Seismogenesis Seminar (7/3)

# Background rates of swarm earthquakes that are synchronized with volumetric strain changes

Takao Kumazawa ,Yoshihiko Ogata ,

Kazuhiro Kimura ,Kenji Maeda ,Akio Kobayashi

*“Earth and Planetary Science Letters”, Vol442,*

*Pages 51-60, 2016*

Kazutoshi Takano
(Koketsu Lab, M1)

# Outline

1. Introduction

2. ETAS model and tectonic seismicity around the Izu Peninsula till 1979

3. Nonstationary ETAS model for swarm seismicity

4. Relationship between the swarm background rates and volumetric strain record

5. Short-term swarm prediction

6. Discussion

7. Conclusion

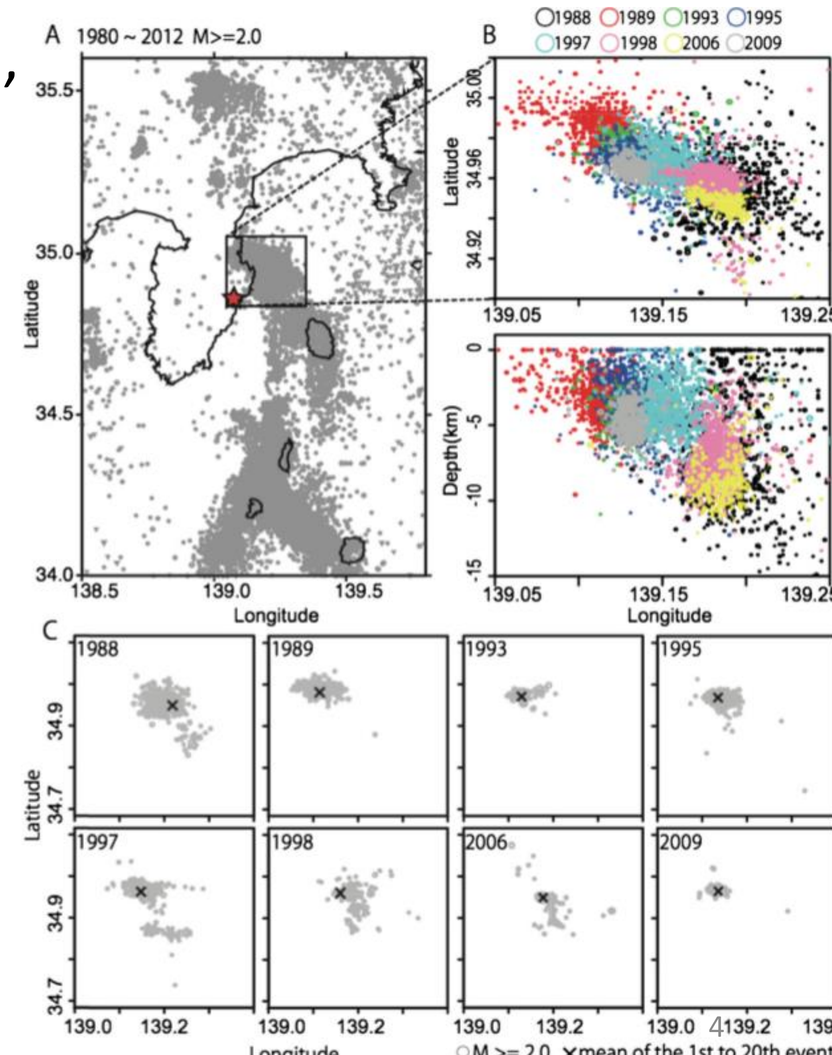
# 1. Introduction

# Background

・Off the east coast of the Izu peninsula, there is an active volcanic region.

・Many earthquake swarms have been repeatedly occurring since 1978.

In previous studies…
geodetic data and the seismic swarms in the study region have been analyzed in an effort to explain the earthquake swarms on the basis of the dike intrusion process. (e.g., Okada and Yamamoto, 1991).



