Analysis of Induced seismicity after the 2011 Tohoku-Oki earthquake by non-stationary ETAS models

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ABSTRACT: The epidemic-type aftershock sequence (ETAS) model is a stationary point process, and provides a good fit to an ordinary seismic activity. Its poor fitting suggests that the earthquake mechanisms are affected by changes in geophysical factors. Fault strength is one of the fundamental factors in a seismogenic zone, and its temporal change can induce nonstationary seismicity. Although changes in fault strength have been suggested to explain various phenomena, such as the remote triggering of seismicity, there has been almost no means of quantitatively monitoring this property in situ. For this purpose, we extend the ETAS model for non-stationary cases. This allows the parameters to be time-variant, which then describes anomalous features of the seismic activity. We prepare Bayesian models, and apply them to the data from inland seismic swarm activities that have been induced by the 2011 Tohoku-Oki earthquake of M9.0.

1. INTRODUCTION: *ETAS model*

The epidemic-type aftershock sequence (ETAS) model (Ogata 1988, 1989) is a statistical model to predict earthquake occurrences in a seismogenic region. It is a specific point process described based on conditional intensity expression of Hawks process (Hawkes, 1971) which is equivalent to the epidemic branching process (Kendall, 1949; Hawkes and Oakes, 1974), and it allows each event to generate (or trigger) offspring events depending on its earthquake magnitude.

$$\lambda_\theta(t \mid H_t) = \mu + \sum_{\{i:S<t_i<t\}} \frac{K_0 e^{\alpha(M_i - M_z)}}{(t-t_i+c)^p} \qquad (1)$$

What is Non-stationary ETAS model?

Non-stationary ETAS model is a variation of ETAS model with time dependent parameters. The model is useful because changes in the parameters let us know the changes in stress state or fault strength.

Which parameter(s) should be modeled as time dependent?

Some of preceding works suggest that background seismicity (seismicity rate that is not triggered by another earthquake) is an important factor to assess seismicity anomalies such as the changes in stress state or fault strength. In particular, stressing rate affects background seismicity but not aftershock productivity (Llenos et al. 2009). Fault strength is known to be affected by underwater pressure, which level is highly correlated with background seismicity (Hainzl and Ogata 2005; Lei et al. 2008).

2. Model

In the model (1), we made the background rate μ and the productivity of aftershocks K_0 to change in time,

$$\lambda_\theta(t \mid H_t) = \mu(t) + K_0(t) \sum_{i;t_i<t} \frac{\exp\{-\alpha(M_i - M_z)\}}{(t-t_i+c)^p} \qquad (2)$$

via introducing non-stationary factors q_μ and q_K,

$$\lambda_\theta(t \mid H_t) = \mu q_\mu(t) + \sum_{\{i:S<t_i<t\}} \frac{K_0 q_K(t_i) e^{\alpha(M_i - M_z)}}{(t-t_i+c)^p} \qquad (3)$$

Our main interest is the changes in background rate μ, but preliminary examinations suggests including time dependent aftershock productivity K_0 improves the ABIC of the model.

q_μ and q_K in (3) are modeled as linear spline functions (Fig.1).

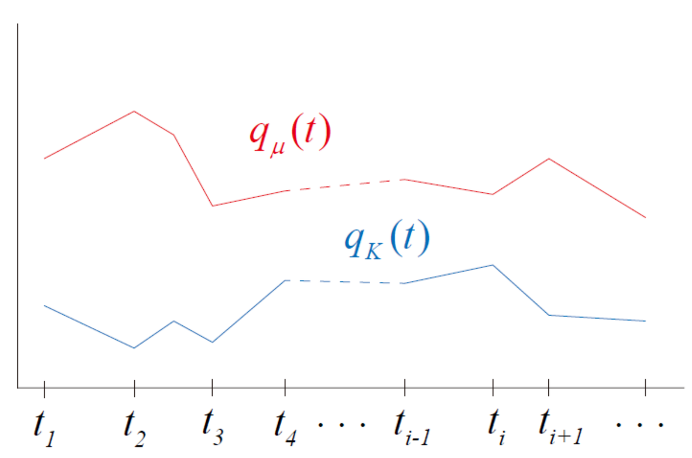

Fig. 1

They are estimated by Bayesian smoothing; optimizing the penalized log-likelihood (4) for q's and ABIC.

$$Q\left(q \middle| w_\mu, w_{K_0}\right) = \log L(q) - w_\mu \Phi_\mu - w_{K_0} \Phi_{K_0} \qquad (4)$$

