, but it raised concern among the affected population owing to the prolonged felt seismicity. This sequence is rather typical in Italian territory where, on average, 10-15 seismic sequences like this one are observed per year.

In Figure 2 the evolution of the weekly probability of an earthquake of magnitude 5.5 or larger for this period of time is shown. In particular, each point of the graph is the probability that in the week after the time it corresponds to, an earthquake equal or larger than 5.5 will be observed in the area pictured by the square in the figure. 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* (CSEP) 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. Worthy of note, IRD is not the same for each citizen (depending on the different vulnerability of the buildings where the citizen 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 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, for example, 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 thousand times greater for risks taken voluntary than from involuntary activities with the same benefit (Starr, 1969). More in general, the definition of a common acceptable IRD across different kinds of threat is a key factor to prioritize funding for a balanced overall risk reduction strategy (e.g. Viscusi, 1992).

Hence, accounting for the consequences in the risk assessment enables 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 engineering of structures failure may be defined around 10^{-5}. A pragmatic approach is often used in United Kingdom where risk management is based on the ALARP (*as low as reasonably practicable*) concept. Instead of using one single threshold to separate acceptable and non-acceptable 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* in United Kingdom (HSE, 2001) set 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 kind 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 Geothetnical Engineering Committee* defines acceptable an 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 $< 3\ 10^{-5}$ - $4\ 10^{-6}$ (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 Mayer, 1997); in Netherland, 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 (Cornell and Mayer, 1997); in Iceland the annual IRD for avalanches is considered acceptable when $< 2\ 10^{-5}$ (Arnalds et al., 2004).

Usually, IRD thresholds are continuously under discussion and negotiation. Nonetheless, it is to note that an annual IRD of 10^{-4} is an upper bound among those quoted in this paper. Assuming that this threshold has to be constant in time, we can rescale this value for one week dividing it by fifty-two to get upper-bound weekly IRD $\sim 2\ 10^{-6}$ (the value reported in Figure 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 above), the corresponding risk during the swarm 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-bound of tolerable IRD, while 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, since the weekly probability of a damaging earthquake typically remains lower than a few percent, it is debated whether it actually is an information useful for risk management. In this study, analyzing a seismic sequence in Italy, we have shown that the probabilities of large earthquake from short-term clustering models may lead to individual risk of death that is comparable or above a threshold taken from literature, beyond which the risk may be considered intolerable. This result reiterates a basic concept of seismic risk assessment; i.e., the risk metric is the loss and associated probability (e.g., IRD), while information about earthquake probability (i.e., the hazard) alone is more limited, mostly because it does not allow: i) direct comparisons with other risks, and ii) 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 paper. 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/risk assessment may provide additional and useful information for the stakeholders. As a matter of fact, the stakeholders are the only ones entitled to evaluate if an 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.

Acknowledgments

The study presented in this paper was developed within the join activities of *Centro di Pericolosità Sismica dell'Istituto Nazionale di Geofisica e Vulcanologia* that is partially funded by the *Dipartimento della Protezione Civile*, and of *Rete dei Laboratori Universitari di Ingegneria Sismica* (ReLUIS) for the research program funded by the Dipartimento della Protezione Civile (2014-2018). Dr. Eugenio Chioccarelli (University of Naples Federico II), who contributed to produce the results presented in the example, is to acknowledge.

REFERENCES

Arnalds, T., K. Jonasson, and S. Sigurdsson (2004). Avalanche hazard zoning in Iceland based on individual risk. *Ann. Glaciol.* **38**, 285-290.

Bell, R., M . Danscheid, and T. Glade (2006). Challenges in defining acceptable risk levels. In: RISK21 - Coping with Risks due to Natural Hazards in the 21st Century. Proceedings of the RISK21 Workshop, Monte Verità, Ascona, Switzerland, 28 November - 3 December 2004. Edited by Walter J . Ammann , Stefanie Dannenmann , and Laurent Vulliet. Taylor & Francis 2006. Pages 77-87

Cornell, C. A. (1968). Engineering seismic risk analysis. Bulletin of the Seismological Society of America, 58(5), 1583-1606.

Cornwell, J.B., and M. M. Meyer (1997). Risk acceptance criteria or "how safe is safe enough?". Presented at: II Risk Control Seminar Petroleos de Venezuela Puerto La Cruz, Venezuela October 13, 1997

Faenza, L., W. Marzocchi, E. Boschi (2003). A non-parametric hazard model to characterize the spatio-temporal occurrence of large earthquakes: An application to the Italian catalogue. *Geophys. J. Int.* **155**, 521-531.

