Foreshocks of M9.0 Tohoku earthquake

Kato et al. (Science 2012)
Foreshocks of M9.0 Tohoku earthquake

Eleven $4.0 \leq m < 5.5$ earthquakes between 14/1/2011 and 27/2/2011
Is this activity in early 2011 anomalous?
The equation for the displacement $y(t)$ is given by:

$$y(t) = a + bt + c \sin(2\pi t) + d \cos(2\pi t) + e \sin(4\pi t) + f \cos(4\pi t) + g H(t - t_0) + k \log\left(1 + \frac{t-t_0}{\tau}\right) H(t-t_0)$$

where:
- $a$, $b$, $c$, $d$, $e$, $f$, $g$, and $k$ are coefficients.
- $H(t)$ is the Heaviside step function.

The displacement can be broken down into:
- **secular**
- **annual + semi-annual**
- **coseismic**
- **postseismic**

The graph shows the measured and modeled displacements over time for the Craig earthquake (Alaska) at station AB49.
Far-field co-seismic:

\[
\begin{align*}
y(t) &= g \, H(t - t_0) \\
g &\sim \frac{M_0}{r}
\end{align*}
\]

[Diagram showing seismic activity with labels for Oita, North of Mt. Aso, Paucity of aftershocks, and specific geographic coordinates.]
Far-field co-seismic (GPS):

\[
y(t) = g H(t - t_0)
\]

\[
g \sim \frac{M_0}{r}
\]

Aftershock triggering: \( N(M_0) \sim M_0^x \) with \( 0.3 < x < 0.7 \)

Marsan and Lengliné 2008

Helmstetter 2014

Japan \( M = 9.1 \)

Sumatra \( M = 9.0 \)

California \( 2 < M < 7.5 \)

\( x = 0.4 \)

\( x = 0.67 \)
\[ y(t) = a + bt + c \sin(2\pi t + \varphi) + d \sin(4\pi t + \psi) + \sum_{i} g_i H(t - t_i) + k_i \log\left(1 + \frac{t - t_i}{\tau_i}\right) H(t - t_i) \]

**GPS:**

Only the largest shocks

**Seismicity:**

\[ N(t) = \text{secular} + \text{triggered} (\text{aftershocks}) \]
CORSSA: the Community Online Resource for Statistical Seismicity Analysis

## CORSSA articles in Theme IV

- Earthquake location accuracy
- Completeness magnitude in earthquake catalogs
- Catalog artifacts and quality control
- What is an instrumental seismicity catalog?

## CORSSA articles in Theme V

- Basic models of seismicity: temporal models
- Basic models of seismicity: spatiotemporal models
- Seismicity models based on Coulomb stress calculations
- Earthquake triggering caused by the external oscillation of stress/strain changes
- Seismicity rate changes
- Seismicity declustering
- Stochastic simulation of earthquake catalogs

## CORSSA articles in Theme VI

- Evaluating earthquake predictions and earthquake forecasts: a guide for students and new researchers
Declustering

= \hspace{1cm}

Removing aftershocks

= \hspace{1cm}

For mainshock H, find its aftershocks

Gardner and Knopoff BSSA 1974
Reasenberg JGR 1985
Declustering = Removing aftershocks = For earthquake $E$, find its trigger among all previous shocks $H_i$

- **Single link clusters** (Davis and Frohlich, GJI, 1991)
- **Stochastic declustering** (Zhuang et al., JASA, 2002)
For earthquake $E$, find its trigger among all previous shocks $H_i$.

Bayes

$$P(H_i|E) = \frac{P(E|H_i)}{\sum_i P(E|H_i)}$$

$$P(E|H_i) = \text{Probability 1 earthquake E in } \begin{cases} \text{volume } [x, x+dx] \\ \text{interval } [t, t+dt] \text{ knowing } H_i \text{ is the trigger} \\ \text{interval } [m, m+dm] \end{cases}$$

$$P(E|H_i) = \lambda_i \, dx \, dt \, dm \quad \rightarrow \quad P(H_i|E) = \frac{\lambda_i}{\sum_i \lambda_i}$$
For earthquake $E$, find its trigger among all previous shocks $H_i$.

An earthquake can also occur **spontaneously**: it is not the aftershock of a (known) previous mainshock.

