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Short-term earthquake forecasting before and during the L'Aquila (Central Italy) seismic sequence of April 2009

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Introduction

The cases of the recent destructive earthquakes that occurred with impressive frequency in Sichuan (China, 2008), central Italy (2009), Haiti (2010), Chile (2010), New Zealand (2010), Tohoku (Japan, 2011), and northern Italy (2012) have shown that, so far, scientific research has achieved little or almost nothing in the implementation of short- and medium-term earthquake forecast, which would be useful for disaster mitigation measures.

This regrettable situation could be ascribed to the present poor level of achievement in earthquake forecast.

On the other hand, another problem of practical implementation of earthquake forecasting could be due to the lack of common understanding and exchange of information between the scientific community and the governmental authorities that are responsible for earthquake damage mitigation in each country.

In particular, the way how seismologists should formulate their forecasts and how they should transfer them to decision-makers and to the public is still an open issue.

Phases for the construction of a forecast model

- *Formulation of the idea* upon which the hypothesis (theoretical framework, model) should be based, generally on the basis of retrospective *phenomenological observations*.

- *Set up of the hypothesis in quantitative form*, through the definition of the necessary *parameters* achievable from the retrospective analysis (*learning phase*).

- *Test of the hypothesis* on a data set *independent of* the data set used in the learning phase, possibly obtained after such a phase.

- *Application* of the methodology to real cases.

Short-term models

- The phenomenon of earthquake clustering, i.e. the increase of occurrence probability for seismic events close in space and time to other previous earthquakes, has been modeled by statistical and physical processes.
- We have built a model of earthquake clustering in which the so-called “epidemic type” concept (ETAS) is applied.
- A definition of the words ***foreshock***, ***mainshock*** *and* ***aftershock*** is not necessary.
- The best fit of the model parameters is carried out by the maximum likelihood criterion on a suitable set of observations.
- The test is carried out without free parameters on a new and independent data set.

Time dependent model (ETAS)

(Ogata, 1998)

Occurrence rate density:

$$\lambda(x, y, t, m) = f_r \cdot \lambda_0(x, y, m) + \sum_{i=1}^{N} H(t - t_i) \cdot \lambda_i(x, y, t, m)$$

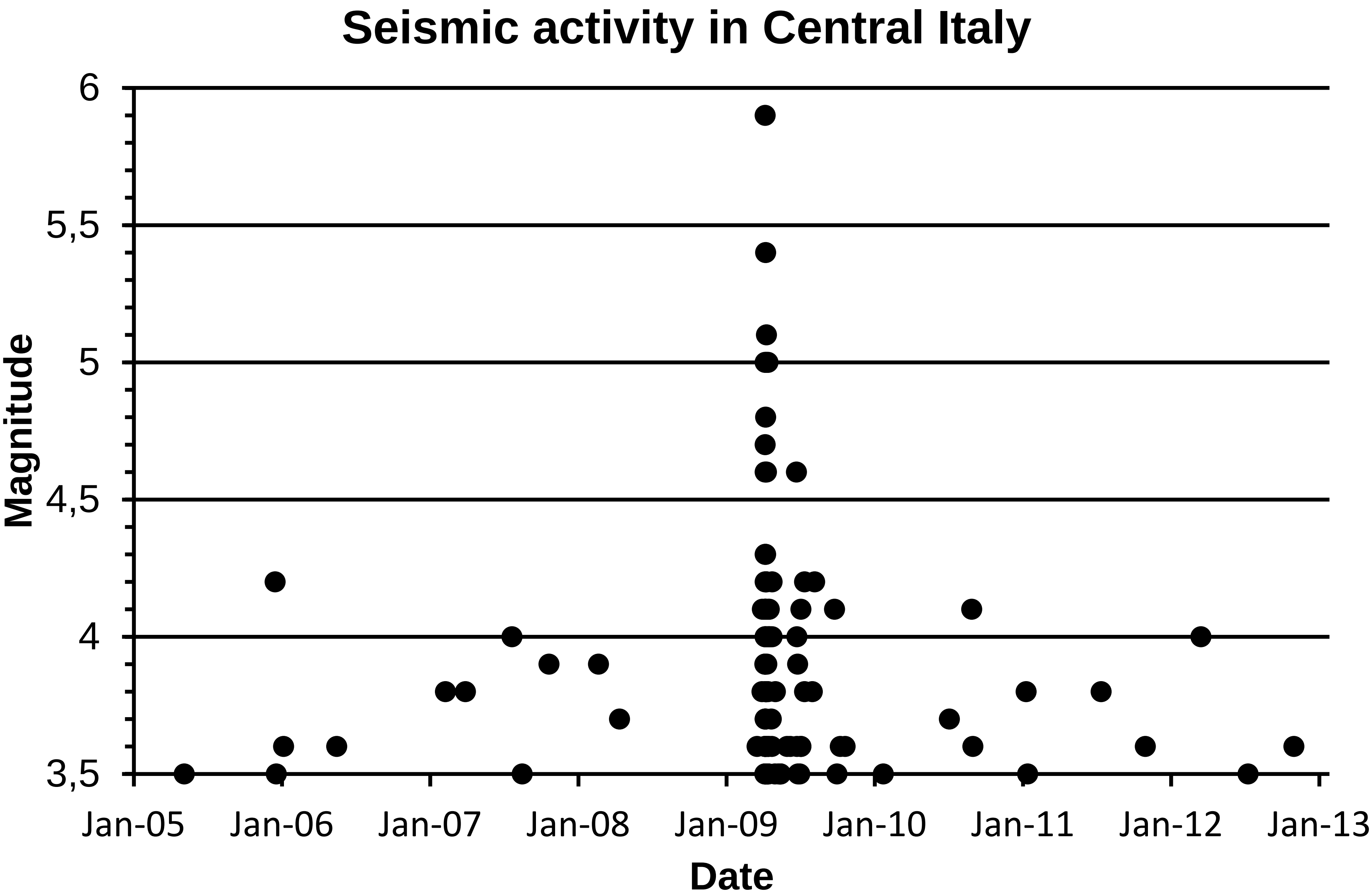
f_r is the fraction of events that occurs spontaneously

