“Forward” Perspectives on Earthquake Forecasting Models

Warner Marzocchi[1]**,** Anna Maria Lombardi[2]

1- Istituto Nazionale di Geofisica e Vulcanologia - Bologna, Italy

2- Istituto Nazionale di Geofisica e Vulcanologia - Roma, Italy

INGV

Research funded by EU NERIES project (JRA2)

Outline of the presentation

1. *Some thoughts on earthquake forecasting*
2. The model proposed: rationale and general features
3. Spatial-time-magnitude window: the seismic catalogs
4. Building the model
5. Testing the model
6. Points to take home

Different (sometimes antithetical) models: why?

Most important critical issues:

❖ The subject of forecasting: *zone* (i.e., population of faults) or *single fault*?

❖ What is the degree of "universality"? Different models for different space-time-magnitude window? (clusters vs. recurrence, characteristic earthquake vs. GR law, etc…)

❖ ***The falsifiability issue***

The cornerstone of the ***"scientific method"*** *is the possibility to test hypotheses/models*

Is earthquake forecasting a "scientific" issue?

TODAY answers:

- NO. Some proposed models are not testable at all!
- YES. Some models are objectively and practically tested (main goal of CSEP/RELM)
- YES/NO. Some others are testable only in theory

Is earthquake forecasting a "scientific" issue?

YES/NO. Some models are testable only in theory

Commonly heard statements shared by some/many (not all!) researchers:

"We can practically test only forecasting models for small-to-moderate earthquakes, but not for the largest ones, because of the too few events to reach a significant conclusion…"
"The occurrence of the largest events does not follow the same rules of smaller events (universality hypothesis does not hold)"

In practice this would mean that *forecasting largest events* is not a scientific issue

An example: We can build a model that is falsifiable in theory, but in practice we need to wait a very long time (i.e., a recurrence model on a single fault).

The only way to make "falsifiable" a model like this (or similar) is to use some sort of *"weak"* universality hypothesis;

- ❖ we have to identify as many as possible fault segments that follow the same physical behavior and to test simultaneously the occurrence of earthquakes on all of them
- ❖ We can learn from smaller events and extrapolate the results

This makes the model "falsifiable", but it introduces new assumptions: *a fault behaves similar to the others, and/or the earthquake occurrence process is independent from magnitude, at least at the first order.*

1. Some thoughts on earthquake forecasting

Our view: We think that the cost of this/these additional assumption/s is by far justified to make the model ***testable***

*There is NO GUARANTEE that the assumptions behind a **"TESTABLE"** model are real (does universality hypothesis hold for seismicity?). Anyway, I do not see other VIABLE OPTIONS if we want to maintain EARTHQUAKE FORECASTING in a **"SCIENTIFIC DOMAIN".***

Our suggestion: *We must start to consider them as a starting hypothesis. Only if they clearly fail, we could decide to move towards more complex, local, and **"untestable"** models, but we have to be aware that the price to pay is to **move from SCIENCE to some sort of METAPHYSICS***

The question now is: *How can we test earthquake forecasting models*?

❖ The observation we want to explain is the *earthquake occurrence*

❖ In order to avoid overfitting we must use data independent from the ones used to build the model: for earthquake occurrence a sure independent dataset is the future

❖ This means to build models able to run in FORWARD applications (main goal of CSEP/RELM initiatives)

Our model is stochastic

Some misconceptions about stochastic/statistical models:

- *they do not explain the "physics" of the process*
- *they play with "points" while earthquakes are NOT points (where is tectonics? No role for peculiarities)*
- *they work satisfactorily ONLY with small to moderate earthquakes*

A stochastic model has only one main characteristic:
IT PRODUCES PROBABILITIES
it can use physics, empirical laws, or rule of thumbs. It is only opposite to a pure deterministic model that aims to predict exactly an event instead of attributing to it a probability (a stochastic model accounts for uncertainties).

Stefan Wiemer's question:
What does "statistical seismology" mean?

Statistical Seismology and Seismology deal with the same issues. The only difference is that the former accounts for uncertainties.

INGV

General features of the model

❖ It is based on a Stepwise Branching process. The data are analyzed at different steps, in order to get different aspects of the earthquake generation processes (see the Boosting approach). This works well when different physical processes are in play.

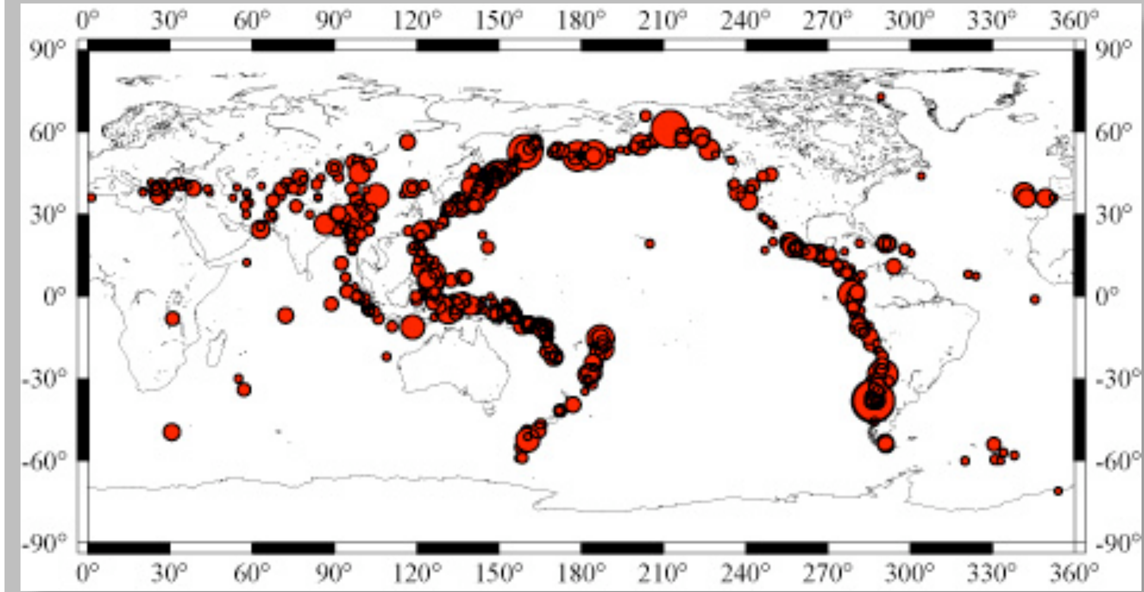
❖ The method deals with *regions* not single faults; this implies limits in the spatial resolution, but we do not mind about possible incompleteness of the faults catalog.

