The M9 Tohoku-Oki Earthquake and Statistical Seismology

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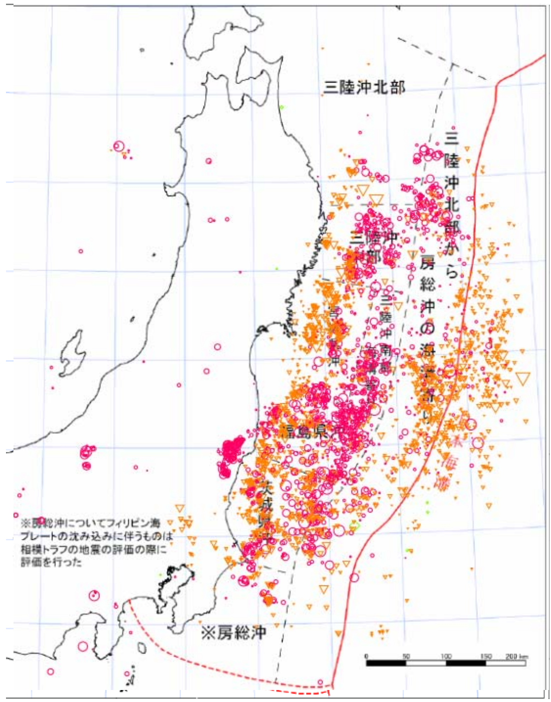
1. Long-term Probability forecasting and repeating earthquakes
2. Prediction and diagnostic analysis of seismic activity
3. Discrimination of foreshocks and their operational forecasting

30 years after

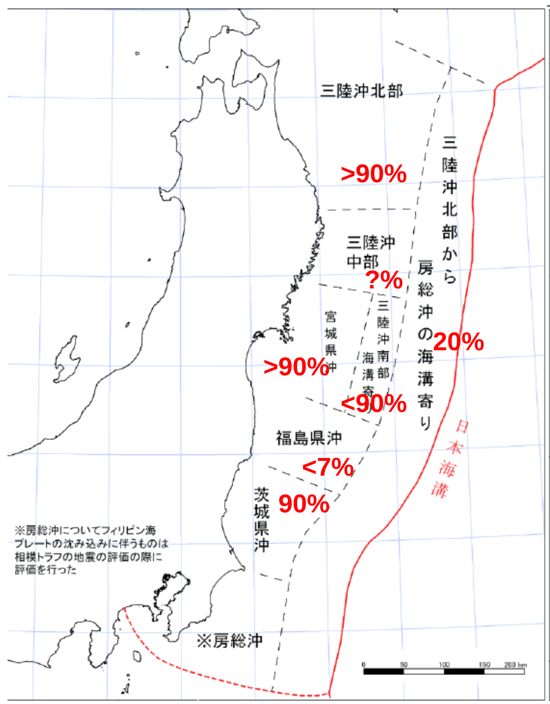


Long-term earthquake forecast

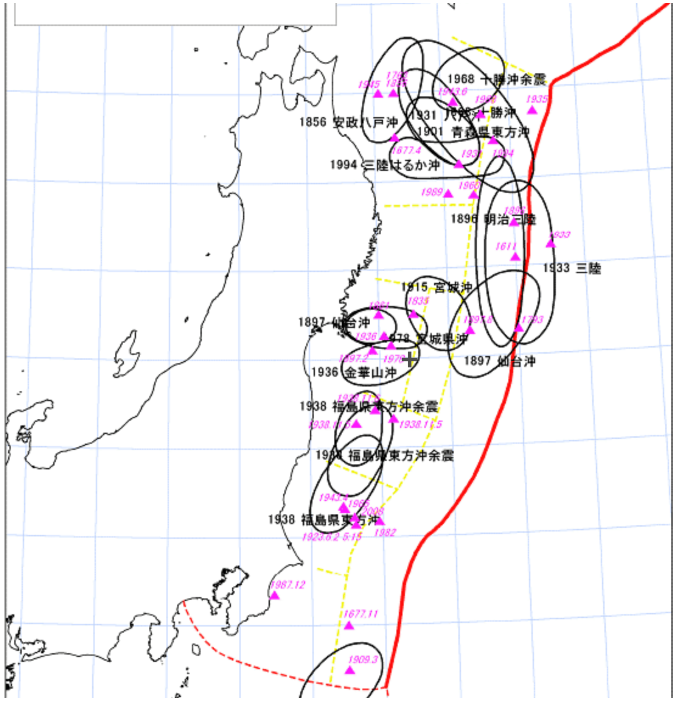
- The Earthquake Research Committee (ERC) of Japan opens the probabilities that earthquakes will occur in the future at main active faults and subduction-zones in Japan to the public.

Long-term evaluation of the subduction-zones

Long-term evaluation of the main active faults

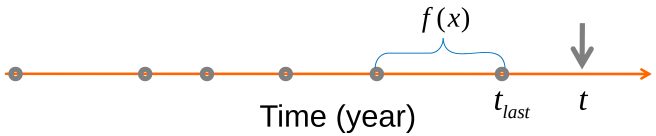


The main focal area of major Earthquakes From Sanriku-Oki to Boso-Oki （**ERC**, **1999**）



Miyagi-Ken-Oki Earthquake

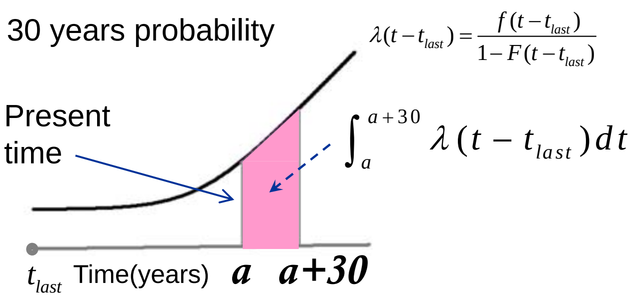
地震発生年月日	前回の地震からの経過年数(年)	地震の規模	備考
1793年2月17日		M8．2程度	連動の場合
1835年7月20日	42．4年	M7．3程度	単独の場合
1861年10月21日	26．3年	M7．4程度	単独の場合
1897年2月20日	35．3年	M7．4	単独の場合
1936年11月3日	39．7年	M7．4	単独の場合
1978年6月12日	41．6年	M7．4	単独の場合



Renewal process models

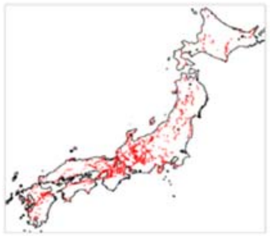
$$\lambda(t \mid History) = \lambda(t - t_{last}) = \frac{f(t - t_{last})}{1 - F(t - t_{last})}$$

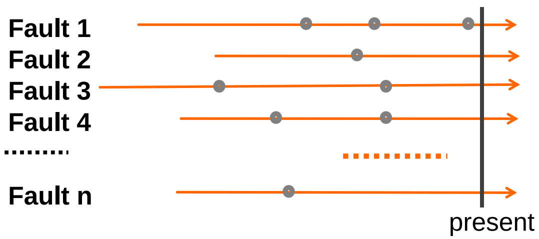
30 years probability



30 years surviving probab. = exp (– Area of ▰)

Active faults





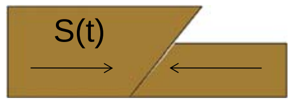
What is the BPT renewal process?

- Probabilistic model for earthquake generation

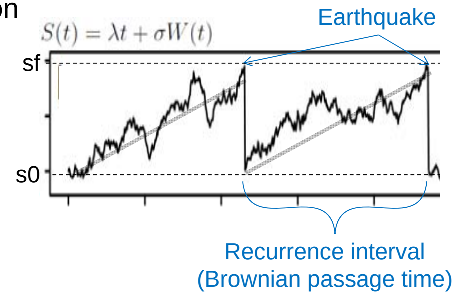
- Brownian relaxation oscillator process

$$S(t) = \lambda t + \sigma W(t)$$

Brownian motion with drift λ



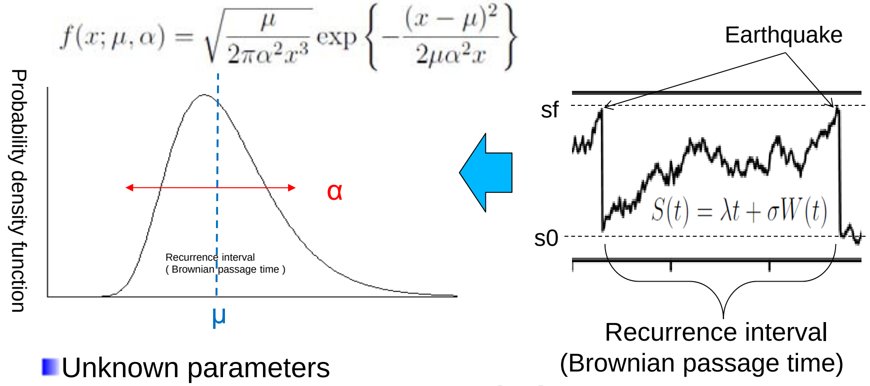
- S(t): Stress accumulation
- W(t): Standard Brownian motion
- λ: Loading rate
- σ: Perturbation rate
- sf: Failure state
- s0:Ground state



What is the BPT renewal process?

- Brownian Passage Time (BPT) distribution

$$f(x;\mu,\alpha) = \sqrt{\frac{\mu}{2\pi\alpha^2 x^3}} \exp\left\{-\frac{(x-\mu)^2}{2\mu\alpha^2 x}\right\}$$



- Unknown parameters

Mean $\mu = E[X_i] = \frac{s_f - s_0}{\lambda}$

Coefficient of variation $\alpha = \frac{\sqrt{Var[X_i]}}{E[X_i]} = \frac{\sigma}{\sqrt{\lambda(s_f - s_0)}}$

Forecasting method by ERC

- Predictive distribution for interval time x from the latest earthquake to the next earthquake

Plug-in predictive density

$$\hat{f}(x) = f(x|\hat{\mu},\hat{\alpha})$$

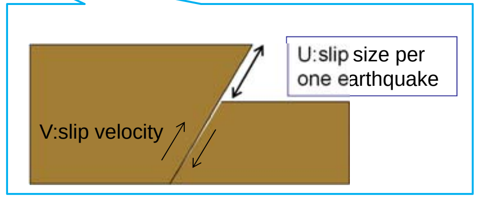
$$\hat{\mu} = \begin{cases} \bar{X} = \sum_{i=1}^{n} X_i/n \\ T = U/V \end{cases}$$

Mean of past intervals **X** = (X1 ･･･ Xn)

or

$$\hat{\alpha} = 0.24$$

MLE from 4 active faults where a lot of earthquakes turned out.



S. Nomura（SOKENDAI D3）

Proposal

- Predictive distribution for interval time x from the latest earthquake to the next earthquake

Bayesian predictive density

$$\tilde{f}(x) = \iint f(x|\mu,\alpha)\,\pi(\mu,\alpha|T,\mathbf{X})\,d\mu\,d\alpha$$

$$\underbrace{\pi(\mu,\alpha|T,\mathbf{X})}_{\text{posterior density}} \propto \underbrace{\pi(\mu,\alpha|T)}_{\text{prior density}} \times \underbrace{L(\mathbf{X}|\mu,\alpha)}_{\text{likelihood (BPT renewal process)}}$$

- Merits of proposal method
  - Its predictive performance will be more stable than plug-in methods.
  - Both slip data T=U / V and past intervals **X**=(X1,･･･,Xn) are used.
  - The estimation of α is not fixed and different among active faults.