λ_0 represents the background seismicity

λ_i is the single contribution of any previous earthquake to the occurrence rate density of the subsequent earthquakes

t_i is the earthquake occurrence time

$H(t)$ is the step function


Seismic activity in Central Italy
Magnitude
6
5,5
5
4,5
4
3,5
Jan-05
Jan-06
Jan-07
Jan-08
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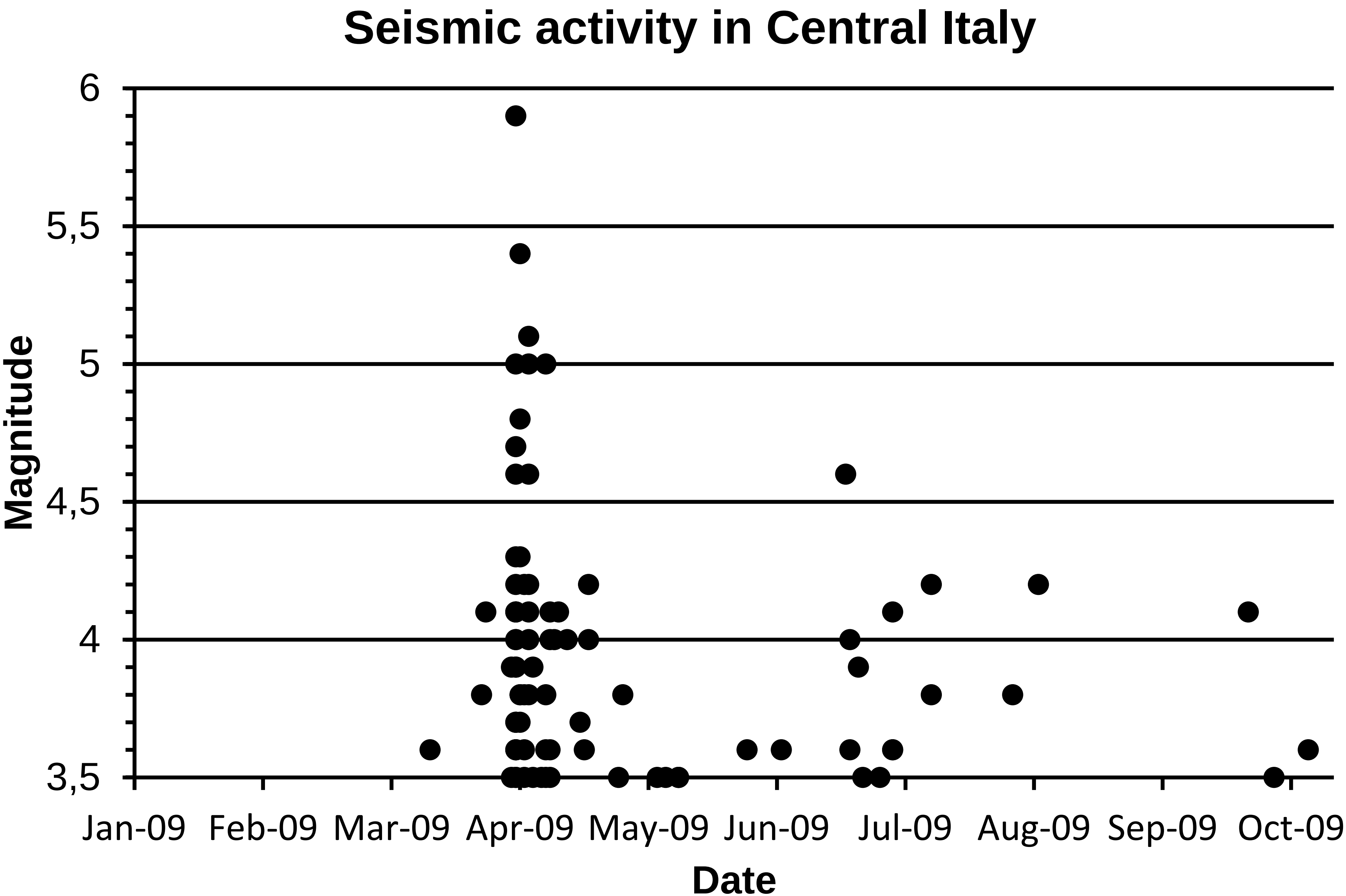
Jan-11
Jan-12
Jan-13
Date


