A Double Branching Model for Earthquake Forecasting in diverse zones of the globe

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Abstract

The purpose of this work is to show the application of a new Earthquake Forecasting Model, called ***Double Branching Model***, both at global and at regional scale, for different zones of the globe. The Double Branching is a time-dependent model and assumes that each earthquake can generate other earthquakes, through physical mechanisms acting on different temporal scales. Remarkably, the model can be used to assess probability forecasts and tested in a forward perspective.
Here we show the forecasting maps obtained for different time-magnitude window in each target region. Moreover we compare them with the predictions provided by a spatially-variable stationary Poisson process, still widely used for Seismic Hazard Assessment and forecasting purpose. The results presented here were obtained within the ***CSEP*** experiment and are currently underway within several testing centers.

The Double Branching Model

The Double Branching Model (*Marzocchi and Lombardi*, 2008) is a stochastic model consisting of a sequential application of two branching processes, in which any earthquake can trigger a family of later events. The main goal of our model is to highlight interactions between events, due to different physical processes and involving largely different spatio-temporal domains.

In the first step of our modeling we apply a version of well-known ***ETAS*** (Epidemic Type-Aftershocks Sequences) Model (Ogata, 1988; 1998), in order to describe the short-term clustering of seismic events in space and time. The intensity function of this first branching model is given by

$$\lambda_1(t,x,y/\mathcal{H}_t) = \mu_1(x,y) + \sum_{t_i<t}\left[\frac{K_1}{(t-t_i+c)^p} e^{\alpha_1(M_i-M_{min})}\frac{C_{d_1,q_1}}{(r_i^2+d_1^2)^{q_1}}\right]$$

where $\mathcal{H}_t$ is the observation history up time t, M_{min} is the minimum magnitude of catalog, C_{d_1,q_1} is normalization constant of triggering spatial function, r_i is the distance between locations *(x,y)* and the epicenter of i-th earthquake and $u_1(x,y)$ is the probability density function (PDF) of locations of spontaneous events (*Ogata*, 1998).

By ETAS modeling it is possible to compute for each earthquake a probability of being a triggered event and consequently to formulate a declustering algorithm, able to remove the short-term triggered events by original dataset (see *Zhuang et al.*, 2002, for details). The second step of our procedure consists in re-applying a branching process to filtered database, obtained by using the ETAS-derived declustering procedure. This second model works at larger space-time scales, compared to smaller domains involved by the short-term clustering, removed after the first step. The time-dependent conditional rate of earthquake occurrence for the second step of our procedure is given by

$$\lambda_2(t,x,y/\mathcal{H}_t) = \mu_2(x,y) + \sum_{t_i<t} K_2 e^{\alpha_2(M_i-M_{min})} e^{-\frac{(t-t_i)}{\tau}} \frac{C_{d_2,q_2}}{(r_i^2+d_2^2)^{q_2}}$$

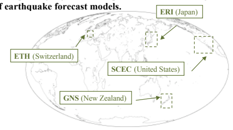
The residual seismicity, obtained by filtering the original database of the short-term triggering effect, is therefore ascribed to superposition of two physical processes: the time-independent and spatially variable tectonic loading and the long-term coupling between events.

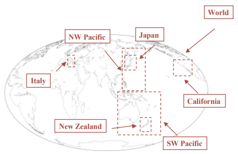
To estimate parameters of both branching processes we use the iteration algorithm developed by *Zhuang et al.* (2002), based on the Maximum Likelihood Method and on a kernel estimation of total seismic rate. Further details on the model and on estimation of its parameters can be found in (*Marzocchi and Lombardi*, 2008).

The CSEP experiment

Successfully predicting the future behavior of earthquake occurrence is worthy goal demanded by society indicating that the system is well-understood.
The ***Collaboratory for the Study of Earthquake Predictability (CSEP)*** (www.cseptesting.org) aims to improve our understanding about the physics and predictability of earthquakes through **rigorous and prospective testing of earthquake forecast models.**

Several *CSEP Testing Centers* are being developed to provide adequate infrastructure for predictability research. They are a multi-compute system running the CSEP Testing Center software. All computer codes are documented and published under the open-source General Public License, to satisfy the criteria of **transparency**.





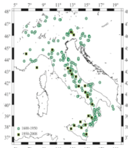
CSEP Testing Regions have been established in California, New Zealand, Japan, Italy, and the western Pacific, besides the worldwide area. Testing regions are to be defined based on the quality and consistency of seismic data and the commitment of network operators to provide their data in a timely and quality controlled fashion.
Experiments currently being evaluated at the CSEP testing centers include seismicity-based forecasts updated at 1-day, 3-mo, and 1-yr intervals, as well as time-independent 5-yr forecasts.

Each Testing Center ensures prospective test of all submitted ***models*** with exactly the same data. An open-source software system has been developed to automate the blind-testing of forecasting and prediction experiments using both ***likelihood and alarm-based scoring methods***. Models are not only tested for consistency with observation but against each other to assess their comparative performance (*Schorlemmer et al.*, 2007).
Modelers have no access to their models after submission, so no bias of a modeler can be introduced into the system.

Applications

ITALY

to be submitted to CSEP



Data-set for model evaluation

Catalogo Parametrico Terremoti Italiani catalog
1600-2003, Mw ≥ 5.5, 203 events

Learning database: 1600-1950, 176 events

Validation database: 1950-2008, 27 events

Validation of Double Branching Model

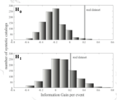
A measure that can be used to compare the performance ***Double Branching Model*** H_1 against the ***null Poisson hypothesis*** H_0 on testing dataset is the ***information gain per event (IGpe)***, i.e. the simple log-likelihood ratio per event

$$IGpe = \frac{L(D/H_1) - L(D/H_0)}{N}$$

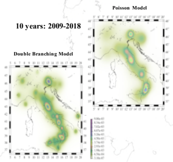
To evaluate the significance level of the test, we compare the real value of IGpe with the theoretical distributions predicted by each of two models. These last are estimated by the empirical distribution of IGpe computed on two sets of 1000 synthetic records.