$H_0 = \text{no seismic trigger}$ \hspace{1cm} $P(E|H_0) = \mu \ dx \ dt \ dm$

$$P(H_0|E) = \frac{\mu}{\mu + \sum_i \lambda_i}$$

$$P(H_i|E) = \frac{\lambda_i}{\mu + \sum_i \lambda_i}$$
For earthquake $E$, find its trigger among all previous shocks $H_i$ only if $H_1$ and $H_2$ are independent.

\[
P(E) = P(E|H_1)P(H_1) + P(E|H_2)P(H_2)
\]

only if $H_1$ and $H_2$ are independent

Is this the case?
Triggering according to rate-and-state friction

Velocity weakening faults already accelerating (nucleation)
\[ \frac{N(t_1) + N(t_2)}{N_1 + N_2} = \frac{\Delta t}{t_a} \]
For earthquake $E$, find its trigger among all previous shocks $H_i$

$$P(E) = P(E|H_1)P(H_1) + P(E|H_2)P(H_2)$$

only if $H_1$ and $H_2$ are independent

Is this the case?

No according to rate-and-state

But:
- Departure is only significant at short time scales
- Departure vanishes when $\Delta t \to \infty$
- Total $N$ is linear
Static stress triggering with rate-and-state

M = 3 earthquake (L = 400 m, u = 1 cm)

\[ \Delta \text{CFF (bars)} \]

Marsan and Lengliné (JGR) 2010
Rate-and-state friction

\[ n = \# \text{ of direct aftershocks in time } [0, t] \text{ and distance } [R_1, R_2] \]

\[ n = \mu(R_1, R_2) \cdot t_a \left\{ \ln \left( e^{t/t_a} + e^{-\Delta CFF/A\sigma} - 1 \right) + \frac{\Delta CFF}{A\sigma} - \frac{t}{t_a} \right\} \]

Dieterich (JGR) 1994
Rate-and-state friction

\[ n = \mu(R_1, R_2) \left( t_a \ln \left( e^{\frac{t}{t_a}} + e^{-\frac{\Delta CFF}{A\sigma}} - 1 \right) + \frac{\Delta CFF}{A\sigma} - \frac{t}{t_a} \right) \]

Background density

\[ \mu(R) \sim R^{1.65} \]

Total number \( N \) grows in \( L^{1.65} \sim M_o^{0.55} \)
FOR: $0 < t < 1$ hour

\begin{align*}
\text{Linear density (a. u.)} & \quad 10^{-10} \\
\text{Distance } r \text{ (km)} & \quad 10^{-2} \quad 10^{-1} \quad 10^0 \quad 10^1 \quad 10^2
\end{align*}

\text{RUPTURE ZONE}

$\text{r}^{-2.2}$

\begin{align*}
\text{Linear density (a. u.)} & \quad 10^{-10} \\
\text{Distance } r \text{ (km)} & \quad 10^{-2} \quad 10^{-1} \quad 10^0 \quad 10^1 \quad 10^2
\end{align*}

\text{RUPTURE ZONE}

$\text{r}^{-2.4}$
For earthquake E, find its trigger among all previous shocks $H_i$

\[ P(E) = P(E|H_1)P(H_1) + P(E|H_2)P(H_2) \]

only if $H_1$ and $H_2$ are independent

Is this the case?

No according to rate-and-state

- Departure is only significant at short time scales
- Departure vanishes when $\Delta t \rightarrow \infty$
- Total N is linear
- Rate decays in $t^{-1}$
- Rate decays in $r^{-\gamma}$ ($\gamma \approx 2$)
- Total N grows in $M_o^x$ ($x \approx 0.5$)
For earthquake $E$, find its trigger among all previous shocks $H_i$

**ETAS (space-time) models:**

- $N$ is linear
- Rate decays in $t^p$
- Rate decays in $r^{-\gamma}$
- Total $N$ grows in $M_0^x$


\[
P(E|H_i) = \lambda_i \, dx \, dt \, dm \quad \Rightarrow \quad P(H_i|E) = \frac{\lambda_i}{\sum_i \lambda_i}
\]

\[
\lambda_i = \frac{Ke^{am}}{(t+c)^p} \left(r+L_m\right)^{-\gamma}
\]
For earthquake $E$, find its trigger among all previous shocks $H_i$

\[ P(H_0 | E) = \frac{\mu}{\mu + \sum_i \lambda_i} \]

\[ P(H_i | E) = \frac{\lambda_i}{\mu + \sum_i \lambda_i} \]

\[ \lambda_i = \frac{K e^{\alpha m}}{(t+c)^p} \left( r + L_m \right)^{-\gamma} \]

- Compute $P(H_i | E)$ and $P(H_0 | E)$ for all earthquakes $E$
- Smooth $P(H_0 | E)$ in space and time
- Iterate until convergence
\[
N(j) = \sum_{i \leq j} P(H_0^i | E_i)
\]
Small scale transients: $\ell = 20$ km, $\tau = 40$ days

