階層的時空間ETASモデルに基づく
短期・中期・長期予測および背景率予測
― 自動予測の開発に向けて

Short-, medium-, long-term and background-rate forecasts based on a hierarchical space-time ETAS model: Towards the development of automated forecasts

統計数理研究所
尾形良彦

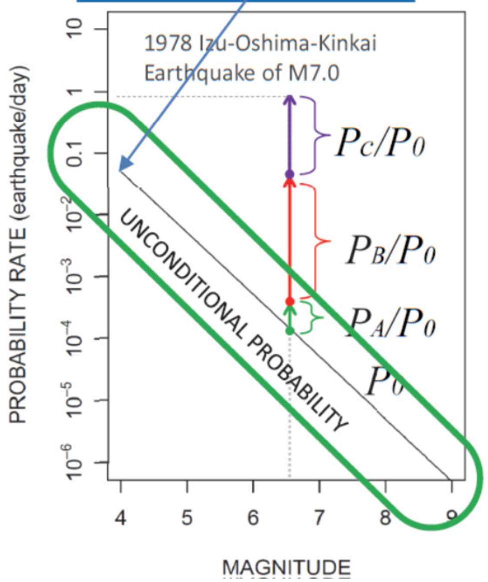
宇津 1979

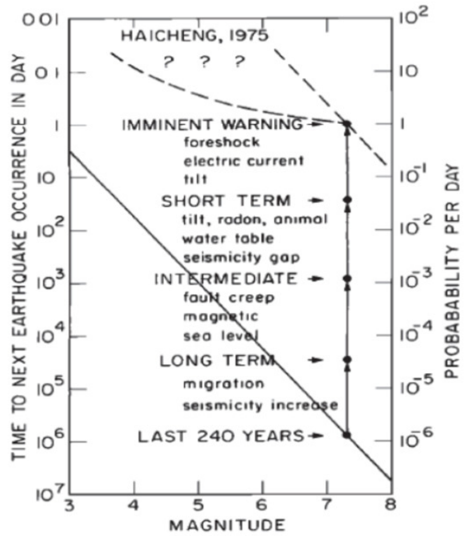
$$P(M \mid A,B,C,\cdots,S) = \frac{1}{1+\left(\frac{1}{P_A}-1\right)\left(\frac{1}{P_B}-1\right)\left(\frac{1}{P_C}-1\right)\Big/\left(\frac{1}{P_0}-1\right)^{3-1}} \approx P_0 \cdot \boxed{\frac{P_A}{P_0}}\,\frac{P_B}{P_0}\,\frac{P_C}{P_0}$$

Aki（1981）

$$\boxed{\text{確率利得}} = \frac{\text{異常現象が大地震の前兆である確率}}{\boxed{\text{大地震の永年確率}}}$$

M≧4基礎地震確率





Cao & Aki (1983) JGR

1975M7.3
海城 9%/day

1976M7.8
唐山 9%/day

1976M7.6
Longlin 7%/day

1976M7.2
Songpan 8%/day

条件付き強度関数

$$\frac{P\left\{\text{an event in } [t,t+\Delta t]\times[x,x+\Delta x]\times[y,y+\Delta y]\times[M,M+\Delta M] \mid H_t,\mathbf{F}_t\right\}}{\Delta t\,\Delta x\,\Delta y\,\Delta M} \approx \lambda(t,x,y,M \mid H_t,\mathbf{F}_t),$$

$$\boxed{\lambda(t,x,y,M \mid H_t,\mathbf{F}_t) = \mu(x,y,M)\,\frac{\lambda_{ETAS}(t,x,y,M \mid H_t)}{\mu(x,y,M)}\prod_{k=1}^{K}\frac{\lambda_k(t,x,y,M \mid F_t^k)}{\mu(x,y,M)}}$$

多項目確率予測式の点過程版

危険度拡大率（Risk enhancement factors）

$$\lambda(t,x,y,M \mid H_t,F_t^1,\cdots,F_t^K)=\mu(x,y,M)\underbrace{\frac{\lambda_{ETAS}(t,x,y,M\mid H_t)}{\mu(x,y,M)}\prod_{k=1}^{K}\frac{\lambda_k(t,x,y,M\mid F_t^k)}{\mu(x,y,M)}}_{\text{危険度拡大率（Risk enhancement factors）}}$$

階層的時空間ETAS (HIST-ETAS)モデルによる予測（標準版）

$$\lambda_{ETAS}(t,x,y,M\mid H_t)=\lambda_{ETAS(M_c)}(t,x,y\mid H_t)\cdot g(M-M_c)$$

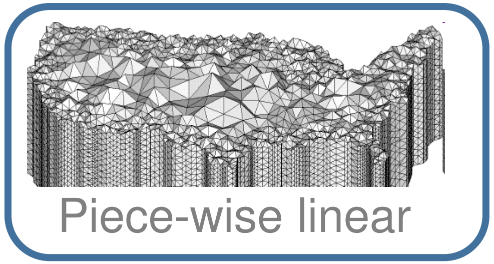
$$\lambda_{ETAS(M_c)}(t,x,y\mid H_t)=\mu_{M_c}(x,y)+\sum_{\{j;t_j<t\}}\frac{K(x_j,y_j)}{(t-t_j+c)^{p(x_j,y_j)}}\left\{\frac{(x-x_j,\ y-y_j)\,S_j\begin{pmatrix}x-x_j\\ y-y_j\end{pmatrix}}{e^{\alpha(x_j,y_j)(M_j-M_c)}}+d\right\}^{-q(x_j,y_j)}$$

標準時空間**ETAS**「危険度拡大率」$=\dfrac{\lambda_{ETAS}(t,x,y,M\mid H_t)}{\mu(x,y,M)}=\dfrac{\lambda_{ETAS(M_c)}(t,x,y\mid H_t)}{\mu_{M_c}(x,y)}$

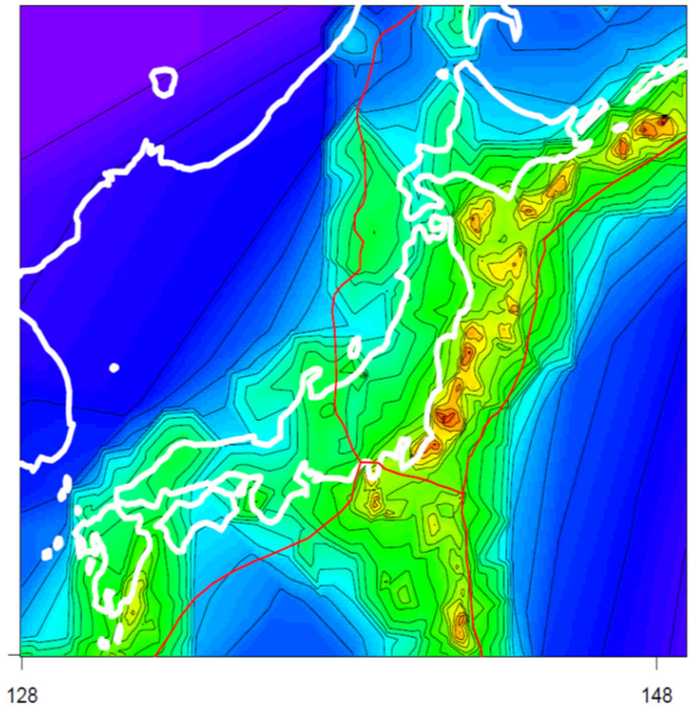
$$=1+\sum_{\{j;t_j<t\}}\frac{K_{Mc}(x_j,y_j)/\mu_{M_c}(x,y)}{(t-t_j+c)^{p(x_j,y_j)}}\left\{\frac{(x-x_j,\ y-y_j)\,S_j\begin{pmatrix}x-x_j\\ y-y_j\end{pmatrix}}{e^{\alpha(x_j,y_j)(M_j-M_c)}}+d\right\}^{-q(x_j,y_j)}$$

背景地震活動率（Background seismicity rate）

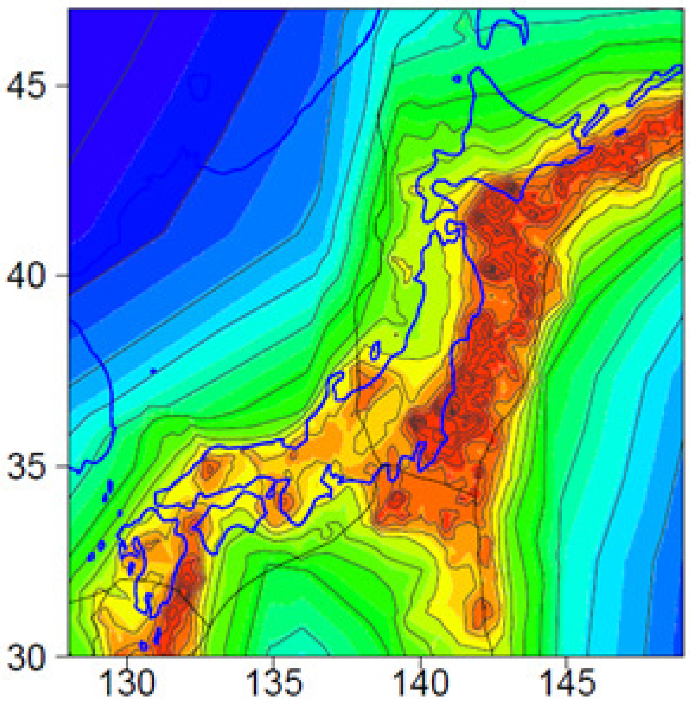
$$\lambda(t,x,y\mid H_t)=\mu(x,y)+\sum_{\{j;t_j<t\}}\frac{K_0(x,y)}{(t-t_j+c)^p}\left\{\frac{(x-x_j,\,y-y_j)\,S_j\begin{pmatrix}x-x_j\\ y-y_j\end{pmatrix}}{e^{\alpha(M_j-M_c)}}+d\right\}^{-q}$$



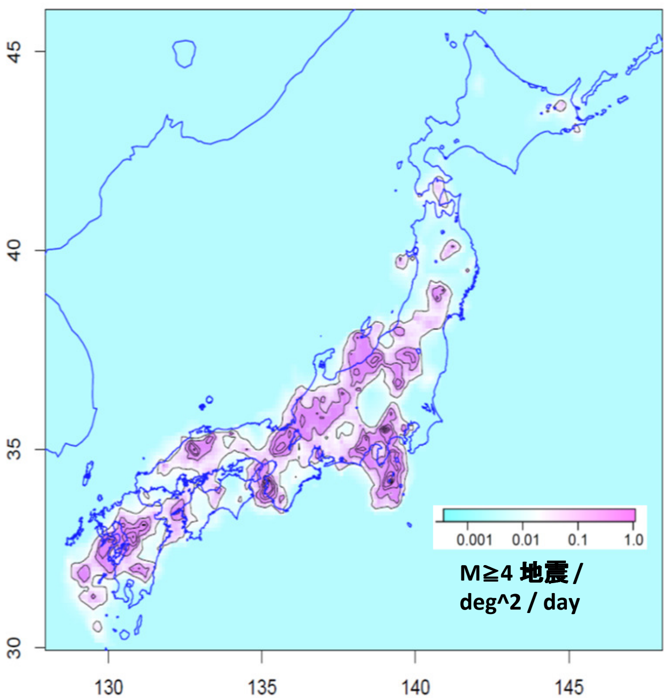
$\mu(x,y)$ **GCMT M≧5.4**



$\mu(x,y)$ **JMA M≧5.0**



$\mu(x,y)$ **JMA 内陸 M≧4.0**



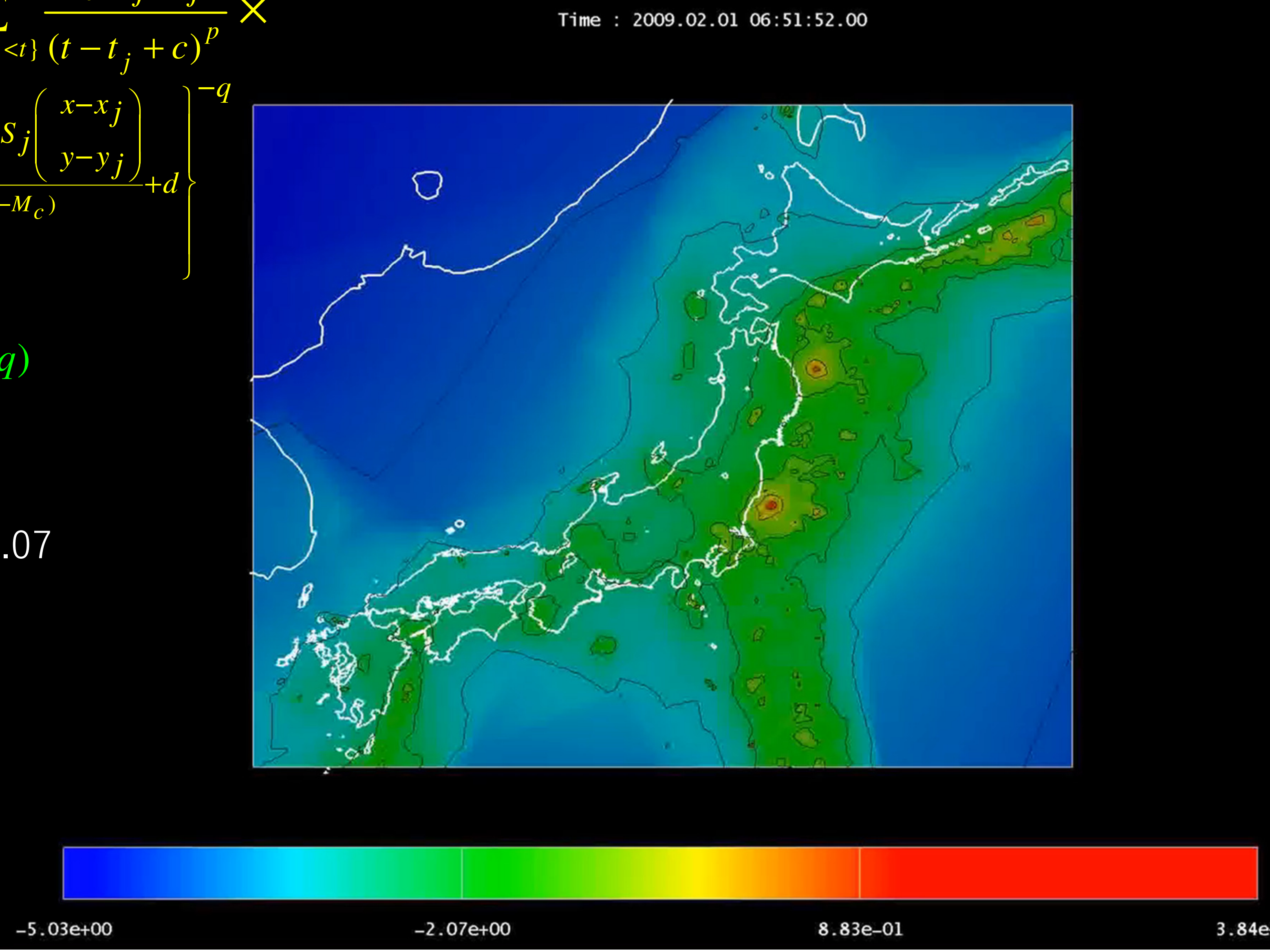
短期予測

Short-term forecast

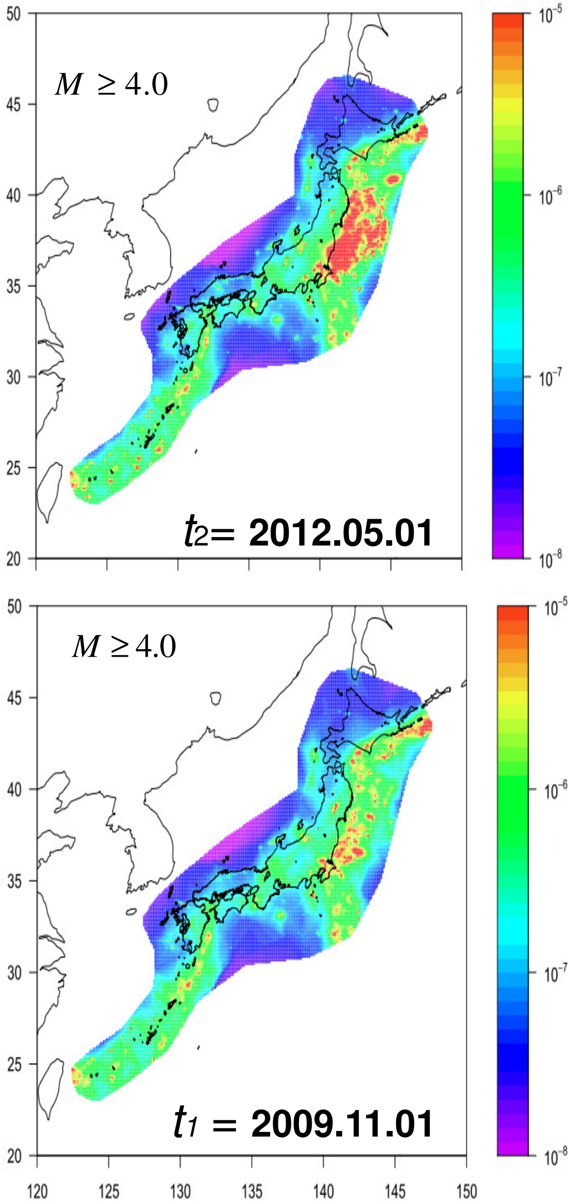
$$\lambda_\theta(t, x, y \mid H_t) = \mu(x, y) + \sum_{\{j; t_j < t\}} \frac{K_0(x_j, y_j)}{(t - t_j + c)^p} \times \left\{ \frac{(x - x_j, y - y_j)\, S_j \begin{pmatrix} x - x_j \\ y - y_j \end{pmatrix}}{e^{\alpha (M_j - M_c)}} + d \right\}^{-q}$$