❖ The model explores different spatial-time-magnitude window in order to check the Universality hypothesis.

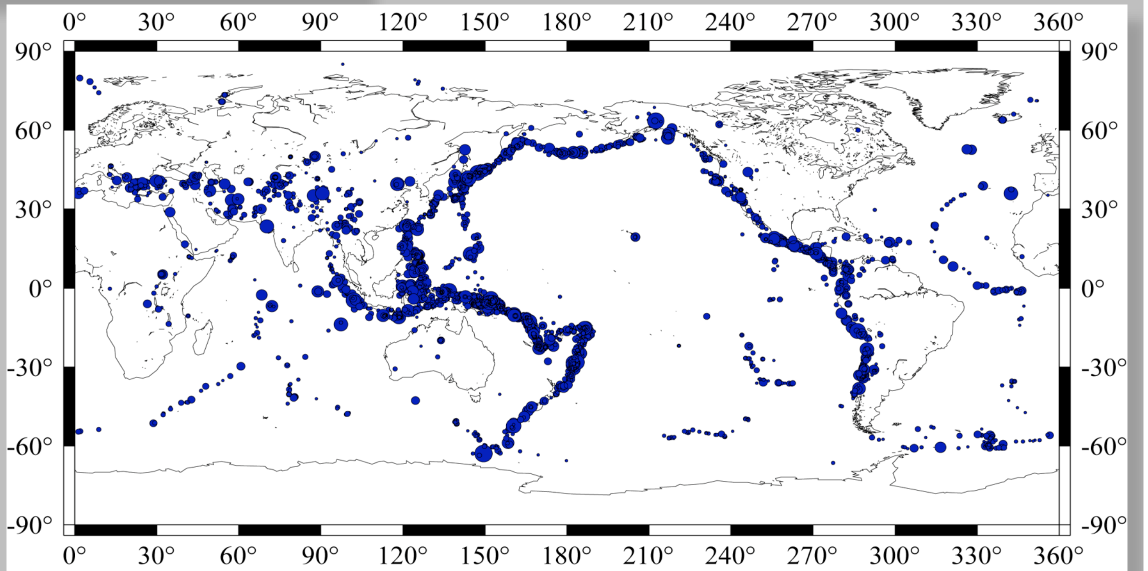
❖ The model is built in a learning period, and it is checked in a validation time interval (retrospective FORWARD test)

❖ The final goal is to produce a code to be submitted to CSEP

Pacheco and Sykes (1992) and NEIC catalogs



1900-1990
M ≥ 7.0
depth ≤ 70km
698 events



1974-2003
M ≥ 6.0
depth ≤ 70km
3197 events

INGV

The model is built in two distinct steps

1 Step: ETAS modeling applied to the catalog

2 Step: Time-dependent background applied to the residuals of the first step

These steps are chosen in according to the results found in Lombardi and Marzocchi, JGR, 2007

- *Clustering in space and time (few years) also for M 7.0+*
- *The "background" is not always constant (variations in decades)*

1 Step: ETAS modeling

$$\lambda(t,x,y/\mathcal{H}_t) = \mu \cdot u(x,y) + \sum_{t_i<t} \frac{K}{(t-t_i+c)^p} e^{\alpha(m_i - M_0)} \frac{c_{dq}}{(r^2+d^2)^q}$$

PS92 Catalog

μ(year^{-1})	k (year^{p-1})	p	c (year)	α	d (km)	q
6.7 ± 0.3	(4.0 ± 1.0) x 10^{-3}	1.1 ± 0.1	(2.0 ± 1.0) x 10^{-4}	1.2 ± 0.2	25.0 ± 4.0	=1.5

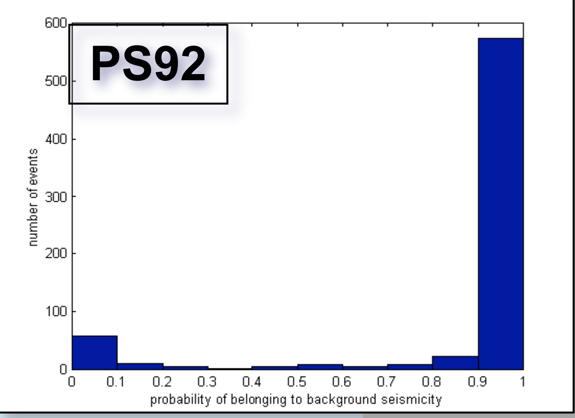
NEIC Catalog

μ (year^{-1})	k (year^{p-1})	p	c (year)	α	d (km)	q
81.0 ± 2.0	(4.0 ± 1.0) x 10^{-3}	1.20 ± 0.02	(1.2 ± 0.2) x 10^{-4}	1.3 ± 0.1	13 ± 0.5	=1.5

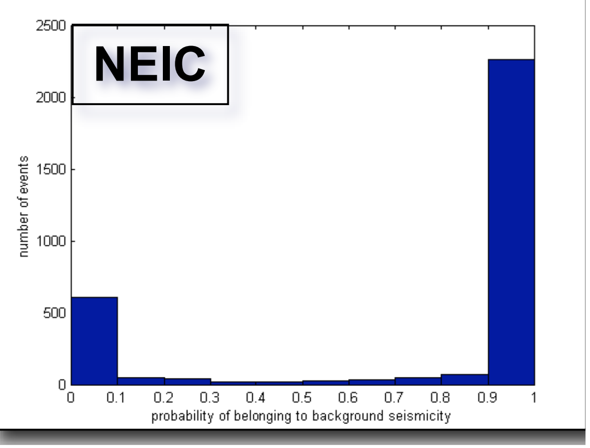
DECLUSTERING PROCEDURE

(Zhuang et al., 2002)

$$\pi_i = \frac{\mu \cdot u(x_i, y_i / \mathcal{H}_{t_i})}{\lambda(t_i, x_i, y_i / \mathcal{H}_{t_i})}$$ probability of belonging to background seismicity