Marsan et al. JGR 2013
Yokota and Koketsu
(Nat. Comm., 2015)
All m \geq 3
Rate change of background activity 1990 – 2011
2008 M7.0 Ibaraki earthquake
Plate interface geometry in the Kanto region and model setting. The blue and red iso-depth contours (10-km intervals) represent the NAM-PHS and NAM/PHS-PAC plate interfaces, respectively. The blue-stippled portion of the NAM-PHS plate interface and the pink-coloured portion of the PHS-PAC plate interface show the model regions for inversion analysis. The blue and red arrows indicate the steady slip vectors at the NAM-PHS and PHS-PAC plate interfaces, respectively. NAM, North American plate; PHS, Philippine Sea plate; PAC, Pacific plate. Noda et al. 2013.
Figure 3

Slip deficit distribution on the Philippine Sea slab deduced from the GPS velocity data in Figure 2. Solid contours show magnitudes of slip deficit vectors. Dashed contours denote the configuration of the Philippine Sea slab. Thick arrows indicate relative plate motion of the Pacific plate (PA-NA) and the Philippine Sea plate (PH-NA) with respect to the North American plate.

Figure 6

Comparison of the slip distribution of the 1996 Boso silent earthquake (DOY 144), the slip deficit distribution in Figure 3, and the plate configuration (dashed contours). Squares denote hypocenters of shallow (depth < 50 km) earthquakes during DOY 136-144 of 1996. Clusters 1 and 2 are seismicity associated with the silent earthquake.
Figure 4. Inferred displacement at Boso, using our estimated background rate, and the relationship of Figure 3. The dashed curve is obtained after removing the SSEs; the thick curve has also the transients $A_1$ - $A_3$ and the direct effect of the 2011 Tohoku-Oki earthquake removed. The best quadratic polynomial fit is shown. It yields a fixed displacement of 11.4 cm between the 1996, 2002, 2007 and 2011 SSEs.

Figure 2. Cumulative number of earthquakes (in red) and time series of the background seismicity rate $\mu_{\text{str}}$ (in blue) for the Boso area. The three transients occurring outside the five known SSEs are labeled $A_1$, $A_2$, and $A_3$. 
Figure 3. Detected swarms and swarm ratios in the southern Japan Trench. (a) Hypocenters of swarms detected by our analysis. Hypocenters of detected swarms are shown as small circles and colored according to their occurrence time. The hypocenter of the 2008 M6.9 Ibaraki-Oki earthquake is indicated by the blue star. The color shading denotes areas where more than 10 m of slip occurred during the 2011 Tohoku earthquake [Ide et al., 2011]. (b) Swarm ratios calculated for each detection circle. The large circle is an example of a detection circle of radius 30 km; the small circles indicate the center of each detection circle and are colored according to the computed swarm ratio.
12 m / 2000 years = **0.6 cm / year** only

(instead of 2 to 3 cm / year)
Only assume **linearity** and search for a **mean-field** solution

\[
\lambda_i = \frac{Ke_{am}}{(t+c)^p} (r+L_m)^{-\gamma}
\]

- OK for aftershocks
- But not for other processes, eg LFE during SSE
Contribution from \#i

\[ \lambda_i(x, t) = \lambda_{j,k,l} \]

Distance from \#i to x

Time \( t - t_i \)

Magnitude \( m_i \)

(Maximization)

\[ \lambda_{j,k,l} = \frac{n_{j,k,l}}{n_l \delta t_k \delta V_j} \]

window duration

shell volume
## Predictive policing

The Chicago Data Portal provides a dataset reflecting reported incidents of crime with the exception of murders where data exists for Crimes - 2001 to present.

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<th>ID</th>
<th>Case Number</th>
<th>Date</th>
<th>Block</th>
<th>IUCCR</th>
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<th>Description</th>
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<td>047XX W VAN BUREN ST</td>
<td>143A</td>
<td>WEAPONS VIOLATION</td>
<td>UNLAWFUL POS OF HANDGUN</td>
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<tr>
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<td>09/20/2017 10:56:00 PM</td>
<td>069XX S WOODLAWN AVE</td>
<td>041A</td>
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<td>AGGRAVATED: HANDGUN</td>
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<td>031A</td>
<td>ROBBERY</td>
<td>ARMED: HANDGUN</td>
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<tr>
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<td>040XX W GLADYS AVE</td>
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<td>DOMESTIC BATTERY SIMPLE</td>
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<td>38</td>
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<td>09/20/2017 10:51:00 PM</td>
<td>080XX S COTTAGE GROVE</td>
<td>5111</td>
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<td>GUN OFFENDER: ANNUAL REGISTRATION</td>
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<td>TO PROPERTY</td>
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<td>ATT: AUTOMOBILE</td>
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<td>ATTEMPT FORCIBLE ENTRY</td>
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<td>THEFT</td>
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<td>1310</td>
<td>CRIMINAL DAMAGE</td>
<td>TO PROPERTY</td>
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**Totals** 6438416
Predpol software is based on exactly the same algorithm as used for stochastic earthquake declustering.
Contribution from #i

\[ \lambda_i(x, t) = \lambda_{j,k} \]

