Empirical forecast of occurrence of mainshocks based on foreshock activities

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Procedure for Selecting Foreshock Candidates

(1) To Eliminate Small Aftershocks
- Condition for Distance: \( \log L \leq 0.5 M_m - 1.8 \)
- Condition for Time: \( t \leq 10^{[0.17+0.85(M_m-4.0)]/1.3} - 0.3 \)
- Condition for Magnitude: \( M_a < M_m - M_d \) (where \( M_d = 1.0 \))

(2) To Segment Investigated Area
- Size of Segmentation: \( D^\circ \) (Latitude) \( \times \) \( D^\circ \) (Longitude)

(3) To Define Number of Earthquakes for Foreshock Candidates
- Magnitude Threshold of Foreshock Candidates: \( M \geq M_{f_0} \)
- Time Window for Counting Earthquakes: \( T_f \)
- Number of Earthquakes to Define Foreshock Candidates: \( N_f \)

(4) To Define Alarm Period for Mainshocks
Alarm period = \( T_a \) (days)
(Mainshocks: \( M \geq M_{m_0} \), All aftershocks are removed. \( \rightarrow \) Target \( M \geq \text{max} (M_{m_0}, M_{f_{\text{max}}}) \))
Schematic Diagram for Foreshock Candidates and Alarm Period

- Segment Size: \( D^\circ \times D^\circ \)
- Magnitude: \( M \geq M_f \)

(In the case of \( N_f = 3 \))

**Alarm Periods**

- Time window for foreshocks
- \( T_f (\text{days}) \)
- \( M_d = 1.0 \)
- \( T_a \text{ days} \)

**M-T Diagram**

- Cumulative Numbers during Past \( T_f \text{ Days} \)
- Occurrence Times of Proposed Foreshocks

\[ \text{[ false foreshock ]} \quad \text{[ true foreshock ]} \]
Indices for Prediction Performance

- Alarm Rate (AR) = (Number of Alarmed Mainshocks) / (Total Number of Mainshocks)

- Truth Rate (TR) = (Number of True Foreshocks) / (Number of Proposed Foreshocks)

- Probability Gain (PG) =
  (Occurrence Rate of M.S. in Predicted Space-Time) / (Background Occurrence Rate of M.S.)

- dAIC = (AIC for the Stationary Poisson Model) - (AIC for the Foreshock-based Prediction Model)
  ↑ The larger, the better.
Target Regions

- North-central Nagano
- San-in
- Off Izu Pen.
- 3 regions along the Japan trench
- Central Kyushu
**Estimating the Best Parameters by Grid Search**

*(Example for 3 Regions along the Japan Trench)*

Optimized period:
1961 – 2010

The range of grid search for Mm ≥ 6.0

Mf:
4.0, 5.0, 6.0

D:
0.25, 0.5, 1.0°

Tf:
10 days

Nf:
1, 2, ..., 10

Ta:
1, 2, ..., 10 days

**An example of grid search for Nf and Ta**
(In the case of Mm ≥ 6.0, Mf ≥ 5.0, D = 0.5°, and Tf = 10 days)

Optimized parameters

- Mf ≥ 5.0  •  D = 0.5°
- Tf = 10d  •  Nf = 3  •  Ta = 4d

**Performance**

- Alarm rate = 38% (=11/29)
- Truth rate = 30% (=13/44)
- PG = 380,  •  dAIC = 115
Prediction Performance for the 3 Regions along the Japan Trench

Best parameters: $D = 0.5^\circ$, $M_f \geq 5.0$, $T_f = 10d$, $N_f = 3$, $T_a = 4d$ for $M_m \geq 6.0$ (Target period: 1961 – 2017/12/31; Optimized period: 1961 – 2010)

Alarmed vs. Target Mainshocks
13/48 = 27%

True vs. Possible Foreshocks
17/79 = 22%
Prediction Performance for off the Izu Peninsula

Best parameters: $D = 0.2^\circ$, $Mf \geq 3.0$, $Tf = 3d$, $Nf = 3$, $Ta = 5d$ for $Mm \geq 5.0$

Alarmed vs. Target Mainshocks
44/65 = 68%

True vs. Possible Foreshocks
44/197 = 22%
**Prediction Performance for North-central Nagano Prefecture**

Best parameters: $D = 0.1^\circ$, $M_f \geq 2.0$, $T_f = 1 \text{ d}$, $N_f = 5$, $T_a = 5 \text{ d}$ for $M_m \geq 5.0$


- Alarmed vs. Target Mainshocks: $5/13 = 38\%$
- True vs. Possible Foreshocks: $8/73 = 11\%$
Foreshock Activity before the 2014 Northern Nagano Earthquake (M6.7)

Best parameters: D = 0.1°, Mf ≥ 2.0, Tf = 1d, Nf = 5, Ta = 5d for Mm ≥ 5.0
Prediction Performance for the Central Kyushu Region

Best parameters: $D = 0.1^\circ$, $M_f \geq 3.0$, $T_f = 10d$, $N_f = 3$, $T_a = 12d$ for $M_m \geq 5.0$

Alarmed vs. Target Mainshocks
$4/13 = 31\%$

True vs. Possible Foreshocks
$3/50 = 6\%$
The M6.4 earthquake on April 15th satisfies the condition of foreshock candidates (D=0.1°, Mf=3.0, Tf=10d, Nf=3).