# Purpose

In this study , we examine the statistical relationship between earthquake swarms (especially, background rates) and volumetric strain records.

key factor: quantification of the difference in their response times

⇨ to develop a model for predicting the changes in background seismicity rate from the station record

# 2. ETAS model and tectonic seismicity around the Izu Peninsula till 1979

# Swarm earthquakes

・Swarms lacks obvious mainshock–aftershock sequence, and their occurrence is one of the clearest signals for temporal variations in the stress conditions and in the strength of faults.

・A swarm is driven by aseismic events.

・magma intrusions or fluid injection
・creep or slow-slip events

・It is difficult to distinguish the direct effect of magma intrusions from secondary triggering by earthquakes.

→ETAS model (Ogata, 1988)

$$\lambda_\theta(t|H_t) = \underbrace{\mu}_{\text{directly}} + \sum_{\{i:S<t_i<t\}} \underbrace{K_0 e^{\alpha(M_i - M_z)}/(t - t_i + c)^p}_{\text{triggering}}$$

# The maximum-likelihood estimate(MLE)

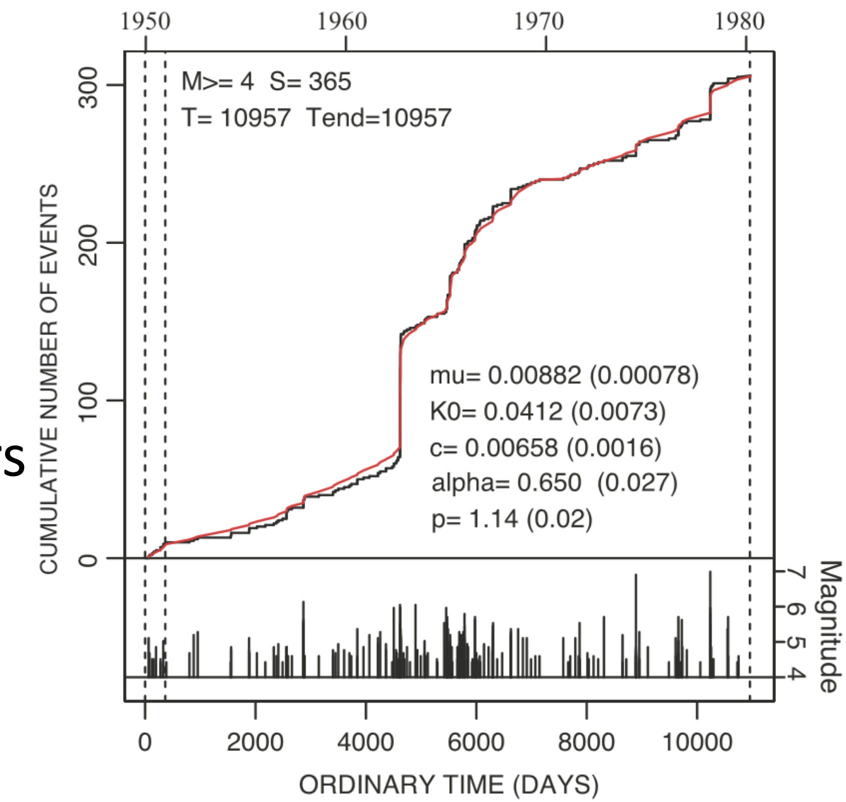
using the log-likelihood function (Ogata, 1988)

$$\ln L(\theta; S, T) = \sum_{\{i:S<t_i<T\}} \ln \lambda_\theta(t_i|H_{t_i}) - \int_S^T \lambda_\theta(t|H_t)dt$$

We assume that…

・the estimates of these parameters from the data before 1980 reflect the tectonic features in the region.

・they are independent of the magnitude threshold and time.




the result for earthquakes with M≥4 during 1950-1979

→$\hat{\mu} = 0.0082$ event/day $\widehat{K_0}$=0.0412 event/day $\hat{c}$=0.00658 0.00658 day

$\hat{\alpha}$=0.650 magnitude$^{-1}$ $\hat{p}$=1.14

# The reference ETAS model

re-estimate the background rate $\mu_{ref}$ and aftershock productivity $K_{ref}$

・using the earthquakes of $\mathrm{M} \geq 2.0$ in each swarm period

・The other parameters are fixed by the same MLE ($\hat{\alpha}$, $\hat{c}$, $\hat{p}$) as the above.