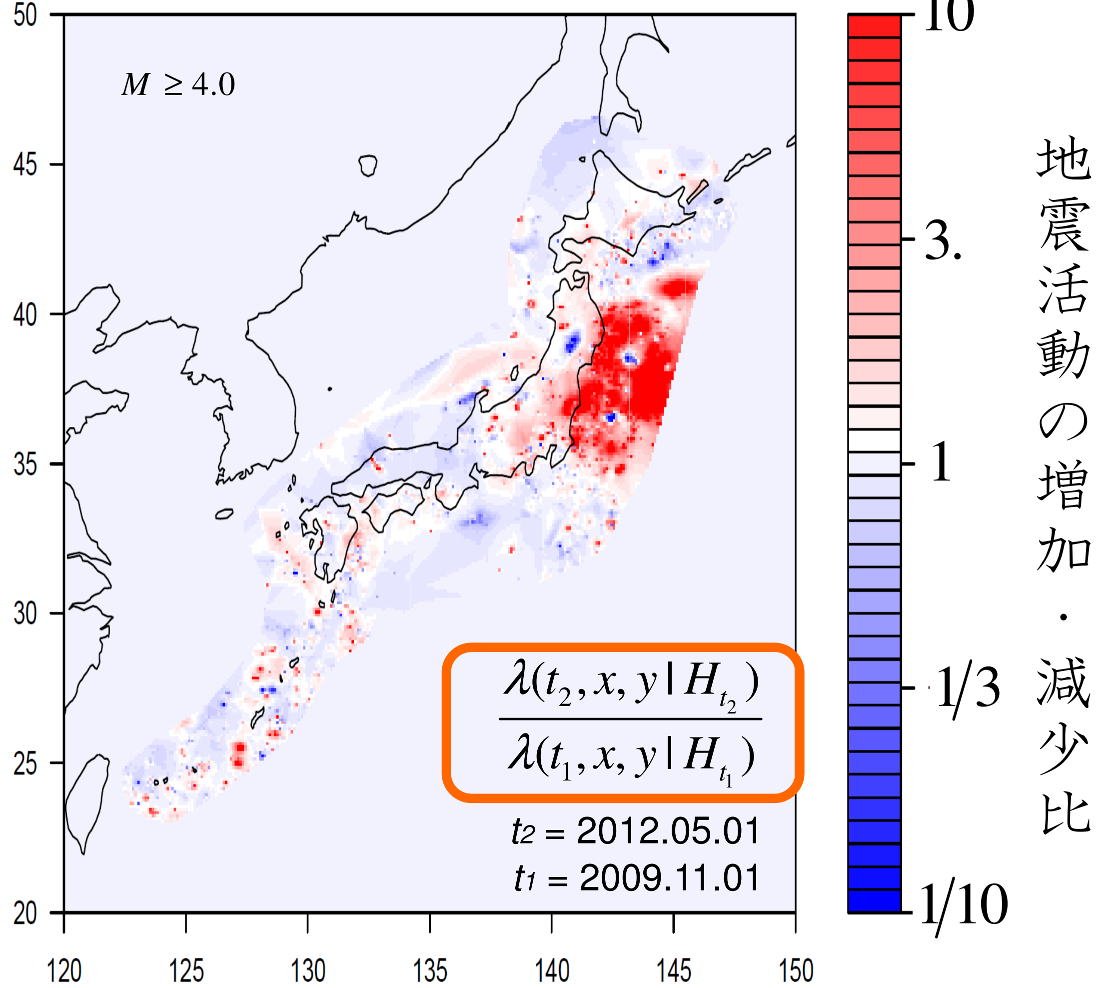
$$\theta = (\mu(x, y), K_0(x, y), c, \alpha, p, d, q)$$

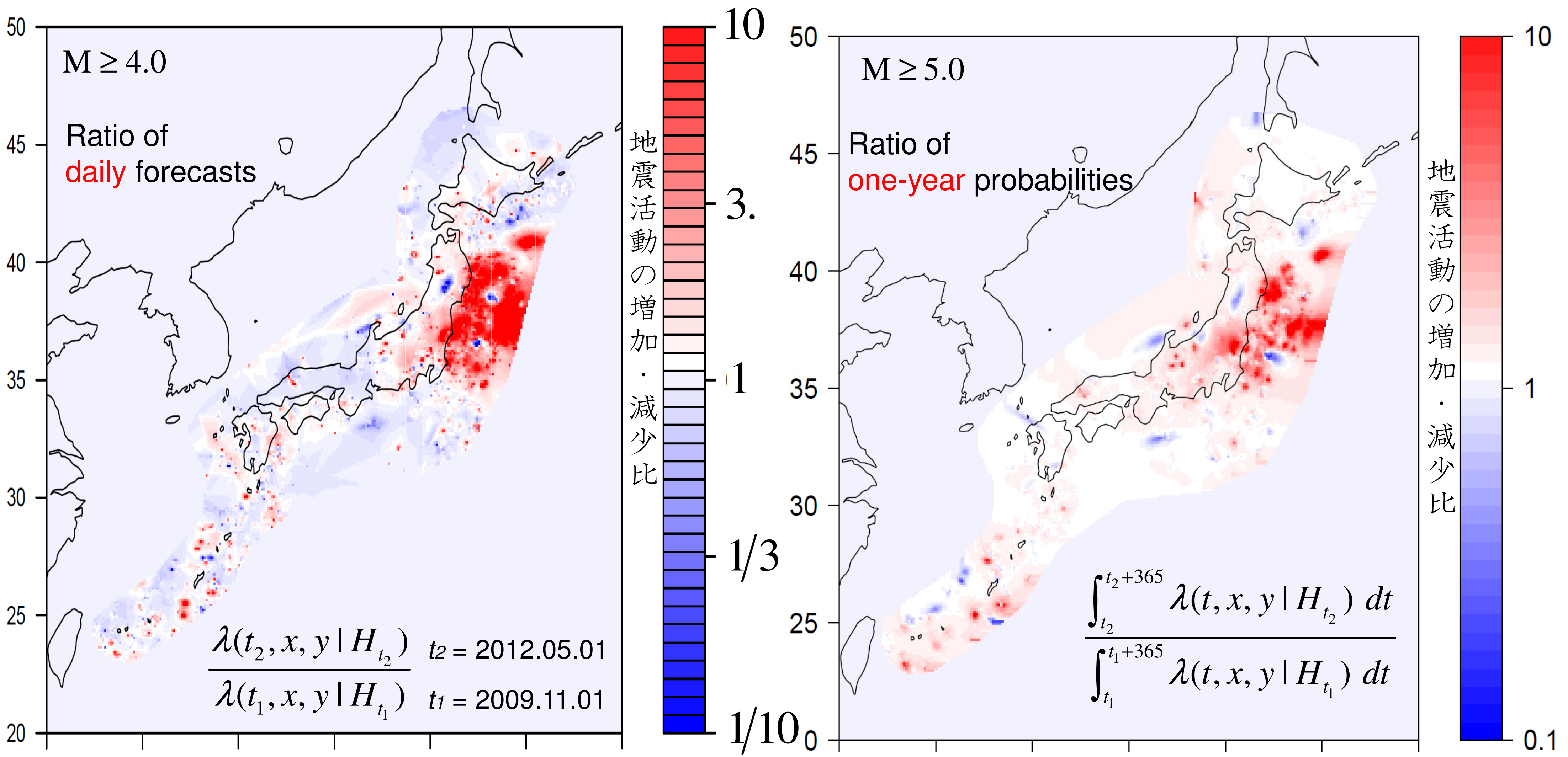
Short-term prediction
Time 2009.01.01 – 2020.11.07
M≧4.0



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

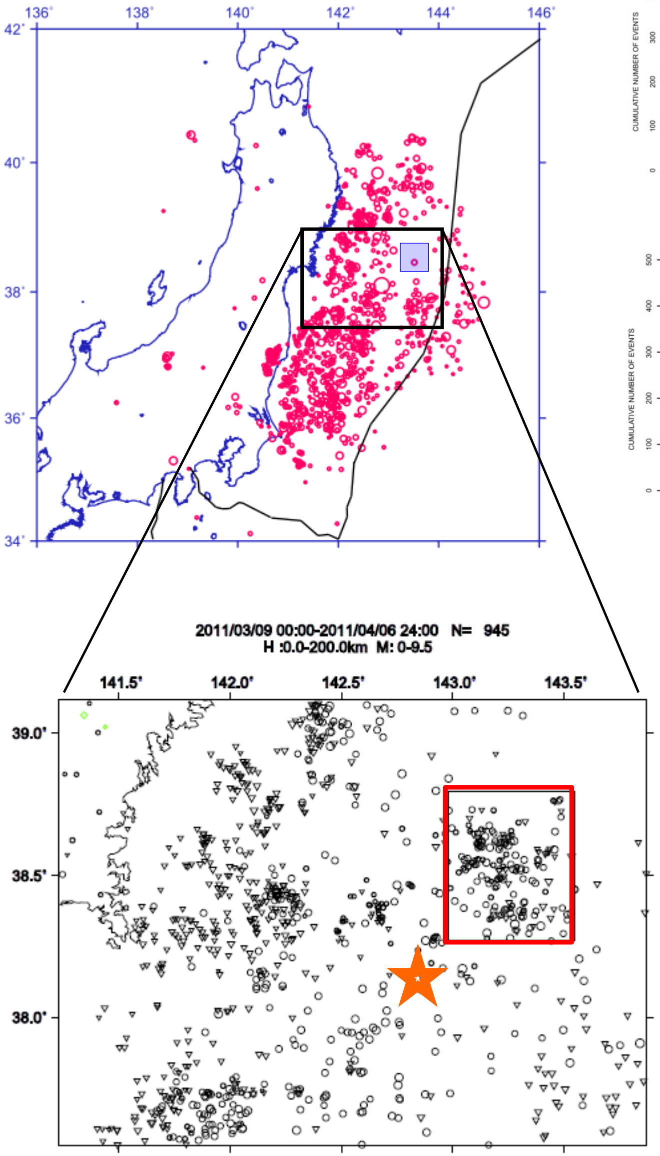


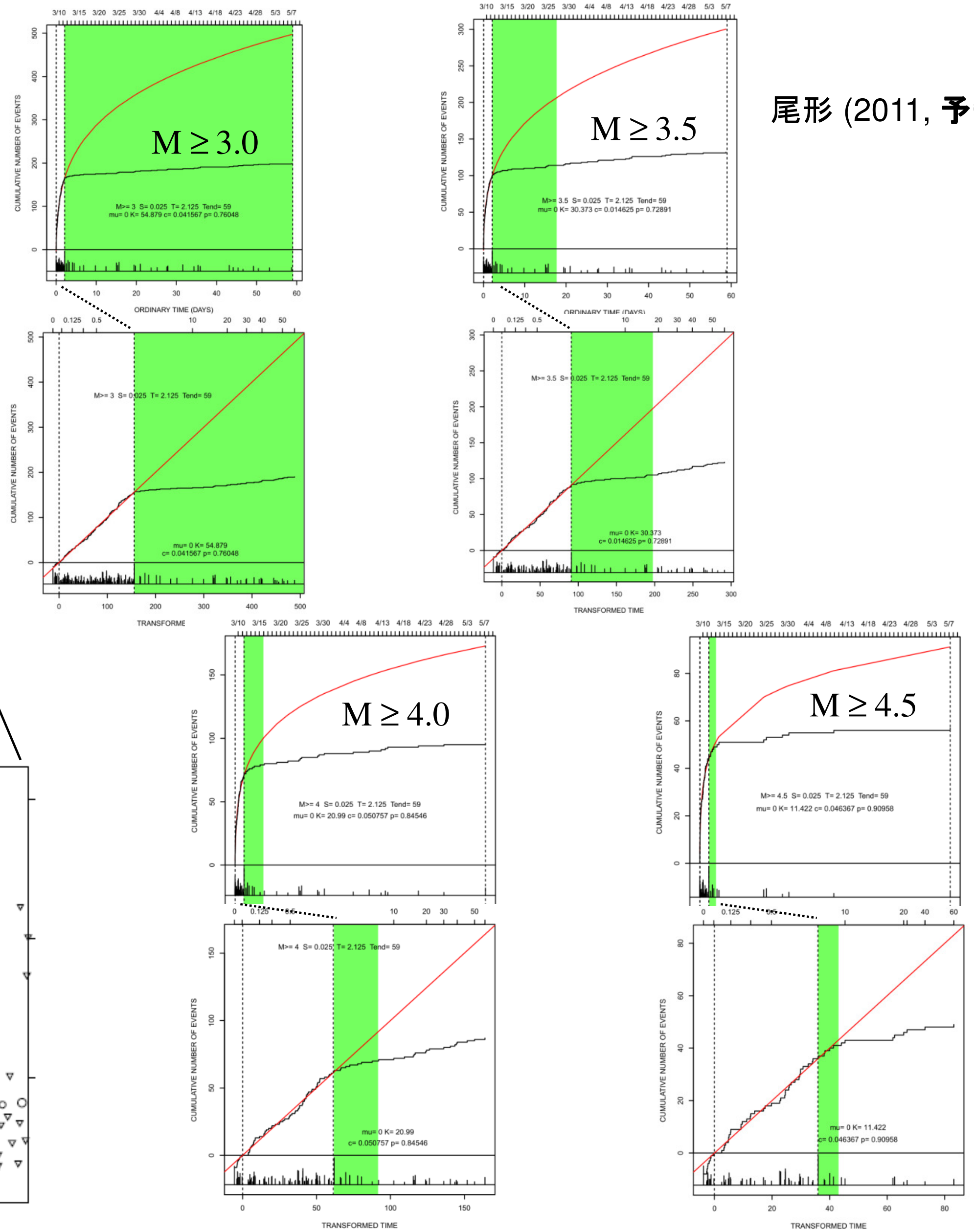




M ≥ 4.0
Ratio of
daily forecasts
$\frac{\lambda(t_2, x, y \mid H_{t_2})}{\lambda(t_1, x, y \mid H_{t_1})}$
t2 = 2012.05.01
t1 = 2009.11.01
地震活動の増加・減少比
10
3.
1
1/3
1/10
M ≥ 5.0
Ratio of
one-year probabilities
$\frac{\int_{t_2}^{t_2+365} \lambda(t, x, y \mid H_{t_2})\, dt}{\int_{t_1}^{t_1+365} \lambda(t, x, y \mid H_{t_1})\, dt}$
地震活動の増加・減少比
10
1
0.1
50
45
40
35
30
25
20
120
125
130
135
140
145
150

