Forecasting M≥5.0 earthquakes in Italy using a new adaptive smoothing seismicity approach

Matteo Taroni and Aybige Akinci

Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Rome, Italy,

matteo.taroni@ingv.it, aybige.akinci@ingv.it

INGV terremoti vulcani ambiente
ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

centropericolositàsismica CPS

4 May 2020 EGU Vienna

EGU General Assembly 2020

Outlines:

- **Methods:** 1) fixed smoothing seismicity (Frankel, 1995); 2) modified fixed smoothing seismicity; and 3) modified adaptive smoothed seismicity that accounts the space–time, and the magnitude completeness in the catalog as given by (Hiemer et al., 2014); 4) *the new proposed approach includes aftershocks, foreshocks, and many small events below the completeness magnitude in the catalog for the seismicity rate model.*
- **Learning Catalog:** Italian instrumental seismic catalog (HORUS) from 1960 to 2009.
- **Metric:** Spatial log-likelihood: considers only the spatial distribution of the earthquakes.
- **Estimated Parameters:** Smoothing distance (σ, for the fixed smoothing) and the NN (number of neighbors, for the adaptive smoothing) are estimated through the Maximum Likelihood approach.
- **Testing Catalogs:**

  1) 10 years, Italian instrumental seismic catalog (HORUS) from 2010 to 2019, $M_w \geq 5.0$;

  2) 300 years, Italian parametric historical catalog (CPTI15) from 1660 to 1959, $M_w \geq 5.95$.
- **Results:** Seismicity rate maps and spatial log-likelihoods of all the models.
- **Discussions:** some considerations about our results.

Methods (1):

- Fixed smoothed seismicity and the Gaussian kernel Frankel (1995)

$$K(i,j) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{r(i,j)^2}{2\sigma^2}\right)$$

where *K(i,j)* is the weight related to the *j-th* spatial cell from the *i-th* earthquake in the catalog, *r(i,j)* is the distance between the *j-th* spatial cell from the *i-th* earthquake in the catalog and sigma (σ) is the smoothing distance.

- Adapted smoothed seismicity where σ depends on the number of neighbors, (Helmstetter et al., 2007).
- Hiemer et al., (2014) provides a correction for different completeness magnitudes long the catalogs:

$$G(i,j) = \frac{10^{b\left(Mc_i - Mc_{min}\right)}}{T_i}$$

where *G(i,j)* is the correction coefficient related to the *j-th* spatial cell from the *i-th* earthquake in the catalog, *b* is the *b-value* of the Gutenberg-Richter law, *Mci* and *Ti* are the completeness magnitude and the temporal length of that completeness magnitude related to the *i-th* earthquake, and *Mcmin* is the minimum between the completeness magnitudes.

Methods (2):

In our method we aim to benefit all events reported in the seismic catalog (i.e. *aftershocks, foreshocks and the events below the completeness magnitude*) and incorporating them into the forecasting model. To do so:

- we first modify the correction parameter defined by (Hiemer et al., 2014). In our approach, the *Mci* in the previous equation is no longer the magnitude of completeness related to the i-th events, but is the one of the mainshock of the seismic sequence that includes the *i-th* event. Then, in order to take into account for the events below the completeness magnitude, when the mainshock magnitude is smaller than the completeness level we consider its magnitude as *Mci.* In this case, small mainshocks can still give spatial information to the model. Thus the events below the completeness magnitude are less counted and weighted in the model, accordingly with their magnitude. For example, if the event has a magnitude far below the completeness magnitude, it is assigned with a very low weight.
- Then, in order to count all the events (aftershocks and foreshocks), we assign a total weight equal to 1 for all events in the seismic sequence using this simple correction:

$$C(i,j) = \frac{1}{N_i}$$

where *Ni* is the number of events in the sequence related to the *i-th* earthquake.

- In this manner we avoid overestimating the rates in the zones that experienced the seismic sequence while we preserve the spatial distribution of aftershocks and foreshocks.