The periods of the investigated earthquake swarms and the estimates of the model parameters.

| Periods | | | #Events in swarm $M \geq 2$ | Reference parameters | |
|---|---|---|---|---|---|
| Year | Start | End | | $\mu_{ref}$ (events/day) | $K_{ref}$ (events/day) |
| 1988 | Jul 26 | Aug 18 | 710 | 0.569 | 0.0267 |
| 1989 | Jul 4 | Jul 14 | 380 | 0.403 | 0.0292 |
| 1993 | May 27 | Jun 3 | 376 | 0.389 | 0.0304 |
| 1995 | Sep 29 | Oct 8 | 510 | 0.596 | 0.0336 |
| 1997 | Mar 3 | Mar 21 | 734 | 0.338 | 0.0308 |
| 1998 | Apr 21 | May 10 | 1110 | 0.598 | 0.0336 |
| 2006 | Apr 17 | May 6 | 291 | 0.376 | 0.0346 |
| 2009 | Dec 17 | Dec 22 | 361 | 0.402 | 0.0345 |

# 3. Nonstationary ETAS model for swarm seismicity

# Nonstationary ETAS model

Our strategy builds upon past works (e.g., Llenos et al., 2009) to identify the modulated signals in the induced seismicity caused by magma intrusions.

→ We extend the ETAS model for the nonstationary earthquake. (Kumazawa and Ogata, 2013, 2014)

$\mu, K_0$ → time-dependent in such manner that $\mu(\mathrm{t})$ and $K_0(\mathrm{t})$

$\alpha, c, p$ →constant

Nonstationary ETAS:

$$\lambda_\theta(t|H_t) = \mu_{ref} q_\mu(t) + \sum_{\{i:S<t_i<t\}} K_{ref} q_K(t_i) e^{\alpha_{ref}(M_i - M_z)} / (t - t_i + c_{ref})^{p_{ref}}$$

# Inversion procedure by the nonstationary ETAS model

$q_\mu(t), q_K$(t) are defined as follows:

$$q_\mu(t) = \sum_{i=1}^{N} I_{(t_i,t_{i+1})}(t)\left\{\frac{q_{\mu,i+1}-q_{\mu,i}}{t_{i+1}-t_i}(t-t_i)+q_{\mu,i}\right\} = \sum_{i=1}^{N} q_{\mu,i}F_i(t),$$

$$q_K(t) = \sum_{i=1}^{N} I_{(t_i,t_{i+1})}(t)\left\{\frac{q_{K.i+1}-q_{K,i}}{t_{i+1}-t_i}(t-t_i)+q_{K,i}\right\} = \sum_{i=1}^{N} q_{K,i}F_i(t),$$

For example, at t ($t_n < t < t_{n+1}$)

$q_\mu(t)$=$\frac{1}{t_{n+1}-t_n}\{q_{K,n}(t_{n+1}-t) + q_{K,n+1}\,(t-t_n)\}$

parameter: $\boldsymbol{q} = (q_{K,i}, q_{\mu,i})$

To avoid over fitting, we use the penalized log-likelihood function (Good and Gaskins, 1970).