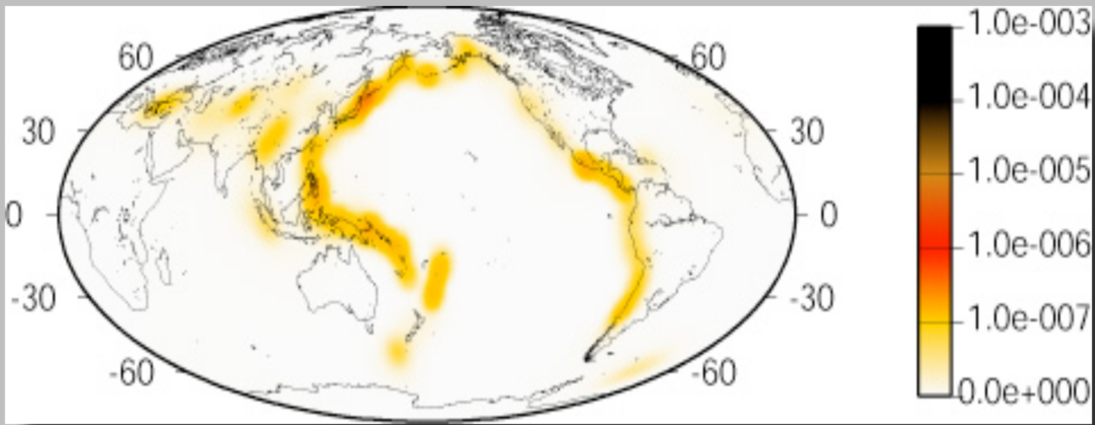


Background seismicity: events for which π_i **> 0.5**



Results of ETAS modeling for PS92 catalog

Background seismicity rate μ·u(x,y)



This is our new database for the second step !

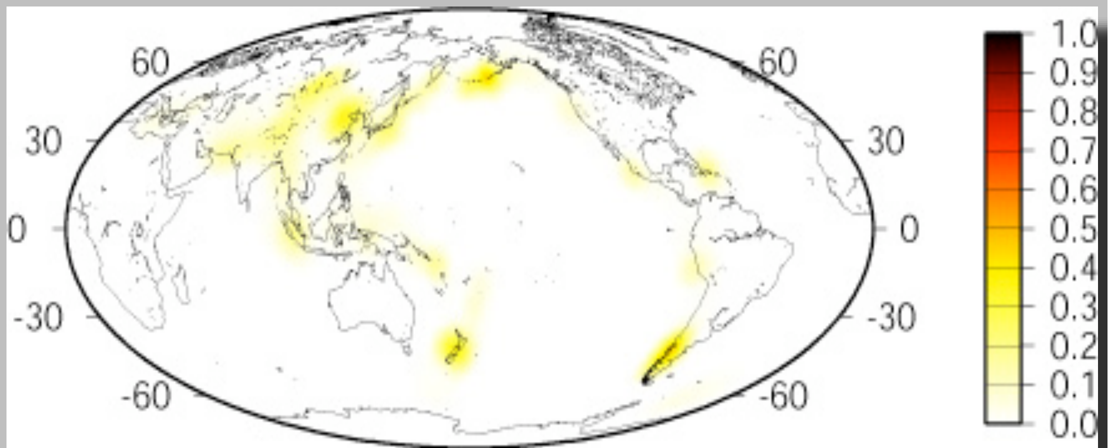
Background events

618 events ($\pi_i \geq 0.5$)

Clustering ratio

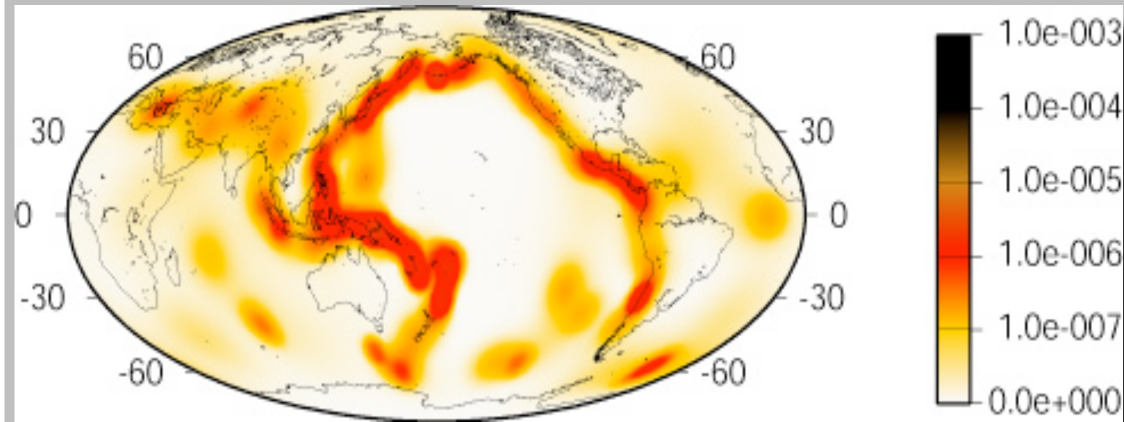
Triggered events

80 events ($\pi_i < 0.5$)



Results of ETAS modeling for NEIC catalog

Background seismicity rate μ·u(x,y)



This is our new database for the second step !