Methods (3):

The final rates *R(j)* at each bin of the spatial cells of the smoothing seismicity models is obtained by summing up all the *Num* events in the catalog:

$$R(j) = \sum_{i=1}^{Num} K(i,j)$$

Frankel (1995)

$$R(j) = \sum_{i=1}^{Num} K(i,j)G(i,j)$$

Hiemer et al., (2014)

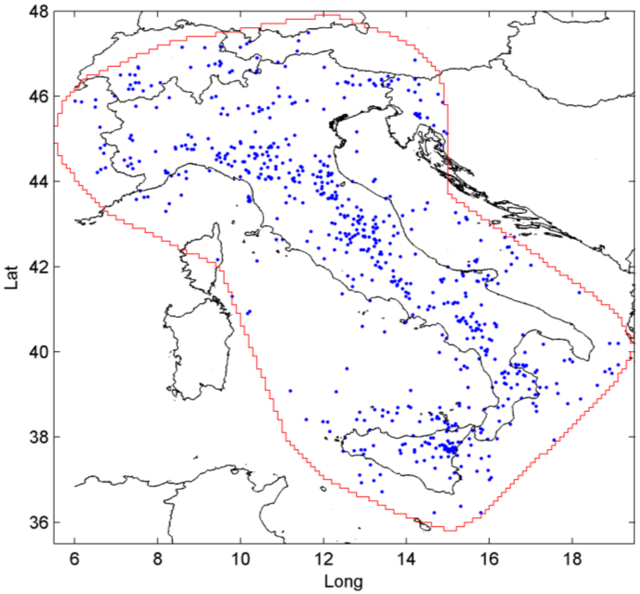
$$R(j) = \sum_{i=1}^{Num} K(i,j)G(i,j)\,C(i,j)$$

New approach, this study

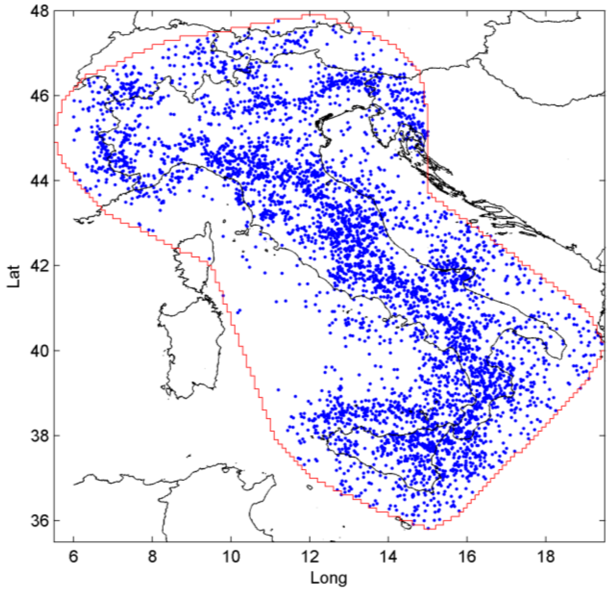
Learning catalog:

The learning catalog span from 1960 to the end of 2009.
The magnitude completeness is Mw 4.0 from 1960, Mw 3.0 from 1981, Mw 2.5 from 1990, Mw 2.1 from 2003 and Mw 1.8 from 2005/4/16.

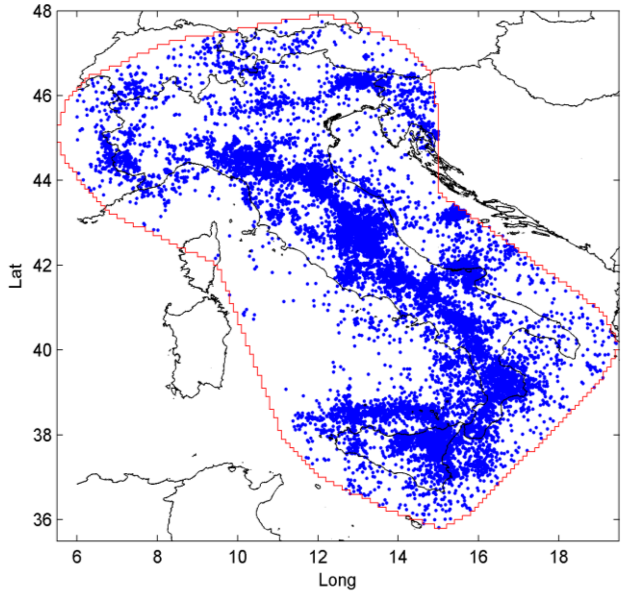
Declustered catalog with GK74 for events magnitude completeness Mw >4.0 from 1960 (**676 events**)



Declustered catalog with GK74 for different magnitude completeness as defined above (**4907 events**)



Non-Declustered catalog, all events in the catalog (**25.279 events**)



*GK74: this method is the classical declustering algorithm of Gardner and Knopoff, 1974

Metric:

In this study we focus on investigating the spatial forecasting performance of difference smoothing earthquake rate models. To do so we employ the spatial log-likelihood:

$$SLL = \sum_{i=1}^{Num} log\left(pdf(\lambda_i)\right)$$

where *SLL* is the spatial log-likelihood, *Num* is the total number of events in the testing catalog, *pdf* the probability mass function of the Poisson distribution and *λi* is the earthquake rate of the spatial cell corresponding to the *i-th* earthquake.