# The maximum a posteriori estimate

the penalized log-likelihood function:

$$Q\left(q|w_{\mu}, w_{K}\right) = \log L(q) - w_{\mu}\Phi_{\mu} - w_{K}\Phi_{K}$$

Where

$$\ln L(q) = \sum_{\{i:S<t_i<T\}} \ln \lambda_q\left(t_i|H_{t_i}\right) - \int_S^T \lambda_q\left(t|H_t\right)dt$$

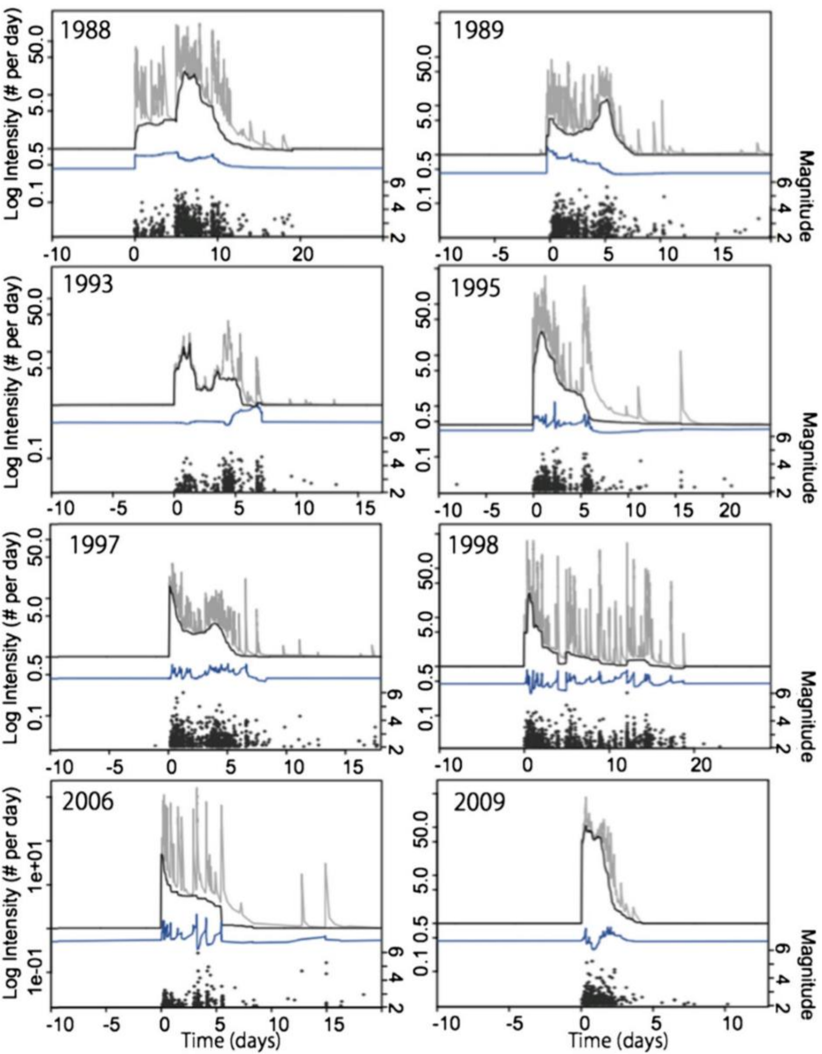
$$\Phi_{\mu} = \sum_{i=0}^{N}\left(\frac{q_{\mu,i+1} - q_{\mu,i}}{t_{i+1} - t_i}\right)^2 (t_{i+1} - t_i) \qquad \Phi_{K} = \sum_{i=0}^{N}\left(\frac{q_{K,i+1} - q_{K,i}}{t_{i+1} - t_i}\right)^2 (t_{i+1} - t_i)$$

$W_{\mu}, W_{K}$: weights that adjust the smoothness constraints

→decided by Akaike\`s Bayesian Information Criterion

(Akaike, 1980)

# Result of estimation




・The typical feature of the background rate is that it increases rapidly at the start of the swarm activity and eventually decreases.

・ The apparent temporal variations of the aftershock productivity $K_0$(t) are difficult to interpret.

・This model with the variable $K_0$ component significantly outperforms the model with constant $K_0$.

# 4. Relationship between the swarm background rates and volumetric strain record

# Volumetric strain record

The volumetric strainmeter is sensitive not only to magma intrusions.