Seismic activity in Central Italy
Magnitude
6
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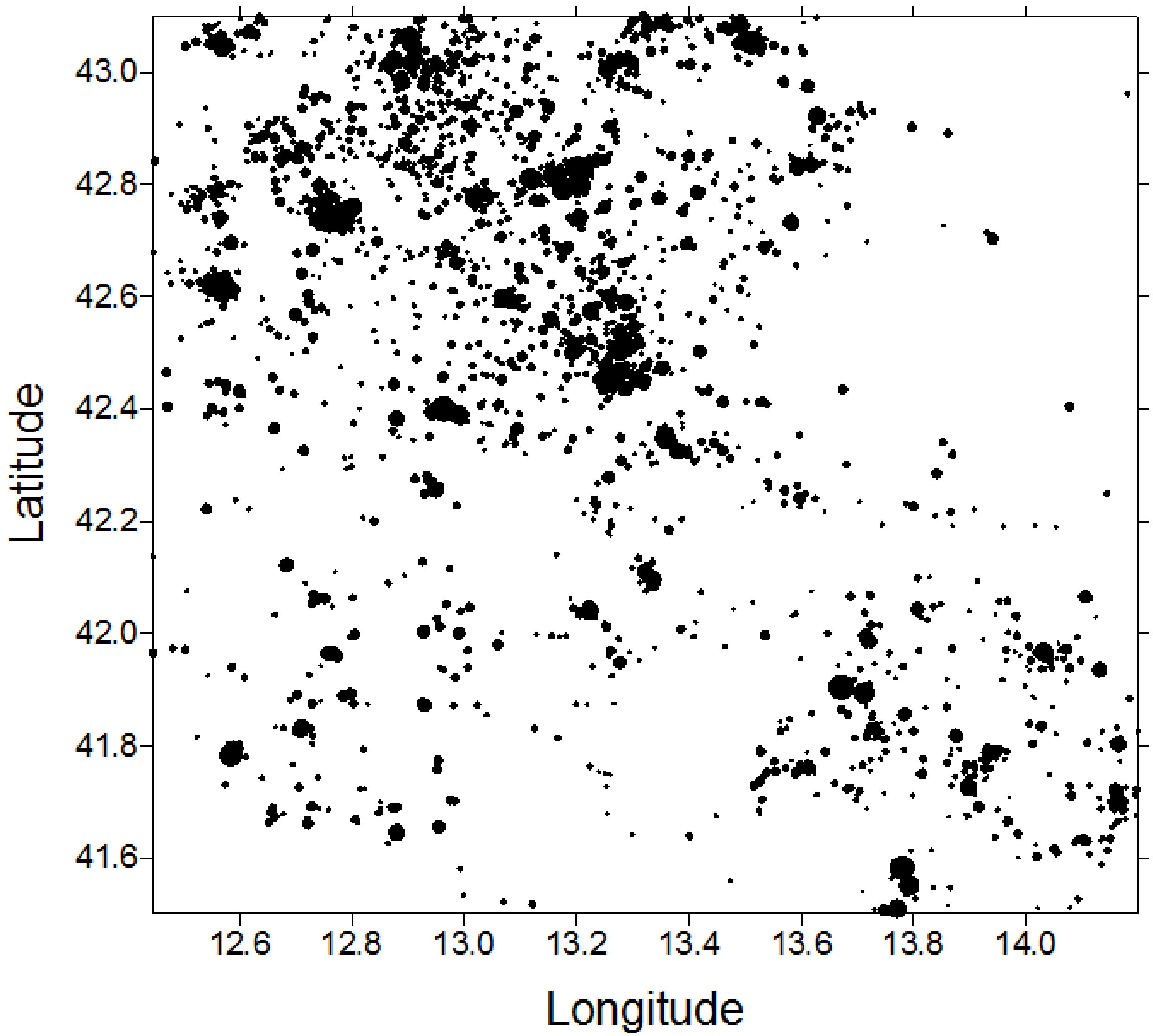
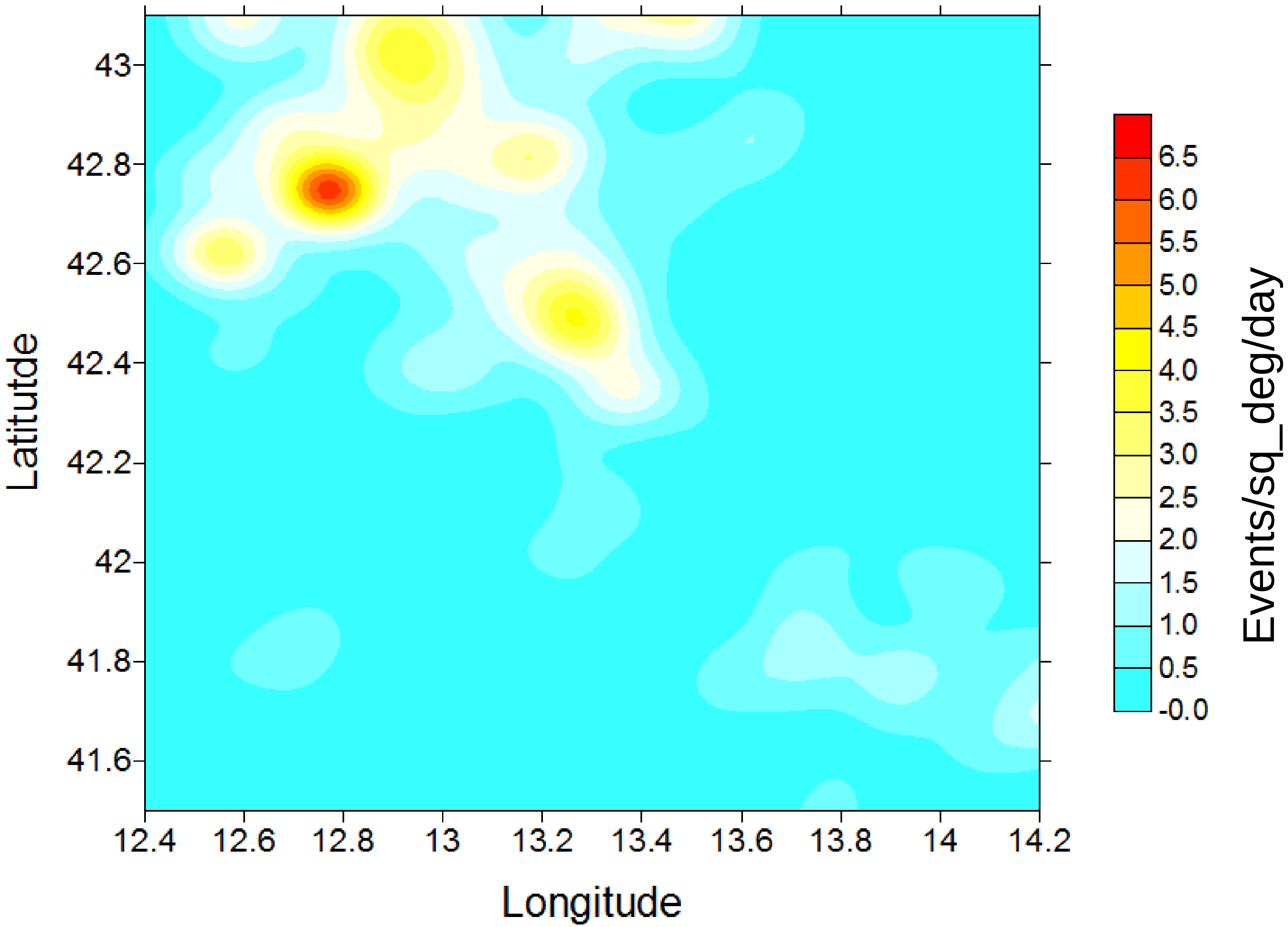
Jan-09
Feb-09
Mar-09
Apr-09
May-09
Jun-09
Jul-09
Aug-09
Sep-09
Oct-09
Date

