Introduction. In recent decades, numerous attempts about prediction [or forecasting: e.g., Marzocchi and Zechar (2011)] of destructive earthquake have been proposed, concerning various zones of the world. The importance of this research is twofold: on the scientific side, a series of well-aimed forecasts corroborates the model adopted and, therefore, may represent an important step forward in the understanding of seismogenetic processes. On the practical side, a reliable forecasting procedure would provide a tool of great interest for the defense against earthquakes.

Some of these proposals investigate the signals that would precede a large earthquake (e.g., Cicerone et al., 2009). Such short-term forecasts should allow us to identify the future epicentral area with an advance from a few months to a few hours before the quake. However, the results so far obtained have been modest, so that some authors question the very existence of seismic precursors - or at least their unreliability (e.g., Bakun et al., 2005 and references therein).

To overcome these difficulties, it has been suggested that analyzing the seismic activity from the statistical point of view would be more appropriate (e.g., Vere-Jones, 2006). In particular, efforts have been made to elaborate forecasting procedures, based on the applications of probabilistic models, in the belief that the spatial and temporal distribution of past earthquakes can provide valuable information about the future seismic activity.

Early predictions for the Italian region, based on time-predictable, slip-predictable, seismic gap and characteristic earthquake hypotheses, were mostly retrospective in nature (e.g., Mulargia and Gasperini, 1995; Mulargia and Geller, 2003; Valensise et al., 2003). On the other hand,
Boschi et al. (1995) modelled historical seismicity by Poissonian and Gaussian models, in order to calculate the probability of strong earthquakes ($M \geq 5.9$) in various Italian source zones for the next 5, 20 and 100 years. However, as pointed out by Marzocchi (2008), such attempt presents some ambiguities and several discrepancies between the predicted and actual seismicity.

In the aftermath of the April 6, 2009 L'Aquila destructive shock, the International Commission on earthquake prediction appointed by the Italian Civil Protection decided to give priority to probabilistic approaches (Jordan et al., 2009). In this context, the International Working Group CSEP (Collaboratory for the Study of Earthquake Predictability) has sponsored an experiment of long-term forecasting for Italy that involves several research groups (e.g., Schorlemmer et al., 2010). Since the prediction intervals were 5 and 10 years, we are now able to evaluate the results obtained for the first time interval (2009-2014), as described in the next section.

In the next section we point out some possible critical points of probabilistic predictions by focusing on a specific methodology (Double-Branching ETAS). In the third part we discuss the problems common to all probabilistic approaches, including the crucial issue of the various interpretations of the probability of earthquakes.

For reasons of space, we cannot provide here a complete review of the various forecasting techniques and results. An exhaustive description of the most relevant probabilistic algorithms is presented by Tiampo and Shcherbakov (2012).

**Recent prediction attempts for the Italian region.** Among the various contributions to the CSEP experiment (Schorlemmer et al., 2010), we have chosen to discuss in some detail the paper by Lombardi and Marzocchi (2010a). Indeed, this work adopts an improved version of the Epydemic-Type Afterhock Sequence (ETAS) methodology, which is one of the most frequently adopted forecasting procedures, as pointed out by Tiampo and Shcherbakov (2012). Moreover, the Authors involved are certainly at the top of the Italian research on probabilistic forecasting of earthquakes. Therefore, the above-mentioned work can be considered an important and representative example in order to evaluate the state-of-art of probabilistic predictions in Italy.

The ETAS approach (e.g., Ogata, 2011 and references therein) mostly relies on the phenomenology of the aftershocks, presumably induced by a strong earthquake due to the stress redistribution on the fault surface. In the context of the ETAS model, seismicity can be either spontaneous (i.e. or controlled by long-term and large-scale plate motions) or induced by previous earthquakes. Moreover, each earthquake may be a potential trigger for the next seismic events. The calculation of the probability of future shocks takes into account such possibilities (e.g., Console et al., 2010; Tiampo and Shcherbakov, 2012).

As part of the aforementioned CSEP experiment, the ETAS procedure have been used to obtain long-term (5 to 10 years) forecasts for the Italian region. The adopted stochastic procedure (Double Branching Model or DBM) would represent a significant improvement in the ETAS model (Lombardi and Marzocchi, 2010a). In particular, DBM algorithms would more adequately take into account the influence of long-term processes (possibly related to post-seismic perturbations and interactions between faults), which operate alongside the short-term concentrations (clustering) of events observed in the aftershocks phenomenology. The DBM model has been applied to a suitably filtered (declustered) Italian seismic catalog in order to predict moderate to large, shallow earthquakes ($M \geq 4.5$; $h \leq 30$ km). The results obtained, which refers to the first forecast period (2009-2014), are reported in Fig. 1.