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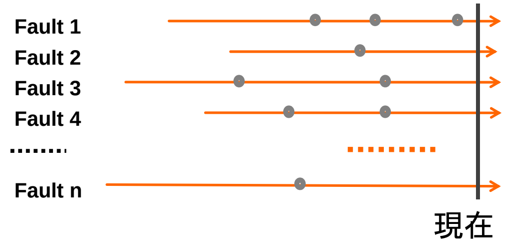
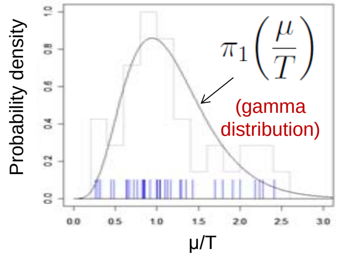
Estimation of prior distribution

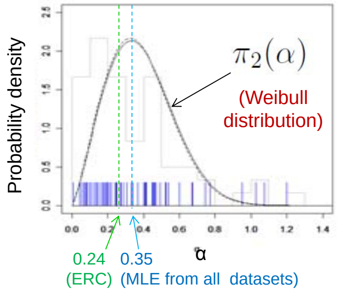




- ABIC and estimated prior distribution

Rows: $\pi_1\left(\frac{\mu}{T}\right)$; columns: $\pi_2(\alpha)$

	Lognormal	Gamma	Weibull	Exp	Uniform
Lognormal	246.62	245.27	244.50	263.00	249.82
Gamma	245.78	244.44	243.67	262.66	249.94
Weibull	246.02	244.66	243.88	262.97	250.46
Exp	268.67	267.38	266.63	285.84	275.17
Uniform	251.86	250.48	249.69	268.92	257.63



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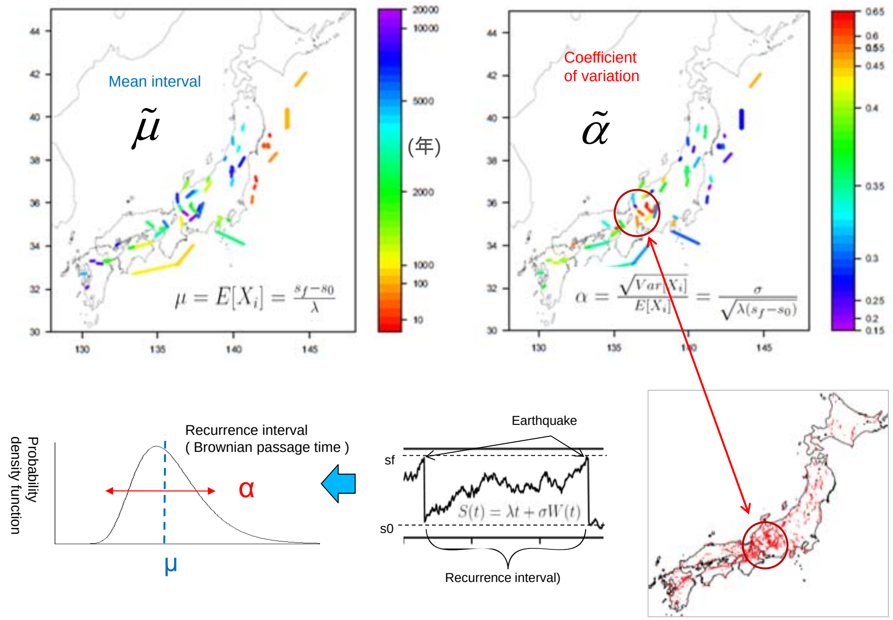
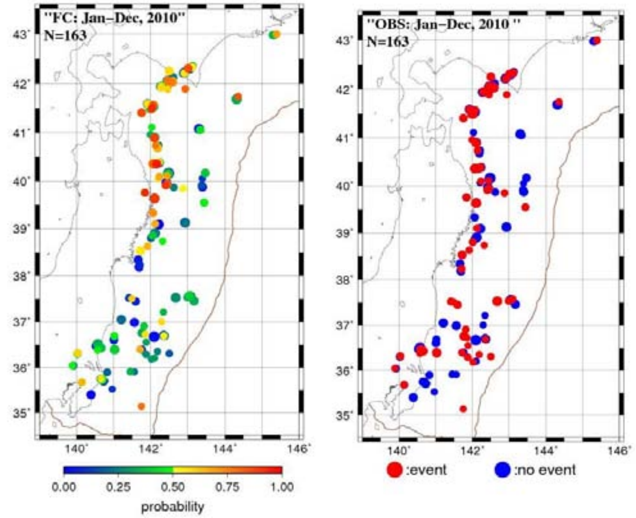
Maximum Posterior estimates



Okada, Uchida, Aoki (2011)

Renewal model (log Normal) for 163 repeating earthquake sequences
Estimation 1993 - 2009

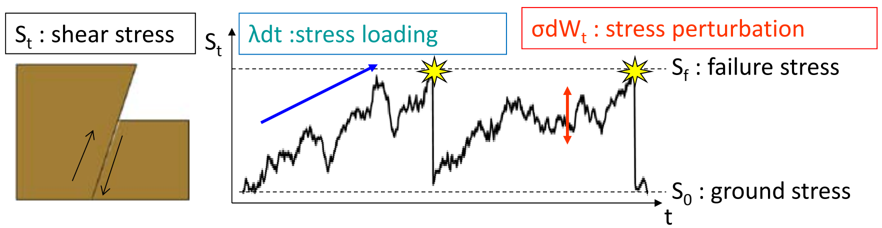
Forecasted for 2010 Result for 2010



Stochastic model for repeating earthquakes

Brownian relaxation oscillator process（e.g. Matthews et al. 2002）

$dS_t = \lambda dt + \sigma\, dW_t$ （W_t standard B.M.）



Interval lengths obey the BPT distribution:

$$f(x|\mu,\alpha) = \sqrt{\frac{\mu}{2\pi\alpha^2 x^3}} \exp\left\{-\frac{(x-\mu)^2}{2\mu\alpha^2 x}\right\}$$

density

mean: $\mu = (s_f - s_0)/\lambda$

variance: $\alpha = \sigma / \sqrt{\lambda(s_f - s_0)}$

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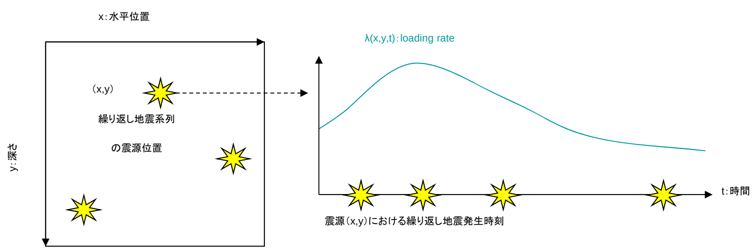
space-time model

- Non-stationary loading rates and dispersions

$$dS_t = \lambda(x,y,t)\, dt + \sigma(x,y,t)\, dW_t$$



- We cannot assume the BPT for the interval distribution.

Assume the following model

- $dS_t = \lambda_0 \lambda(x,y,t)dt + \sigma_0 \sqrt{\lambda(x,y,t)}\, dW_t$
  - λ_0 : Background loading rate
  - σ_0 : Background perturbation rate
  - $\lambda(x,y,t)$: space-time rates relative to the background loading rate λ_0

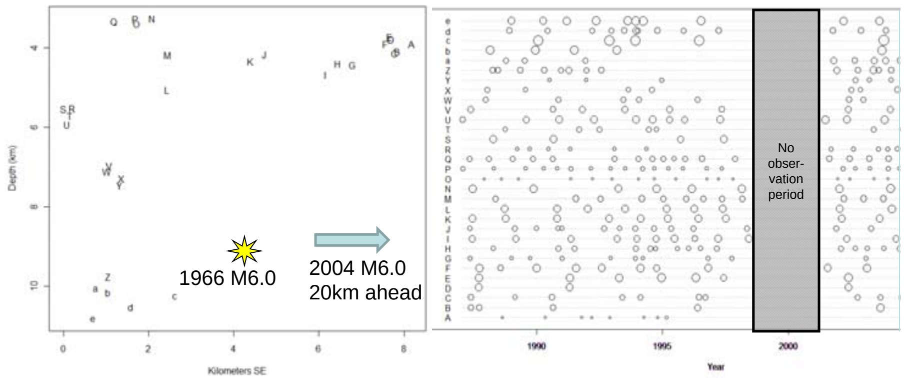
Then we have the BPT intervals for each (x,y) by time transformation $t' = \int \lambda(x,y,t)\,dt$

- $\lambda(x,y,t)$ is regarded as changes of stress loading velocity, and parameterized by a 3D spline function with smoothness constraints.
- Objective Bayesian procedure (ABIC) is applied to attain the optimal constraints.

Parkfield data (Nadeau)

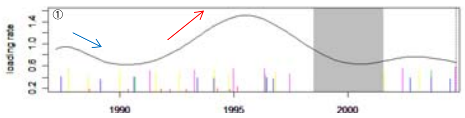
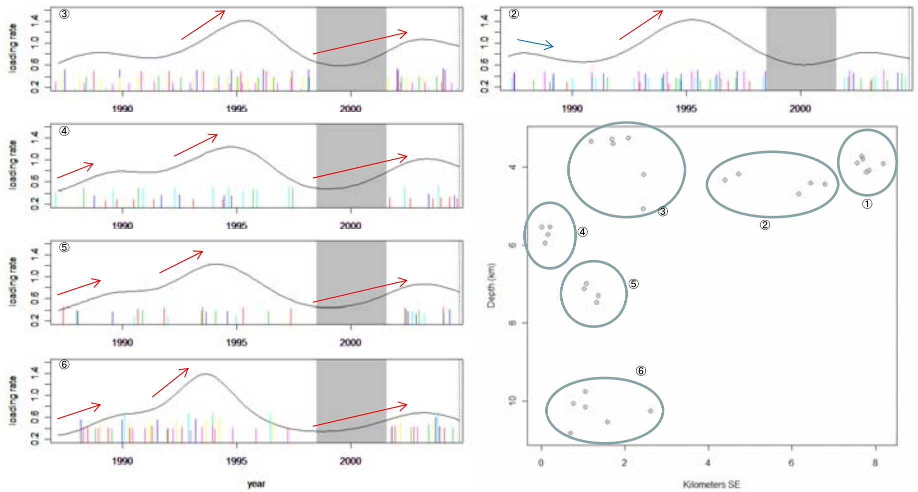
Micro-earthquakes (HRSN, Magnitude range −0.5～2)

- period 1987/1/1～2004/9/28（preceding 2004 Parkfield） with missing data during 1998/7/1～2001/7/26



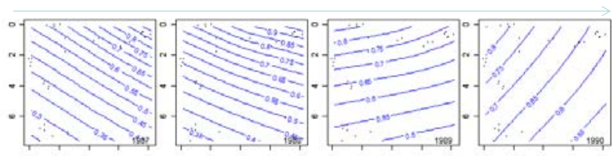
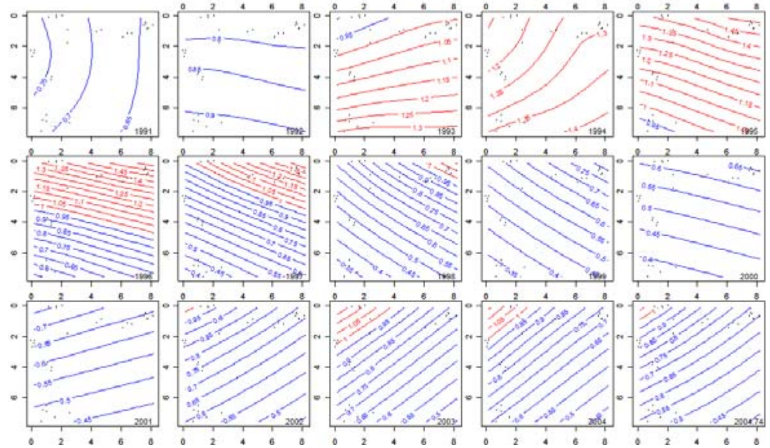
Result

Loading rate change at each sub-region

Result

Spatial change in time

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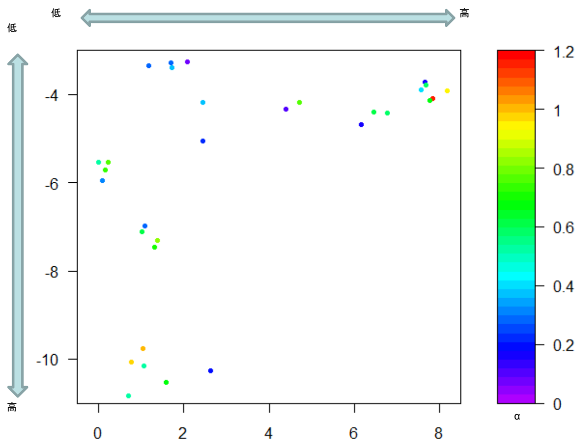
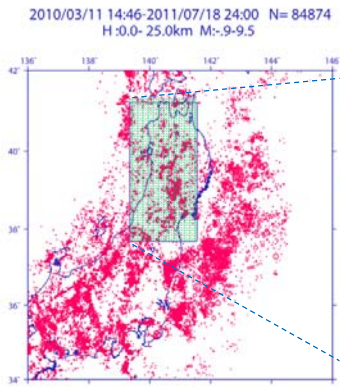
Result on the dispersion coeff.α

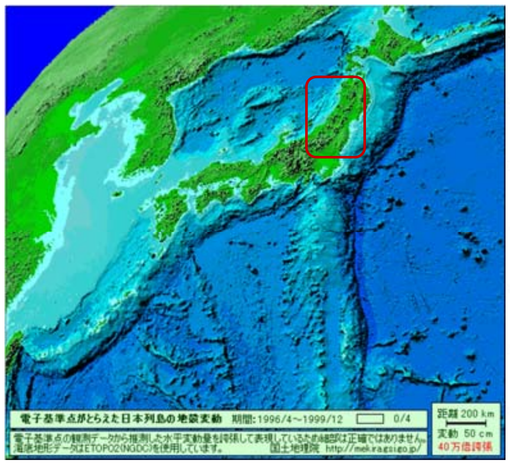
Dispersion coefficientα(proportional to the perturbation rate σ) is affected by the nearby earthquakes