Foreshocks led by the M7.3 event



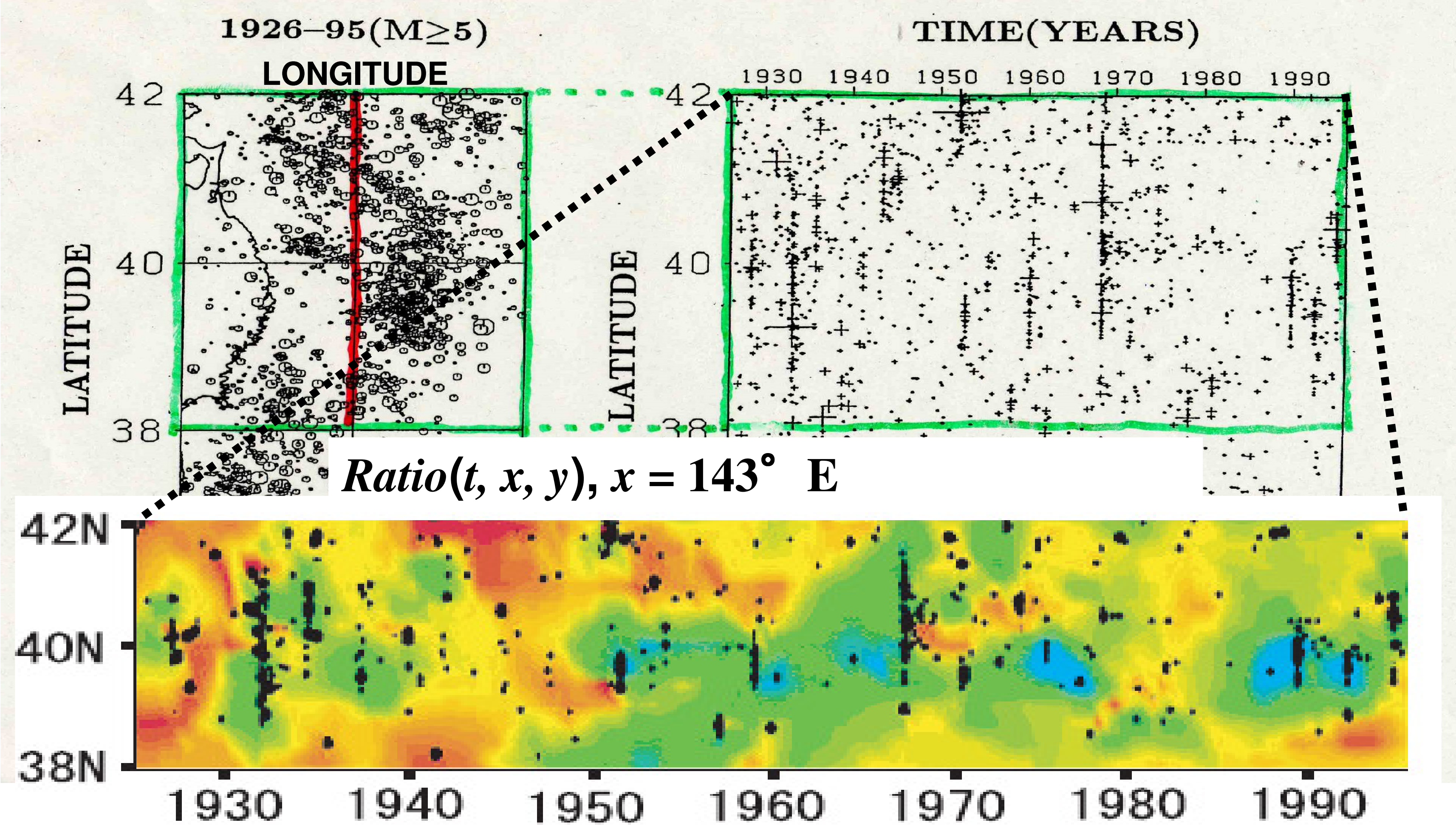


尾形 (2011, **予知連会報**, 3-20)

$$\lambda(t, x, y \mid \theta_{space,time}) = \hat{\lambda}(t, x, y \mid \hat{\theta}_{space}) \cdot \boxed{Ratio(t, x, y \mid \theta_{space,time})}$$

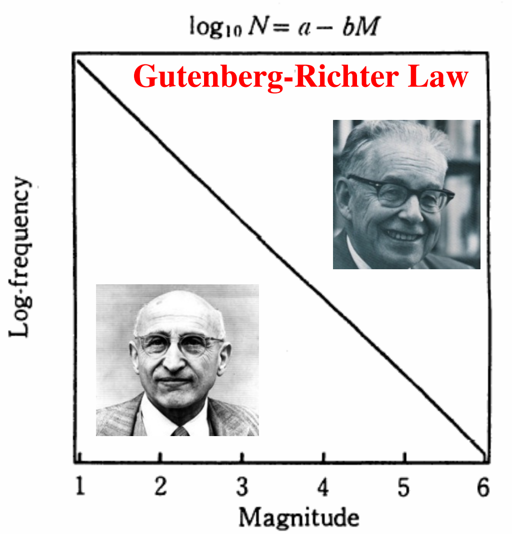
$\Uparrow$ Real Seismicity $\Uparrow$ HIST-ETAS Model $\Uparrow$ Ratio Function

Ogata et al. (2003, *JRSSC*)

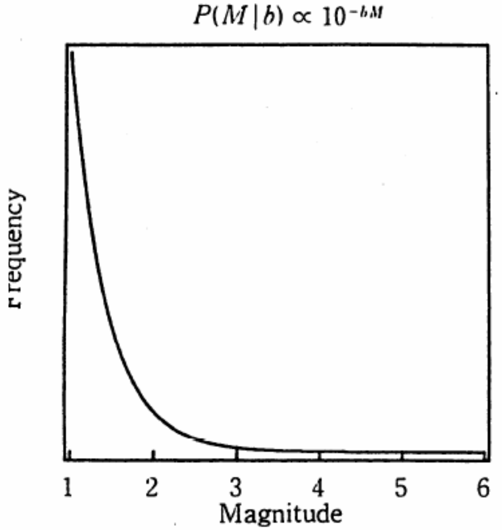


Magnitude Frequency distribution and Earthquake Detection Rates

Ogata & Katsura (1993, *GJI*)

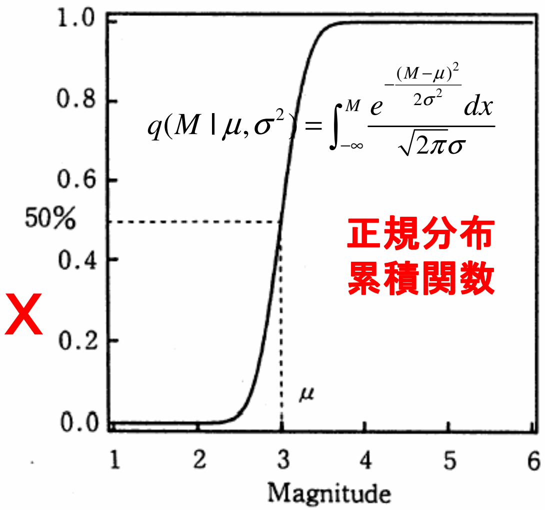


(b) Gutenberg-Richter law



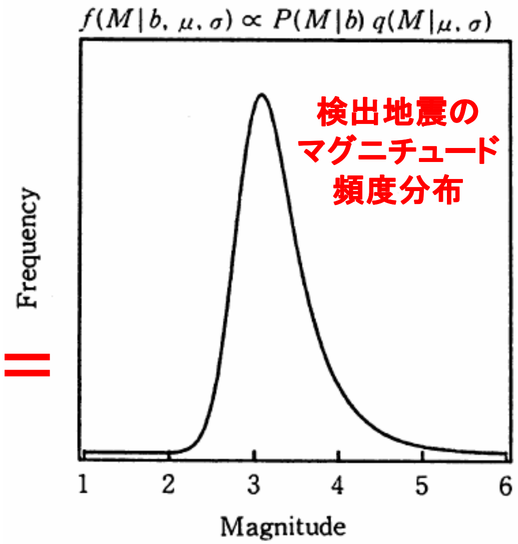
(a) Exponential distribution

X

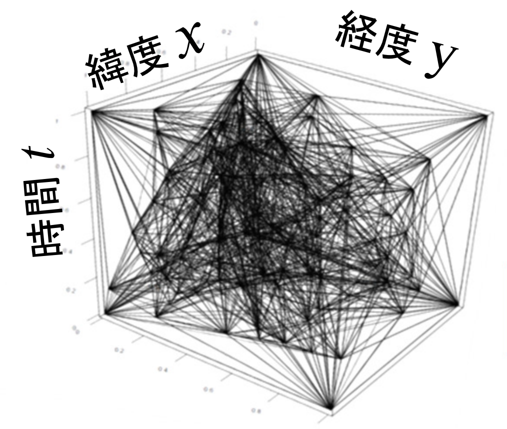


(c) Detection rate

=



(d) Detected events

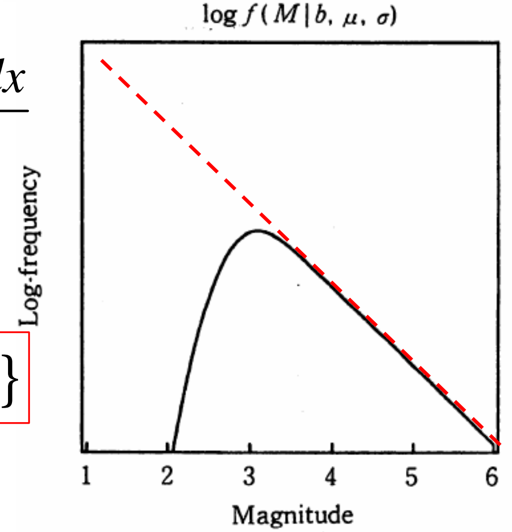


デロネ4面体分割網

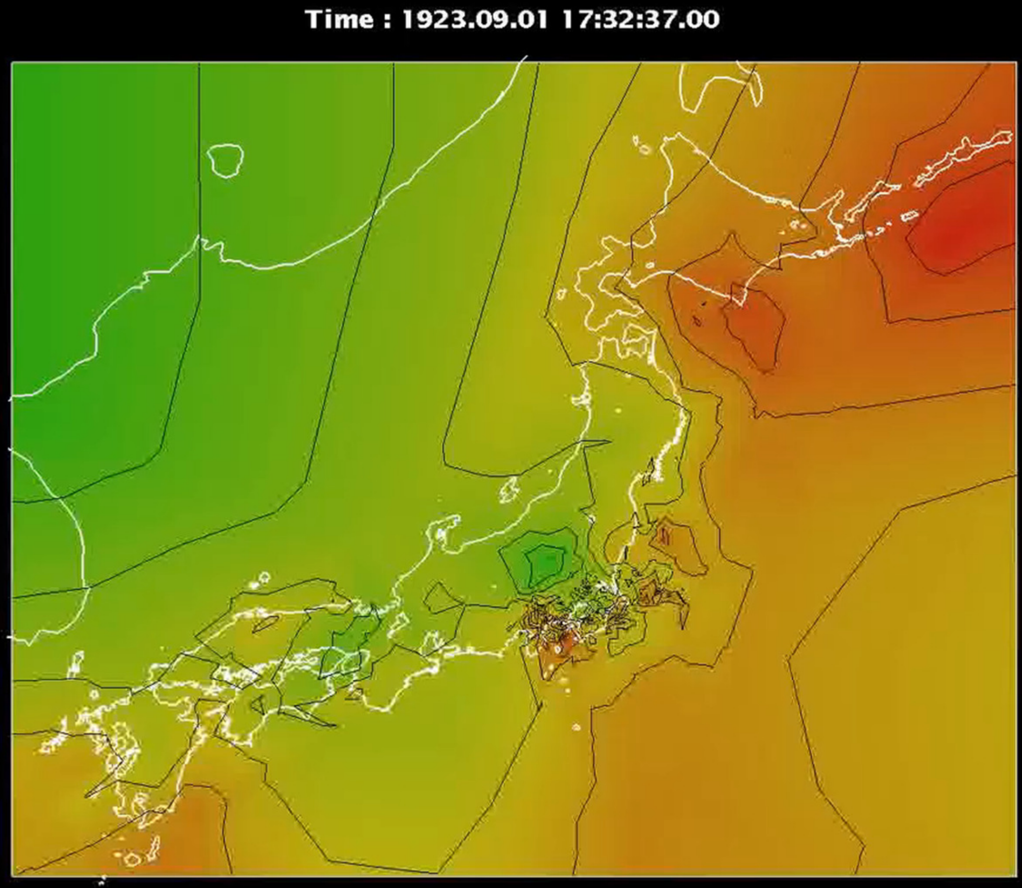
$$q(M \mid \mu, \sigma^2) = \int_{-\infty}^{M} \frac{e^{-\frac{(M-\mu)^2}{2\sigma^2}}}{\sqrt{2\pi}\sigma} dx$$

時空間地震検出モデル

$$\boxed{\lambda(t, x, y, M) = 10^{a + b(t,x,y)(M - M_0)}\, q\{M \mid \mu(t, x, y), \sigma(t, x, y)\}}$$