3. Application: *a triggered earthquakes near Lake Inawashiro*

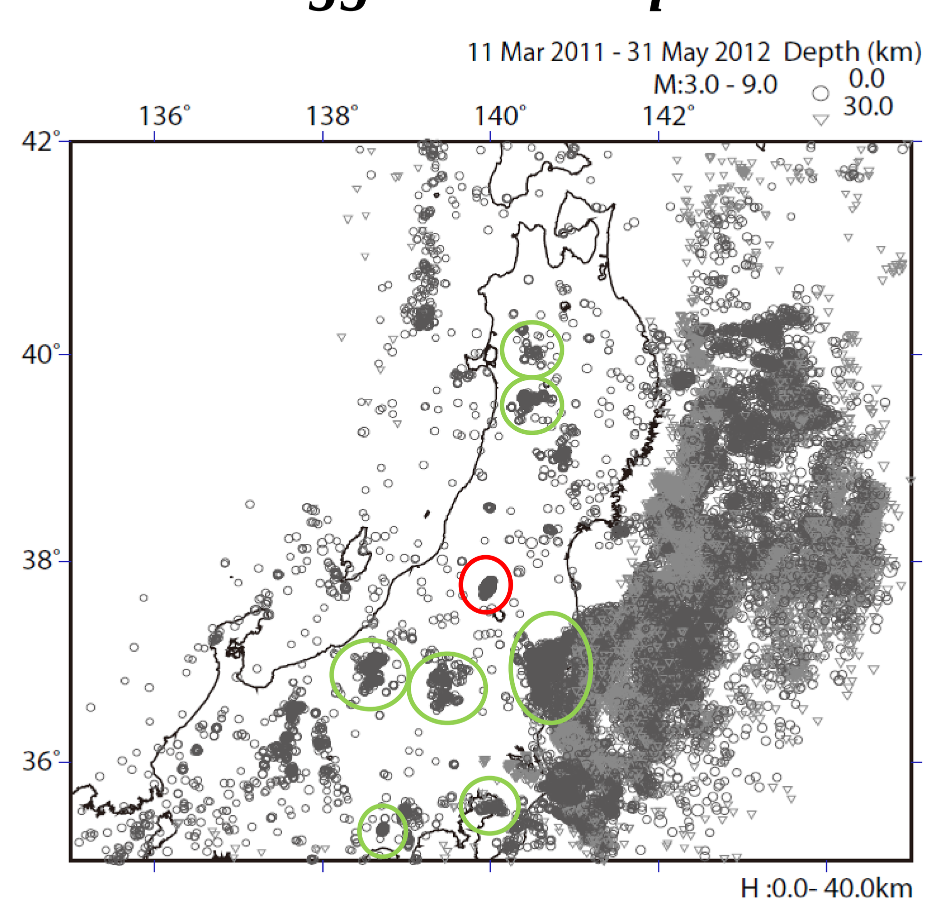

Fig. 2

The M9.0 Tohoku-Oki earthquake on 11th Mar. 2011 triggered several unexpected seismicity activities in the northern Japan (Fig.2), and the earthquake cluster near Lake Inawashiro is the most unusual one. It started by intense swarm events possibly triggered by underwater intrusion (Terakawa et al. 2013), then normal "mainshock–aftershock" type activities followed.

Figure 3 shows the result of our method. The background seismicity (red curve) is high in the early period, then gradually decrease. The early high level background supports the triggering via fault strength reduction by underwater intrusion. Then following background decrease suggests the recovery of the fault strength, by underwater draining out.

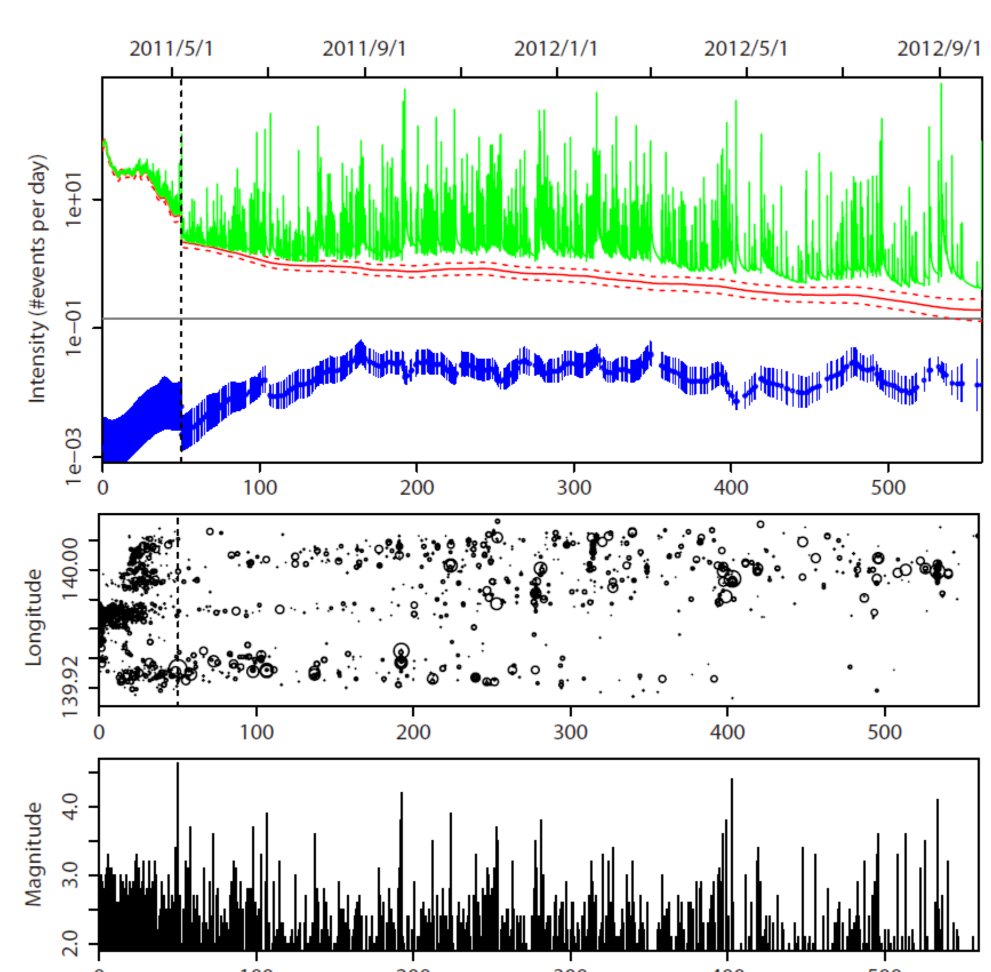

Fig. 3