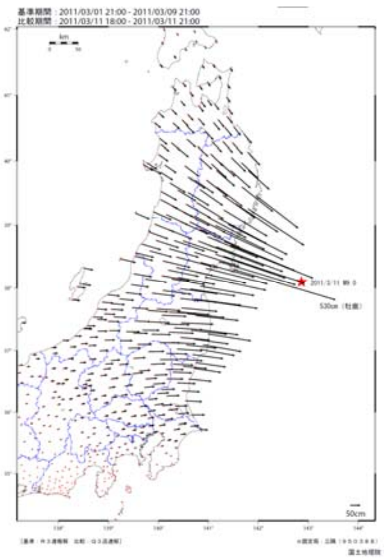
Prediction and diagnostic analysis of seismic activity

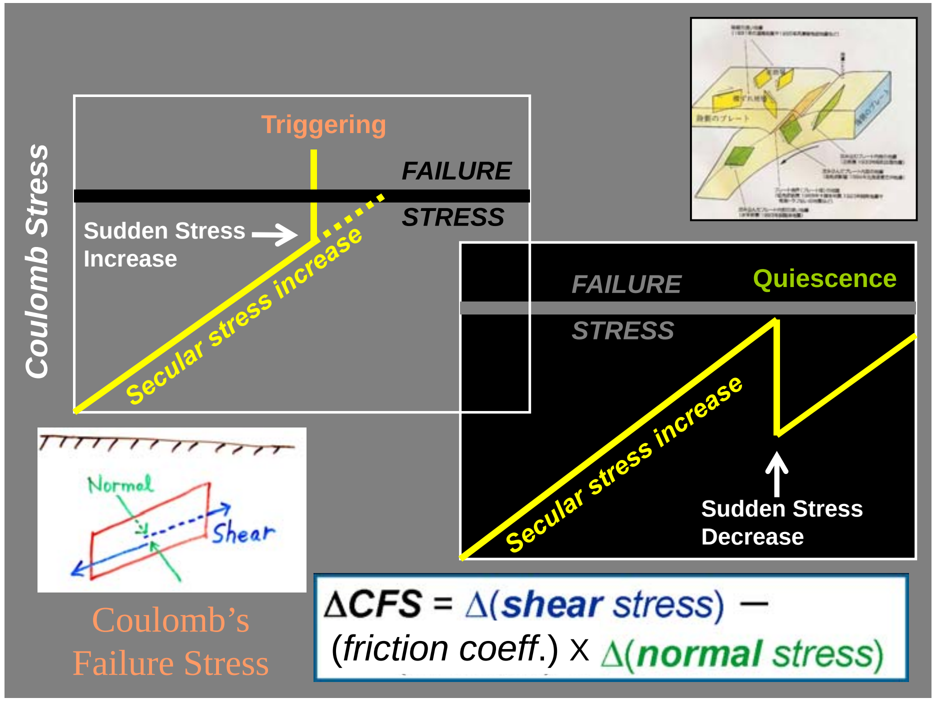


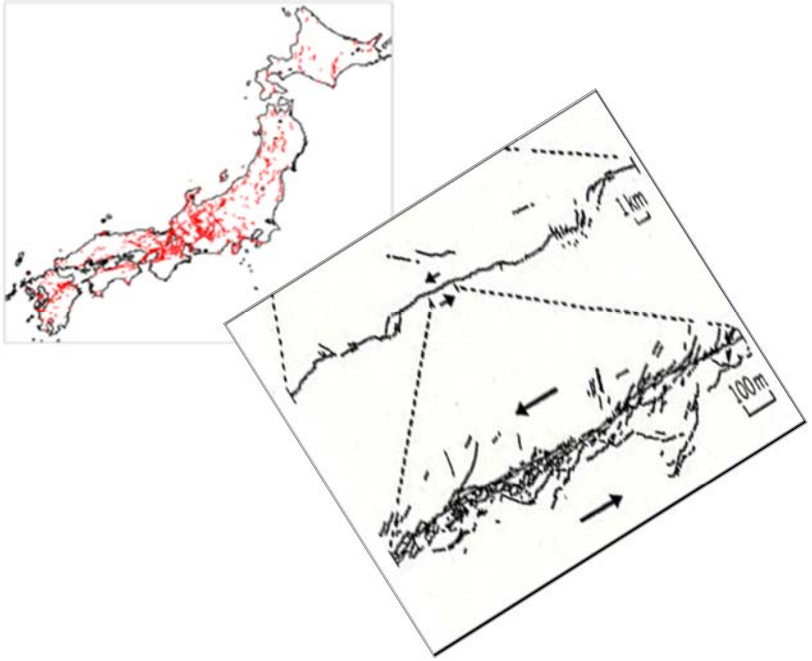
Geographical Survey Institute
Deformation of Japanese islands



Coseismic dislocations of Tohoku-Oki earthquake of M9







ETAS model: (Epidemic Type Aftershock Sequence model)

$$\lambda(t) = \mu + \sum_{\{j:\, t_j < t\}} e^{\alpha\{M_j - M_c\}}\, \nu(t - t_j)$$

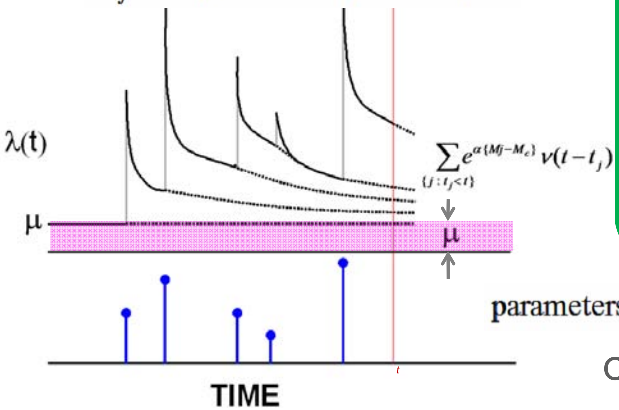
where

t_j is occurrence time of jth event;

M_j is magnitude of jth event;

$$\nu(t) = \frac{K}{(t+c)^p}$$

Omori-Utsu formula for aftershock decay



parameters are (μ, K, c, α, p).

Ogata (1988, *JASA*)

Ogata (1988, *J. Amer. Statist. Assoc.*)

Observed time interval: $[S, T]$

Occurrence time data; $t_1, t_2, \cdots, t_n$

Log-likelihood function:

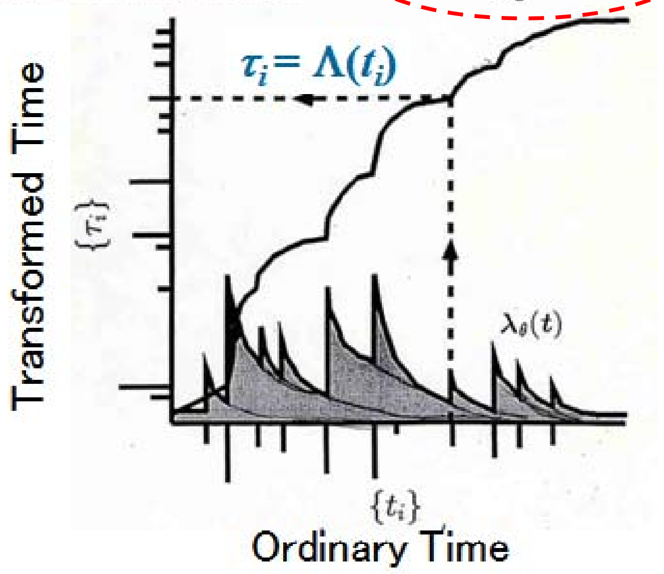
$$\ln L(\theta; S, T) = \sum_{S < t_i < T} \ln \lambda_\theta(t_i) - \int_S^T \lambda_\theta(t)\,dt$$

parameters are (μ, K, c, α, p).

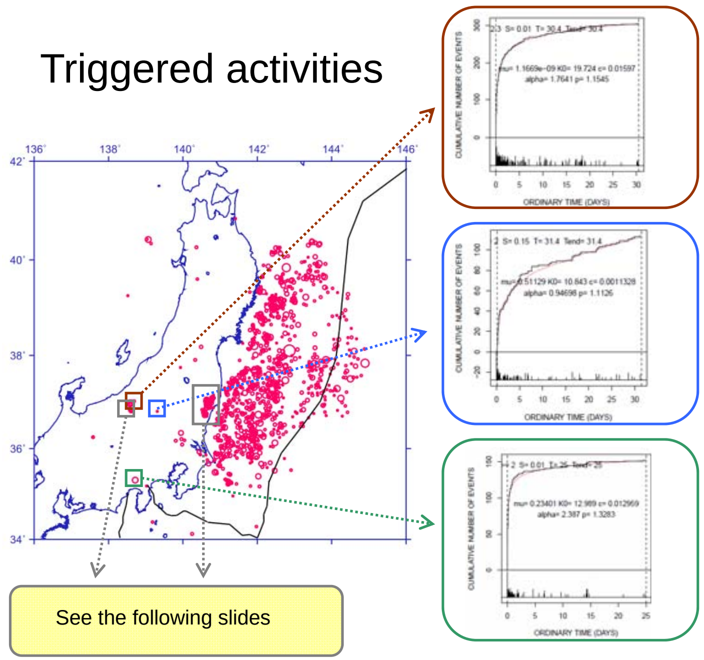
Maximize the function $\Rightarrow \hat{\theta} = (\hat{\mu}, \hat{K}, \hat{c}, \hat{\alpha}, \hat{p})$ **M.L.E.**

Computer codes available. Please visit WEB home page of our project team:
http://www.ism.ac.jp/~ogata/Ssg/ssgE.html

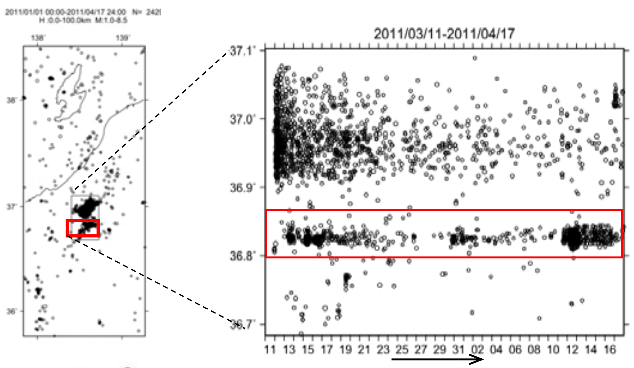
Theoretical cumulative number of the events: $\Lambda(t) = \int_0^t \lambda(s)\, ds$

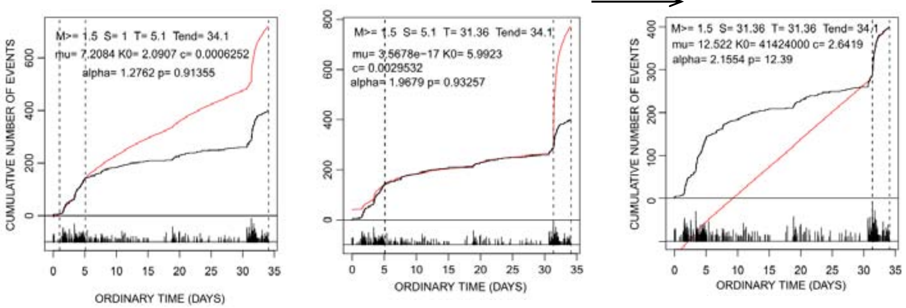


Triggered activities

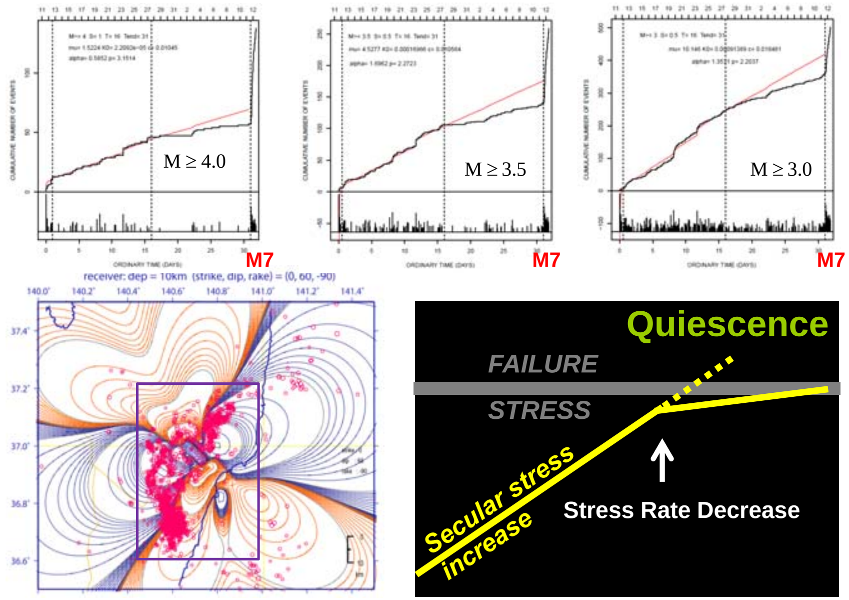


Northern Nagano Pref. Sakae Vil.