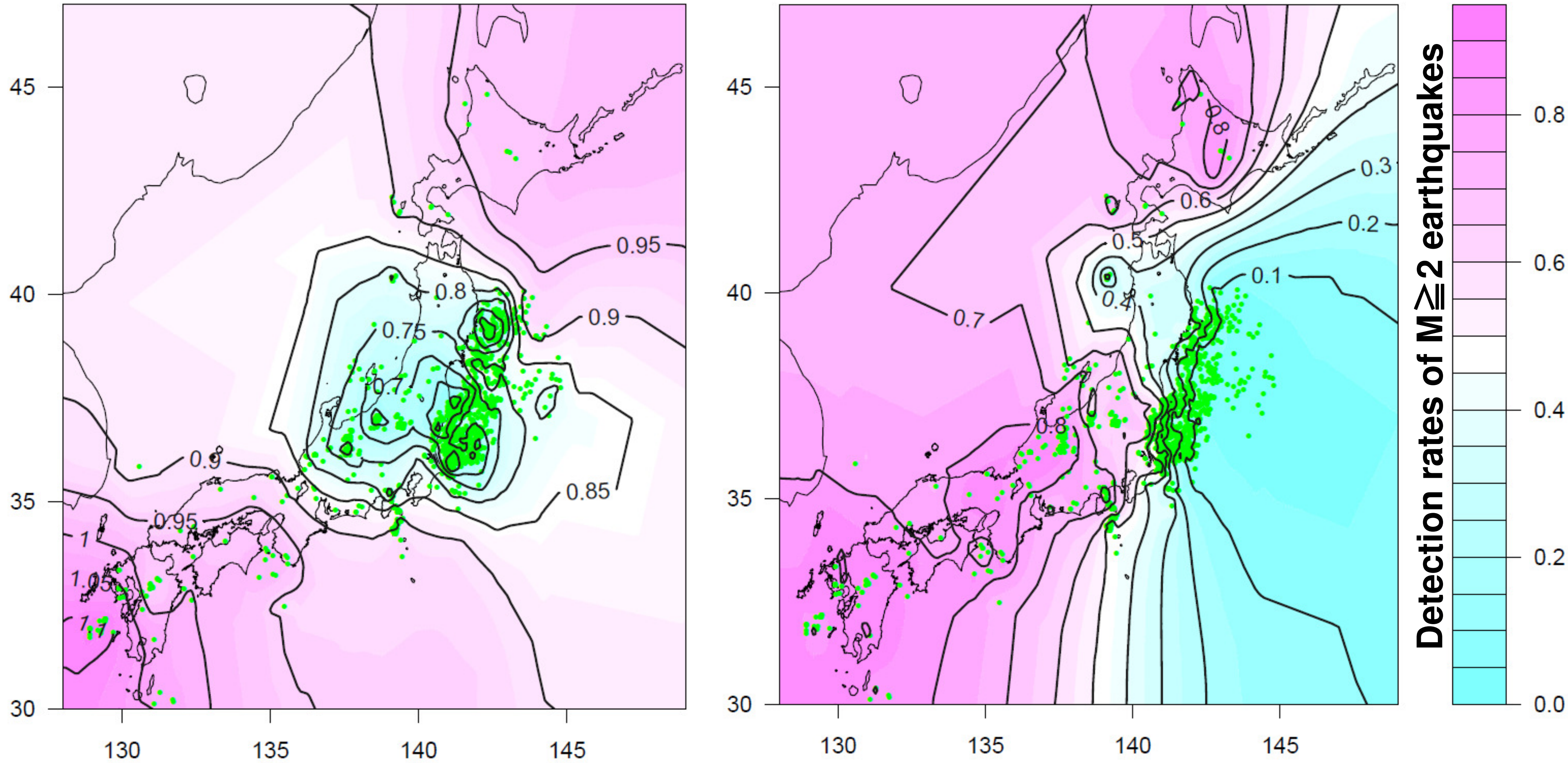


(e) Detected events

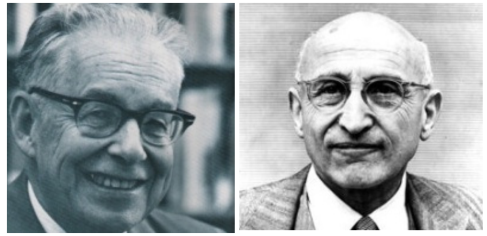


50%検出されるマグニチュード $\mu(t, x, y)$

2011年3月11日本震直後



b 値　　　M≧2.0余震の検出率



地震マグニチュードの予測モデル

$$\lambda(t,x,y,M \mid H_t) = \lambda_{ETAS(M_c)}(t,x,y \mid H_t) \cdot g_{GR}(M - M_c)$$

基準モデル: Gutenberg-Richter 則 （b＝定数 ~ 0.9）

$$g_{GR}(M \mid b) \propto 10^{-b(M-M_c)}; \quad M \geq M_c$$

履歴に依存するマグニチュード分布

$$g\left(M \mid t_j, x_j, y_j, M_j;\, t_j < t\right); \quad M \geq M_c$$

基準モデルより予測が良くなるものを構成できるか？

→**前震識別** Ogata Utsu & Katsura (1996, *GJI*)

群内の<u>次の地震</u>のマグニチュード(前震)予測モデル

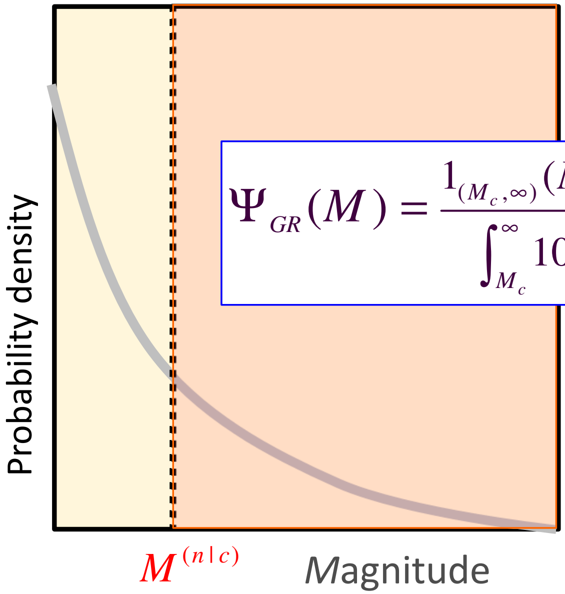
(Ogata et al., 2018, *SRL*)

Leaping Magnitude Threshold : $M^{(n|c)} = \max\{M_k;\ k = 1, \cdots, n \mid \text{in cluster } c\} + 0.5$

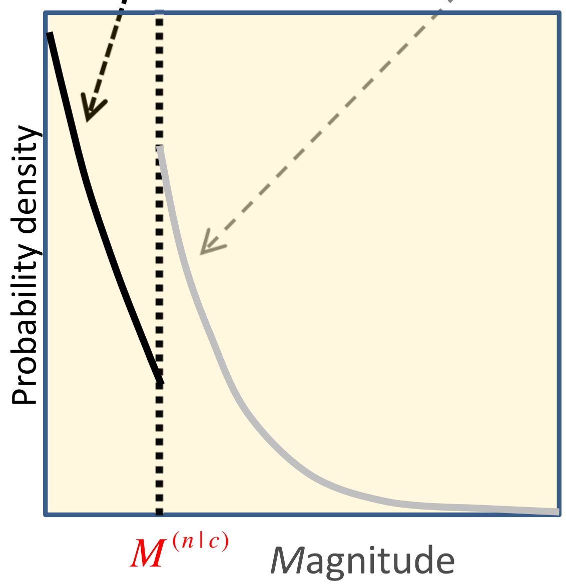
Probability of M≧Mmax+0.5 of the next magnitude; $p_{n|c} = P\{M_{n+1} \geq M^{(n|c)} \mid in\ c\}$

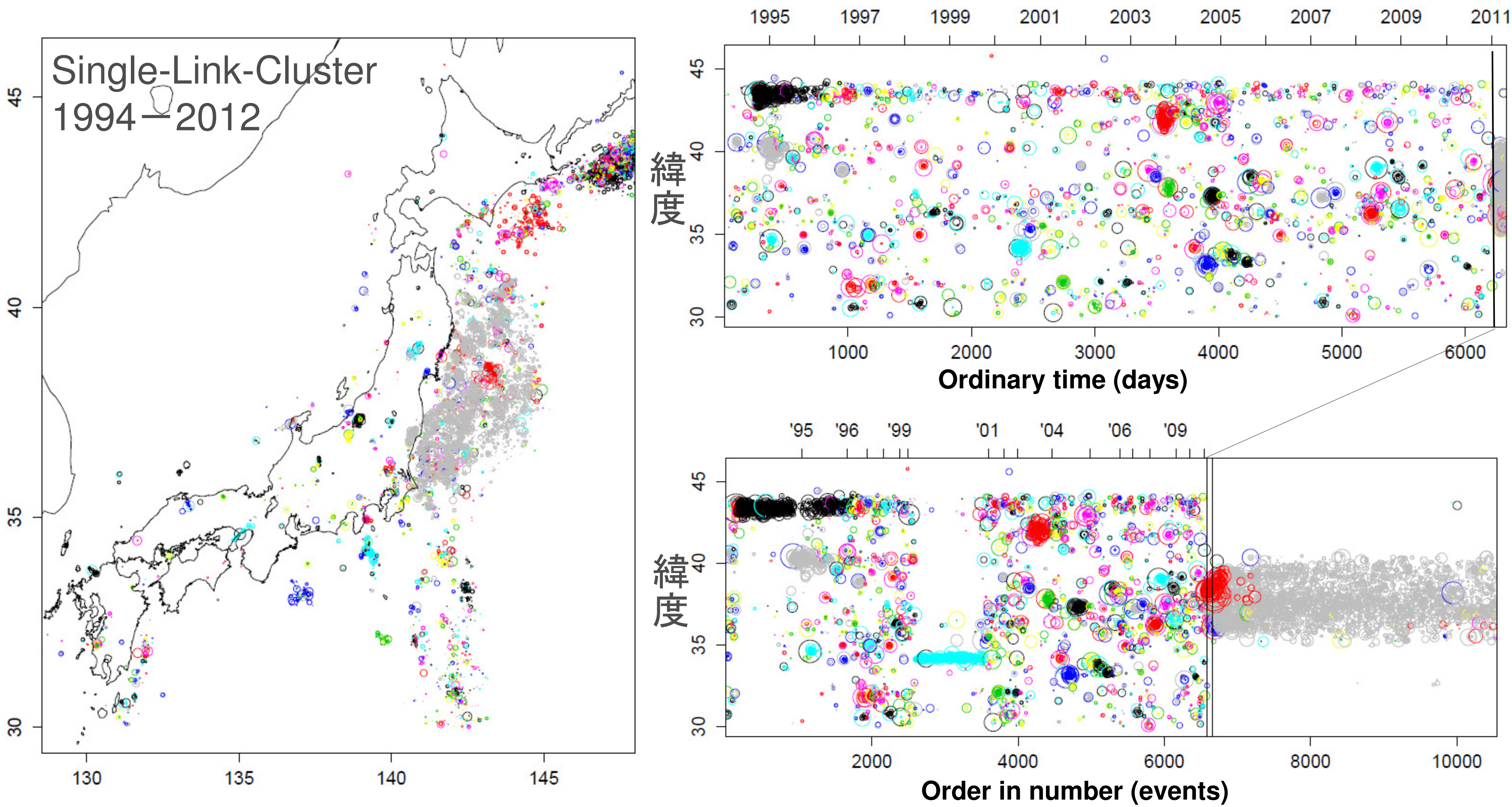
If $(t_{n+1}, x_{n+1}, y_{n+1})$ is connected to c,

$$\Psi(M \mid M_1, \cdots, M_n) = (1 - p_{n|c}) \frac{1_{(M_c,\, M^{(n|c)})}(M) \cdot 10^{-bM}}{\int_{M_c}^{M^{(n|c)}} 10^{-bM}\, dM} + p_{n|c} \frac{1_{(M^{(n|c)},\, \infty)}(M) \cdot 10^{-bM}}{\int_{M^{(n|c)}}^{\infty} 10^{-bM}\, dM}$$

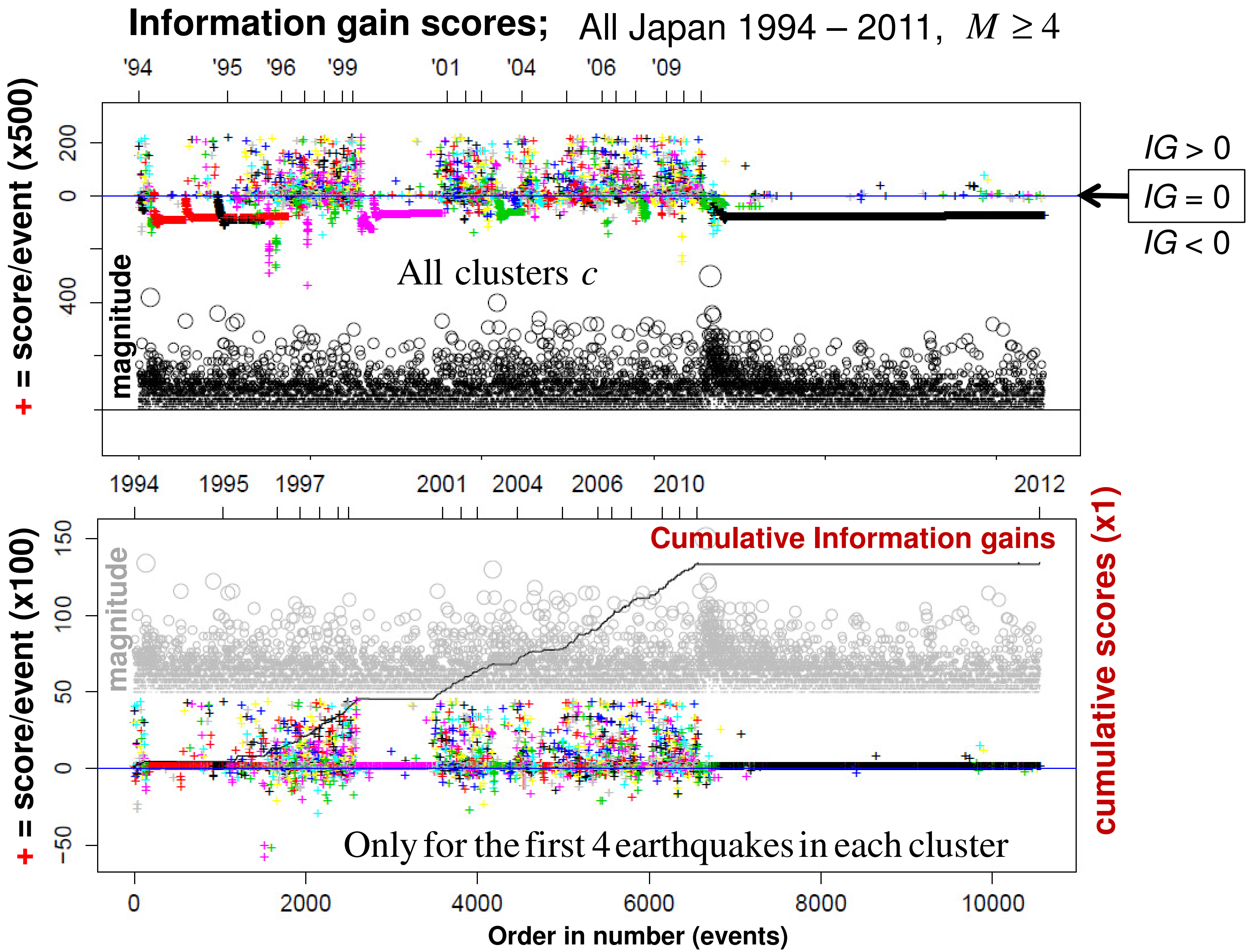


$$\Psi_{GR}(M) = \frac{1_{(M_c, \infty)}(M) \cdot 10^{-bM}}{\int_{M_c}^{\infty} 10^{-bM}\, dM}$$

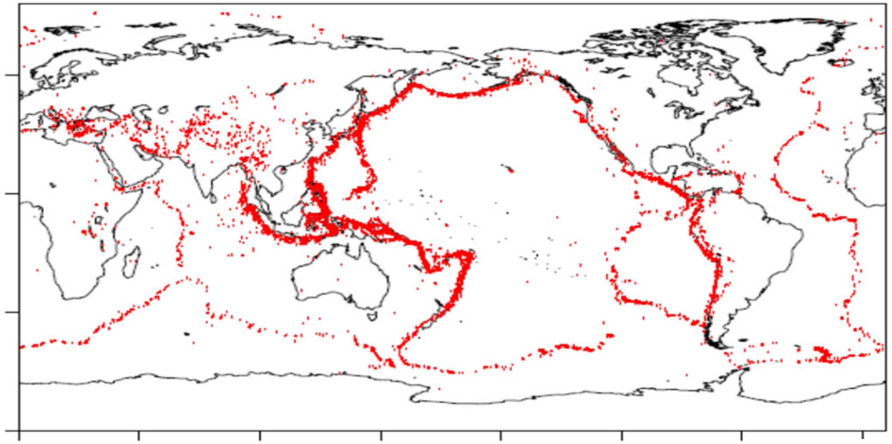




Single-Link-Cluster
1994－2012
45
40
35
30
130
135
140
145
1995
1997
1999
2001
2003
2005
2007
2009
2011
緯度
1000
2000
3000
4000
5000
6000
Ordinary time (days)
'95
'96
'99
'01
'04
'06
'09
2000
4000
6000
8000
10000
Order in number (events)