Distance from #i to x

Time \( t-t_i \)

(Maximization)

\[ \lambda_{j,k} = \frac{n_{j,k}}{n_l \delta t_k \delta V_j} \]

window duration

shell surface
3. A SELF–EXCITING POINT PROCESS MODEL OF BURGLARY

For the purpose of modeling burglary we consider an un-marked self-exciting model for the conditional intensity of the form

$$\lambda(t, x, y) = v(t)\mu(x, y) + \sum_{\{k : t_k < t\}} g(t - t_k, x - x_k, y - y_k). \quad (10)$$
3. A SELF-EXCITING POINT PROCESS MODEL OF BURGLARY

For the purpose of modeling burglary we consider an unmarked self-exciting model for the conditional intensity of the form

$$\lambda(t, x, y) = \nu(t)\mu(x, y) + \sum_{\{k: t_k < t\}} g(t - t_k, x - x_k, y - y_k). \quad (10)$$

Figure 4. Marginal $g_{75}(t)$ (left) and marginal $g_{75}(x)$ (right) estimated using KDE based upon offspring/parent interpoint distances sampled from $P_{75}$. 
Flag the N spots with highest $\mu$ values
**Prediction Results**

PredPol predicts a greater number of gun homicides using its unique prediction methodology compared with alternative approaches.

---

**Track Record**
Third Year In L.A. Still Having An Effect

-20%

Foothill Division Property Crime
Jan’14-June’14
(year over year)

Source: LAPD’s Capt. Sean Malinowski, July 2014
Expanding and Starting CSEP Natural Laboratories

D. Schorlemmer¹, J. D. Zecher¹, and T. H. Jordan¹
¹ University of Southern California, Los Angeles, USA.

Abstract

Natural laboratories are a key concept in the Collaboratory for the Study of Earthquake Predictability (CSEP). They define regions in which earthquake generation models are tested and the rules of those tests. Defining natural laboratories requires profound knowledge about available data sources, e.g., earthquake catalogs. This includes knowledge about data generation, uncertainties, and derived properties and completeness of catalogs. CSEP employs working groups for data, test, and model standardization and guidelines for natural laboratory development. We present the already implemented natural laboratory of California and the efforts in establishing laboratories in New Zealand, the Basin & Range region, the Western Pacific region, and for global testing.

Datasets
- Euro-Med Natural Laboratory
  - Data sources: Catalogs, catalogs, catalogs
  - Models: Emphasis on European-Mediterranean region

- New Zealand Natural Laboratory
  - Data sources: Catalogs, catalogs, catalogs
  - Models: Emphasis on New Zealand

- Western Pacific Natural Laboratory
  - Data sources: Catalogs, catalogs, catalogs
  - Models: Emphasis on Western Pacific

Summary

These examples illustrate a few of the increasing challenges of defining a natural laboratory:
- Identifying the appropriate earthquake catalogs
- Working with regions containing multiple authoritative sources (e.g., California)
- Testing with regions where an authoritative source has been identified (e.g., Basin & Range)
- Testing across the broader geographical boundaries (e.g., Italy)
- Working in regions with substantial sources (e.g., New Zealand)

All of these issues arise from the simplest forms of observation. Sensitivity analysis, as CSEP exercises, the experiment space to include other data such as LPS or fault models, careful consideration should be given to the process of defining the natural laboratory.
Uchida and Matsuzawa (EPSL) 2013

(a) Graph showing cumulative slip from 1985 to 2010 with a scale of 50cm.
(b) Graph showing cumulative slip from 1985 to 2010 with a scale of 50cm.
(c) Graph showing cumulative slip from 1985 to 2010 with a scale of 50cm.
(d) Graph showing cumulative slip from 2011 with a scale of 50cm.
(e) Graph showing cumulative slip from 2011 with a scale of 50cm.
(f) Graph showing cumulative slip from 2011 with a scale of 50cm.
(g) Map with labeled sections and cumulative slip values.

Time (Year) / Cumulative Slip
RE time series show clustering just as well as « normal » seismicity