Hunter, P.R., and L. Fewtrell (2001). *Acceptable risk*. In: 2001 World Health Organization (WHO). Water Quality: Guidelines, Standards and Health. Edited by Lorna Fewtrell and Jamie Bartram. Published by IWA Publishing, London, UK. ISBN: 1 900222 28 0

HSE (2001). *Reducing risks, protecting people: HSE's decision-making process.* Her Majesty’s Stationery Office, St Clements House, 2-16 Colegate, Norwich NR3 1BQ

Iervolino, I., E. Chioccarelli, M. Giorgio, W. Marzocchi, G. Zuccaro, M. Dolce, and G. Manfredi (2015). Operational (short-term) earthquake loss forecasting in Italy. *Bull. Seismol. Soc. Am.* doi:10.1785/0120140344

Iervolino I., Giorgio M., Manfredi G. (2007). Expected loss-based alarm threshold set for earthquake early warning systems. *Earthq. Eng. Struct. Dyn.* **36**,1151-1168.

Iervolino I., Giorgio M., Polidoro B. (2014) Sequence-based probabilistic seismic hazard analysis. *Bull. Seismol. Soc. Am*. **104**, 1006-1012.

Jordan, T.H., Y.-T. Chen, P. Gasparini, R. Madariaga, I. Main, W. Marzocchi, G. Papadopoulos, G. Sobolev, K. Yamaoka, and J. Zschau (2011). Operational earthquake forecasting: state of knowledge and guidelines for utilization. *Ann. Geophys.* **54**, 315-391.

Jordan, T.H., W. Marzocchi, A. Michael, and M. Gerstenberger (2014). Operational earthquake forecasting can enhance earthquake preparedness. *Seismol. Res. Lett.* **85**, 955-959.

Kagan, Y., and L. Knopoff (1987). Statistical short‑term earthquake prediction. *Science* **236**, 1563-1567.

Kagan, Y.Y., D.D. Jackson (1991). Long-term earthquake clustering. *Geophys. J. Int.* **104**, 117-133.

Marzocchi, W., A.M. Lombardi (2008). A double branching model for earthquake occurrence. *J. Geophys. Res.* **113**, B08317.

Marzocchi, W., J. D. Zechar, and T.H. Jordan (2012). Bayesian forecast evaluation and ensemble earthquake forecasting, *Bull. Seismol. Soc. Am*. **102**, 2574-2584.

Marzocchi, W. (2013). Seismic hazard and public safety. *EOS*, *Tran. AGU* **94**, 240-241.

Marzocchi, W., and M. Taroni (2014). Some thoughts on declustering in probabilistic seismic hazard analysis, *Bull. Seismol. Soc. Am.* **104**, 1838-1845.

Marzocchi, W., A.M. Lombardi, and E. Casarotti (2014). The establishment of an operational earthquake forecasting system in Italy. *Seismol. Res. Lett*. **85**, 961-969.

Ogata, Y. (1988). Statistical models for earthquake occurrences and residual analysis for point processes. *J Am Stat Assoc* **83**, 9-27.

Parsons, T. (2002). Global Omori law decay of triggered earthquakes: Large aftershocks outside the classical aftershock zone, *J. Geophys. Res*. **107**, 2199.

Starr, C. (1969). Social benefit versus technological risk. *Science* **165**, 1232-1238.

van Stiphout, T., S. Wiemer, and W. Marzocchi (2010). Are short-term evacuations warranted? Case of the 2009 L'Aquila earthquake. *Geophys. Res. Lett.* **37**, L06306.

Viscusi, W. K. (1992). *Fatal Tradeoffs: Public and Private Responsibilities for Risk*, Oxford Univ. Press, New York.

Vrijling, J.K., W. van Hengel, and R.J. Houben (1998). Acceptable risk as a basis for design. *Reliability Eng. System Safety* **59**, 141-150

Wang, K., and G. C. Rogers (2014). Earthquake preparedness should not fluctuate on a daily or weekly basis, *Seismol. Res. Lett*. **85**, 569-571.

Wein, A., and J. Becker (2013). Communicating aftershock risk: Roles for reassuring the public, *Risk Frontiers* **13**, no. 3, 3-4.

Woo, G., and W. Marzocchi (2013). Operational earthquake forecasting and decision-making. In: *Early Warning for Geological Disasters - Scientific Methods and Current Practice*, F. Wenzel and J. Zschau (eds.); ISBN: 978-3-642-12232-3, Springer Berlin Heidelberg New York, 2013.