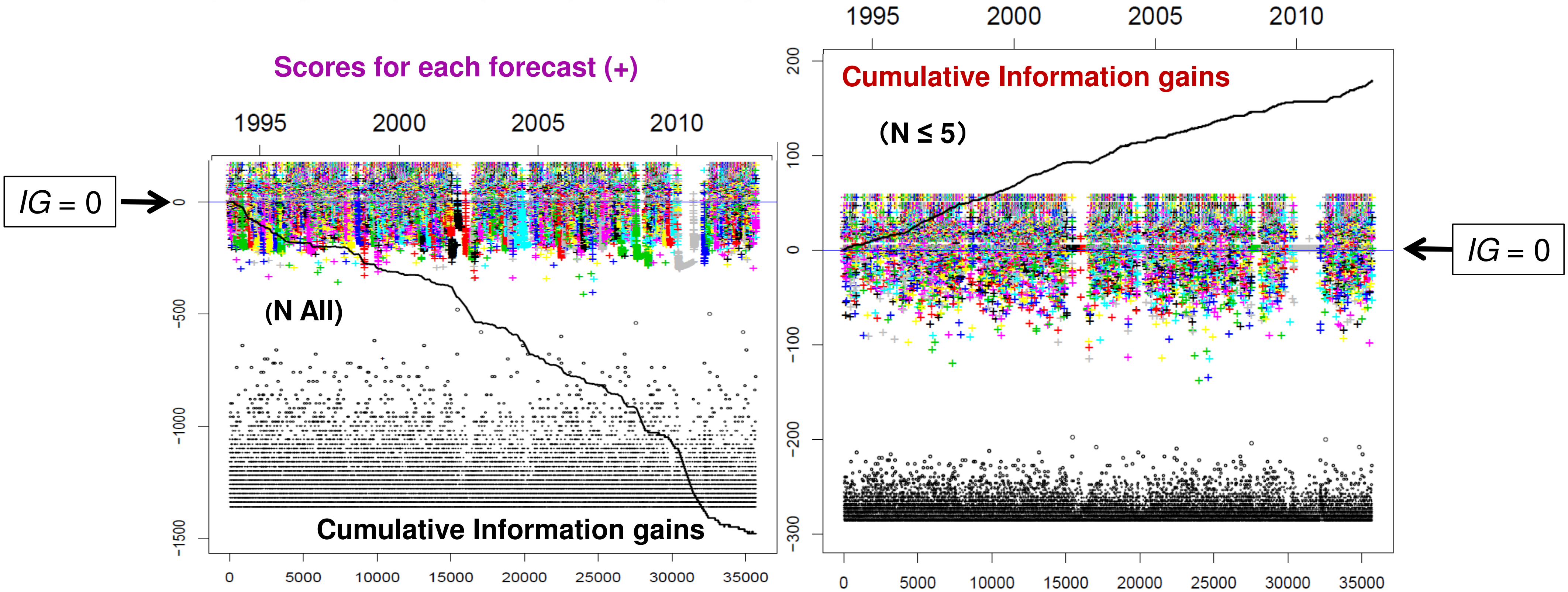


Information gain scores; All Japan 1994 – 2011, $M \geq 4$
'94 '95 '96 '99 '01 '04 '06 '09
+ = score/event (x500)
200
0
400
magnitude
All clusters c
$IG > 0$
$IG = 0$
$IG < 0$
1994 1995 1997 2001 2004 2006 2010 2012
+ = score/event (x100)
150
100
50
0
−50
magnitude
Cumulative Information gains
cumulative scores (x1)
Only for the first 4 earthquakes in each cluster
0 2000 4000 6000 8000 10000
Order in number (events)

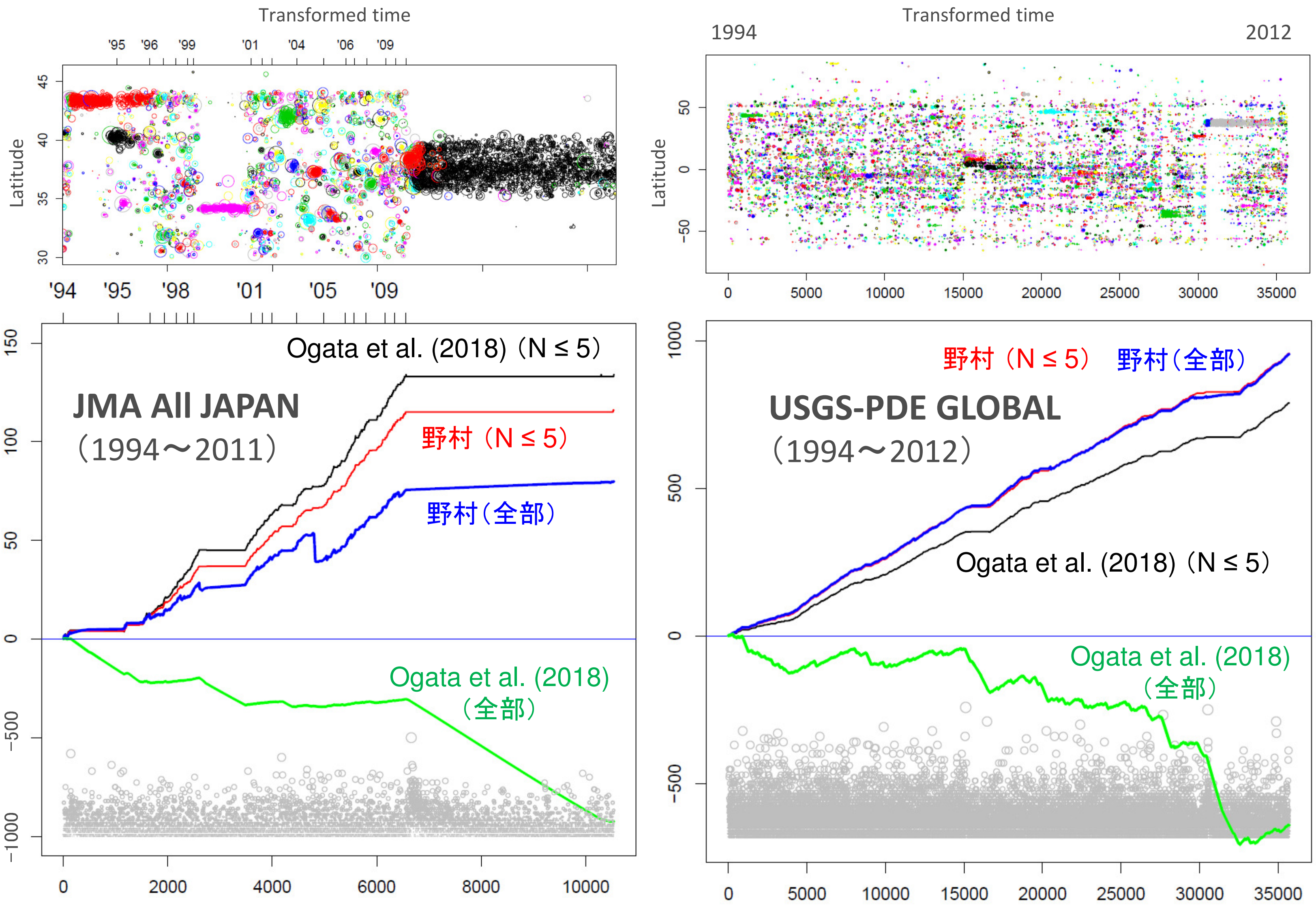


USGS-PDE

Forecasting probability for the first five earthquakes in each cluster; otherwise, Based on the reference G-R law



群内の**次の地震**のマグニチュード予測性能検証



Ogata & Katsura (2014, JGR)

マグニチュード列　　ETASモデル

$$\lambda(t,x,y,M \mid H_t) = f(M \mid H_t) \times \lambda_{ETAS}(t,x,y \mid H_t)$$

1. ETAS / M_{JMA}(4.0):

気象庁データのマグニチュード列 $\{M_j;\ M_j \ge 4.0\}$ の順序を変えない

2. ETAS / M_{BRS}(4.0):

気象庁データのマグニチュード列 $\{M_j;\ M_j \ge 4.0\}$ からBootstrap。

3. ETAS / M_{JMA}(4.0|2.0):

気象庁データのマグニチュード列 $\{M_j;\ M_j \ge 2.0\}$ の順序を変えない

で作った時空間ETASカタログを $M_c \ge 4.0$ を残してカット。

4. ETAS / M_{BRS}(4.0|2.0):

$\{M_j;\ M_j \ge 2.0\}$ の気象庁データのマグニチュード列からBootstrap

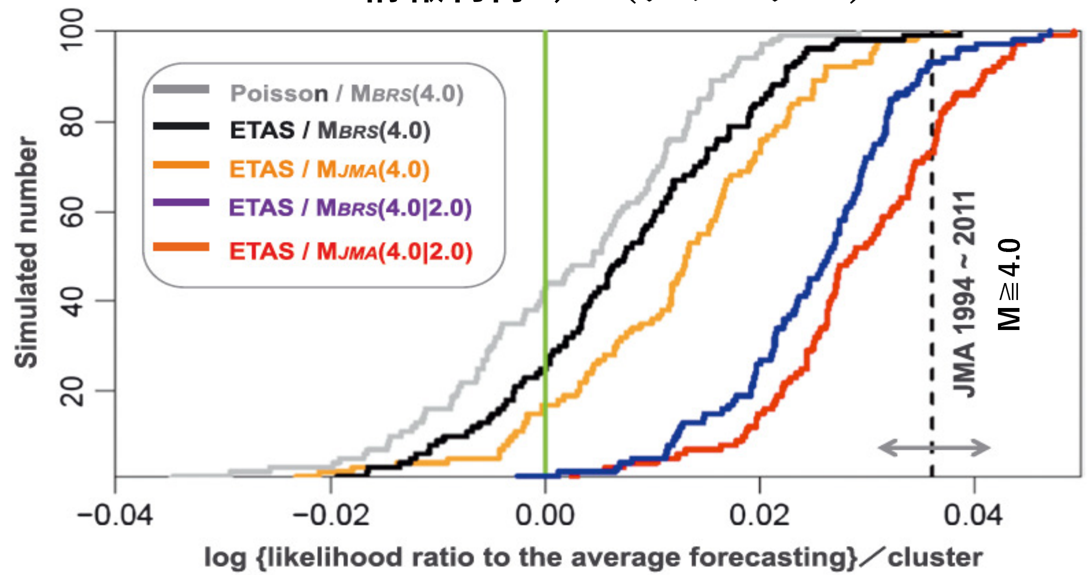
し、それで作った時空間ETASカタログを $M_c \ge 4.0$ を残してカット。

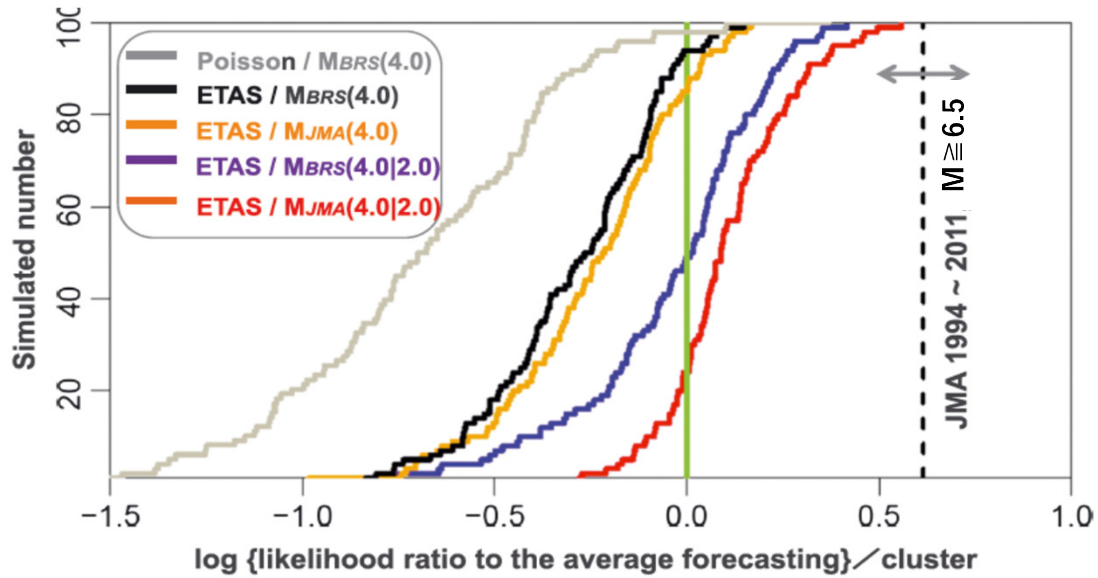
5. Poisson / M_{BRS}(4.0):