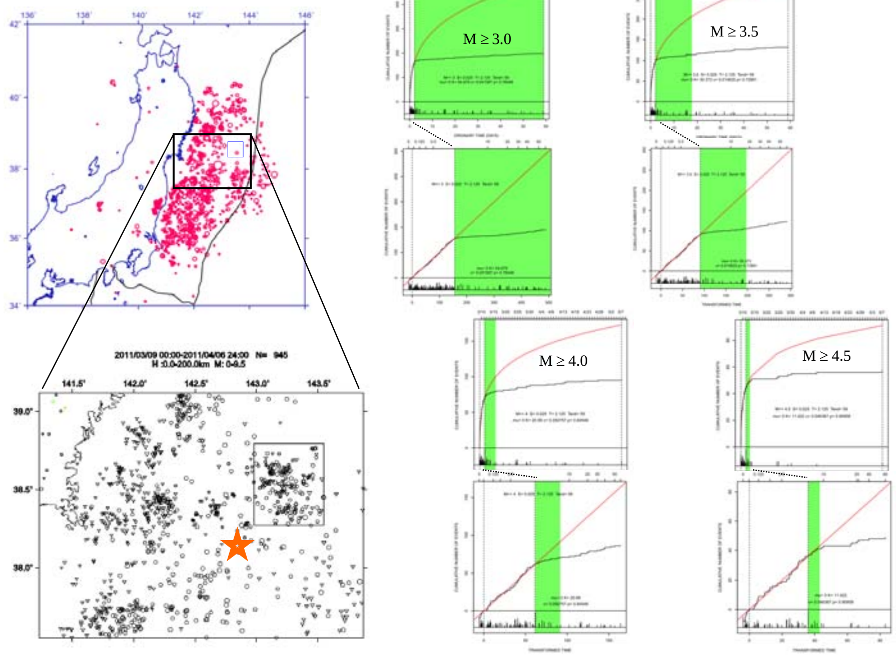


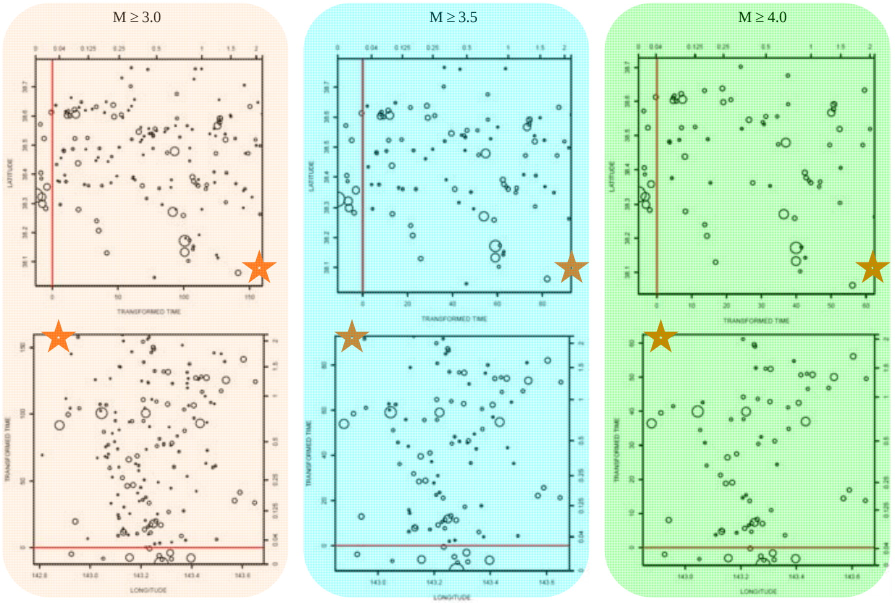


福島県いわき市付近の誘発地震活動

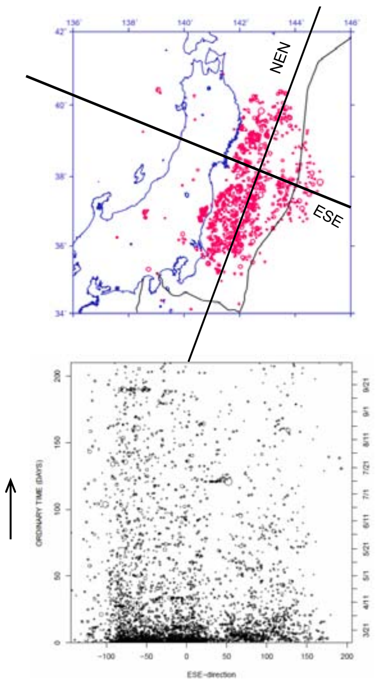


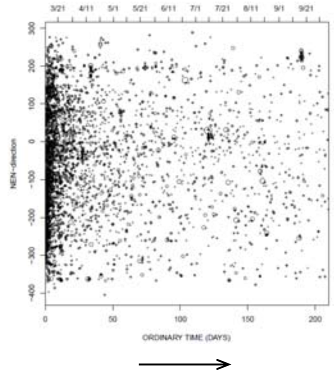
Foreshocks led by the M7.3 event





Space vs transformed-time plot of the foreshock activity till M9 mega event

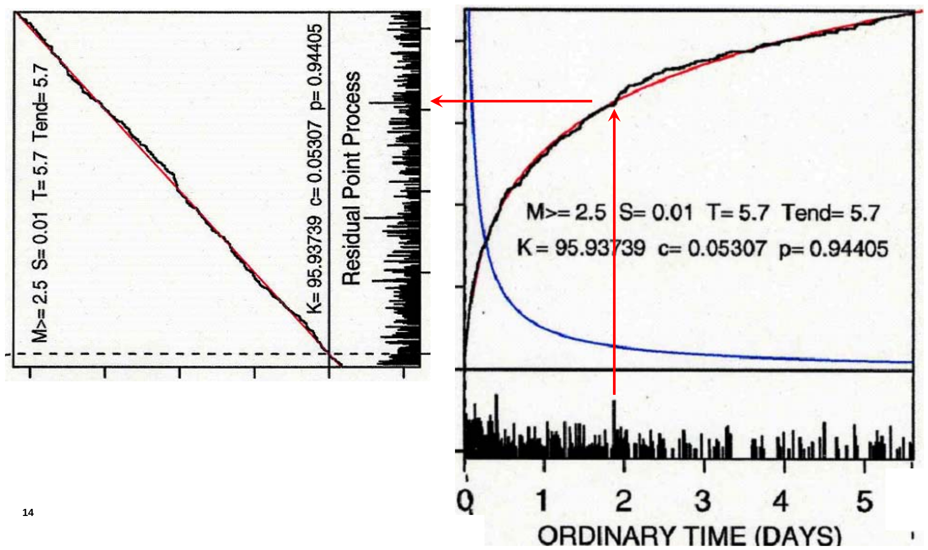




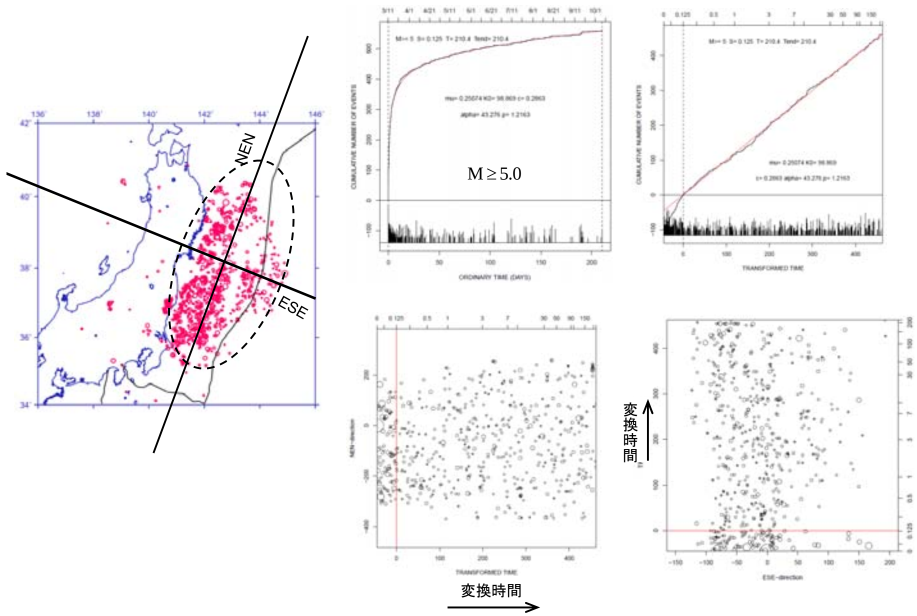
Aftershocks of Tohoku-Oki
Earthquake of M9

Theoretical cumulative number of the events:

$$\Lambda(t) = \int_0^t \lambda(s)\, ds$$

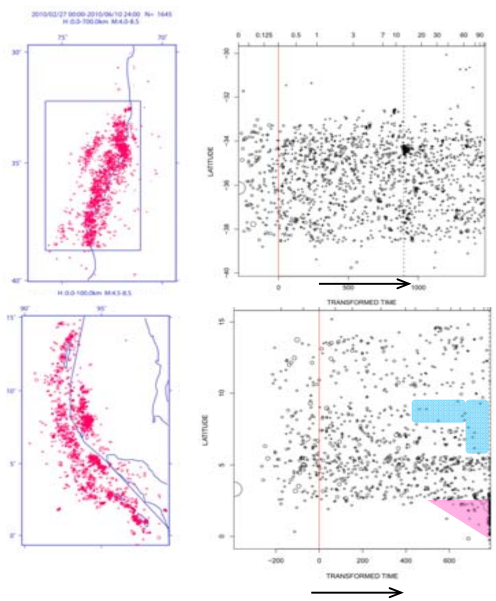


Aftershocks of Tohoku-Oki Earthquake of M9 (cont.)

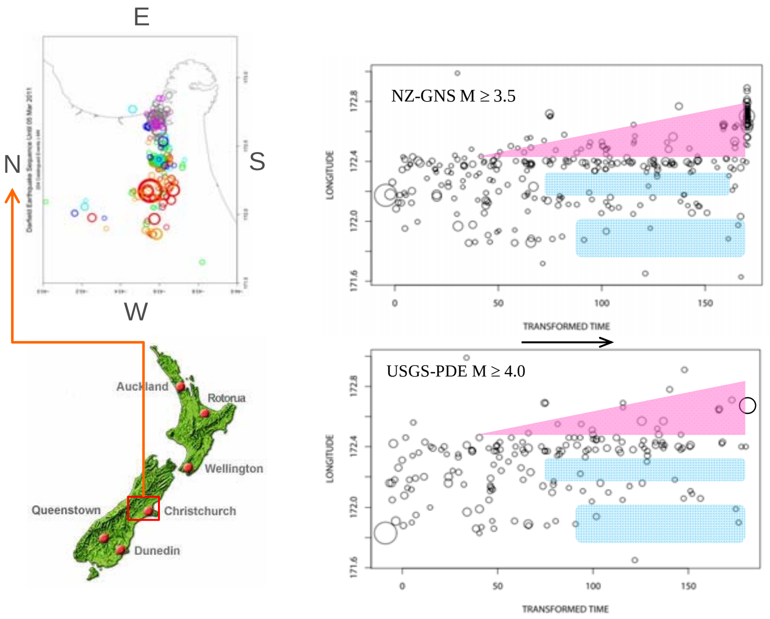


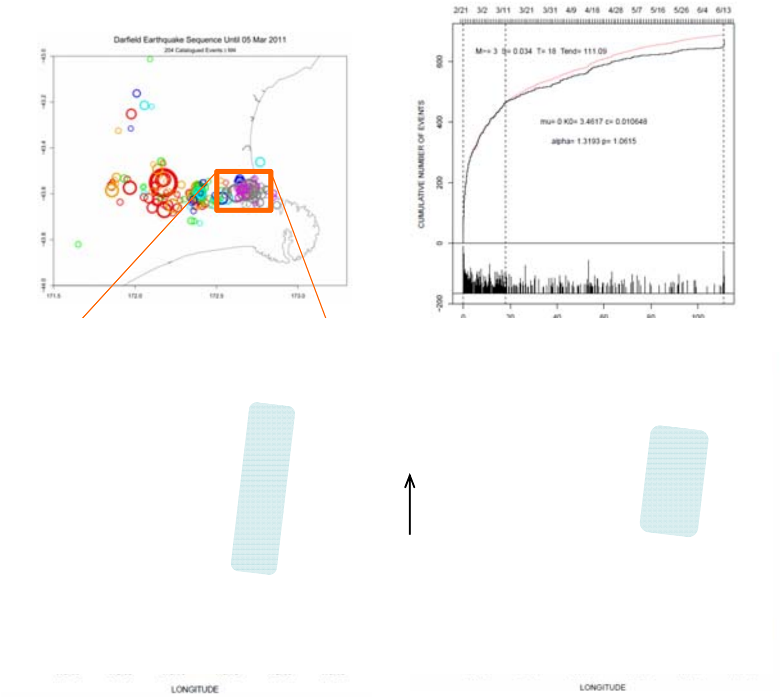
2010 Chili Earthquake
（Mw8.8）Aftershocks