Zechar, J.D., M. Herrmann, T. van Stiphout, and S. Wiemer (2014). Forecasting Seismic Risk as an Earthquake Sequence Happens. In: Earthquake Hazard, Risk, and Disasters (Edt. M. Wyss, and J. F. Shroder), pp 176-182. Elsevier, Amsterdam, http://dx.doi.org/10.1016/B978-0-12-394848-9.00007-9.

Figure captions

Figure 1. a) Seismicity above M_l 2.5 in the Pollino region in the period October 20, 2011, until July 15, 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) that occurred on October 25, 2012; b) the black rectangle shows the location of the Pollino region in Italy.

Figure 2. Snapshot of 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 October 26, 2012 (the maximum value for the whole period investigated). d) The same calculation relative to the last run of the system (May 12, 2015).

Figure 3. OELF outcome (Iervolino et al., 2015). The continuous lines of different colors show the evolution of the weekly 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. 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 (the updating is more frequent during the rapidly evolving seismic sequence).

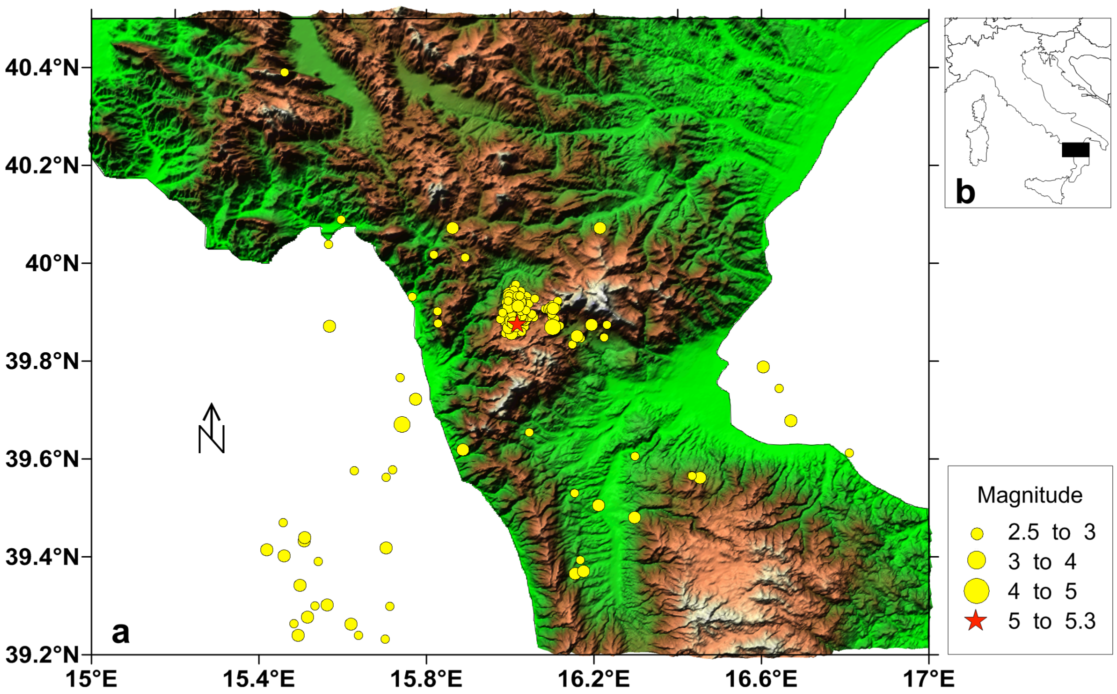
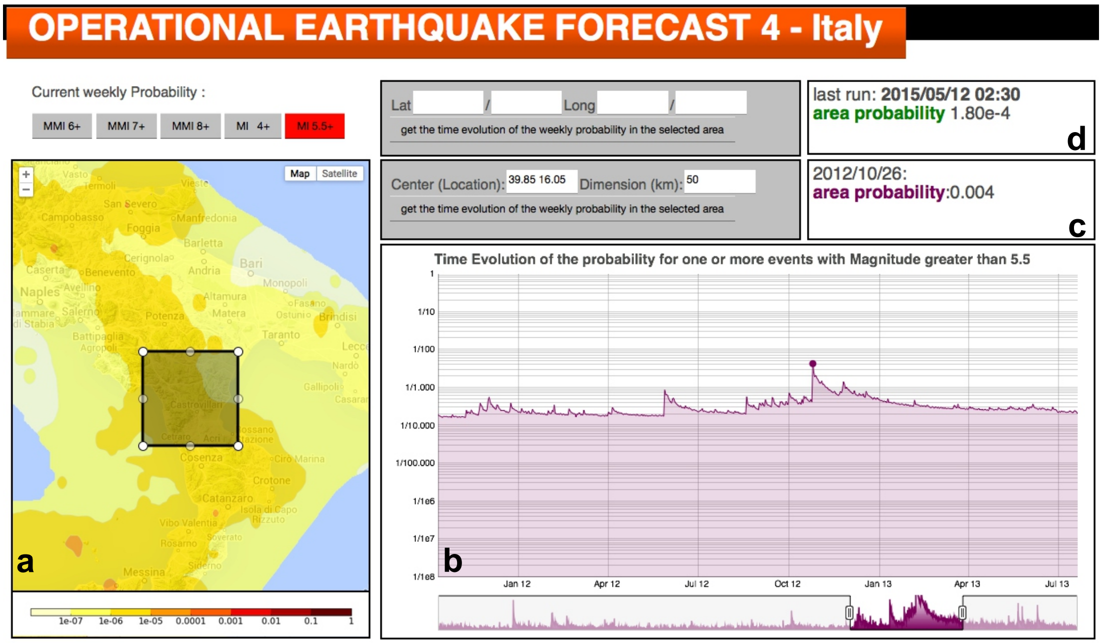