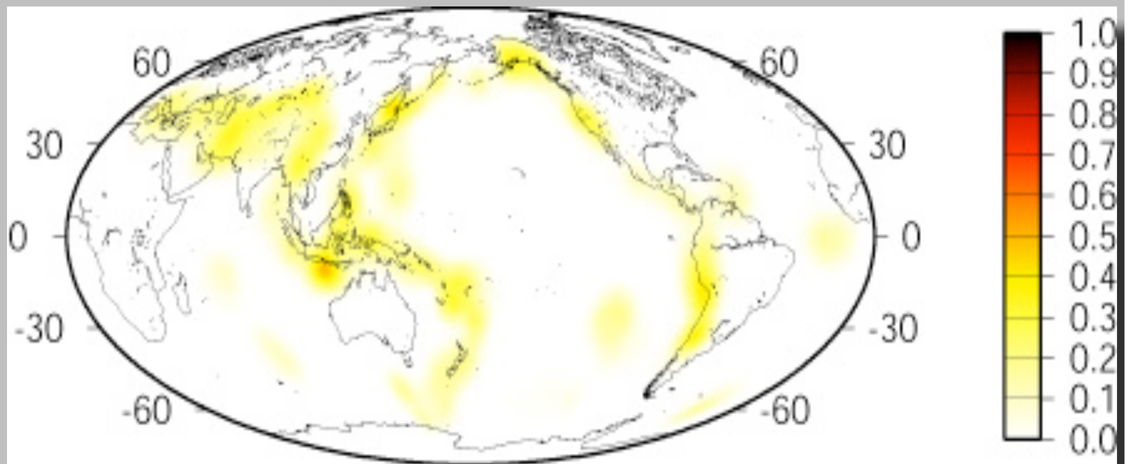
Background events

2450 events ($\pi_i \geq 0.5$)

Clustering ratio

Triggered events

747 events ($\pi_i < 0.5$)



2 Step: Time-dependent background

Modeling the "background" obtained by the first step

$$\lambda(t,x,y/\mathcal{H}_t) = \mu \cdot u(x,y) + \sum_{t_i<t} k e^{-\frac{t-t_i}{\tau}} e^{\alpha(m_i - M_0)} \frac{c_{dq}}{(r^2 + d^2)^q}$$

Possible physical mechanism: Postseismic stress variations, or a generic "persistence"

τ **Characteristic time of "relaxation" or "persistence"**

VALIDATION OF THE MODEL

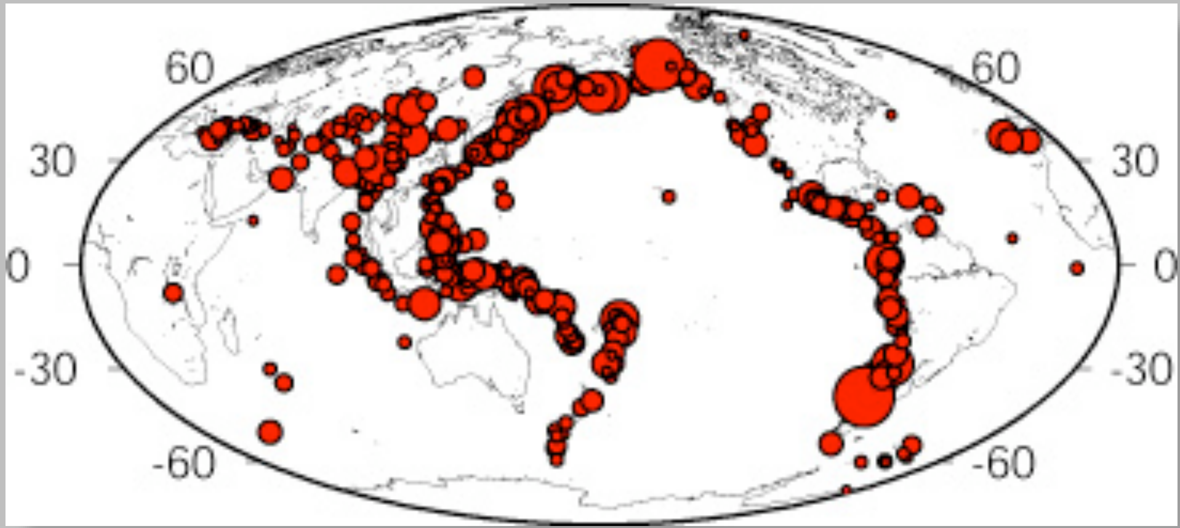
DECLUSTERED CATALOG
(background seismicity)

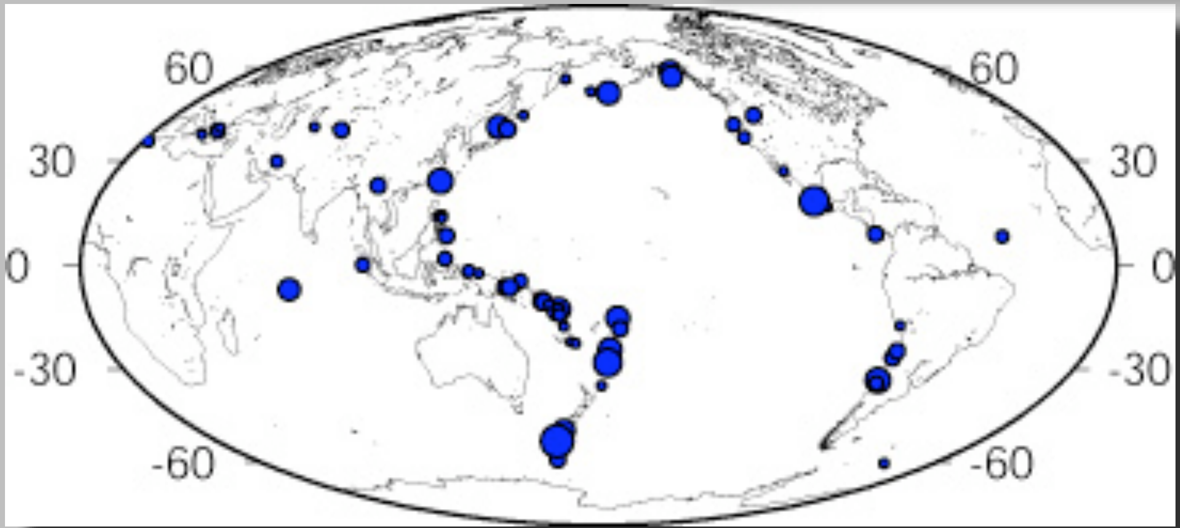
- **LEARNING PHASE : SET UP OF MODEL**
- **VALIDATION PHASE: CHECK OF MODEL**

This procedure mimics a (retrospective) "forward" test, and it guarantees that the parameters of the model are independent from the results obtained (NO OVERFIT!!!!)