2004 Sumatra Earthquake
（Mw9.0）Aftershocks



New Zealand Darfield Earthquake Aftershocks and Christchurch Earthquake





Extensive Quiescence before the M9 earthquake

Space-Time ETAS model (Ogata, 1998, AISM)

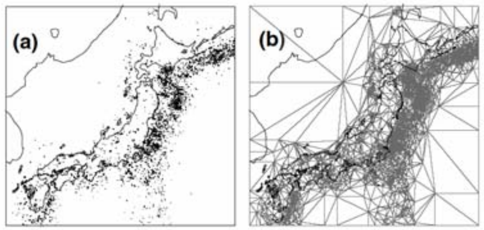
$$\lambda(t,x,y) = \mu + \sum_{\{j:\, t_j<t\}} \frac{K}{(t-t_j+c)^p} \left\{ \frac{Q_j(x,\ y)}{e^{\alpha M_j}} + d \right\}^{-q}$$

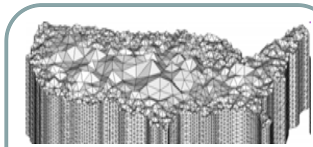
Heterogeneity in Space (Ogata, 2004, *JGR* and 2011, *EPS*)

$$\mu \Longrightarrow \mu(x,y);$$

$$K \Longrightarrow K(x_j,y_j);\quad \alpha \Longrightarrow \alpha(x_j,y_j);$$

$$p \Longrightarrow p(x_j,y_j);\quad q \Longrightarrow q(x_j,y_j)$$





Delaunay-based function: an illustration

Location Dependent Space-Time ETAS model and occurrence data $\{(t_i, x_i, y_i, M_i);\ \ i = 1, \cdots, n\}$ in $[0, T] \times A$ are given. Then **Log Likelihood** is

$$\log L(\theta) = \log L\left(\mu_{\theta_1}, K_{\theta_2}, \alpha_{\theta_4}, p_{\theta_5}, q_{\theta_7}\right)$$
$$= \sum_{i=1}^{n} \log \lambda_\theta(t_i, x_i, y_i) - \int_0^T \iint_A \lambda_\theta(t, x, y)\,dt\,dx\,dy.$$

where $\theta = (\theta_1, \theta_2, \theta_4, \theta_5, \theta_7)$

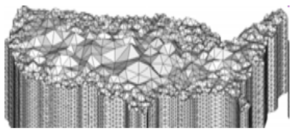
Penalized Log Likelihood

$$Q(\theta |\ w_\mu, w_K, w_\alpha, w_p, w_q)$$
$$= \log L(\theta) - penalty(\theta |\ w_\mu, w_K, w_\alpha, w_p, w_q)$$

where the *penalty* is

$$\iint_A dxdy \left\{w_1(\mu_x^2 + \mu_y^2) + w_2(K_x^2 + K_y^2) + w_3(\alpha_x^2 + \alpha_y^2) + w_4(p_x^2 + p_y^2) + w_5(q_x^2 + q_y^2)\right\}$$

Flatness constraints



Delaunay-based function: an illustration

$$\boldsymbol{\rho} = (w_\mu, w_K, w_\alpha, w_p, w_q)$$

$$posterior(\theta \mid \boldsymbol{\rho}) = \frac{L(\theta) \cdot prior(\theta \mid \boldsymbol{\rho})}{\Lambda(\boldsymbol{\rho})}$$

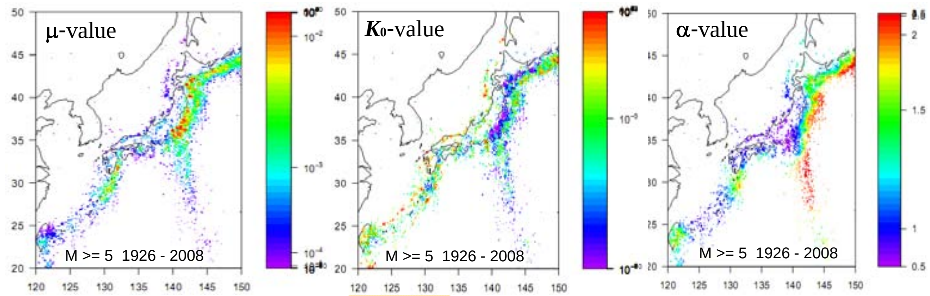
$$\Lambda(\boldsymbol{\rho}) = \int \cdots \int L(\theta) \cdot prior(\theta \mid \boldsymbol{\rho}) d\theta$$

(**Likelihood** of a Bayesian model; *Good* 1965)

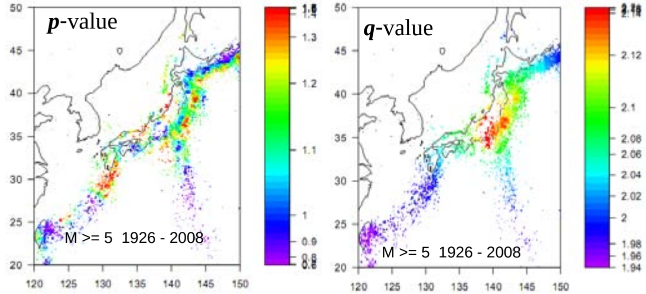
Choose $\boldsymbol{\rho}$ that maximize $\Lambda(\boldsymbol{\rho})$ **or minimize**

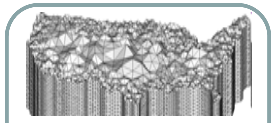
$$ABIC = (-2) \max_{\boldsymbol{\rho}} \{\log \Lambda(\boldsymbol{\rho})\} + 2 \times \dim(\boldsymbol{\rho})$$

Akaike Bayesian information criterion (Akaike, 1980)



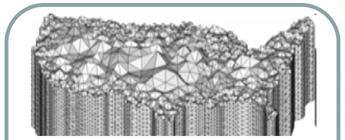
$$\lambda(t, x, y \mid H_t) = \mu(x, y) + \sum_{\{j;\, t_j < t\}} \frac{K_0(x_j, y_j)}{(t - t_j + c)^{p(x_j, y_j)}} \left[\frac{(x - x_j, y - y_j)\, S_j\, (x - x_j, y - y_j)^t}{e^{\alpha(x_j, y_j)(M_j - M_c)}} + d\right]^{-q(x_j, y_j)}$$



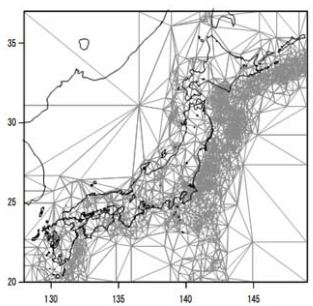


Delaunay-based function:

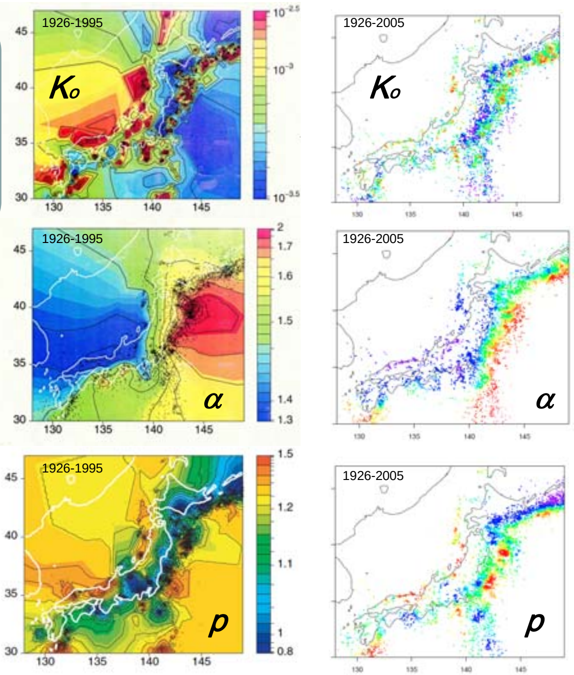
Precursory period 1885 - 1925



Delaunay-based function: an illustration



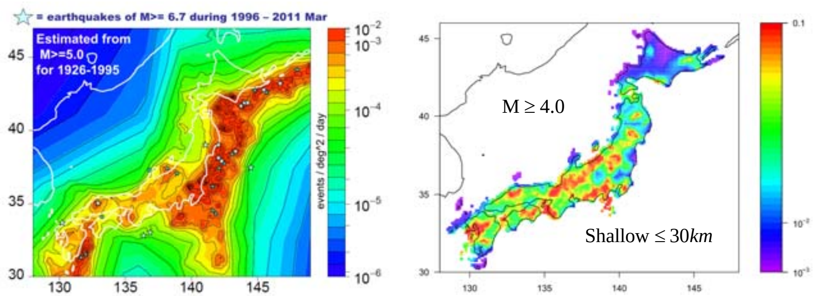
$$\lambda(t, x, y) = \mu + \sum_{\{j:\, t_j < t\}} \frac{K}{(t - t_j + c)^p} \left\{\frac{Q_j(x, y)}{e^{\alpha M_j}} + d\right\}^{-q}$$



Hierarchical Space-time ETAS model (HIST-ETAS)

$$\lambda(t, x, y \mid H_t) = \mu(x, y) + \sum_{\{j;\, t_j < t\}} \frac{K(x, y)}{(t - t_j + c)^{p(x, y)}} \left[\frac{(x - x_j, y - y_j)\, S_j\, (x - x_j, y - y_j)^t}{e^{\alpha(x, y)(M_j - M_c)}} + d\right]^{-q(x, y)}$$