Therefore, in our computation, the magnitude frequency distribution of events is ignored at this stage of the process.

Parameter estimation:

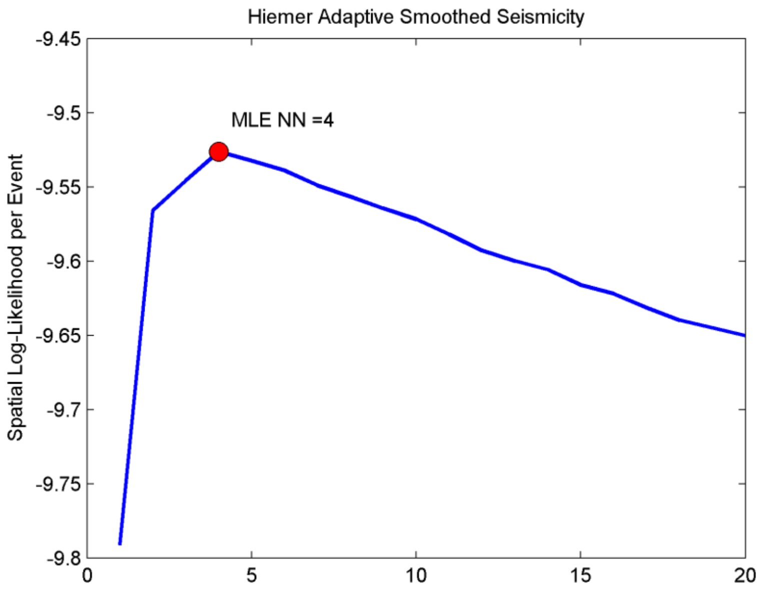
The maximum likelihood approach is followed estimating the fixed smoothing distance, σ and the neighbor number, NN.

All the data from 1960 to 1999 is considered to construct the earthquake rate models while the events Mw≥4.0 from 2000 to 2009 are practiced to perform the best estimations for σ and NN parameters.

The results are summarized in the next table:

Model	MLE
Fixed (Frankel)	Sigma = 50 Km
Fixed (Hiemer)	Sigma = 45 Km
Adaptive (Hiemer)	NN = 4
Fixed (New)	Sigma = 30 Km
Adaptive (New)	NN = 50