PS92: Learning and validation dataset

PS92 Learning database
1900-1979
554 events

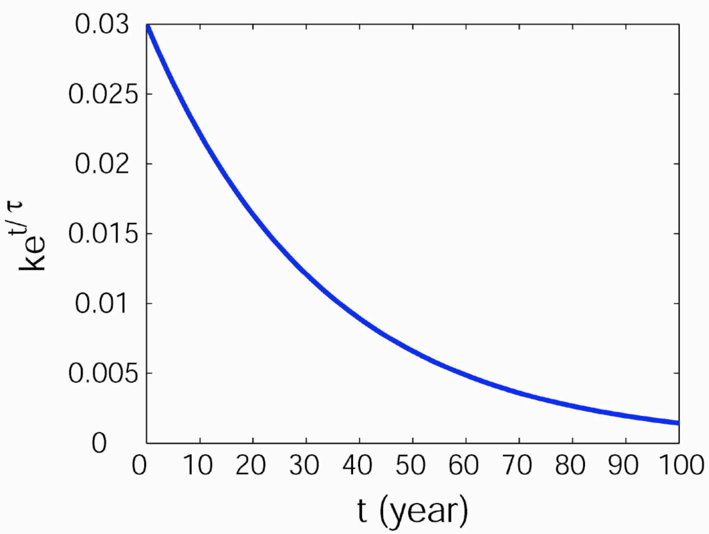


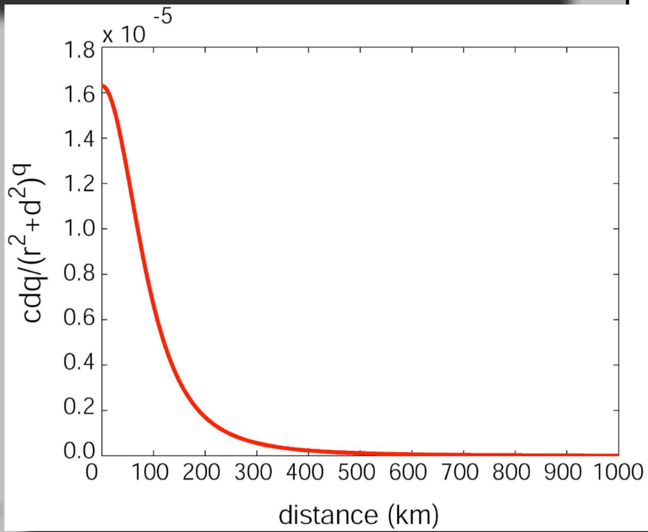


PS92 Validation database
1980-1990
64 events

PS92: learning phase

$$\lambda(t,x,y/\mathcal{H}_t) = \mu \cdot u(x,y) + \sum_{t_i<t} k e^{-\frac{t-t_i}{\tau}} e^{\alpha(m_i-M_0)} \frac{c_{dq}}{(r^2+d^2)^q}$$





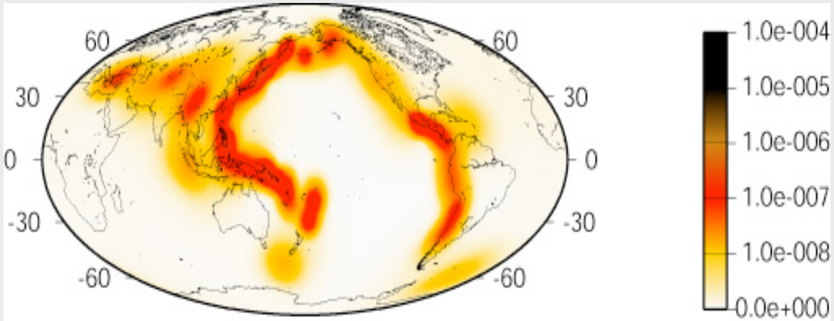
Parameter	Poisson Model	Branching Model
μ (year^{-1})	6.9 ± 0.3	2.4 ± 0.2
K (year^{-1})		0.030 ± 0.005
τ (year)		33 ± 6
α		~ 0.0
d (km)		120 ± 25
q		1.7 ± 0.2
Loglik	-9831.6	-9544.7

τ → relaxation time ~ 30 years
Compatible with viscosity of the upper layers

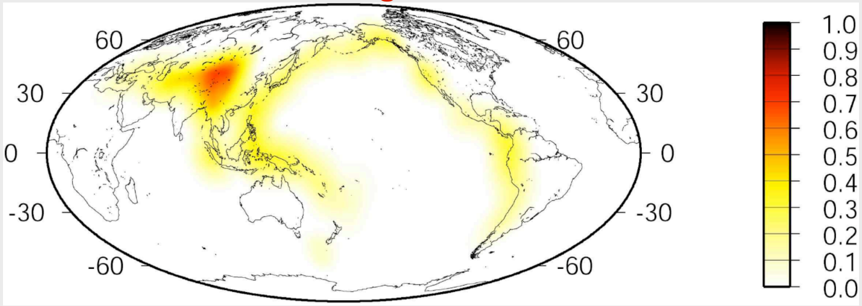
α = 0 → too small magnitude range?