This map shows that the highest probability of strong earthquakes is assigned to the areas recently hit by major shocks, in particular to the sector of the Central Apennines affected by the 2009 seismic crisis. Other relative maxima of probability are located in Friuli, Parma and Romagna Apennines, Irpinia, Calabria and eastern Sicily (Fig. 1). However, it should be noted that within the forecast interval, no shock with $M \geq 4.5$ have occurred in Abruzzo (see e.g. the seismic archive at http://cnt.rm.ingv.it/tdmt.html). Also, no significant shallow event has took place in the Parma and Romagna Apennines. The Friuli region and southern Italy have been affected by few notable events ($4.5 \leq M \leq 5$): Pordenone September 6, 2012, Cosenza October, 25
The shocks that occurred in northwestern Tuscany (Garfagnana January 25, 2013 and Lunigiana June 21, 2013) and eastern Marche (Ancona July 21, 2013) do not seem to be well correlated with the areas of highest probability (Fig. 1). The same also holds for the May-June 2012 sequence (8 shocks with M≥4.5), which has took place in the Modena-Ferrara zone near the boundary between the orange and yellow in Fig. 1. Finally, shocks with M≥4.5 have occurred in zones associated with very low probability values (Fig. 1): southern Tyrrhenian Sea August 16, 2010; Rovigo July 17, 2011 and Romagna coastal zone June 6, 2012. In summary, the location of the main shocks actually occurred is poorly correlated with the spatial pattern of probability values.

The estimation of the probability is performed for a regular grid of small-area cells (0.1°x0.1°). This results in a smoothed map of the expected seismicity (Fig. 1), which poses some problems to the practical use of such product. For instance, the possible epicentral areas of major shocks are poorly constrained. Moreover, the computed probabilities are everywhere very small (10^{-3} to 10^{-6}), in spite of the sharp colour contrast adopted in Fig. 1. It is not clear which would be the threshold value that implies special attention by the users of the map. Also, the fact that even minor shocks (4.5≤M<5.5) are considered, does not make the forecast more effective. Predicting that the whole Apennine belt will be hit within a few years by a series of small earthquakes is a plausible statement, but does not add much to what is already known about the seismicity pattern of the Italian region. To plan appropriate prevention activities, the prediction should focus to identify in advance the zones prone to destructive events (M≥5.5).

In addition, several objections concerns the ETAS methodology. First, the results obtained strictly depend on the many parameters of the stochastic model. The numerical value of these parameters is usually obtained by the statistical analysis of the seismic catalog, often using the first half of the catalog to retrospectively predict the second part (e.g., Lombardi and Marzocchi,
2010a, 2010b). However, the same authors point out the possible dependence of the model parameterization by local seismotectonic features (e.g., Lombardi and Marzocchi, 2010a, 2010b). This fact casts doubt on the reliability of the results, like the probability map shown in figure 1, which has been obtained by adopting a model parameterization defined on a national scale.

Another important shortcoming is the fact that the physical mechanisms of fault interaction are actually neglected. In the ETAS procedure, the possibility of an earthquake to trigger further shocks in a given site depends on its magnitude and distance from the point considered, by means of empirical relationships derived by the study of the aftershock phenomenology (Tiampo and Shcherbakov, 2012). Instead, the probabilistic algorithm does not incorporate the known processes of co-seismic and post-seismic stress redistribution (e.g., Freed, 2005). Furthermore, the ETAS procedure takes into account neither the focal mechanism of the triggering shock, nor the geometry and kinematics of the fault that would be activated.

Finally, Lombardi and Marzocchi (2010b) admits that the knowledge of the seismotectonic processes occurring in the study area is not considered by the forecasting procedures so far developed.

The ETAS model has also been used to forecast the short-term (days) evolution of seismic swarms and, in particular, the occurrence of aftershocks following strong earthquakes (e.g., Lombardi and Marzocchi, 2010b; Marzocchi et al., 2012). The latter use is perhaps the most appropriate, given that the methodology is in part based on the aftershock phenomenology, as discussed earlier. However, this kind of application is still relatively uncommon. The most relevant short-term prediction attempt refers to the May-June 2012 seismic sequence in the Modena-Ferrara zone (Marzocchi et al., 2012). In this case, there is not a close relationship between the temporal pattern of estimated probability and the occurrence of the main aftershocks. Indeed, some events have took place when the probability was the highest, but other shocks (such as the June, 3 2012 one) occurred when the probability was very low (see Fig. 3 by Marzocchi et al., 2012).

Most of the shortcomings pointed out for the ETAS forecasting procedure, concerning theoretical basis, model parametrization and obtained results, can be observed in other long-term predictions performed in the framework of the CSEP experiment (e.g., Akinci, 2010; Faenza and Marzocchi, 2010; Falcone et al., 2010; Gulia et al., 2010). For instance, the probability maps provided by these attempts, referred to the prevision interval 2009-2014, show relatively high probability values for zones where minor or no seismic activity has actually occurred (e.g., Friuli, Gargano and eastern Sicily). On the other hand, no of the aforementioned forecasts has clearly pointed out the possibility of destructive shocks in the Po Plain (Modena-Ferrara zone) within the considered prevision interval.