Background rate

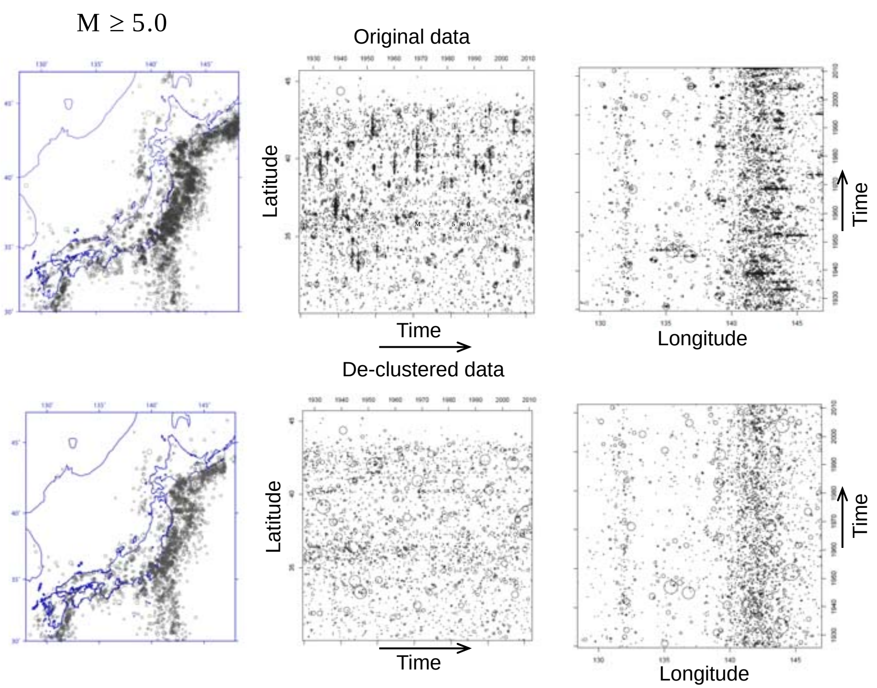


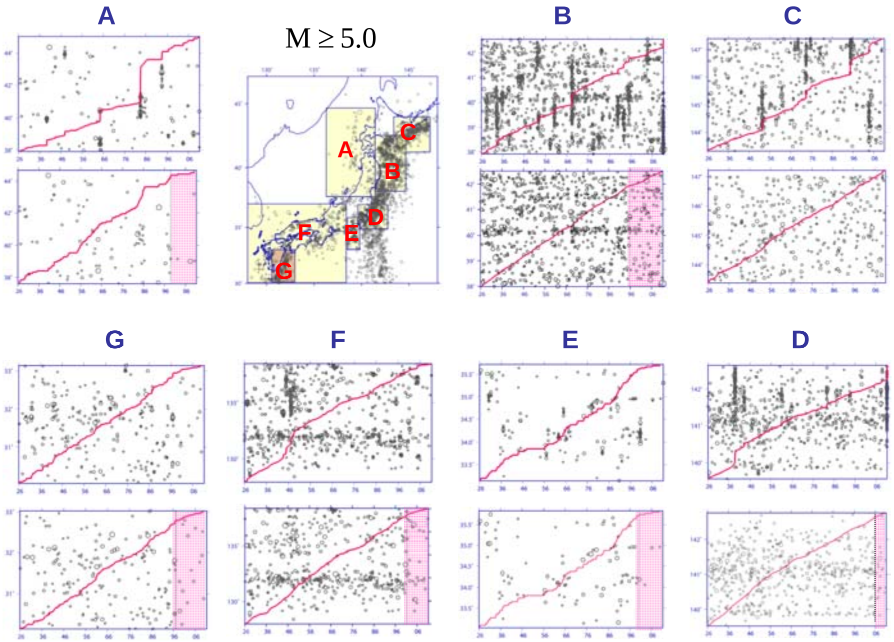
Stochastic declustering

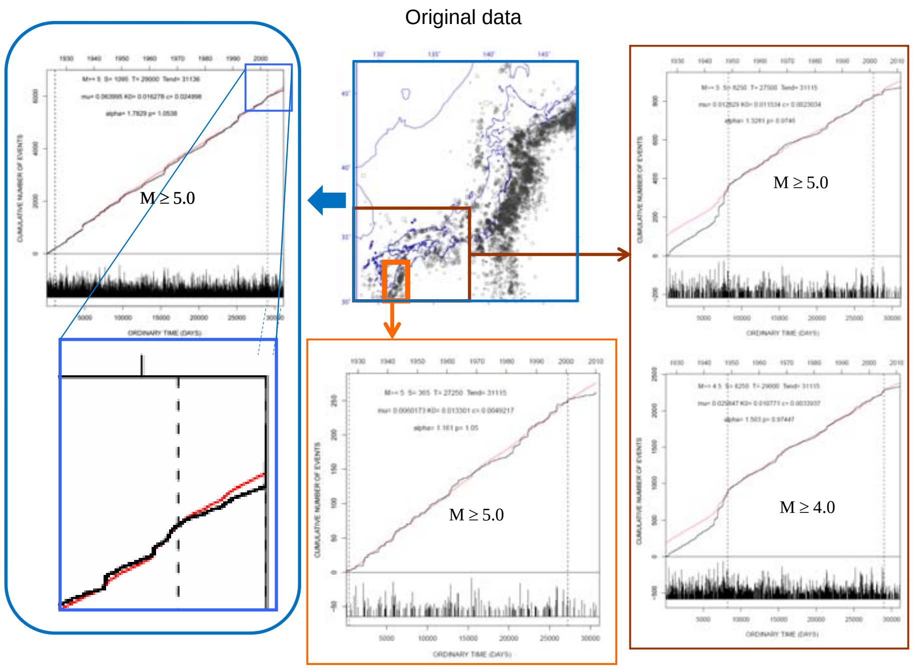
(Zhuang, Ogata & Vere-Jones., 2004 *JASA* and 2005, *JGR*)

Accept earthquake i as a **background event** with probability:

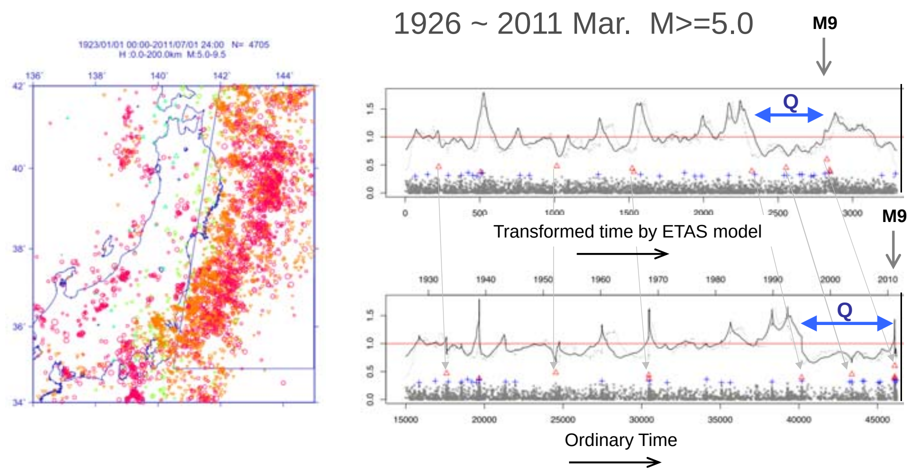
$$\frac{\mu(x_i, y_i)}{\lambda(t_i, x_i, y_i \mid H_{t_i})}$$



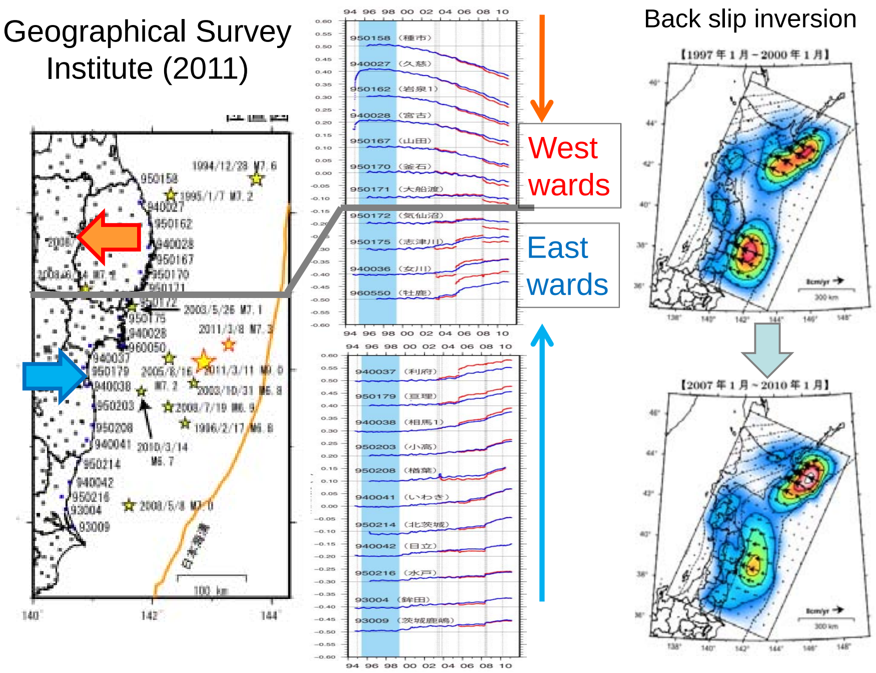




T. Kumazawa（SOKEN-DAI D3)

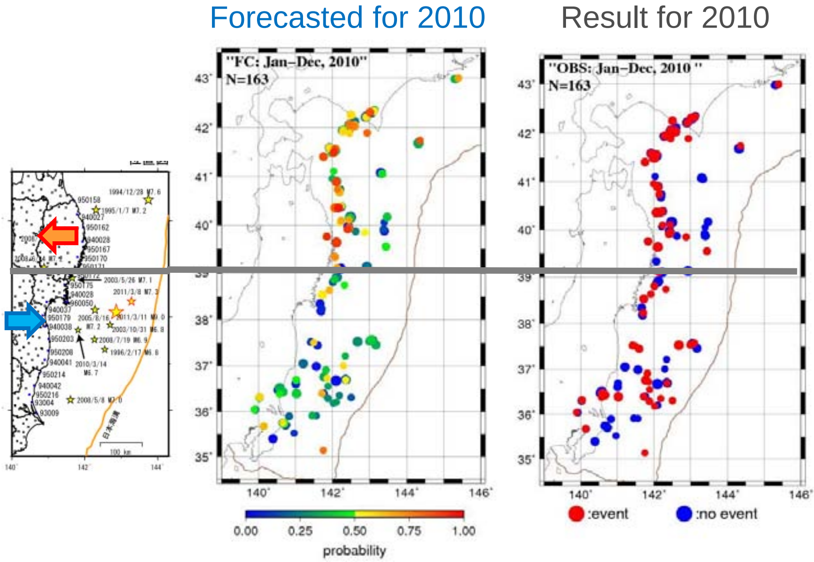


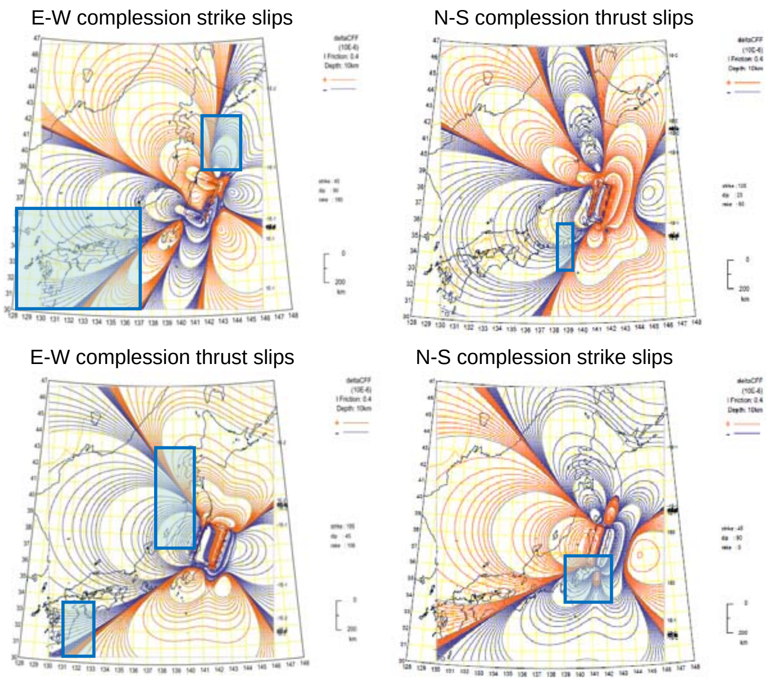
Geographical Survey Institute (2011)



Okada, Uchida, Aoki (2011)

Renewal model (log Normal) for 163 repeating earthquake sequences
Estimation 1993 - 2009





Operational Probability Forecasting of Foreshocks and Evaluations:

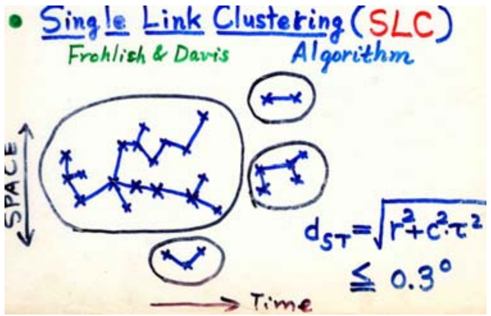
15 years periods till the Tohoku-Oki Event

(1) How do we recognize that it is initial earthquake of a cluster?
(2) What is definition of foreshocks?