PS92: learning phase

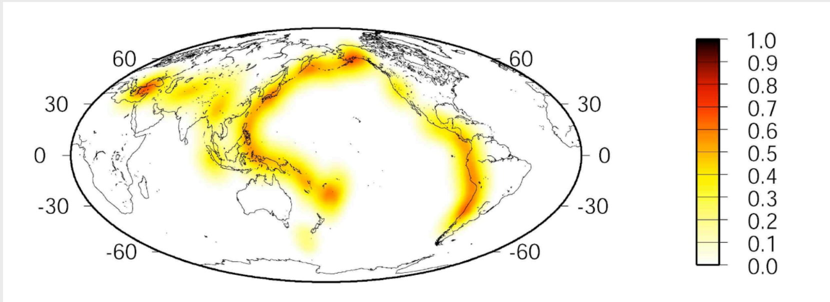
Total rate



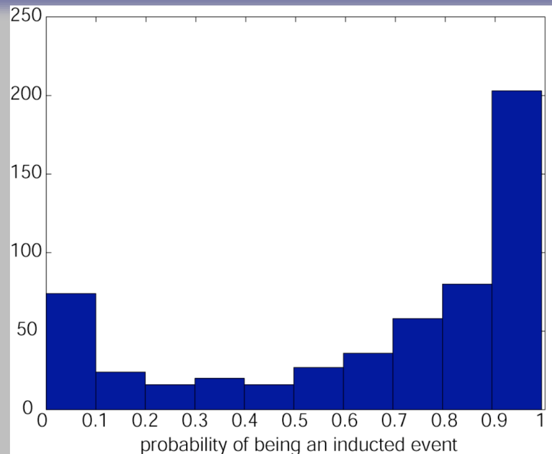
Ratio between background and total rate



Ratio between the triggering rate and the total rate



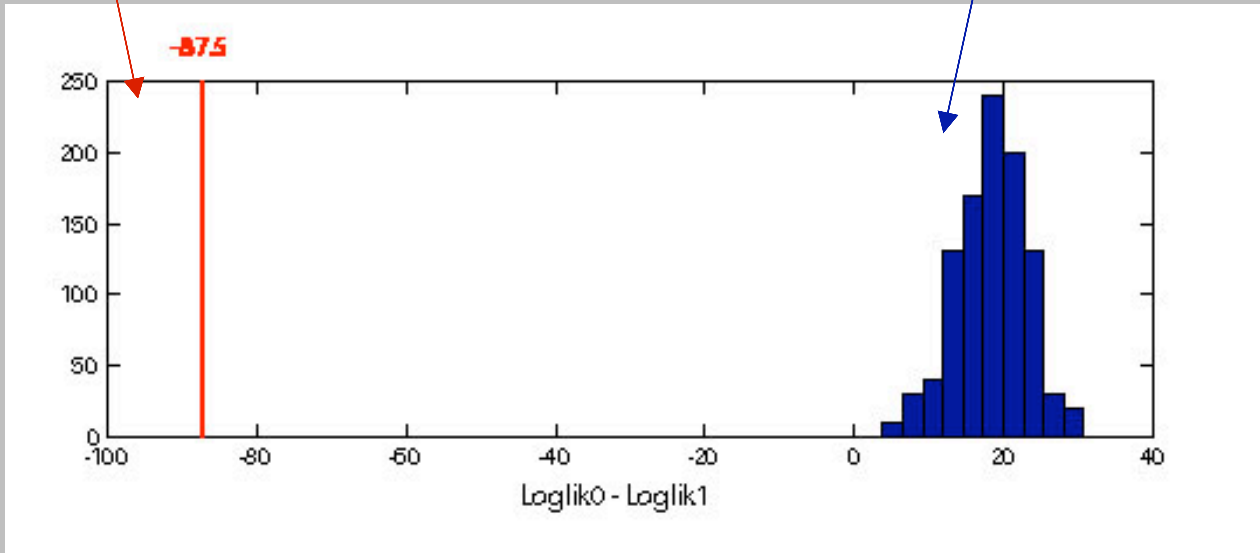
About 200 events (about 36% of the total) have a probability larger than 90% to be an induced event!



PS92: validation phase

PS92 catalog

1000 Poissonian Simulated Catalogs



Significance level << 0.01

PS92 Validation dataset
(1980-1990; 64 events)