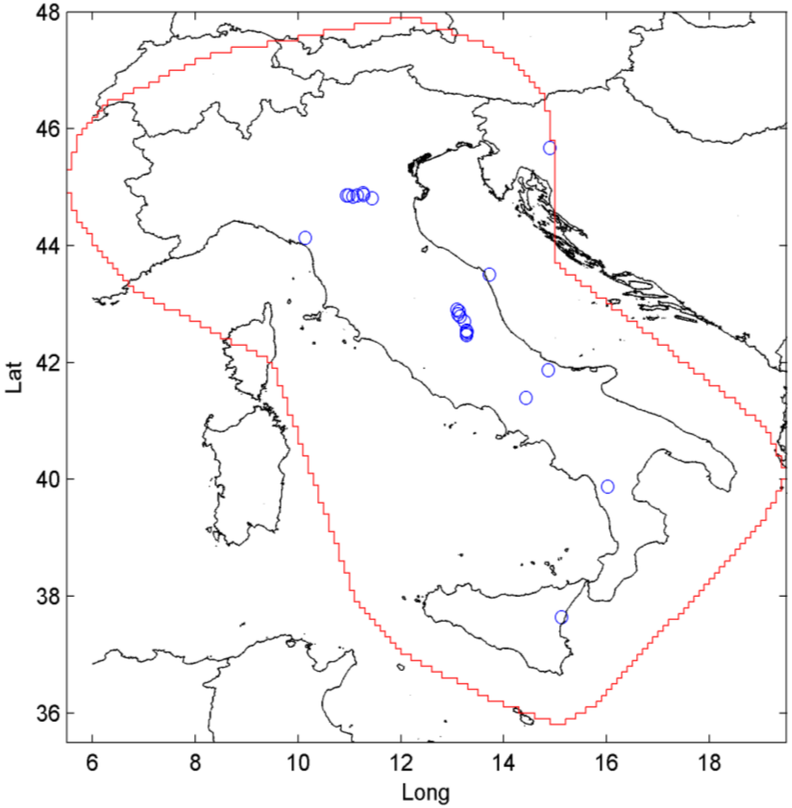
Example



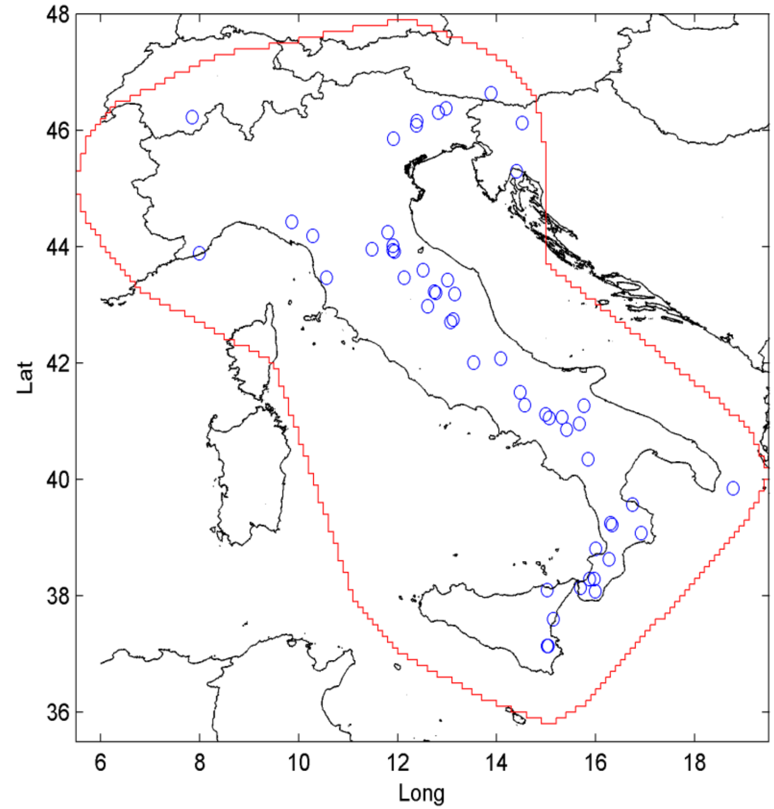
This huge number of neighbors is due to the incredibly high number of evens in the learning catalog for the new approach.

Testing catalogs:

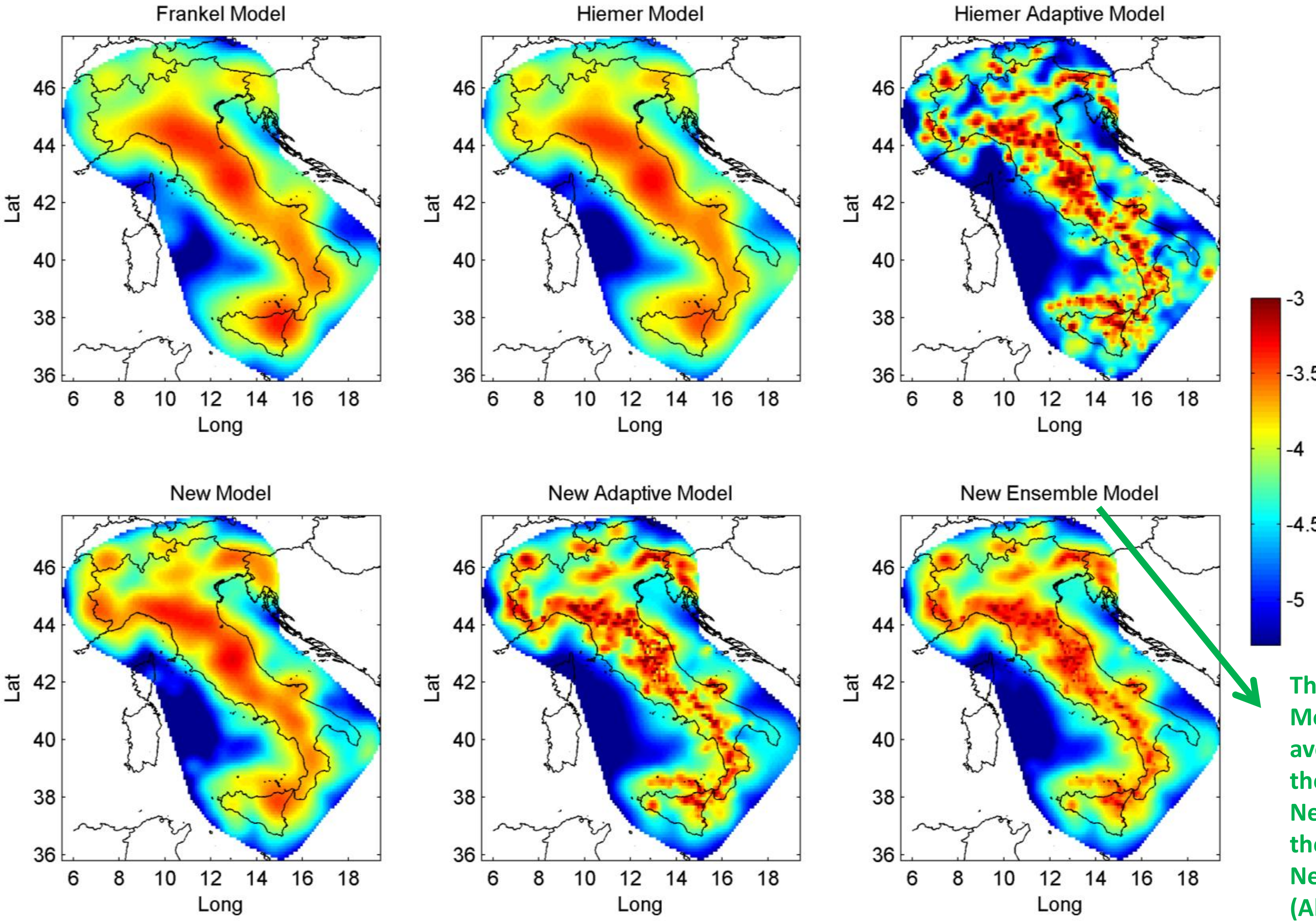
10 years testing catalog
from the HORUS instrumental catalog,
from 2010 to 2019, Mw ≥5.0
(**23 events**)