Problems of the probabilistic methods. The series of unpredicted, very large earthquakes that have hit various zones of the world in the last decade has raised many concerns about the reliability of the stochastic models adopted for long-term forecasting (e.g., Stein et al., 2012). So, discussing the major points of weakness underlying the probabilistic algorithms helps understanding the reliability of this approach to the earthquake prediction.

First, probabilistic procedures rely on the assumption that the analysis of the past seismicity allows us to forecast (with some uncertainty) the occurrence of future shocks. This implies the availability of accurate, complete and reasonably long seismic catalogs. However, reliable information for the Italian region is reduced to the last millennium (e.g., Rovida et al., 2011). This time interval is much shorter than the duration of the present seismotectonic setting, presumably started in the Middle Pleistocene (e.g., Mantovani et al., 2009). The shortness of the available seismic history may crucially affect the results of forecasting procedures (Swafford and Stein, 2007).

Second, the relative rarity of strong earthquakes implies that often there are not enough data to test or discriminate among competing stochastic models. This fact poses serious problems for the validation of the probabilistic predictions (Luen and Stark, 2008).
Third, the various interpretations of probability so far proposed cannot easily be applied to earthquake prediction (e.g., Freedman and Stark, 2003; Marzocchi and Zechar, 2011). The classical interpretation, developed to analyze gambling, is poorly linked to the phenomenology of seismic events. The objective (or propensity) interpretation is also inadequate, since it properly applies to events that can be repeatable, like the outcomes of a controlled laboratory experiment. This is not the case for large earthquakes, which represent unique episodes in the evolution of the earth system, and irreversibly perturb the system itself. At least, the verification of the prediction would imply very long periods of observation, amounting to many consecutive prediction intervals. The subjective (or Bayesian) interpretation, representing the degree of belief of the forecaster, implies the substantial impossibility of validate the prediction by usual statistical tests (e.g., Marzocchi and Zechar, 2011).

In summary, the many uncertainties involved in probabilistic models make these tools inherently unreliable, as admitted by Marzocchi and Zechar (2011): “In practice this means that any forecast model that worked satisfactorily in a given period may fail in future experiments.” It is also worth recalling the sharp remarks by Freedman and Stark (2003): “Making sense of earthquake forecasts is difficult, in part because standard interpretations of probability are inadequate… The problem in earthquake forecasts is that the models (unlike the models for coin-tossing) have not been tested against relevant data. Indeed, the models cannot be tested on a human time scale, so there is little reason to believe the probability estimates. … although some parts of the earthquake models are constrained by the laws of physics, many steps involve extrapolating rules of thumb far beyond the data they summarize; other steps rely on expert judgment separate from any data; still other steps rely on ad hoc decisions made as much for convenience as for scientific relevance.”

Conclusions. Long-term earthquake prediction by probabilistic approaches presents severe shortcomings. The interpretation of their basic outcome (i.e. probability values) is still debated. The assumption that future shocks can be predicted by stochastic models of past seismicity is crucially weakened by the shortness of known seismic history. The implementation of probabilistic algorithms often neglects basic aspects of seismogenic processes, such as fault interactions and stress perturbation processes. The practical use of the probability maps is made difficult by the usually very low estimated probability values. Finally, recent attempts performed for the Italian region have not forecast the most important earthquakes occurred during the 2009-2014 prevision interval.

Taking into account the above problems, we suggest that the identification of the zones most prone to the next destructive shocks should be pursued by alternative approaches. In this regard, a number of papers has been devoted to the elaboration of a deterministic methodology for the Italian region (Mantovani et al., 2009, 2010, 2012, 2014; Viti et al., 2011, 2012, 2013). This methodology relies on the assumption that past and future seismic activity are closely related to the development of tectonic processes, mostly controlled by the interaction between the Adriatic plate and the surrounding orogenic belts (i.e., Hellenides, Dinarides, Alps, Apennines and Calabrian Arc).

In particular, the spatio-temporal distribution of the past strong events can significantly influence the location of the next earthquakes. Thus, the recognition of regularity patterns of seismicity in the central Mediterranean, in terms of migration of seismic activity and interrelation between seismic sources, may provide valuable information about the location of the future destructive shocks in Italy. Furthermore, a detailed knowledge of the post-early Pleistocene tectonic setting of the Apennines has allowed us to propose reliable explanations for the interaction among the main seismic zones of the Italian region. Then, the physical plausibility of the presumed interactions has been tested by numerical experiments based on the long-term and long-range post-seismic stress perturbation processes. The results of the above mentioned researches provide a sound basis for the identification of which sectors of the Italian region may first be affected by strong earthquakes, as described in detail by Mantovani et al. (2014).
References
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