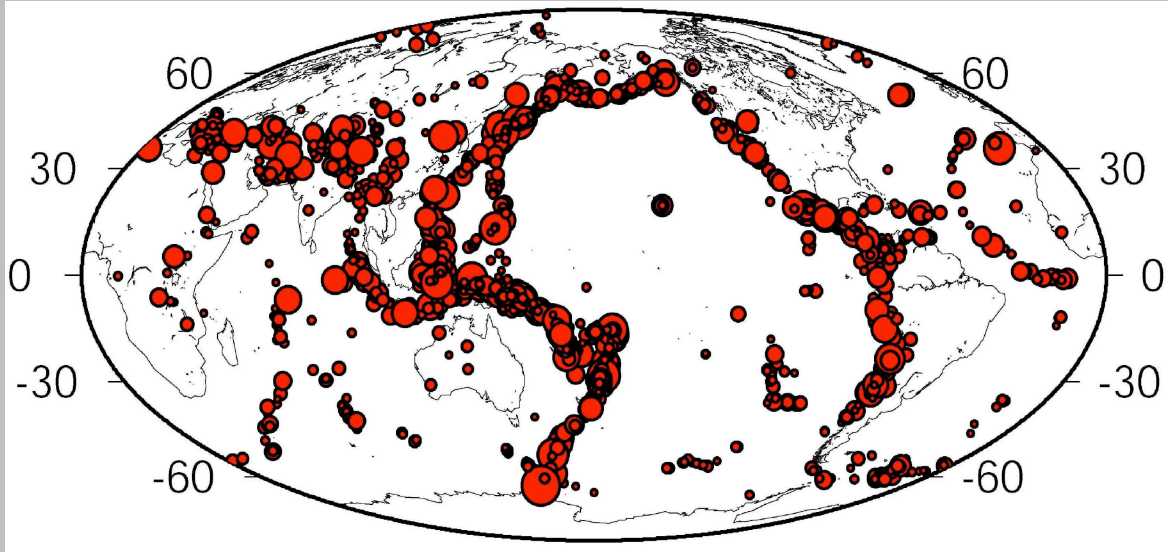
Poisson Model:
Loglik0 = -1164.0

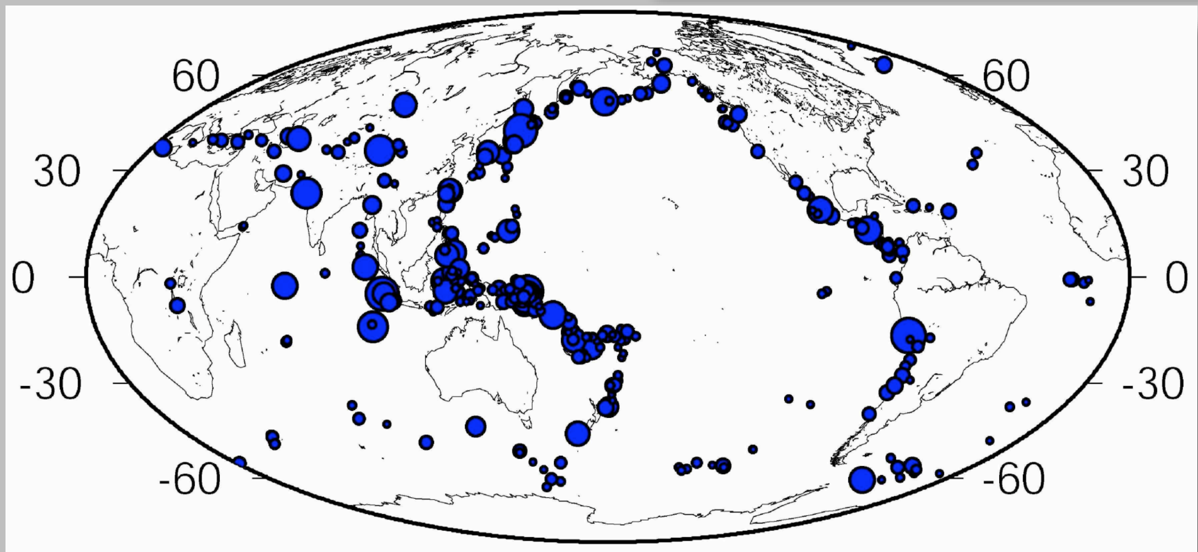
Branching Model:
Loglik1 = -1076.5

PROBABILITY GAIN: 3.92

NEIC: Learning and validation dataset

NEIC Learning database
1974-1999
2070 events

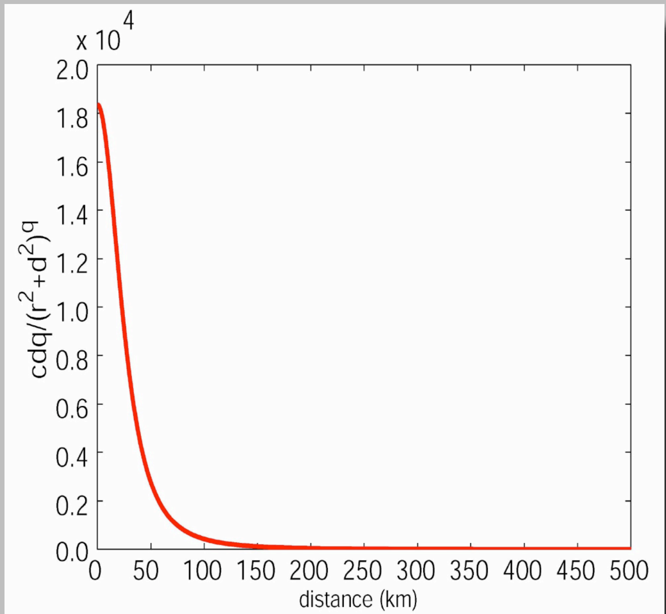




NEIC Validation database
2000-2003
380 events

NEIC: learning phase

$$\lambda(t,x,y/\mathcal{H}_t) = \mu \cdot u(x,y) + \sum_{t_i<t} k e^{-\frac{t-t_i}{\tau}} e^{\alpha(m_i - M_0)} \frac{c_{dq}}{(r^2+d^2)^q}$$



Parameter	Poisson Model	Branching Model
μ (year^{-1})	80.0 ± 2.0	35.0 ± 2.0
K (year^{-1})		0.058 ± 0.002
τ (year)		= 30.0
α		~ 0.0
d (km)		35.0 ± 4.0
q		1.7 ± 0.1
Loglik	-30478.4	-29456.1

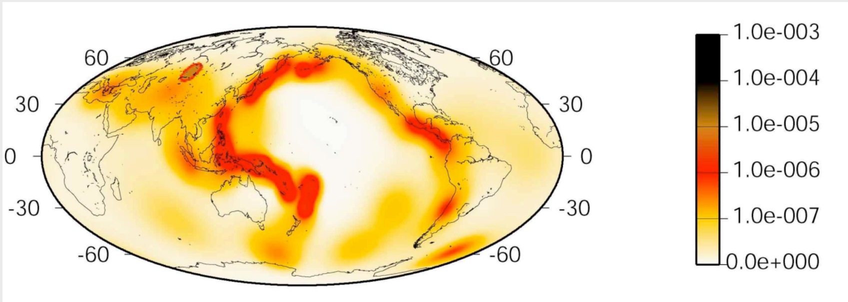
τ → relaxation time set to 30 years (see PS92)