Figure 1

Figure 1. a) Seismicity above M_l 2.5 in the Pollino region in the period October 20, 2011, until July 15, 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) that occurred on October 25, 2012; b) the black rectangle shows the location of the Pollino region in Italy.



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

last run: **2015/05/12 02:30**
area probability 1.80e-4

2012/10/26:
area probability:0.004

Figure 2. Snapshot of 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 October 26, 2012 (the maximum value for the whole period investigated). d) The same calculation relative to the last run of the system (May 12, 2015).

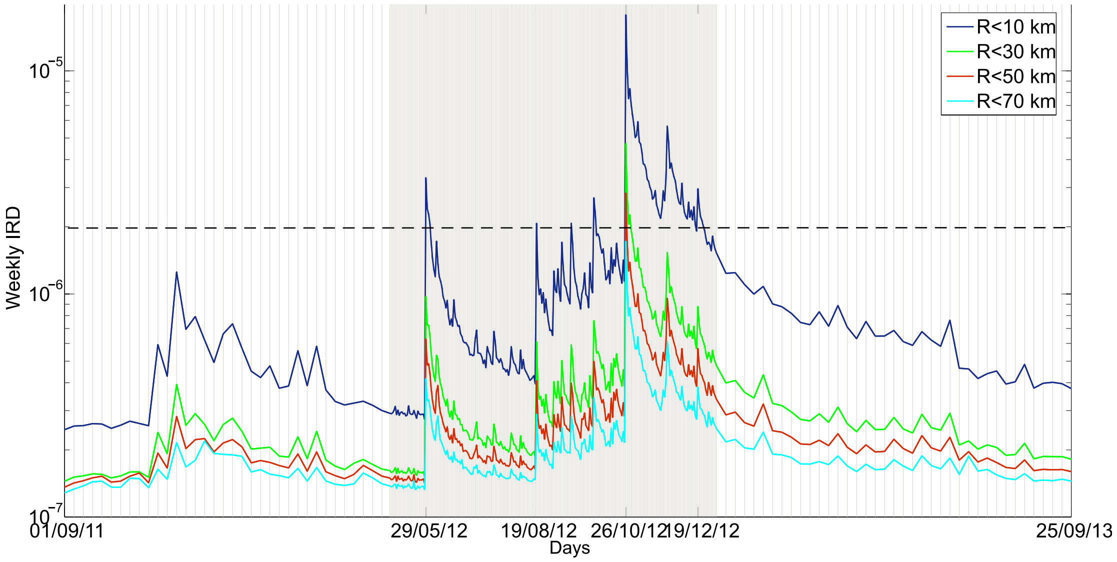


Figure 3. OELF outcome (Iervolino et al., 2015). The continuous lines of different colors show the evolution of the weekly IRD caused by earthquakes for circular areas of different radius from the center of the seismic sequence located at latitude 39.85° N and longitude 16.05° E. IRD is computed as the 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 (the updating is more frequent during the rapidly evolving seismic sequence).