→remove the effect of precipitation

(Kimura et al., 2015)

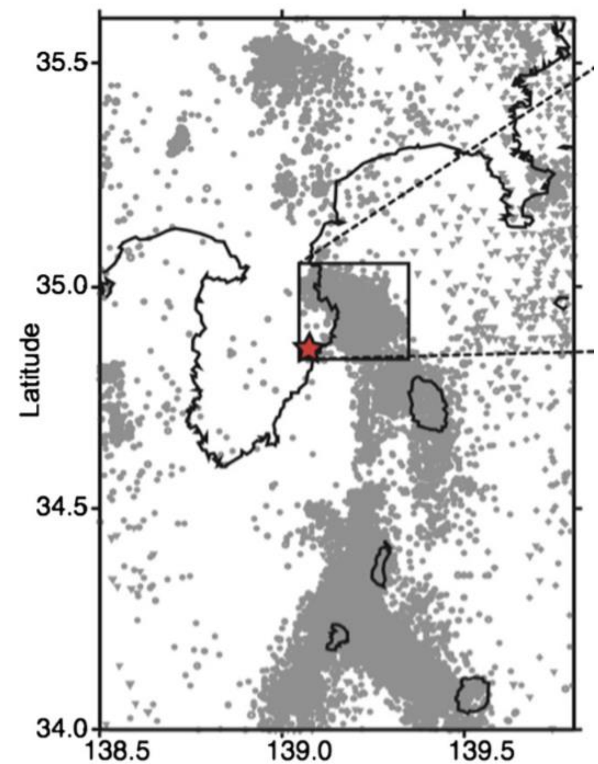
tidal effect

(Tamura et al., 1991)

barometric pressure

(Hikawa et al., 1983)