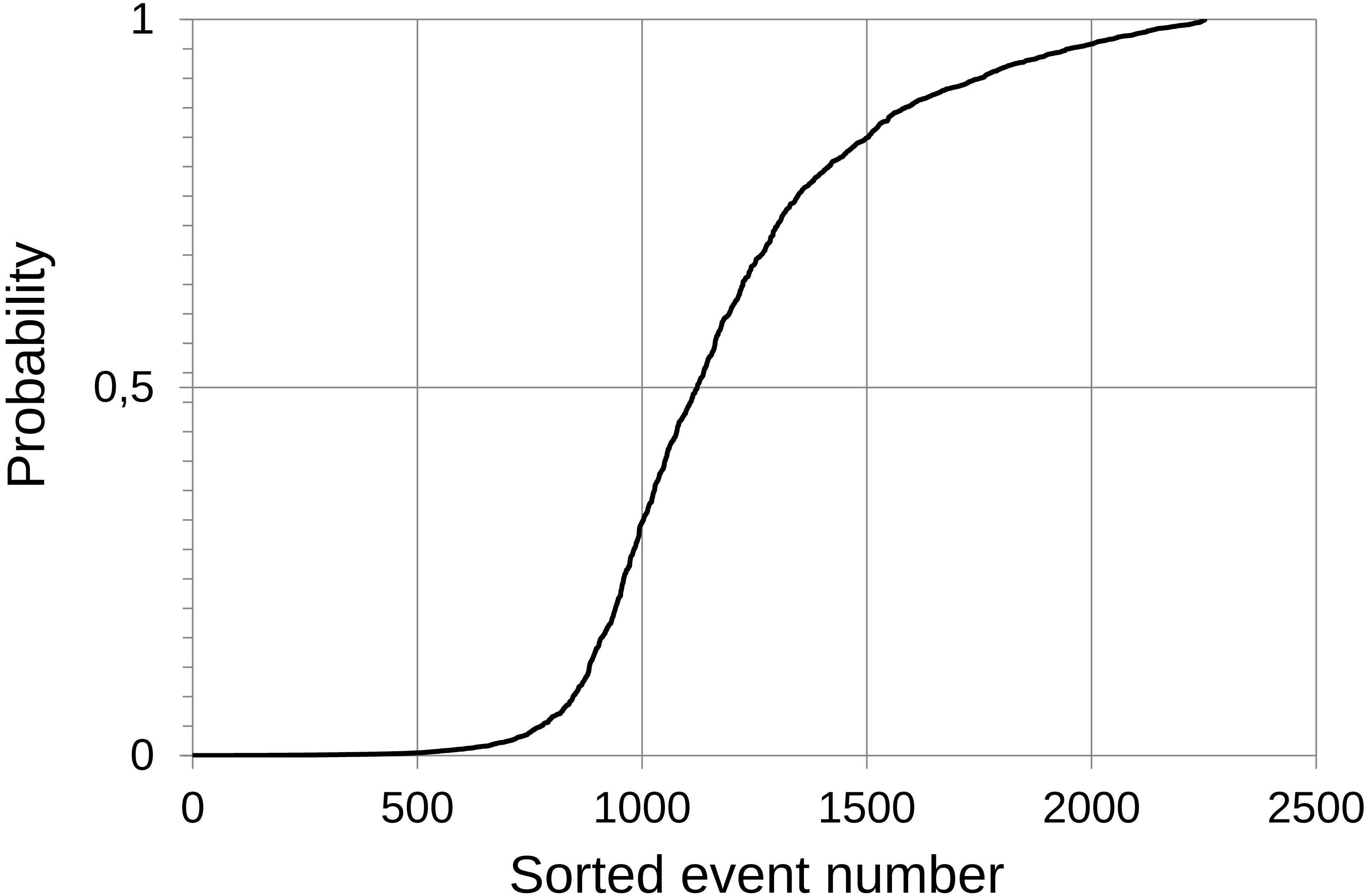
Learning period: 17/04/2005-15/03/2009
1431 days, 2588 events M ≥1.6