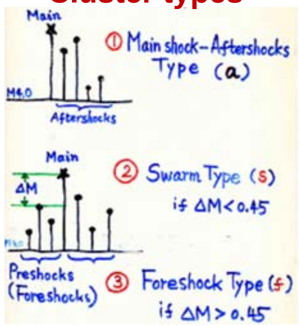
Earthquakes (M≧4.0) in JMA catalog during 1994 ~ Mar. 2011 are connected by the distance criterion

$$d_{ST} = \sqrt{\Delta^2_{space} + (c\Delta_{time})^2} \le 0.3^\circ \text{ (or 33.33km)}$$

where c is the constant so as to hold 1day = 1km



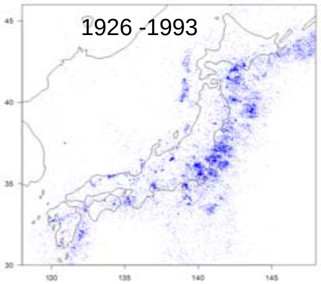
Cluster types



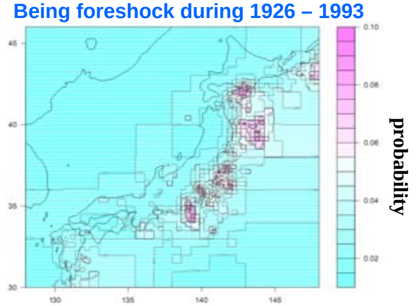
Single-link-clustering 1926-1993, M≧4 from the old JMA catalog

Cluster member#	Foreshocks #c	Foreshocks ratio(%)	Foreshocks s.e.(%)	Swarms #c	Swarms ratio(%)	Swarms s.e.(%)	M.A. #c	All clusters #c
≧1	467	3.7	±0.2	--	--	--	11676	12727
≧2	125	6.5	±0.6	584	30.5	±1.1	1207	1916
≧3	57	8.0	±1	271	37.9	±1.8	387	715
≧4	33	8.7	±1.5	153	40.5	±2.5	192	378
≧5	18	7.4	±1.7	93	38.4	±3.1	131	242
≧6	12	6.8	±1.9	63	35.6	±3.6	102	177
≧7	10	7.9	±2.4	44	34.6	±4.2	73	127
≧8	8	7.8	±2.6	31	30.1	±4.5	64	103
≧9	8	9.2	±3.1	29	33.3	±5.1	50	87
≧10	8	10.3	±3.4	25	32.1	±5.3	45	78

Initial earthquakes of clusters or Isolated earthquakes



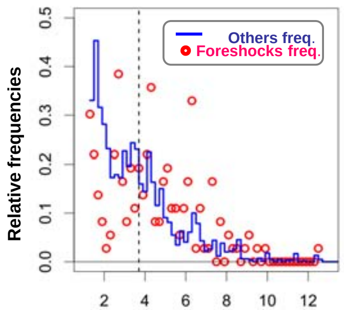
Probability of the initial earthquakes Being foreshock during 1926 – 1993



Forecasted results for 1994 – Mar

Forecast	0-2.5%	2.5-5%	5%-	All
Foreshocks	33	84	65	182
Others	1572	1849	770	4191
All types	1605	1933	835	4373
Ratio(%)	2.1	4.3	7.8	4.2

Diff. entropy = -22.7
Diff. AIC = -40.0 (cross-table)



Measuring inter-events concentrations in a cluster and magnitude increments

$(t_i^c, x_i^c, y_i^c, M_i^c)$: Hypocenters in a cluster $c \in C$

① Origin-time differences

$t_{ij}^c = t_j^c - t_i^c$

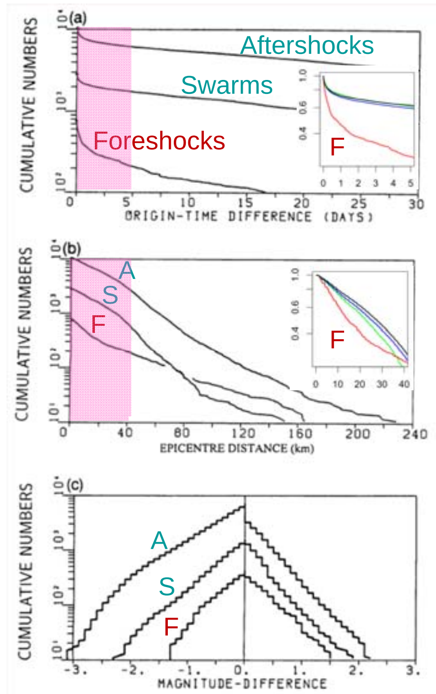
for any pairs i, j such that $i<j$

② Epicenter separations

$r_{ij}^c = \sqrt{(x_j^c - x_i^c)^2 + (y_j^c - y_i^c)^2}$ $(i<j)$

③ Magnitude differences

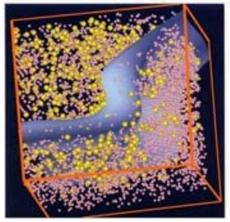
$M_{ij}^c = M_j^c - M_i^c$ $(i<j)$



Time difference, Distance & Magnitude difference Normalization

$$(t, r, g) \rightarrow (\tau, \rho, \gamma) \text{ in } [0,1]^3 \quad \equiv$$

Normalized time differnce, distance & magnitude difference in the unit cube



Time Interval Transformation

$$\tau = \begin{cases} 0 & \text{for} \quad t \le 0.01 \\ \log(100t)/\log(3000) & \text{for } 0.01 < t \le 30 \\ 1 & \text{for} \quad 30 \le t \end{cases}$$

Epicenter Separation Transformation

$$\rho = 1 - \exp\{-\min(r, 50)/20\}$$

Magnitude Difference Transformation

$$\gamma = \begin{cases} (2/3)\exp\{g/\sigma_1\} & \text{for } g \le 0 \\ (2/3) + (1/3)[1 - \exp\{-g/\sigma_2\}] & \text{for } g > 0 \end{cases}$$

ただし　$\sigma_1 = 6709, \sigma_2 = 0.4456$

Algorithm of foreshock probability calculations in case of plural earthquakes in a cluster

For plural earthquakes in a cluster, time differences t_{ij} (days), epicenter separation r_{ij} (km), magnitude difference g_{ij} are transformed into the unit cube

$$(t_{i,j}, r_{i,j}, g_{i,j}) \rightarrow (\tau_{i,j}, \rho_{i,j}, \gamma_{i,j}) \in [0,1]^3$$

Probability p_c is calculated sequentially

$$\text{logit}(p_c) = \text{logit}\{\mu(x_1, y_1)\} + \frac{1}{\#\{i<j\}} \sum_{i<j} \left[a_1 + \sum_{k=1}^{3} b_k \gamma_{i,j}^{\ k} + \sum_{k=1}^{3} c_k \rho_{i,j}^{\ k} + \sum_{k=1}^{3} d_k \tau_{i,j}^{\ k} \right]$$

Here $\mu(x, y)$ indicates probability of initial earthquake at location (x,y), and the 2nd term calculates arithmetic mean of polynomials of the normalised space-time magnitude variables for all pairs of earthquakes $(i < j)$ in a cluster, where the coefficients a, b, c, d are as follows.

Ogata, Utsu and Katsura, 1996, *GJI*)

k	a_k	b_k	c_k	d_k
1	8.018	−33.25	−1.490	−10.92
2		62.77	2.805	295.09
3		−37.66	−2.190	−1161.5

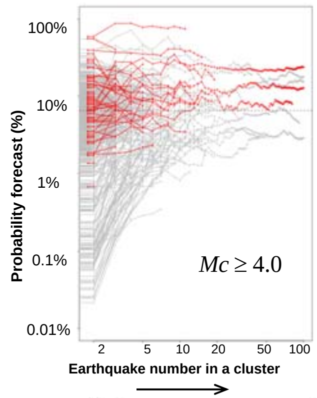
Forecasted sequence and evaluation（1994－2011Mar ）

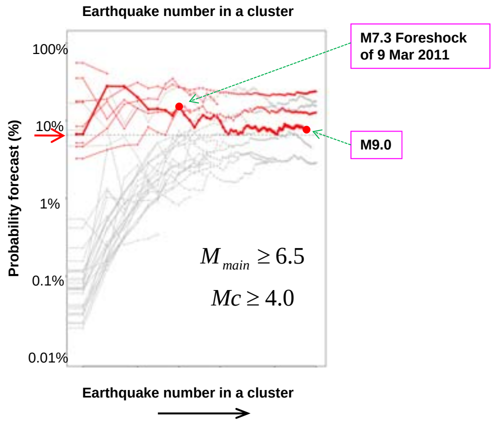
#	F?	#C	Pc	ENTRPY	CU~ENT	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
1	-	1	5.14%	-0.01537	-0.01537	5.14%									
2	-	2	10.06%	-0.06863	-0.08400	7.46%	12.66%								
3	-	1	18.58%	-0.16822	-0.25222	18.58%									
4	-	1	10.71%	-0.07592	-0.32814	10.71%									
5	-	1	0.15%	0.03586	-0.29228	0.15%									
6	-	1	1.70%	0.02028	-0.27200	1.70%									
7	-	4	9.50%	-0.06243	-0.33443	9.14%	11.17%	7.87%	9.82%						
8	-	1	6.03%	-0.02484	-0.35927	6.03%									
9	-	1	1.77%	0.01950	-0.33977	1.77%									
10	+	1	13.14%	1.27605	0.93628	13.14%									
…..															
→ 875	+	80	9.2%	0.923	28.649	6.7%	27.8%	27.7%	20.1%	14.0%	14.2%	13.6%	11.6%	15.7%	11.9%
						10.1%	8.2%	10.1%	11.7%	10.9%	10.6%	11.5%	11.1%	9.9%	8.2%
						7.2%	6.8%	7.6%	7.3%	7.4%	6.7%	7.0%	7.0%	8.0%	8.5%
						8.6%	8.2%	8.0%	8.1%	8.4%	7.8%	7.3%	7.5%	7.8%	8.1%
						8.1%	7.8%	7.4%	7.7%	7.8%	7.6%	7.2%	7.2%	6.9%	6.8%
						6.7%	7.4%	8.0%	7.8%	7.6%	7.7%	8.3%	9.0%	8.7%	8.5%
						8.6%	8.3%	8.4%	8.2%	8.2%	8.0%	7.9%	7.9%	8.4%	8.4%
						8.6%	8.5%	8.6%	8.4%	8.2%	8.4%	8.3%	8.3%	8.1%	7.9%
…..															
880	-	11	2.44%	0.01266	31.60644	4.69%	4.77%	6.21%	3.42%	1.74%	1.24%	1.04%	0.90%	0.83%	0.97%
						1.03%									
881	-	16	2.11%	0.01604	31.62248	0.03%	0.25%	0.51%	0.83%	2.77%	2.21%	2.02%	3.19%	2.78%	2.50%
						2.43%	3.07%	2.92%	2.74%	2.84%	2.68%				
882	-	7	1.47%	0.02259	31.64507	0.06%	0.79%	1.70%	2.06%	1.90%	1.90%	1.88%			
883	-	1	4.51%	-0.00878	31.63629	4.51%									
884	-	1	3.84%	-0.00178	31.63451	3.84%									
885	+	7	5.04%	0.31698	31.95149	6.89%	7.42%	4.88%	3.98%	3.56%	4.05%	4.49%			
886	-	1	2.84%	0.00853	31.96002	2.84%									
887	-	1	7.00%	-0.03518	31.92483	7.00%									
888	-	1	7.65%	-0.04219	31.88264	7.65%									
889	-	1	7.83%	-0.04419	31.83845	7.83%									

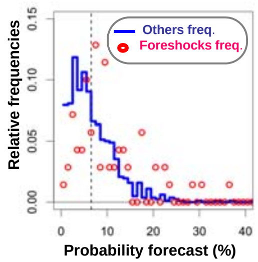
M7.3 Foreshock of 9 Mar 2011 (→ 15.7%)

M9.0 (→ 7.9%)

2*Entropy0 = 523.96;　2*Entropy = 460.29:　　2*ΔEntropy = –63.68







2*Entropy0 = 523.96 / 2*Entropy = 460.29
2*ΔEntropy = –63.68

Forecast & performance　　1994年 - 2011年3月

2.5	5%	10%	15%		
4	10	30	12	14	70
179	211	263	115	51	819
183	221	293	127	65	889
2.2	4.5	10.2	9.4	21.5	7.9

aic0 = 3178.62　aic1 = 3157.15
Δaic = –21.47

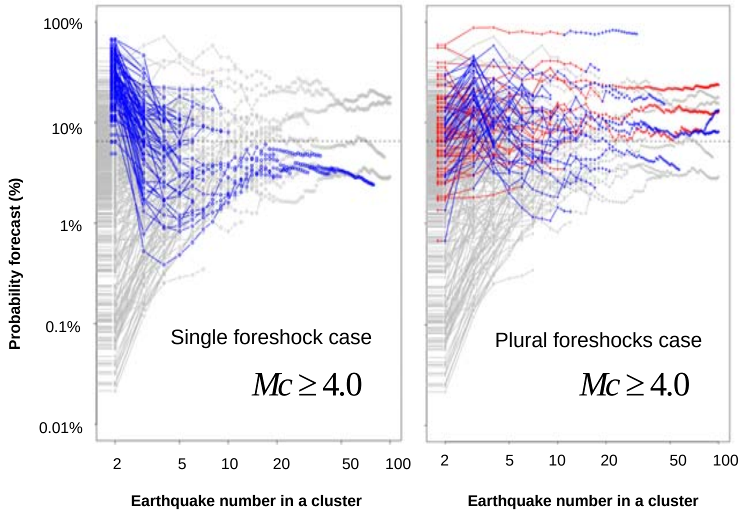
Thank you very much for your attention.