$\{M_j;\ M_j \ge 4.0\}$ の気象庁データのマグニチュード列からBootstrap

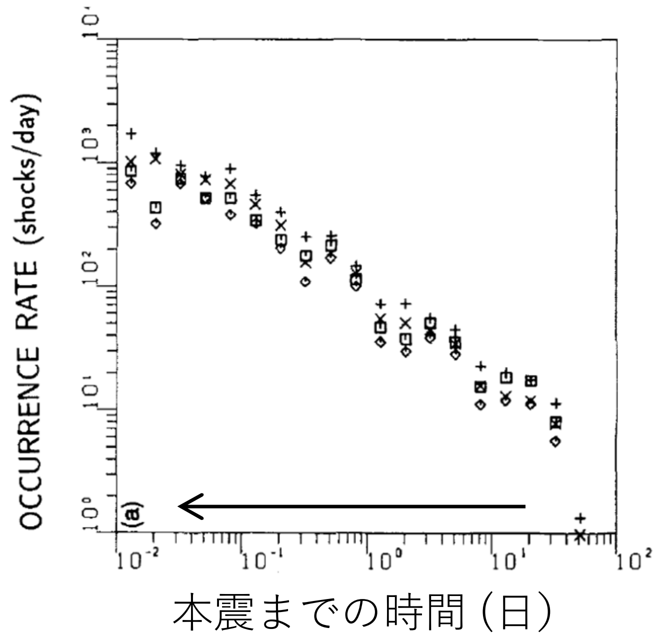
し、それで作ったポアソン過程。

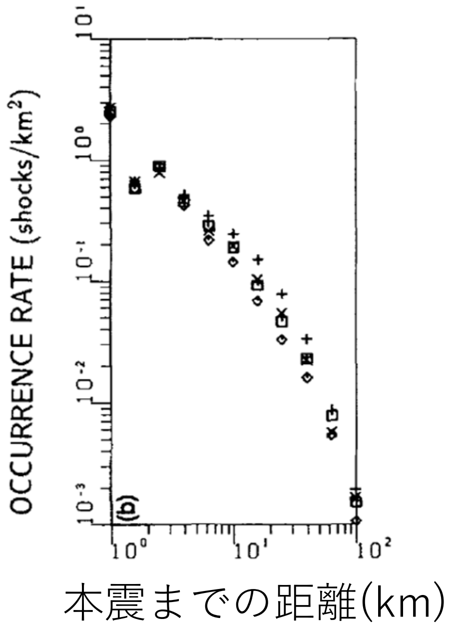
情報利得 ／（クラスター）

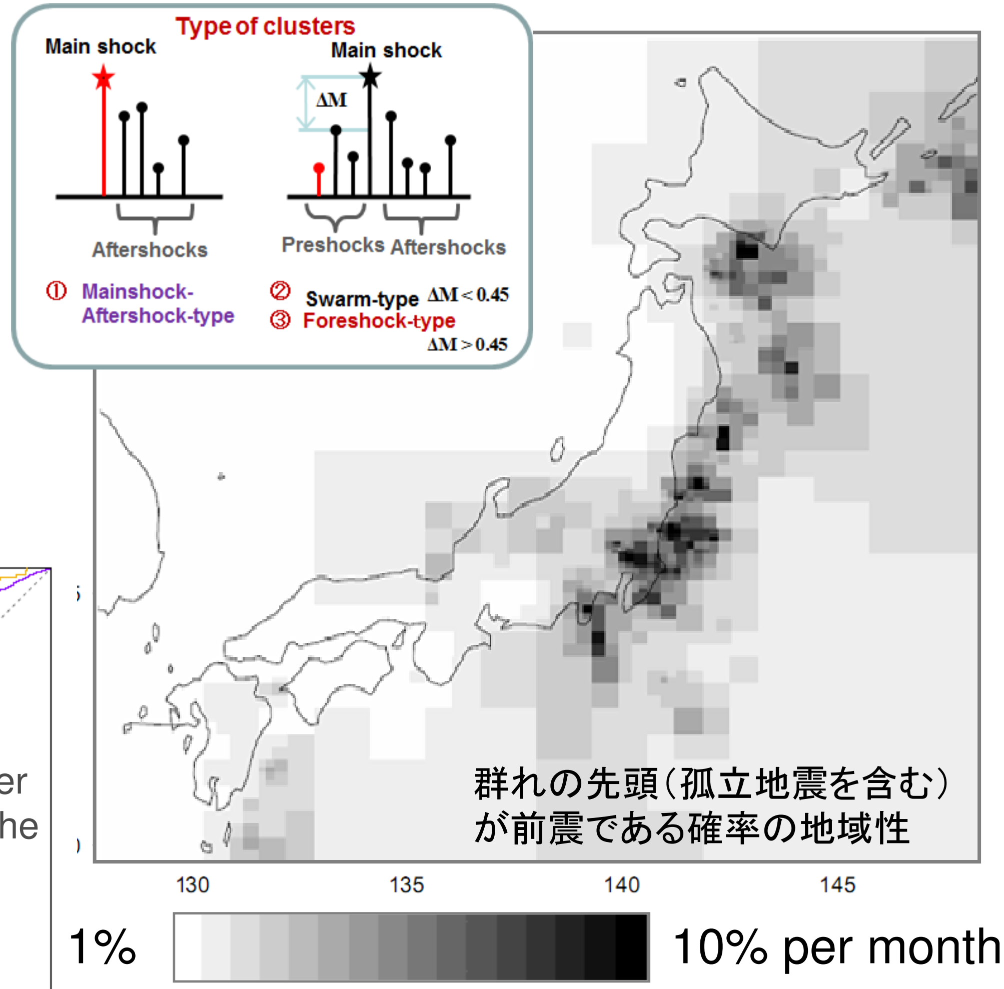


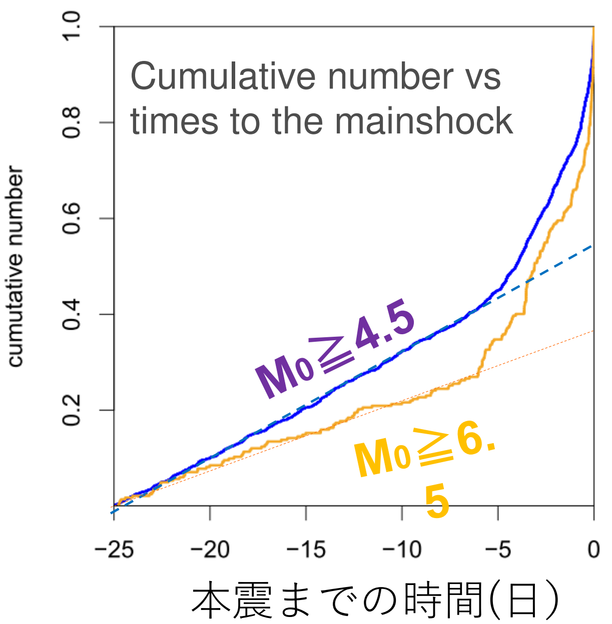


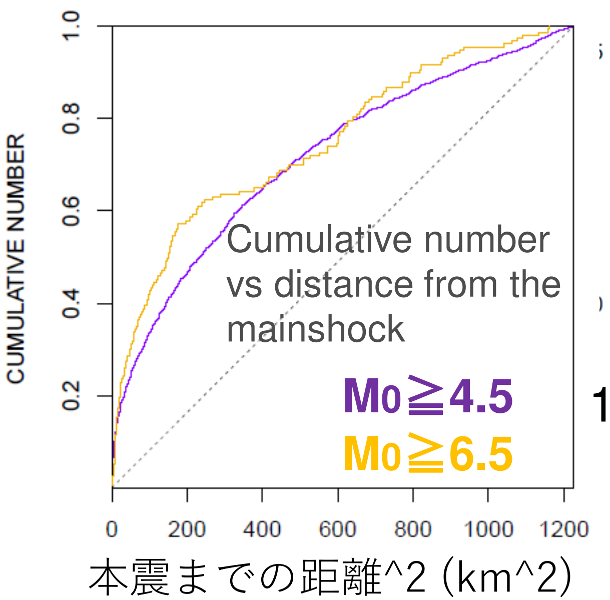
Ogata, Utsu, Katsura, 1995, 1996, *GJI*











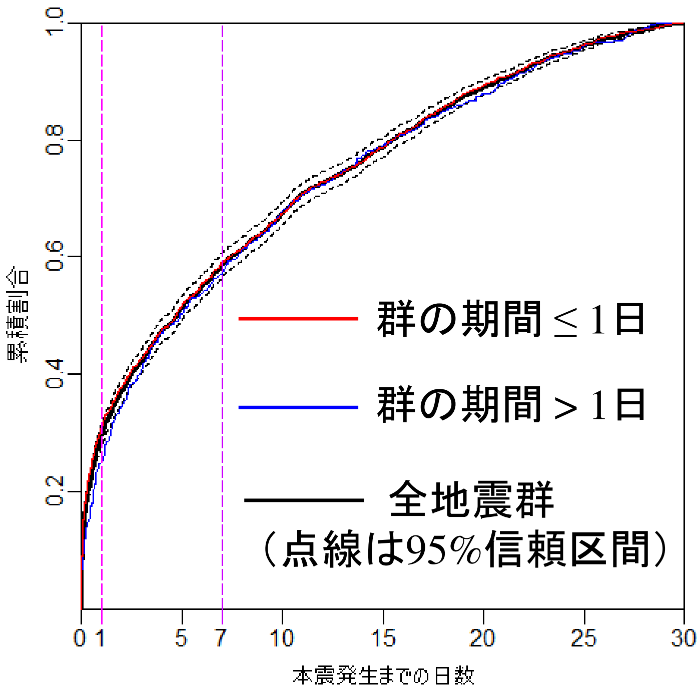
平均 3.9% for Single Link Clusters

Ogata, Katsura, 2014 *JGR*

野村, 尾形 **予知連会報103** (12-8), 2019

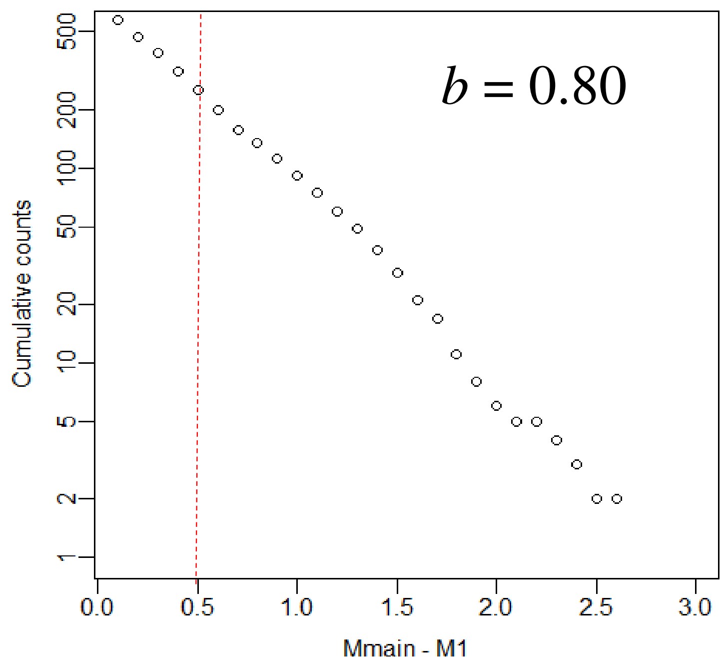
本震発生までの日数予測

- 前震群の定義における評価時点からの本震予測期間を30日から変えたとき、前震確率



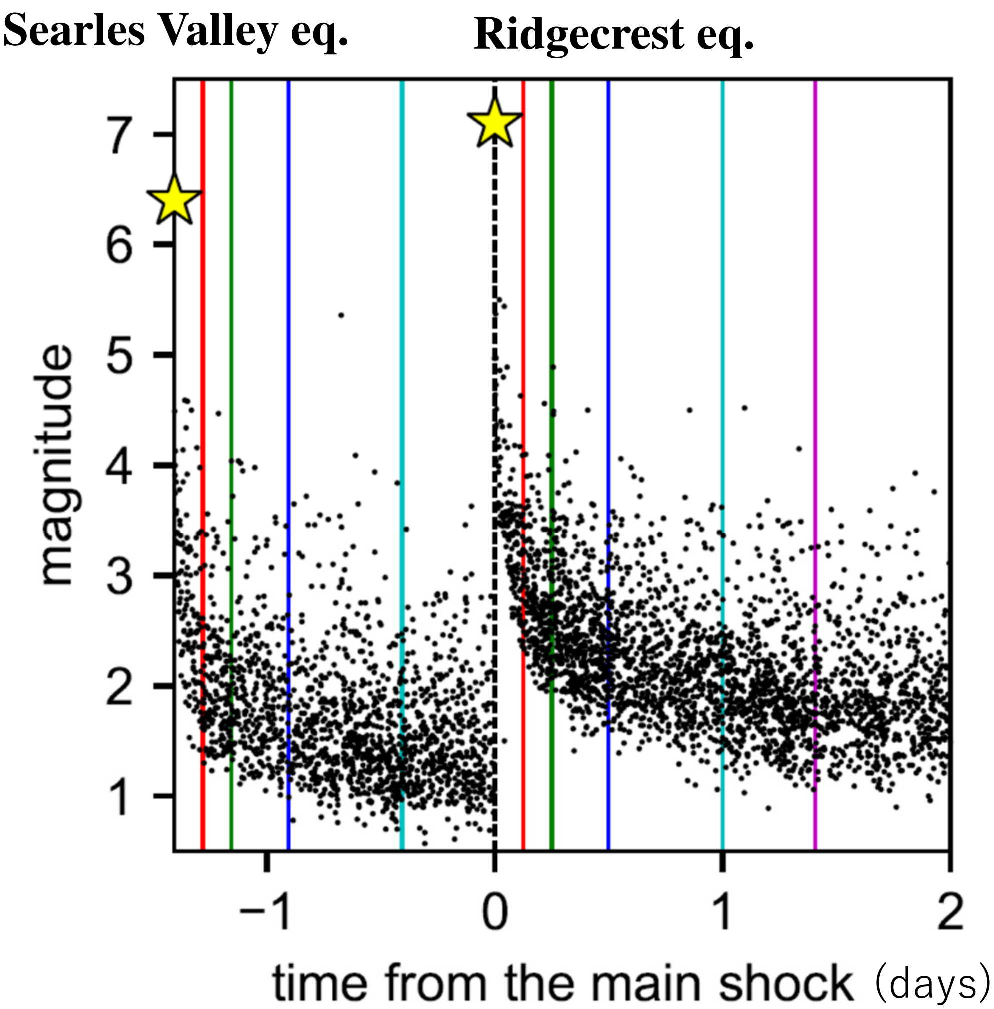
本震マグニチュード予測

$$p(M_{main} > M_1 + m \mid \text{foreshock}, M_1) = 10^{-0.8m}, \quad m = 0, 0.1, 0.2, \ldots$$



Ogata & Omi (2020, *BSSA*)

早期余震予測は前震確率も含む

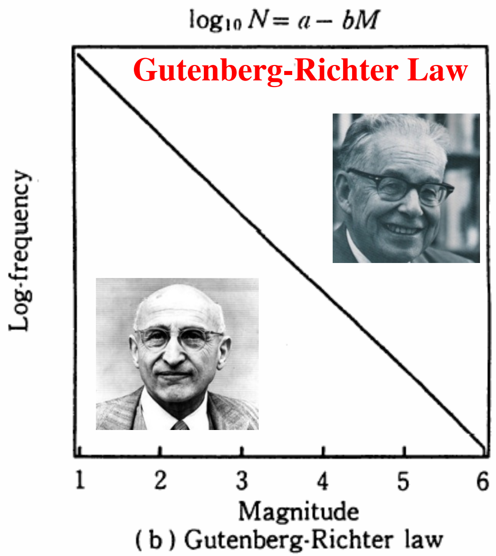


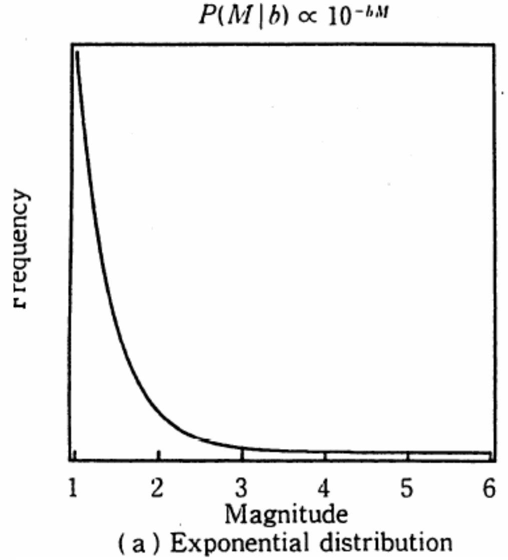
Aftershocks

ANSS ComCat.

Real time data

Magnitude Frequency distribution and Earthquake Detection Rates





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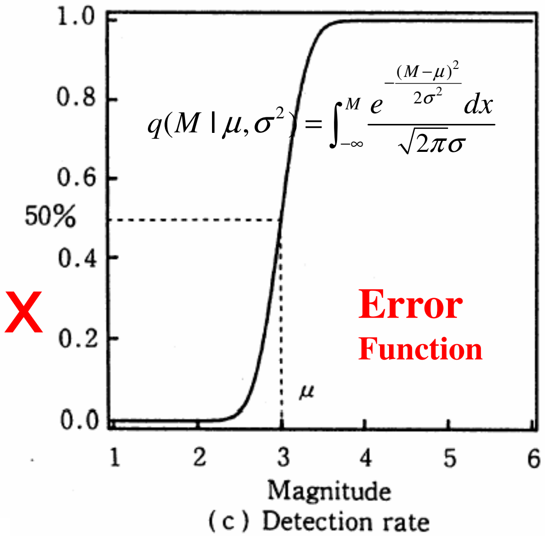

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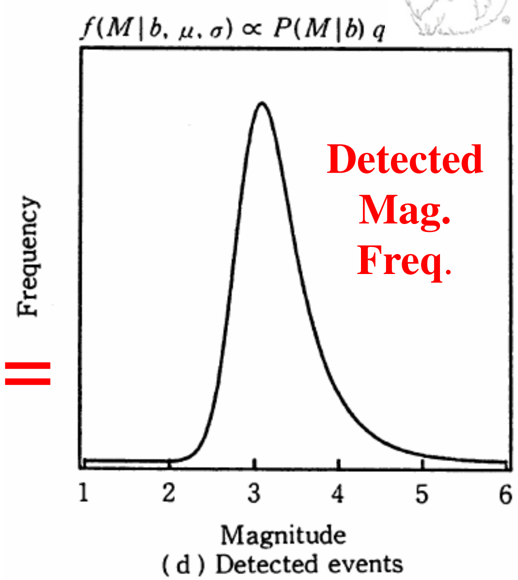