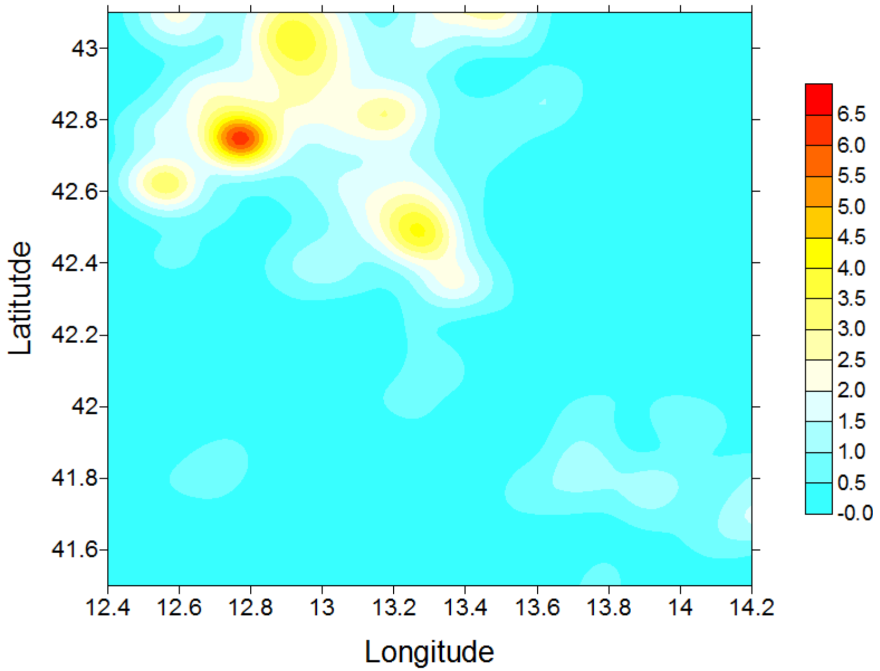
Learning period: 17/04/2005-15/03/2009
Initial spatial distribution (function $\mu_0(x, y)$)
(smoothing distance d = 8 km)