H_0: Poisson Process

H_1: Double Branching Model



10 years: 2009-2018

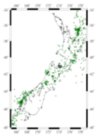


Forecasting Calculations

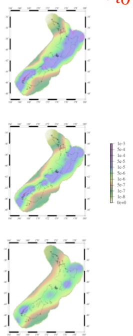
In order to judge influence of a time-dependent modeling, we compare the forecastings obtained with Double Branching and Poisson models. Both models are updated by using all available information up to 2008 (time span 1600-2008).
Predictions are in a form of probability of occurrence for at least one earthquake with M≥5.5, within a zone of 100 km², in the next 10 (2009-2018) years in Italy. The Double Branching model identifies as most dangerous zones the regions interested by most recent earthquakes: Friuli region, part of the Central and Southern Apennines. Moreover it forecasts a lower probability for Calabria region to be shaken by an earthquake, respect to Poisson Model. On the other side the occurrence of recent intense seismicity in Sicily region causes a clear increase of probability to have an event by Double Branching model respect to Poisson process

NEW-ZEALAND

to be submitted to CSEP



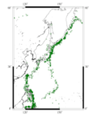
Geonet catalog
(www.geonet.org.nz
)
1951-2008, M ≥ 5.0
depth ≤ 40km
825 events



The application of Double Branching Model shows that about the 50% of events are due to short-term stress interactions and the 30% to long-term triggering effect. This last is stronger respect to Western Pacific region and has a characteristic time (τ) equal to about 30 years.

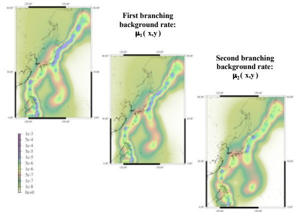
NW PACIFIC

submitted to CSEP



Centroid Moment Tensor (CMT) catalog

1977-2008, M ≥ 5.8, depth ≤ 70km
1062 events



The application of Double Branching Model shows that about the 35% of events are due to short-term stress interactions and only the 10% to long-term triggering effect. In this area the long-term stress triggering appear to be weaker that in Italy and New Zealand regions. However it is not negligible and the Double Branching Model describes the spatio-temporal evolution of local seismicity better than a simple ETAS model

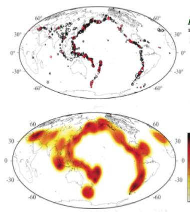
WORLD

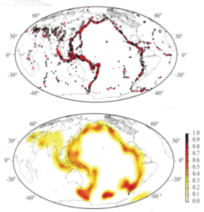
submitted to CSEP

Data-sets for model evaluation

Pacheco and Sykes catalog
1900-1989, M ≥ 7.0, 698 events
Learning database: 1900-1979, 629 events
Validation database: 1980-1989, 69 events

NEIC catalog
1974-2006, M ≥ 6.0, 2590 events
Learning database: 1974-2002, 2064 events
Validation database: 2003-2006, 526 events



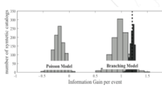


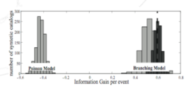
Spatial distribution of long-term triggering effect

Map of proportion of seismic rate due to long-term triggering effect respect to total rate obtained by declustered catalogs (*background learning datasets*). This last is estimated by applying the first step of our procedure (ETAS model). The plots show that the seismicity due to long-term stress transfer is mostly apparent in Pacific Ring, in Sumatra Island and in Turkey.

Validation respect to Poisson process

For each of two datasets the graph shows the IGpe for a representative version (vertical dashed lines) and for 1000 stochastic versions (dark gray bars) of background declustered dataset, obtained by applying the *Zhuang et al.* [2002] procedure. The light gray bars represent the theoretical distribution of IGpe for both Poisson and Double Branching Models. This test permits to reject the Poisson model at 0.01 s.l. per both datasets and to not reject the Double Branching Model at least for a s.l. of 0.1.



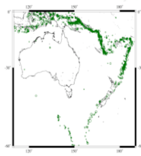


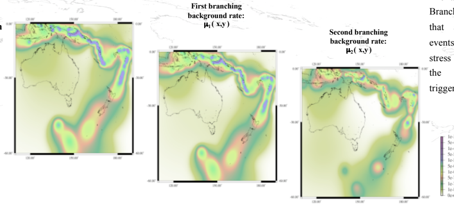
SW PACIFIC

submitted to CSEP

Centroid Moment Tensor (CMT) catalog

1977-2008, M ≥ 5.8, depth ≤ 70km
1799 events





The application of Double Branching Model shows that about the 30% of events are due to short-term stress interactions and about the 16% to long-term triggering effect.

Conclusions

- The application of Double Branching Model, both to global as to regional scale, highlights a long-term clustering of earthquake occurrence. This feature has a major importance in practice because it raises several doubts on the feasibility of the Poisson hypothesis that stands behind almost all classical seismic hazard assessment as well as many reference models for evaluating the performance of earthquake forecasting model or earthquake predictions.
- The characteristic temporal scale of this feature is well larger the time of the aftershocks occurrence and it is compatible with post-seismic stress transfer that we propose as the most likely driving mechanism.
- The impact of long-term interactions on earthquake occurrence changes with the tectonic features of the seismogenic regions.
- The testing of the performance of Double Branching Model, within the CSEP framework, at both regional as global scales, is a decisive step to corroborate the reliability of basic features of the model and to check its forecasting capability.

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