300 years testing catalog
from the CPTI15 historical
earthquake catalog,
from 1660 to 1959, Mw ≥5.95
(**53 events**).



Results: maps



Log10 of the spatial density (the sum of all the rates of a spatial density is 1).

The New Ensemble Model is build by averaging the 50% of the spatial rates of the New Model and 50% of the spatial rates of the New Adaptive Model (Akinci et al., 2018).

Results:

model performance with the spatial log-likelihoods

The results are shown using the spatial log-likelihood per event (SLL/Num).

Model	Test 1: 10 years Mw 5.0 2010-2019	Test 2: 300 years Mw 5.95 1660-1959
Fixed Sm.(Frankel, 1995)	**-9.13**	**-9.39**
Fixed Sm. (Hiemer et al., 2014)	**-9.11**	**-9.37**
Adaptive Sm. (Hiemer et al., 2014)	**-8.95**	**-9.22**
Fixed Sm. (New, this study)	**-9.12**	**-9.26**
Adaptive Sm. (New, this study)	**-9.11**	**-9.04**
Ensemble Sm. (New, this study)	**-9.07**	**-9.11**

Green for the best performing model, **red** for the worst model.

Conclusions:

Our results show that:

- The adaptive smoothing model obtained following the Hiemer et al., (2014) approach is performed better forecasting the M≥5.0 earthquakes in the ten years testing periods of 2010-2019.
- However the new adaptive smoothing model better predicts the observed seismicity rates for M ≥5.95 events in 300 years window from 1660 to 1959 in the historical seismicity.
- In general we observe that the adaptive smoothing seismicity models perform better than the fixed smoothing seismicity models.
- Including smaller earthquakes improves our model predictability for the future M≥5.0 and ≥5.95 earthquakes.

References:

- Akinci, A., Moschetti, M. P., & Taroni, M. (2018). Ensemble smoothed seismicity models for the new Italian probabilistic seismic hazard map. *Seismological Research Letters*, *89*(4), 1277-1287.
- Frankel, A. (1995). Mapping seismic hazard in the central and eastern United States. *Seismological Research Letters*, *66*(4), 8-21.
- Gardner, J. K., & Knopoff, L. (1974). Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian?. *Bulletin of the Seismological Society of America*, *64*(5), 1363-1367.
- Helmstetter, A., Kagan, Y. Y., & Jackson, D. D. (2007). High-resolution time-independent grid-based forecast for $M \geq 5$ earthquakes in California. *Seismological Research Letters*, *78*(1), 78-86.
- Hiemer, S., Woessner, J., Basili, R., Danciu, L., Giardini, D., & Wiemer, S. (2014). A smoothed stochastic earthquake rate model considering seismicity and fault moment release for Europe. *Geophysical Journal International*, *198*(2), 1159-1172.
- Lolli, B., Randazzo, D., Vannucci, G., & Gasperini, P. (2019, January). HOmogenized instRUmental Seismic catalog (HORUS) of Italy from 1960 to present. In *Geophysical Research Abstracts* (Vol. 21).
- Rovida, A., Locati, M., Camassi, R., Lolli, B., & Gasperini, P. (2020). The Italian earthquake catalogue CPTI15. *Bulletin of Earthquake Engineering*, 1-32.