1894 **1969**


Reasenberg and Jones (1989, 94, *Science*)

$$\lambda(t, M) = m(M)n(t) = \frac{10^{a+b(M_0-M)}}{(t+c)^p}$$

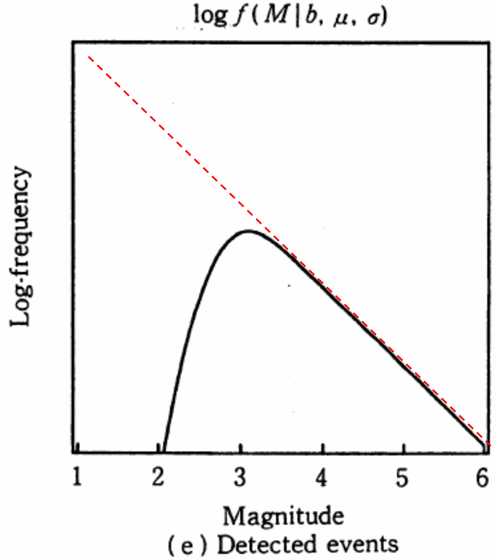
= (**Gutenberg - Richter Law of magnitude frequency**)

×(**Omori - Utsu Law of aftershock decay rate in time**)

Plug-in forecast by MLE (Ogata, 1983, *JPE*)

Observed aftershocks, Ogata & Katsura (2006, *GRL*)

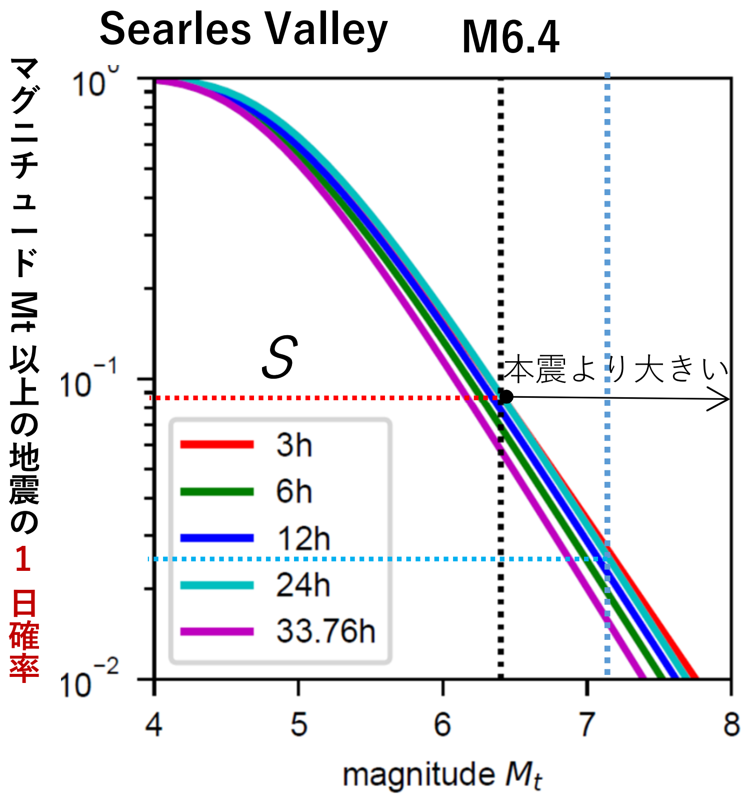
$$\lambda(t, M) = \frac{10^{a+b(t)(M-M_0)}}{(t+c(t))^{p(t)}} \times q\{M \mid \mu(t), \sigma\}$$

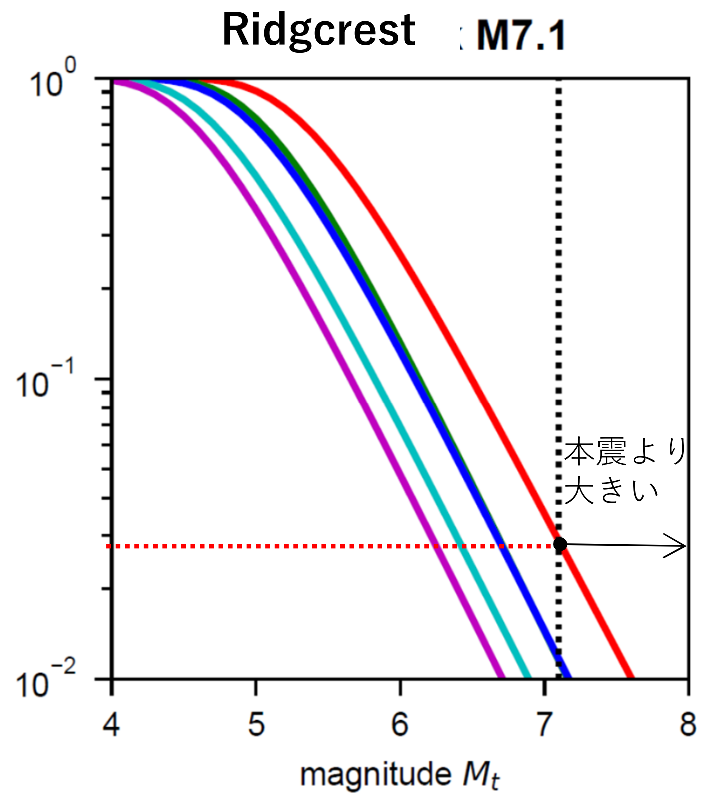


Ogata & Omi (2020, *BSSA*)

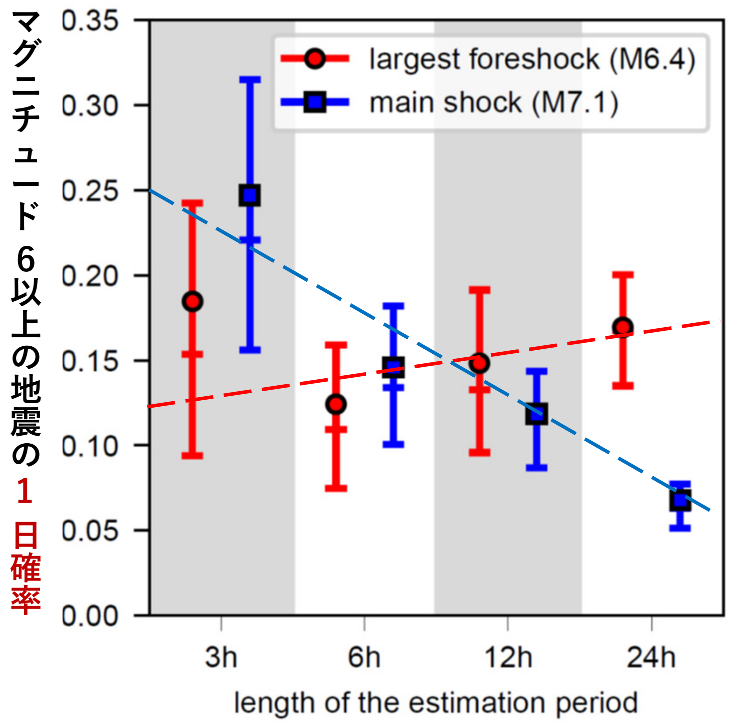
マグニチュード*Mt*を超える余震の観測時*S*から1日（24時間）以内の確率予測図

$$\Lambda_\theta(M;\,[S, S+1_{\mathbf{day}}]) = \int_S^{S+1} \frac{K\cdot 10^{-bM}}{(t+c)^p}\,dt$$





次の1日(24時間)以内にM≧6.0の余震が少なくとも1回発生する1日確率

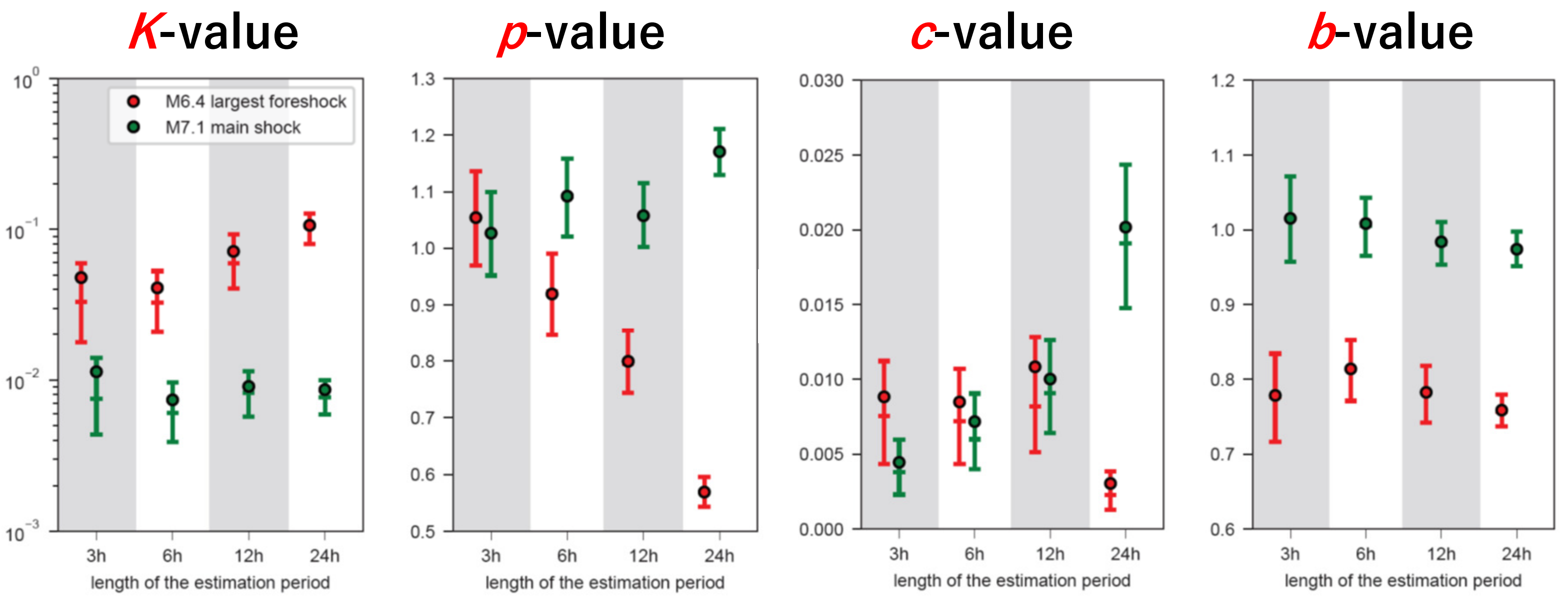


Ogata & Omi (2020, *BSSA*)

2つの余震列の1日以内でのパラメータ値の違いと誤差

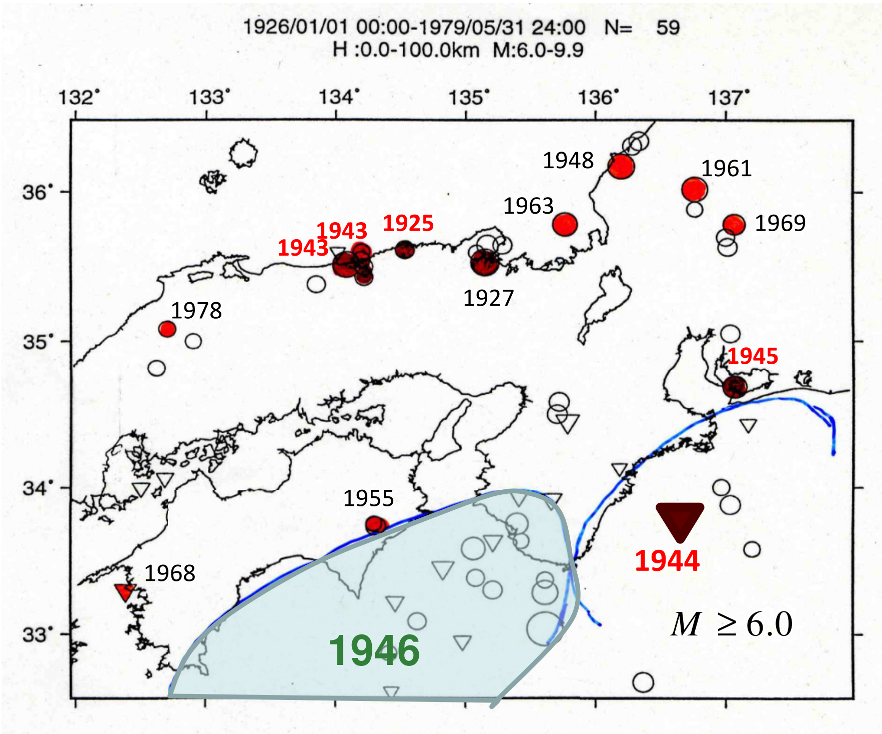
Reasenberg-Jones model　本震後の検出率モデル

$$\lambda_\theta(t,M) = \frac{K\cdot 10^{-bM}}{(t+c)^p}\int_{-\infty}^{M}\frac{1}{\sqrt{2\pi}\sigma}e^{-\{z-\mu(t)\}^2/\sigma^2}$$



中期予測

Intermediate-term forecast



1946年南海地震M8.2前後の内陸余震活動

上図の赤円盤の地震

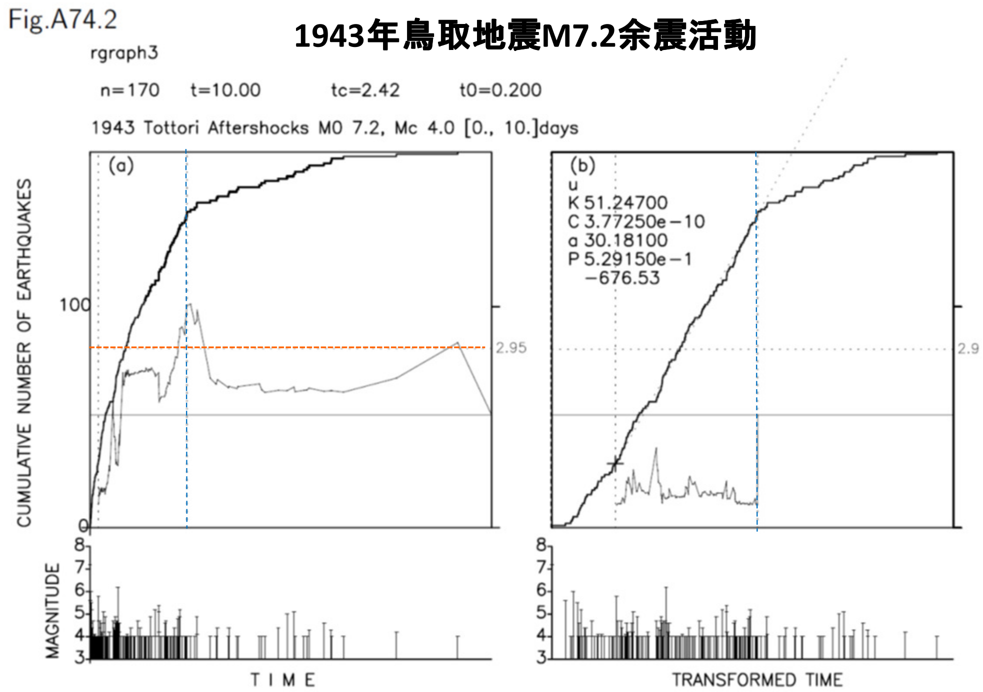
内陸部地震	本震 M	余震系列の下限マグニチュード
1925 但馬地震	6.8	**有感** **5.0**
1927 北丹後地震	7.3	0.0 4.5
1943 鳥取県東部	6.2	**有感** **3.6**
1943 鳥取地震	7.4	**有感** **4.4** **4.7** 5.0
1945 三河地震	6.8	**有感** **0.0** **4.4** 4.8
1948 福井地震	7.1	有感 0.0 3.5 4.0 **4.5** 4.7
1955 徳島県南部	6.4	0.0 3.0
1961 北美濃地震	7.0	0.0
1963 越前岬沖	6.9	0.0
1968 愛媛県西岸	6.6	3.5 4.0
1969 岐阜県中部	6.6	0.0 3.9
1978 島根県中部	6.1	0.0 3.3 3.7

注。**太字**の下限マグニチュードはその余震データ系列が相対的静穏化がみられたことを示し、その他は順調な推移を示す。「有感」と「0.0」は、それぞれ、有感の余震