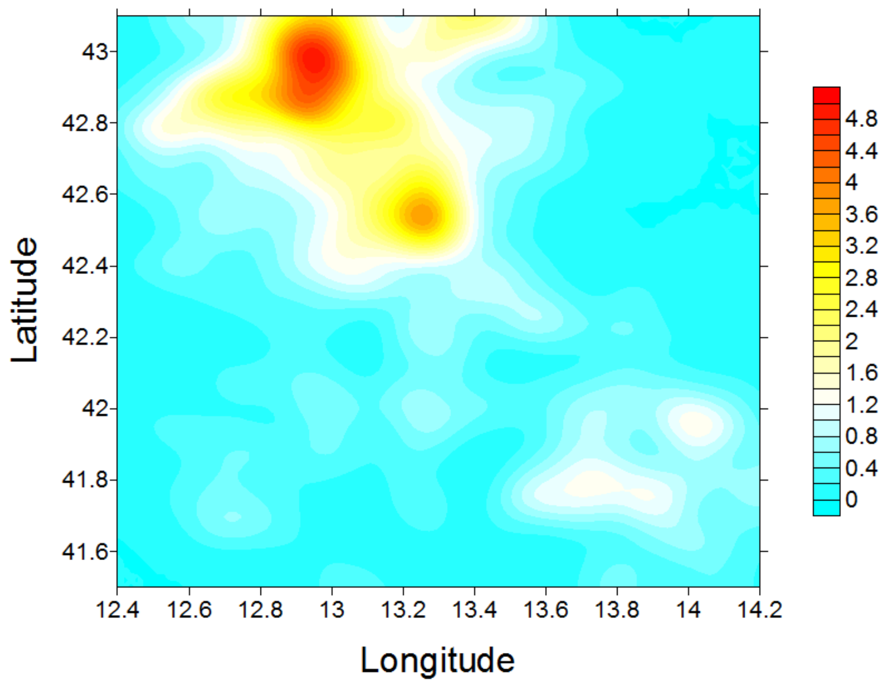


Distribution of probability for an event to be spontaneous



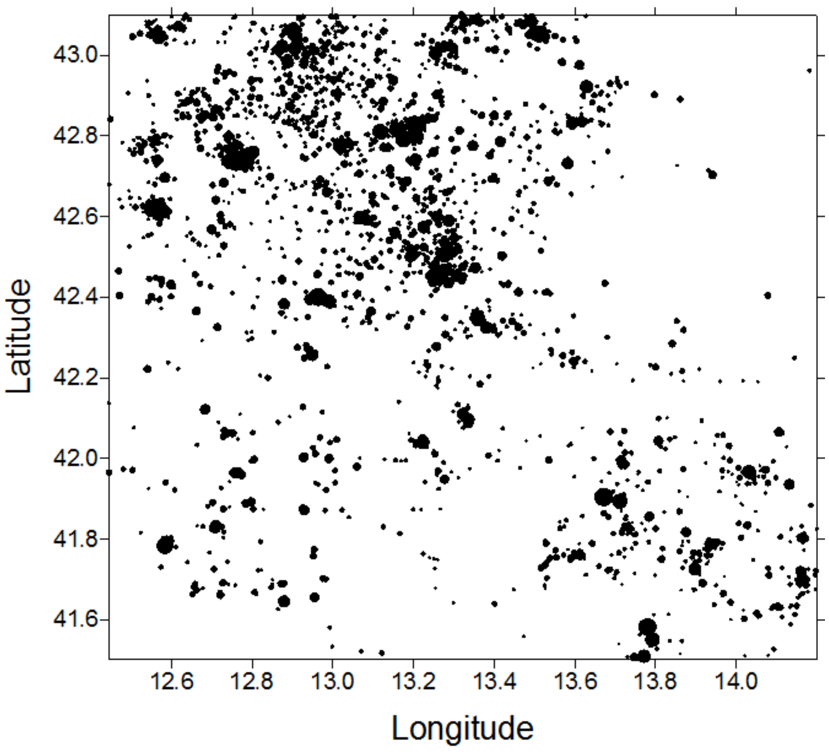
Learning period: 17/04/2005-15/03/2009 Comparison between the inital and final spatial distribution (ev/sq_deg/day)