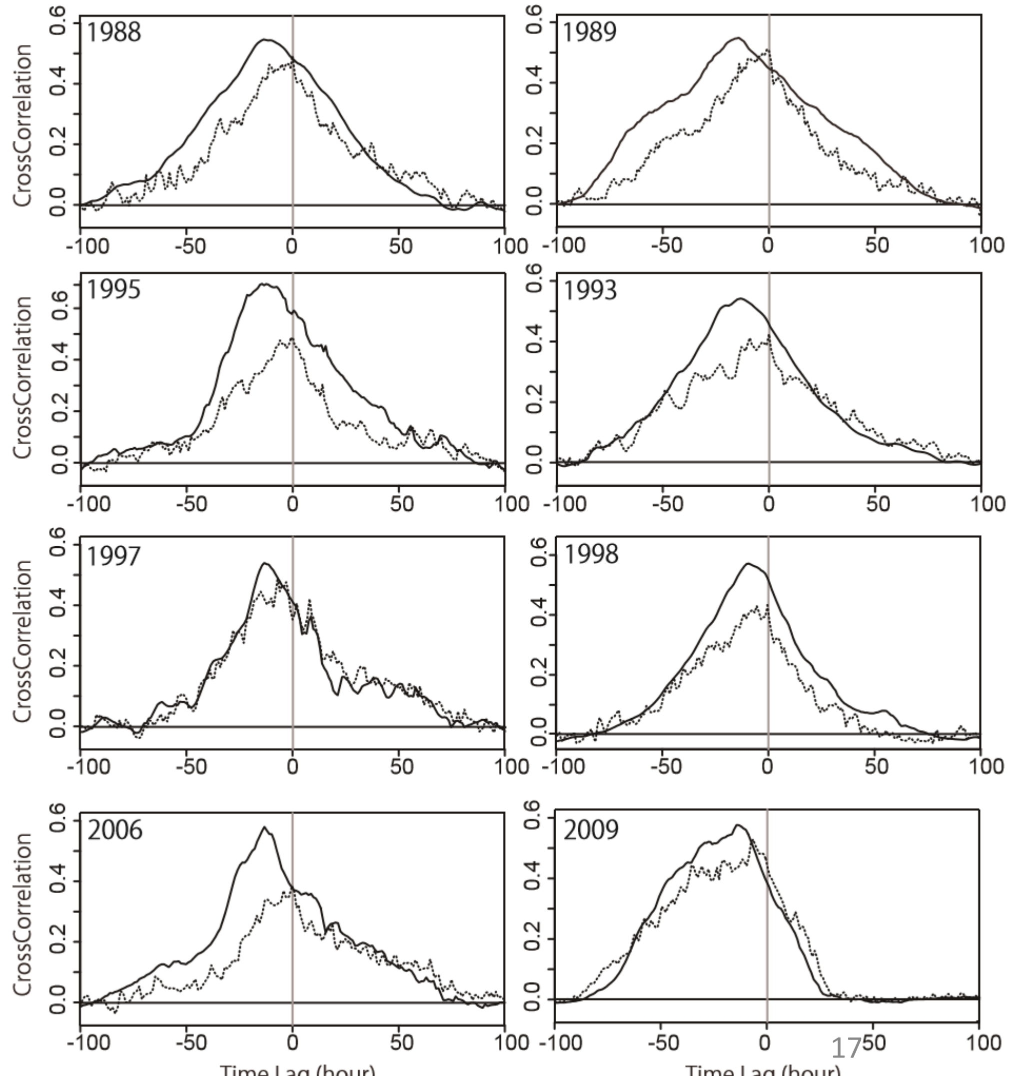
changes due tocoseismic effects



# Response times

・The corrected strain time series has higher cross-correlations to the background rate than to the occurrence rate of the earthquakes during each of the swarm periods.

・The background rate synchronizes more closely to the strain changes with lags of around half a day .



# The relation betweenthe volumetric strain increments and background rate

We examine whether the volumetric strain increments $Z_t$ can be used to predict the background rate.

$$\mu(t) = \sum_{k=0}^{K} \beta e^{-\sigma k} z_{t-k}$$

- MLE

  ETAS, $(\beta, \sigma, K_{ref}, \hat{\alpha}, \hat{c}, \hat{p})$

- the least squares method

→ Both estimates are close to each other, as listed in Table 2.

**Table 2**
Estimates of Equation (3).

| | MLE | | LS | | Distance (km) | AIC difference |
|---|---|---|---|---|---|---|
| | $\hat{\beta}(\times 10^7)$ (events/day) | $\hat{\sigma}$ ($h^{-1}$) | $\hat{\beta}_{LS}(\times 10^7)$ (events/day) | $\hat{\sigma}_{LS}$ ($h^{-1}$) | | |
| Total | 1.15 (.03) | 0.078 (.004) | 1.16 | 0.078 | | |
| 1988 | 0.96 (.05) | 0.076 (.006) | 0.95 | 0.074 | 22.14 | −182.3 |
| 1989 | 0.98 (.07) | 0.080 (.009) | 0.99 | 0.080 | 20.73 | −124.0 |
| 1993 | 1.18 (.08) | 0.074 (.009) | 1.19 | 0.074 | 19.85 | −56.1 |
| 1995 | 1.30 (.06) | 0.080 (.007) | 1.28 | 0.081 | 19.74 | −69.5 |
| 1997 | 1.10 (.05) | 0.075 (.006) | 1.10 | 0.074 | 19.96 | −43.0 |
| 1998 | 1.07 (.04) | 0.079 (.005) | 1.06 | 0.080 | 20.24 | −150.5 |
| 2006 | 1.11 (.09) | 0.078 (.011) | 1.11 | 0.078 | 19.95 | −23.3 |
| 2009 | 1.37 (.07) | 0.078 (.009) | 1.39 | 0.078 | 19.68 | −84.7 |

←$\hat{\sigma}$ is common to all swarm periods, whereas $\hat{\beta}$ varies in such a manner that they are inversely proportional to the distances between the station and the onset locations of the swarm events.