The M7.3 mainshock occurred after 25 hours (within the alarm period of Ta = 12d).
Best parameters: $D = 0.1^\circ$, $M_f \geq 2.0$, $T_f = 5$ d, $N_f = 2$, $T_a = 12$ d for $M_m \geq 5.0$

Alarmed vs. Target Mainshocks 9/21=43%
True vs. Possible Foreshocks 11/509=2%
Prediction Performance for the San-in Region
(Using parameters with constrain of TR ≥ 5%)

Best parameters: \(D = 0.1^\circ\), \(M_f \geq 3.0\), \(T_f = 1\)d, \(N_f = 2\), \(T_a = 24\)d for \(M_m \geq 5.0\)

Alarmed vs. Target Mainshocks
5/21 = 24%

True vs. Possible Foreshocks
4/37 = 11%
Prediction Performance for Inland Japan
(Using parameters for off the N.C. of Nagano)

Best parameters: D = 0.1°, Mf ≥ 2.0, Tf = 1d, Nf = 5, Ta = 5d for Mm ≥ 5.0
(Target period: 1998 – 2017/12/31; Optimized for N.C. of Nagano)

Alarmed vs. Target Mainshocks
8/90=9%

True vs. Possible Foreshocks
10/509=2%
Prediction Performance for Inland Japan
(Using parameters for off the Izu peninsula)

Best parameters: $D = 0.2^\circ$, $M_f \geq 3.0$, $T_f = 3d$, $N_f = 3$, $T_a = 5d$ for $M_m \geq 5.0$
(Target period: 1977 – 2017/12/31; Optimized for off the Izu peninsula)

Alarmed vs. Target Mainshocks 23/196=12%

True vs. Possible Foreshocks 30/672=4%
## Summary of Prediction Performance

<table>
<thead>
<tr>
<th>Target Regions</th>
<th>Target Periods</th>
<th>Best Parameters D, Mf₀, Tf, Nf, Ta, Mm₀ (optimized period)</th>
<th>Alarm Rates</th>
<th>Truth Rates</th>
<th>PG (for optimized period)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 regions along the Japan trench</td>
<td>1961～*</td>
<td>0.5, 5.0, 10, 3, 4, 6.0 (1961～2010)</td>
<td>27% (=13/48)</td>
<td>22% (=17/79)</td>
<td>380</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1, 3.0, 3, 5, 5.0 (1977～2013/6)</td>
<td>68% (=44/65)</td>
<td>22% (=44/197)</td>
<td>225</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1, 2.0, 1, 5, 5, 5.0 (1998～2014)</td>
<td>38% (=5/13)</td>
<td>11% (=8/73)</td>
<td>333</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1, 3.0, 10, 3, 12, 5.0 (1970～2016/5)</td>
<td>31% (=4/13)</td>
<td>6% (=3/50)</td>
<td>365</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1, 2.0, 5, 2, 12, 5.0 (1977～2016)</td>
<td>43% (=9/21)</td>
<td>2% (=11/509)</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1, 3.0, 1, 2, 24, 5.0 (under TR ≥ 5%)</td>
<td>24% (=5/21)</td>
<td>11% (=4/37)</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1, 2.0, 1, 5, 5, 5.0 (from Nagano case)</td>
<td>9% (=8/90)</td>
<td>2% (=10/509)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2, 3.0, 3, 3, 5, 5.0 (from Izu case)</td>
<td>12% (=23/196)</td>
<td>4% (=30/672)</td>
<td>-</td>
</tr>
<tr>
<td>Off the Izu pen.</td>
<td>1977～*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N.C. of Nagano</td>
<td>1998～*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central Kyushu</td>
<td>1970～*</td>
<td></td>
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<td></td>
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<tr>
<td>San-in</td>
<td>1977～*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inland of Japan (not optimized)</td>
<td>1998～*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1977～*</td>
<td></td>
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</tr>
</tbody>
</table>

* 2017/12/31
Comparison with the ETAS Model

Procedure of calculating probability based on the ETAS model

1. Estimate the **b-value** and **parameters** of the ETAS model
data: $M \geq M_{th}$, optimized for each region

2. Calculate the **expected occurrence rate** of the target events
target period: $T_a$ days after each event
target $M$: $M \geq \max (M_{m_0}, M_{f_{max}})$
target area: all area within the each region
magnitude distribution: G-R model
constant rate during $T_a$ days

3. Calculate probability assuming **Poisson process** during $T_a$ days
$P(n \geq 1) = 1 - e^{-\lambda \cdot T_a}$
Foreshocks vs. ETAS Model
(N-C. Nagano Prefecture)