$\alpha = 0$ → as for PS92

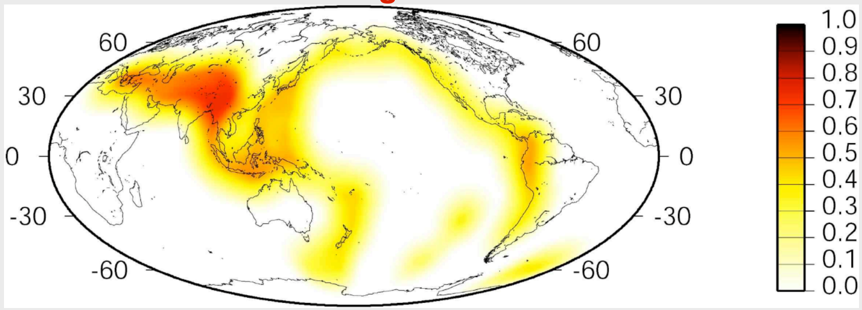
INGV

NEIC: learning phase

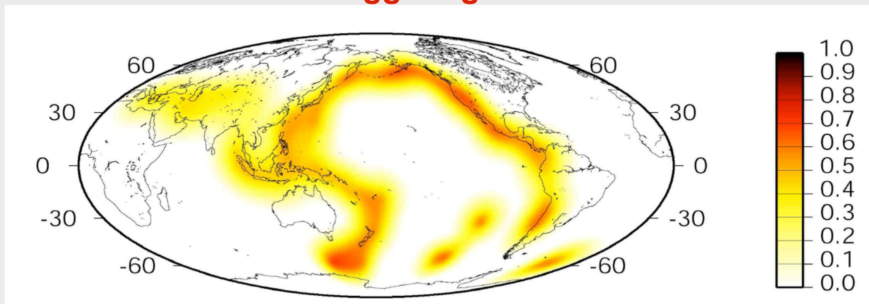
Total rate

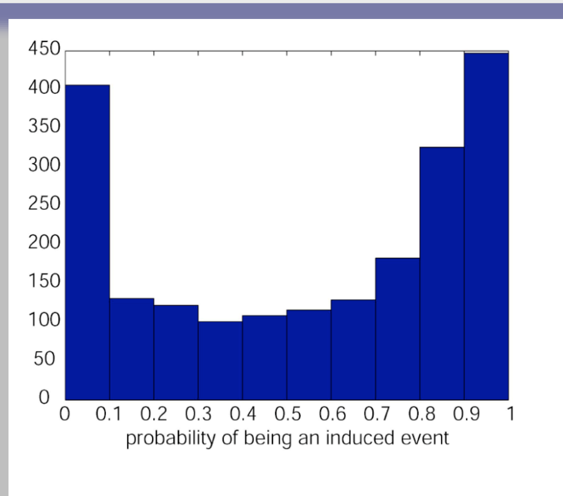


Ratio between background and total rate



Ratio between the triggering rate and the total rate

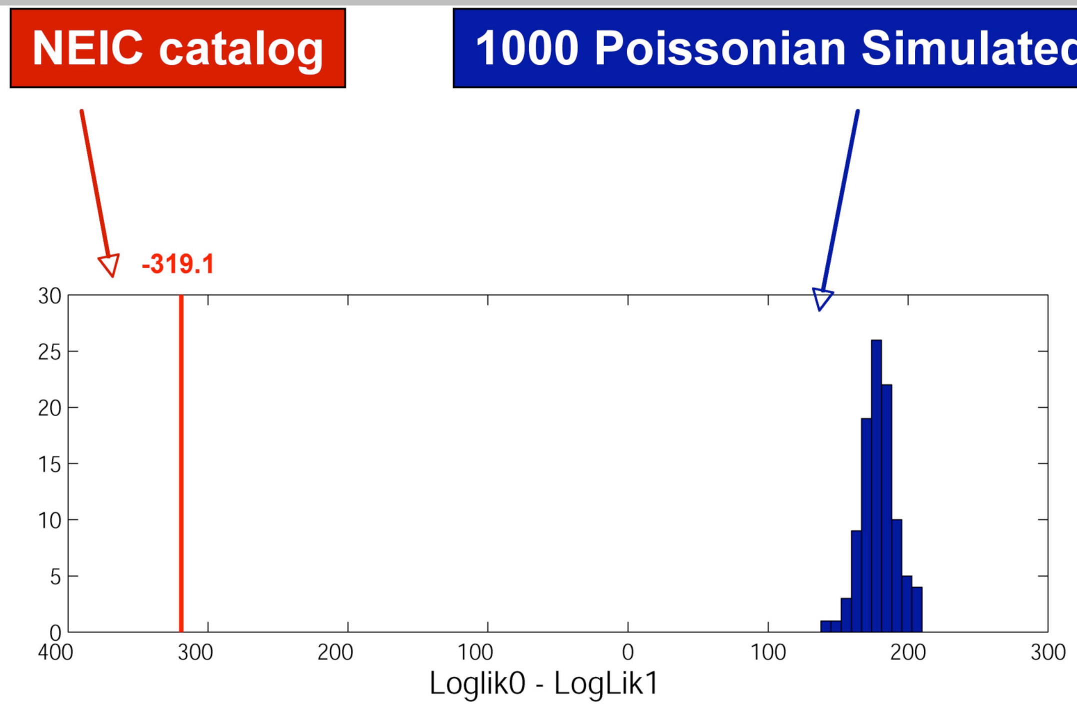




About 450 events (about 22% of the total) have a probability larger than 90% to be an induced event!

5. Testing the model

NEIC: validation phase



NEIC Validation dataset
(2000-2003; 380 events)

Poisson Model:
Loglik0 = -5608.1

Branching Model:
Loglik1 = -5289.0

Significance level << 0.01

PROBABILITY GAIN: 2.32

INGV

6. Points to take home

❖ Earthquakes in different spatial-time-magnitude domains behave similar. The "universality" hypothesis seems to work on the range considered.

❖ Earthquakes cluster in space and time regardless the threshold magnitude.

❖ Earthquakes rate varies through time with different characteristic times: few years, and few decades

❖ A stepwise branching model describes earthquakes occurrence better than Poisson and classical ETAS model. (The code *FREESBE - FoRecasting EarthquakEs through Stepwise Branching modEl - will be submitted to CSEP for validation)*

INGV

- No matter the NATURE of the model is…. MAKE IT TESTABLE

- SUPPORT CSEP initiative!!!! SCIENCE requires TESTS

INGV