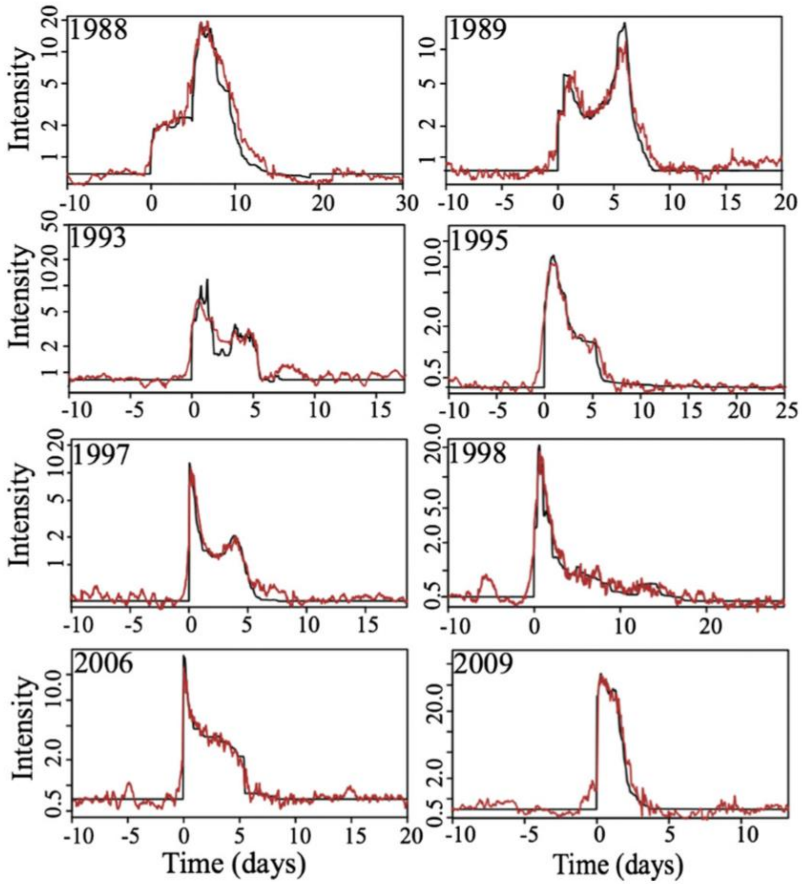
# Modulated ETAS

We replace the background parameter $\mu$ by the following.

$$\tilde{\mu}(t) = \left(q_1 + \frac{q_2}{q_3 + d(x, y)}\right) \sum_{k=0}^{K} e^{-\sigma k} z_{t-k}$$

i.e.

$$\lambda_\theta(t|H_t) = \tilde{\mu}(t) + \sum_{\{i:S<t_i<t\}} K_0 e^{\hat{\alpha}(M_i - M_z)}/(t - t_i + \hat{c})^{\hat{p}}$$




where $d(x, y)$ is the distance in meters between the station and the swarm onset location $(x, y)$. The coefficients are $q_1 = -9.14 \times 10^6$ (events/day), $q_2 = 1.41 \times 10^6$ (m) ($m$ events/day), $q_3 = -1.937 \times 10^3$ (m), $\sigma = 0.078$ ($h^{-1}$) for distances of 19.68–22.14 km.

# 5. Short-term swarm prediction

・Identifying the onset location is critical to the predictions of background and swarm seismicity rates.

・We have to be careful with the potential drawbacks of incorrect forecasts owing to possible erroneous strainmeter record processing.

・Incorporating other local instrumentation (GPS or other strainmeter data) would vastly improve the robustness of the prediction.

# 6. Discussion

- $R_E(t) = \beta \exp(-\sigma t)$ and $R_D(t) = {}^{a}/_{\{b+exp(-\sigma t)\}}$

The curve of $R_D(t)$ fits the data reasonably well although the goodness of fit is slightly worse than $R_E(t)$ in the AIC comparison.

- ${}^{1}/_{r}$relationship of the strain change and the distance

The far-field relationships do not appear to be quite appropriate, given the size of the intrusions and the proximity to the station.

# 7.Conclusion

We applied the nonstationary ETAS model to the swarms in the east Izu region. As a result, we found that…

・background rate changes coincide with thechanges of exponentially weighted averages of volumetric strain increments.

・this relationship consistently depends on the distance between thestrainmeter station and the location of the swarm onset.