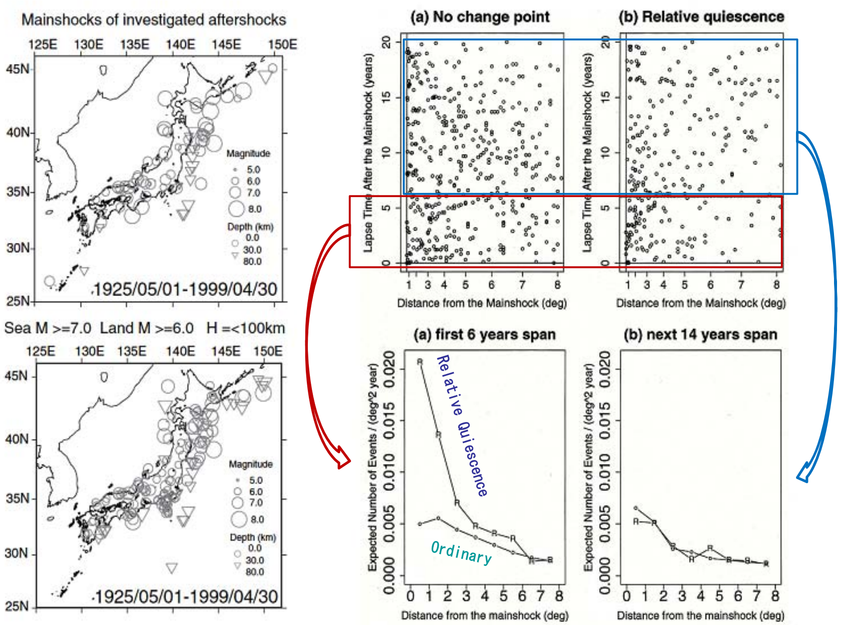
Software available for the ETAS fitting, diagnostic analysis and its manual. Please visit WEB home page of our project team:

http://www.ism.ac.jp/~ogata/Ssg/ssgE.html

Very soon, computer programs are available for the Hierarchical Space-Time ETAS (HIST-ETAS) by a Bayesian procedure (ABIC).

How foreshock forecast probabilities (BLUE LINES) changed after actual mainshock occurred in case of foreshock-mainshock-aftershock sequence?





Single−link−clustering 1926−1993, M≧4 from the old JMA catalog

Cluster member#	Foreshocks #c	ratio(%)	s.e.(%)	Swarms #c	ratio(%)	s.e.(%)	M.A. #c	All clusters #c
≧1	467	3.7	±0.2	−−	−−	−−	11676	12727
≧2	125	6.5	±0.6	584	30.5	±1.1	1207	1916
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≧4	33	8.7	±1.5	153	40.5	±2.5	192	378
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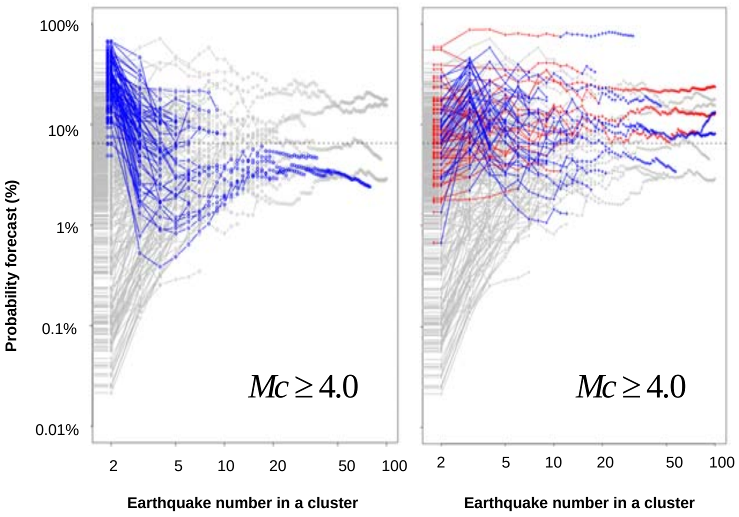
≧9	8	9.2	±3.1	29	33.3	±5.1	50	87
≧10	8	10.3	±3.4	25	32.1	±5.3	45	78

Single−link−clustering 1926−2009, M≧4 from the new JMA catalog

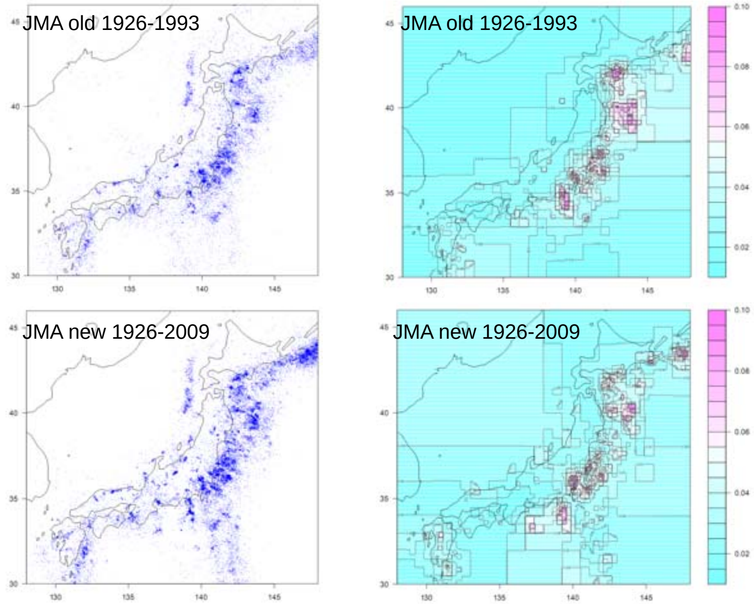
Cluster member#	Foreshocks #c	ratio(%)	s.e.(%)	Swarms #c	ratio(%)	s.e.(%)	M.A. #c	All clusters #c
≧1	1088	6.5	±0.2	−−	−−	−−	14872	16784
≧2	156	5.6	±0.4	824	29.6	±0.9	1800	2780
≧3	78	7.6	±0.8	366	35.4	±1.5	589	1033
≧4	46	8.2	±1.2	213	38.2	±2.1	299	558
≧5	30	7.9	±1.4	145	38.1	±2.5	206	381
≧6	20	7.1	±1.5	108	38.2	±2.9	155	283
≧7	15	7.0	±1.7	77	36.0	±3.3	122	214
≧8	13	7.6	±2	59	34.7	±3.7	98	170
≧9	11	7.9	±2.3	46	33.1	±4	82	139
≧10	11	8.7	±2.5	44	34.9	±4.2	71	126

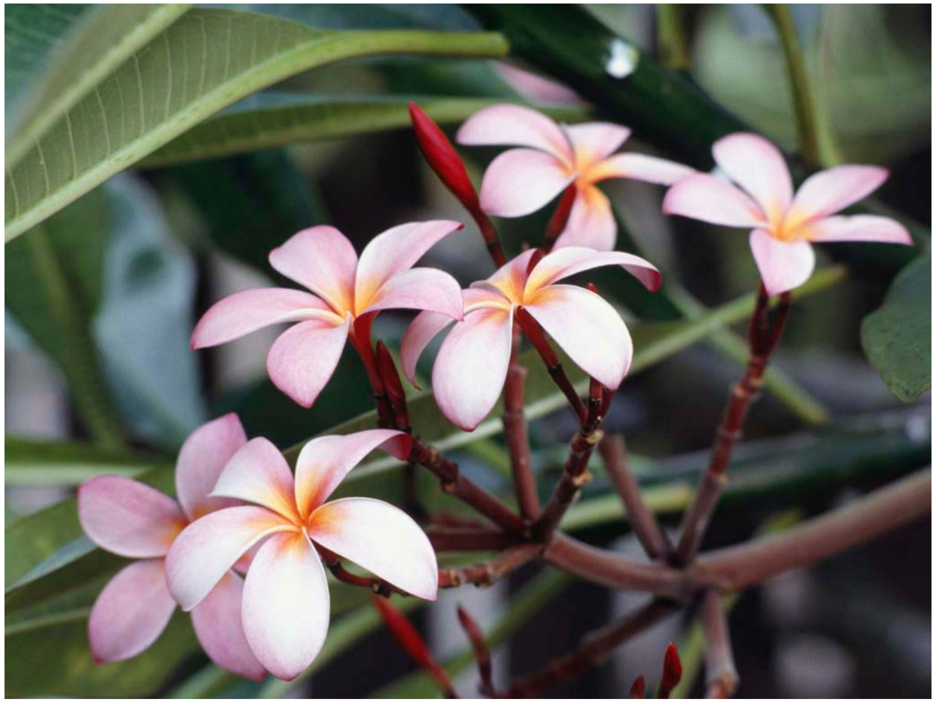
前震の確率は本震が起きてからどのように変わったか？

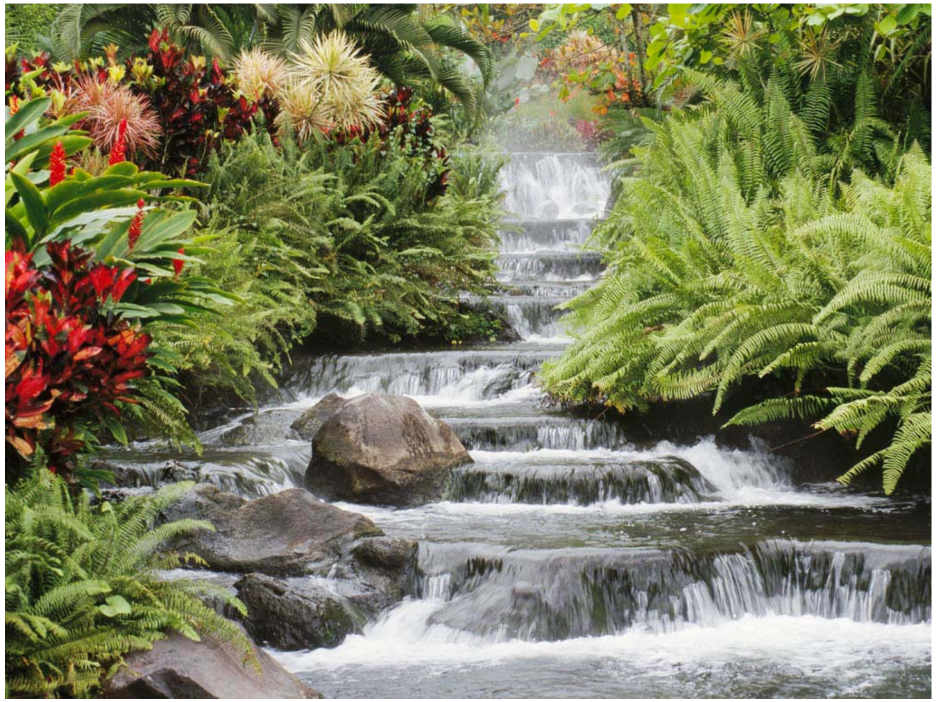
. 青線が本震直前以降の確率変化。左図が一個の前震の場合で右図が複数個の前震（赤線）の場合。

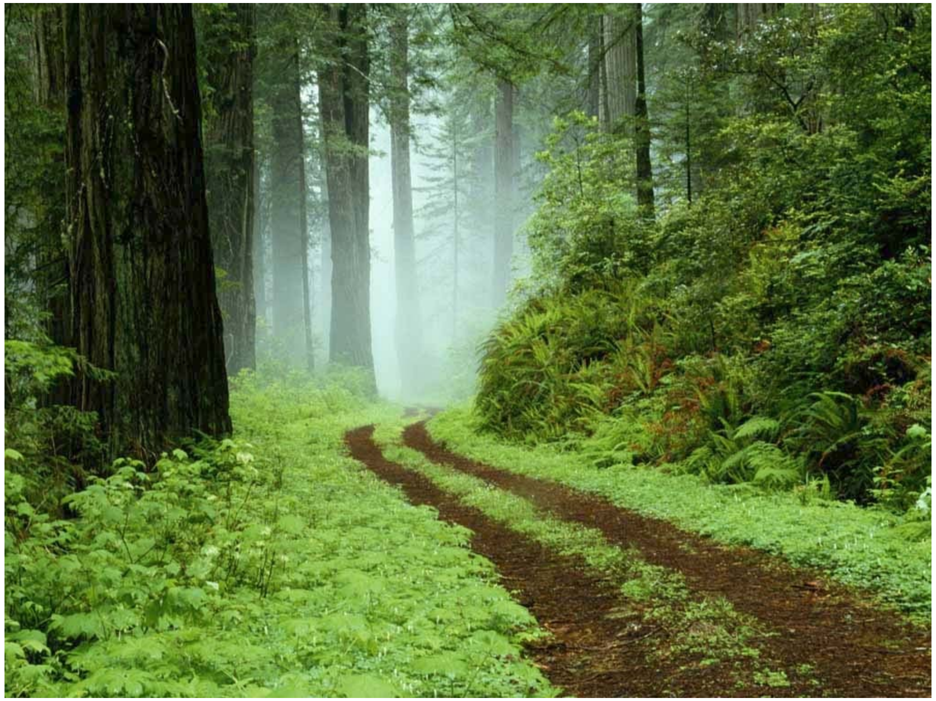


群れの先頭（孤立地震を含む）が前震である確率の地域性









Thank you very much for your attention

Software available.
Please visit WEB home page of our project team:

http://www.ism.ac.jp/~ogata/Ssg/ssgE.html