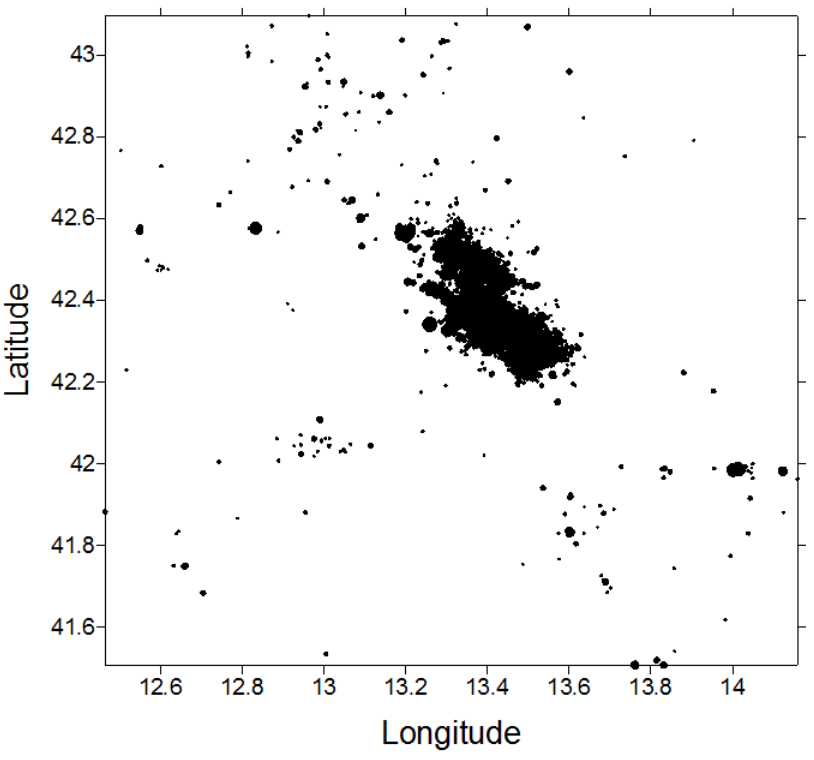


Comparison between the spatial distributions in the learning and testing periods

17/04/2005-15/03/2009



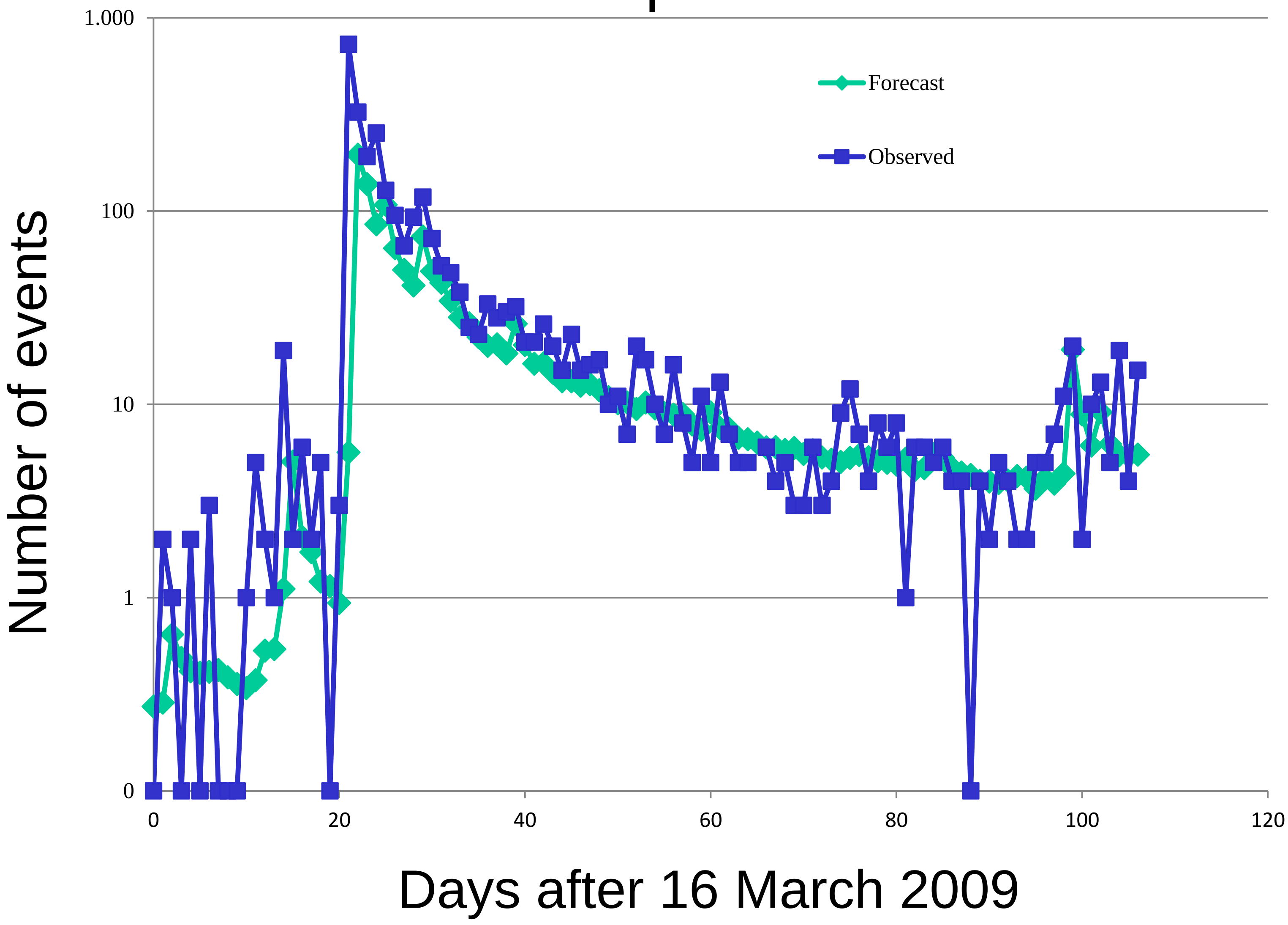
16/03/2009-30/06/2009



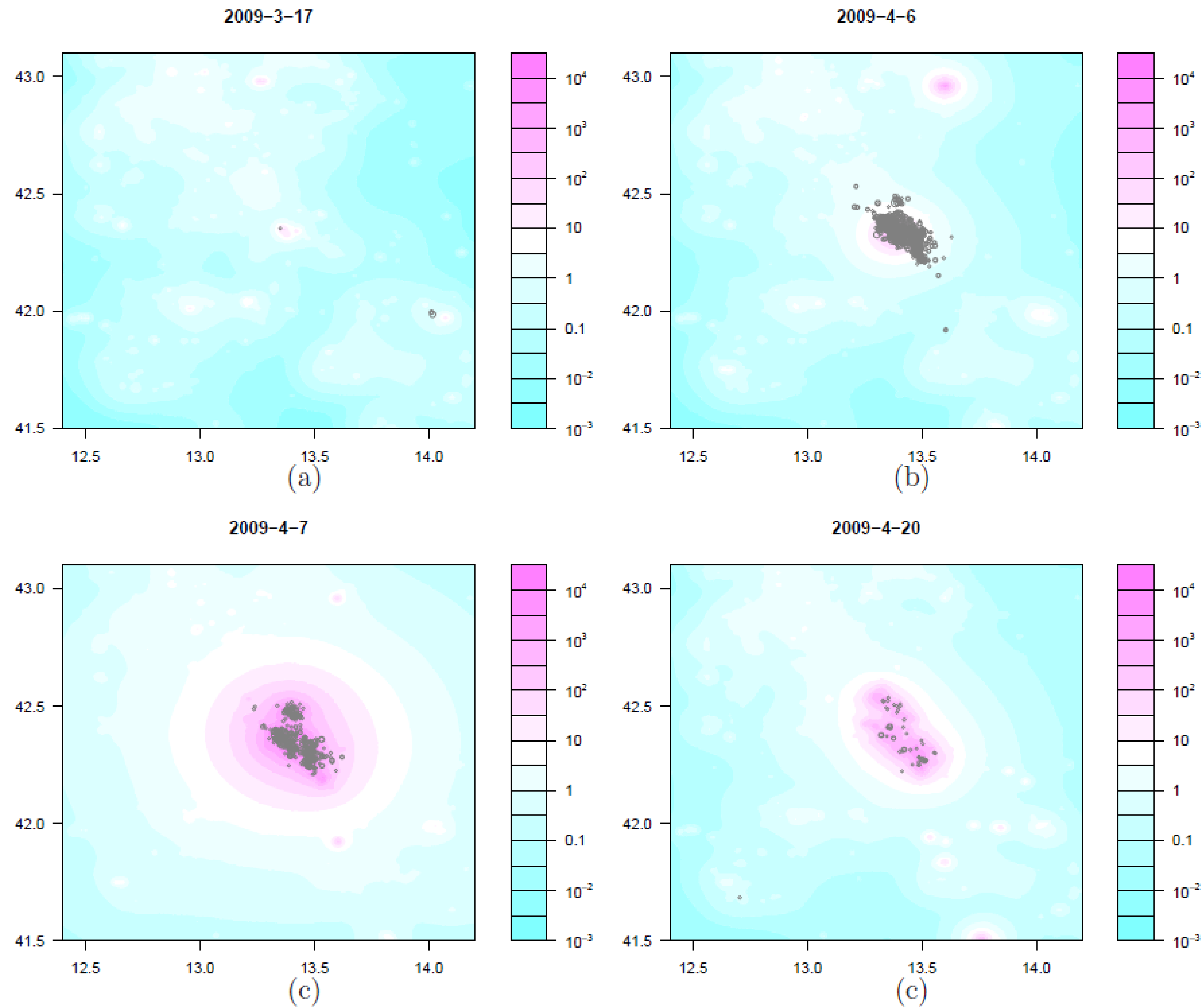
Overall results

Applying the ETAS model with the parameters obtained from the ML best fit in the learning phase, we obtain a very large performance factor with respect to the time-independent Poisson model.
The average log-performance factor per event (information gain) is equal to 50,241/7,149 = 7.03 (natural logarithms are used).
It means that for each event the average probability gain is of the order of 1,000.

Comparison between forecast and observed rates (events M ≥ 2.0 per day) during L'Aquila, 2009 sequence



Maps of expected seismicity rate (events M≥2.0/day/deg^2)



Probability of an earthquake of magnitude ≥ 5 in 24 hours in the area of L'Aquila (ETAS model)

1 December 2008	0.02 %	
27 March 2009	0.06 %	
		← M4.1
31 March 2009	1.5 %	
5 April 2009 22:00	0.4 %	
		← M3.9
5 April 2009 23:00	1.6 %	
6 April 2009 01:00	2.0 %	
		← M5.9
6 April 2009 04:00	8.3 %	
		← M5.0
6 April 2009 12:00	12.8 %	
		← M5.4
20 April 2009	7.6 %	
10 May 2009	4.4 %	

Before the mainshock

The total conditional probability for an earthquake of magnitude M≥5.0 during the week preceding the 5 April mainshock was 0.39 %.
This probability was about 30 times larger than the background probability, due to the occurrence of some “foreshock” activity. However, this level seems still low for justifying the implementation of effective risk mitigation measures.
The expected instantaneous occurrence rate density increased by several times in the few hours before the mainshock

After the mainshock

The forecasted number of events with $M \geq 5.0$ was systematically smaller than the real one in the first month of the aftershock sequence. Afterwards, the forecasted and observed occurrence rates became more similar.

CONCLUSIONS

The retrospective application of the ETAS model to the 2009 seismic sequence occurred in Central Italy has shown its capability of forecasting the behaviour of seismic activity during an aftershock sequence.

However, despite the fairly high probability gain achieved through the ETAS model, the forecast of main shocks preceded by moderate foreshocks is characterized by rather low occurrence rates for magnitudes larger than 5.0.