- 8 cases are successful
- target period: 5 days
- target M:
  \[ M \geq \max(5.0, M_{f_{\text{max}}}) \]
- **Red line**: Truth rate of the foreshock model (10.9%)
- **Blue line**: Probability by the ETAS model
- The ETAS value is at just before the target event

### ETAS Parameters
Region: N-C. Nagano
Period: 1998-2014/10
\[ M_{\text{th}} = 1.95 \]
\[ b = 0.84 \]
\[ \mu = 0.14 \]
\[ K = 0.0191 \]
\[ c = 0.0012 \]
\[ \alpha = 1.30 \]
\[ p = 1.05 \]

### Foreshock Parameters
1998-2014
\[ D = 0.1^\circ \]
\[ M_f \geq 2.0 \]
\[ Tf = 1d \]
\[ N_f = 5 \]
\[ Ta = 5d \]
\[ M_m \geq 5.0 \]
The ETAS values are lower than the truth rate of the foreshock model for all the 8 cases.
Foreshocks vs. ETAS Model
(Central Kyushu District)

- 3 cases are successful
- target period: 12 days
- target M: $M \geq \max (5.0, M_{f_{\text{max}}})$
- Red line: Truth rate of the foreshock model (6.0%)
- Blue line: Probability by the ETAS model
- The ETAS value is at just before the target event

ETAS Parameters
Region: C. Kyushu
Period: 1970-2016/3
$M_{\text{th}} = 2.95$
$b = 0.74$
$\mu = 0.03$
$K = 0.0104$
$c = 0.0074$
$\alpha = 1.38$
$p = 1.11$

Foreshock Parameters
1970-2016/5
$D = 0.1^\circ$
$M_f \geq 3.0$
$T_f = 10d$
$N_f = 3$
$T_a = 12d$
$M_m \geq 5.0$

Largest foreshock
1977/6/17 8:30:58 M3.3
Foreshock: 6.0%
ETAS: 1.9%
1977/6/28 11:46:42 M5.3

2 1984/8/4 14:51:17 M3.1
Foreshock: 6.0%
ETAS: 1.4%
1984/8/5 17:28:13 M5.0
1984/8/6 17:30:5 M5.7

3 2016/4/15 0:3:46 M6.4
Foreshock: 6.0%
ETAS: 4.4%
2016/4/16 1:25:5 M7.3

Red line: Truth rate of the foreshock model (6.0%)
Blue line: Probability by the ETAS model
The ETAS value is at just before the target event
Foreshocks before the 2011 Off Tohoku Eq. (2011/3/11 14:46, M9.0)
Foreshocks vs. ETAS Model
(2011 Off Tohoku Eq. (M9.0))

- Case: 2011.3.11 M9.0
- target period: 4 days
- target M:
  \[ M \geq \max (6.0, M_{f_{\text{max}}}) \]
- Red line: Truth rate of the foreshock model (21.5%)
- Blue line: Probability by the ETAS model (1.8%)
- The ETAS value is at just before the target event and for broad area along the Japan trench.

**ETAS Parameters**
Region: along the Japan trench
Period: 1961-2011/2
\[ M_{th} = 4.95 \]
\[ b = 0.99 \]
\[ \mu = 0.06 \]
\[ K = 0.0184 \]
\[ c = 0.0265 \]
\[ \alpha = 1.76 \]
\[ p = 1.10 \]

**Foreshock Parameters**
1961-2010
\[ D = 0.5^\circ \]
\[ M_{f} \geq 5.0 \]
\[ T_{f} = 10d \]
\[ N_{f} = 3 \]
\[ T_{a} = 4d \]
\[ M_{m} \geq 6.0 \]

Red line: Truth rate of the foreshock model (21.5%)
Blue line: Probability by the ETAS model (1.8%)
Aseismic Slip during Foreshock Activity (2011 Off Tohoku Eq. (M9.0))

- Migration
- Aseismic slip following the foreshock

[Tohoku Univ. (2011)]

[Ohta et al. (2012)]

[Kato et al. (2012)]
Aseismic slip during Foreshock Activity
(2016 Kumamoto Eq. (M7.3))

Aseismic slip may be an additional or a main triggering source.

A prediction model should take this effect into account appropriately.

One of the reason why our foreshock model gives higher probability than ETAS may be that our model may implicitly include this effect more appropriately than ETAS.
We have proposed a method to select foreshock candidates, which produces relatively high performance for predicting mainshocks.

For example, the performance are

AR = 27%, TR = 22%, PG = 380 for 3 regions along the Japan Trench
AR = 68%, TR = 22%, PG = 225 for off the Izu Peninsula
AR = 38%, TR = 11%, PG = 333 for the North-central Nagano Prefecture
AR = 31%, TR = 6%, PG = 365 for the Central Kyushu District

Our model tend to calculate higher probability values at the mainshock occurrence time than those by the ETAS model.

Aseismic slip during foreshock activity may have an important role to trigger a mainshock, which should be taken into account appropriately in the model.