1996年 - 2000年：地震予知総合研究振興会
科学技術庁委託プロジェクト「南海トラフにおける
海溝型巨大地震災害軽減のための地震発生機構のモデル化、
観測システムの高度化に関する総合的検討委員会」

相対的静穏化

1943年鳥取地震M7.2余震活動



調査した余震**76例**と 下限 magnitudes　34例 (45%): 有意な相対的静穏化

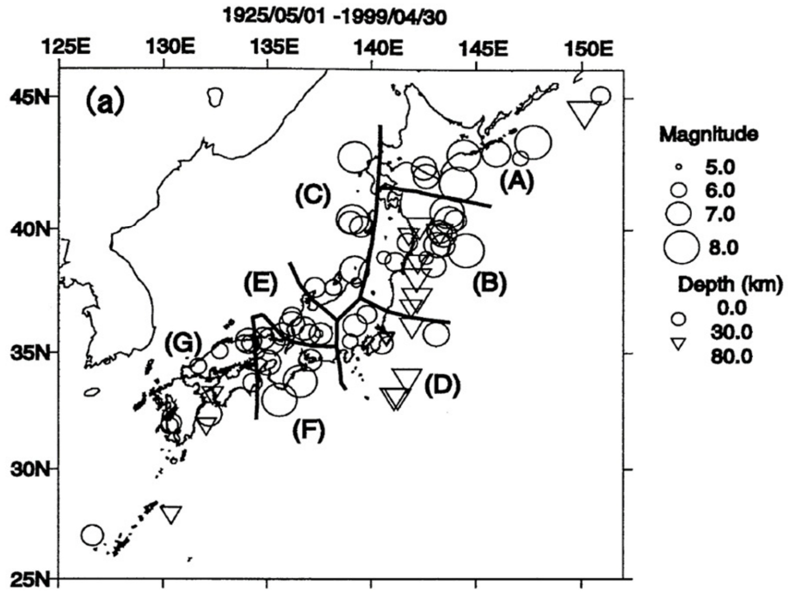
Ogata 2001 *JGR*

Table 1. Studied Aftershocks[a]

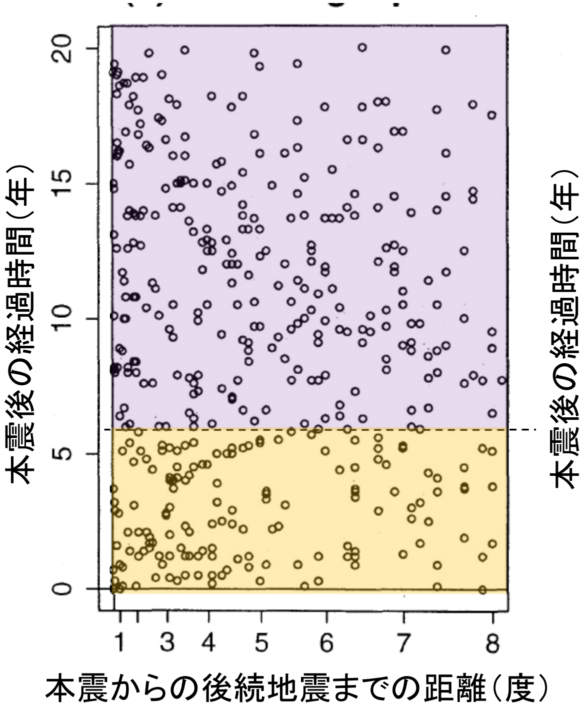
Date	Name	M_J	Epicenter	Threshold Magnitudes[b]
	Off the East Coast of Hokkaido (Region A)			
Dec. 04, 1995	Off Iturup Island	7.9	150.1 44.6	(4.0) (4.5) 5.0
Oct. 04, 1994	Hokkaido-Toho-Oki	8.1	147.7 43.4	4.5 5.0 (5.5*A*) 6.0
Aug. 18, 1994	Hokkaido-Toho-Oki	6.4	150.9 45.1	(3.5) (4.0) (4.5)
Jan. 15, 1993	Kushiro-Oki	7.8	144.4 42.9	3.0 3.5 4.0
April 01, 1990	Hokkaido-Toho-Oki	6.0	147.1 42.8	(0.0) (3.6) (3.8) (4.0)
March 21, 1982	Urakawa-Oki	7.1	142.6 42.1	3.3 3.6 4.0 4.2
June 17, 1973	Nemuro-Hanto-Oki	7.4	146.0 43.0	(4.0) (4.5) (4.8) 5.2
March 04, 1952	Tokachi-Oki	8.2	144.1 41.8	0.0 5.0 5.5 6.0
Nov. 26, 1932	Hidaka-Chubu	7.0	142.5 42.4	unfelt (felt) (4.5)
	Off the East Coast and Inland of Tohoku District (Region B)			
Aug. 11, 1996	Onikobe	5.9	140.6 38.9	2.5 3.1 3.5 (3.8) (4.0)
Jan. 07, 1995	Sanriku-Haruka-Oki (secondary)	7.2	142.3 40.2	3.0 3.5 4.0 4.5
Dec. 28, 1994	Sanriku-Haruka-Oki (long)	7.5	143.7 40.4	4.0 4.5 5.0 5.4
Dec. 28, 1994	Sanriku-Haruka-Oki (short)	7.5	143.7 40.4	4.0 (4.5) (4.9)
April 08, 1994	Sanriku-Oki	6.6	144.0 40.6	3.5 4.0
Dec 28, 1992	Sanriku-Oki	5.9	142.6 38.9	(3.0) (3.5) (3.9) (4.4)
July 18, 1992	Sanriku-Haruka-Oki	6.9	143.7 39.4	(3.5) (3.7) 3.8 4.0 (4.5) 5.0
Nov. 02, 1989	Iwate-ken-Oki	7.1	143.1 35.8	4.0 4.5 5.0
Jan. 09, 1987	Iwate-Ken-Hokubu	6.6	141.8 39.8	0.0 3.0
Jan. 19, 1981	Miyagi-Ken-Oki	7.0	143.0 38.6	0.0 3.6 4.1 4.6
June 12, 1978	Miyagi-Ken-Oki	7.4	142.2 38.2	3.4 4.0 4.2 (4.5) (4.9)
Feb. 20, 1978	Near Ojika-Peninsula	6.7	142.2 38.8	3.0 3.3 (3.5)
June 12, 1968	Tokachi-Oki (Southern)	7.2	143.1 39.4	4.5 5.0 5.5
May 16, 1968	Tokachi-Oki (Northern)	7.9	143.6 40.7	4.5 5.0 5.5 5.9
April 30, 1962	Miyagi-Ken-Hokubu	6.5	141.1 38.7	(0.0) 4.0
March 21, 1960	Iwate-Ken-Oki	7.2	143.4 39.8	0.0 4.4 4.9 5.4
Nov. 05, 1938	Shioya-Oki-Swarm	7.5	142.2 37.3	4.5 4.7 (5.0) 5.5
March 03, 1933	Sanriku-Oki	8.1	144.5 39.2	(0.0*A*)(6.0*N*)5.5(5.8*A*)(6.0)(6.2)
Nov. 04, 1931	Iwate-Ken-Tobu	6.5	141.7 39.5	(unfelt) (felt) (felt*A*) 4.0
May 27, 1928	Iwate-Ken-Oki	7.0	143.3 40.0	0.0 5.1 (5.3) (5.5)
	Eastern Limb in Sea of Japan (Region C)			
Apr. 01, 1995	Niigata-Ken-Chubu	5.5	139.3 37.9	(2.8*A*) 3.0 3.2 (3.5)
July 12, 1993	Hokkaido-Nansei-Oki	7.8	139.2 42.8	(4.0*A*) 4.5 5.0
Feb. 07, 1993	Noto-Hanto-Oki	6.6	137.3 37.7	(3.0) 3.5 (4.0)
May 26, 1983	Nihonkai-Chubu	7.7	139.1 40.4	4.0 4.5 (5.0) (5.2) (5.3)
June 16, 1964	Niigata earthquake	7.5	139.2 38.4	felt 4.0 4.5 5.0
May 07, 1964	Oga-Hanto-Oki	6.9	139.0 40.3	unfelt felt 0.0
May 01, 1939	Oga-Hanto-Oki	6.8	139.5 40.1	0.0 4.1
	Kanto and Tokai District and Their Offshore Regions (Region D)			
June 01, 1990	Chiba-Ken-Hokubu	6.0	140.7 35.7	2.0 2.5 3.0
March 06, 1989	Chiba-Ken-Hokubu	6.0	140.7 35.6	(2.0) (2.5) 3.0 (3.5)
Dec. 17, 1987	Chiba-Ken-Toho-Oki	6.7	140.5 35.4	(2.5) (3.0) (3.5) (4.0)
Aug 08, 1983	Yamanashi-Ken-Tobu	6.0	139.0 35.5	2.5 (2.7) (2.9) (3.0)
July 23, 1982	Ibaragi-Ken-Oki	7.0	142.0 36.2	3.2 (3.7) 4.2
Dec. 04, 1972	Hachijo-Jima-Oki	7.2	141.1 33.2	3.6 4.0 4.5
Feb. 29, 1972	Hachijo-Jima-Oki	7.1	141.3 33.2	(3.6) (4.0) (4.6)
Nov. 26, 1953	Boso-Oki	7.4	141.7 34.0	0.0 5.0 5.5
Dec. 26, 1949	Imaichi	6.4	139.8 36.6	felt 4.2
May 23, 1938	Ibaragi-Ken-Oki	7.3	141.6 36.7	0.0 4.1
Sept. 21, 1931	Saitama-Ken-Seibu	6.9	139.2 36.2	0.0 3.0 3.5 (3.8) (4.0)
	Hokuriku and Chubu District (Region E)			
Sept. 14, 1984	Nagano-Ken-Seibu	6.8	137.6 35.8	3.5 4.0 4.5
Oct. 07, 1978	Nagano-Ken-Swarm	5.3	137.5 35.8	(2.5) (3.0) 3.5
Sept. 09, 1969	Gifu-Ken-Chubu	6.6	137.1 35.8	0.0 3.9
March 27, 1963	Echizen-Misaki-Oki	6.9	135.8 35.8	0.0
Aug. 19, 1961	Kita-Mino	7.0	136.8 36.0	0.0
March 07, 1952	Daishoji-Oki	6.5	136.2 36.5	(felt) (0.0) (4.2) (4.5)
June 28, 1948	Fukui	7.1	136.2 36.2	felt 0.0 3.5 4.0 (4.5) 4.7
July 15, 1941	Nagano	6.1	138.2 36.7	(felt) (0.0)

Table 1. (continued)

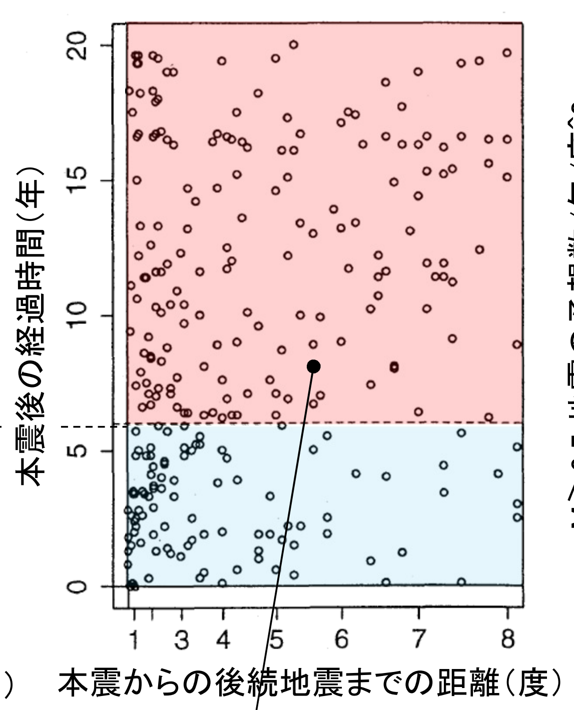
Date	Name	M_J	Epicenter	Threshold Magnitudes[b]
	Kinki District and Offshore Regions (Region F)			
Jan. 17, 1995	Hyogo-Ken-Nanbu	7.2	135.0 34.6	3.0 3.5 4.0 4.2
Nov. 09, 1994	Inagawa Swarm	4.0	135.4 34.9	(2.0) (2.3) (2.5) (2.6)
May 30, 1984	Yamasaki Fault	5.6	134.6 35.0	(2.5) 2.6 3.0
Dec. 21, 1946	Nankaido	8.0	135.6 33.0	(4.0) (4.5) (4.9) 5.0 5.5
Jan. 13, 1945	Mikawa	6.8	137.1 34.7	(felt) (0.0) (4.4) 4.8
Dec. 07, 1944	Tonankai	7.9	136.6 33.8	4.0 (4.5) (4.8) 5.0
March 07, 1927	Kita-Tango	7.3	135.2 35.5	0.0 4.5
May 23, 1925	Tajima	6.8	134.8 35.6	(felt) (5.0)
	Southwestern Japan (Region G)			
June 25, 1997	Yamaguchi/Shimane-Ken Border	6.1	131.7 34.5	(2.6) (3.0) 3.4
May 13, 1997	Northern Satsuma	6.2	130.3 31.9	(2.5) 2.8 3.0 3.3
March 26, 1997	Northern Satsuma	6.5	130.4 32.0	(2.7) (3.0) (3.5)
Oct. 18, 1995	Amami-Oshima-Oki	6.6	130.4 28.0	(3.5) 3.8 4.0 4.5
March 18, 1987	Miyazaki-Ken-Oki	6.6	132.1 32.0	2.5 2.9 3.4
Aug. 07, 1984	Miyazaki-Ken-Oki	7.1	132.2 32.4	2.8 3.3 3.8
Oct 31, 1983	Tottori-Ken	6.2	133.9 35.4	(2.3) (2.5) (2.7) (2.8) 3.0
Mar 03, 1980	Okinawa-Hokusei-Oki	6.7	126.6 27.0	(0.0) (4.2) (4.5)
June 04, 1978	Shimane-Ken-Chubu	6.1	132.7 35.1	0.0 3.3 3.7
Aug. 06, 1968	Ehime-Ken-Seigan	6.6	132.4 33.3	3.5 4.0
July 27, 1955	Tokushima-Ken-Nanbu	6.4	134.3 33.8	0.0 3.0
Sept. 10, 1943	Tottori	7.4	134.1 35.5	(4.0) (4.4) (4.7) 5.0
March 04, 1943	Eastern Tottori	6.2	134.2 35.4	(felt) (3.6)

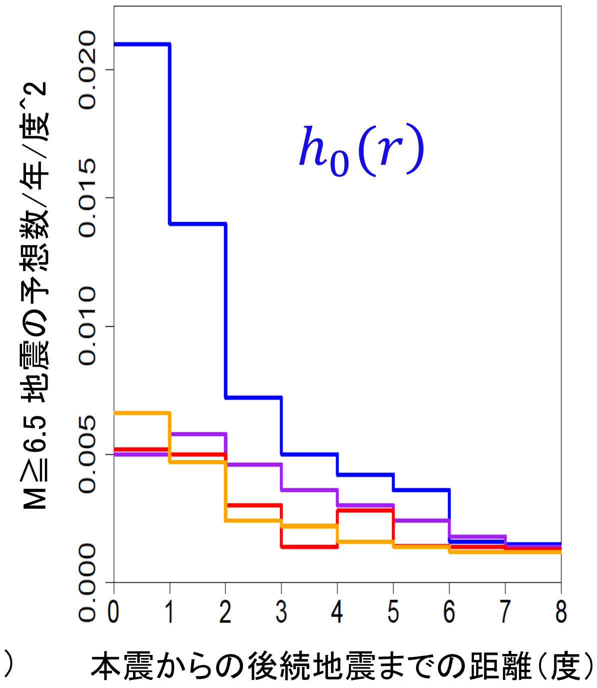


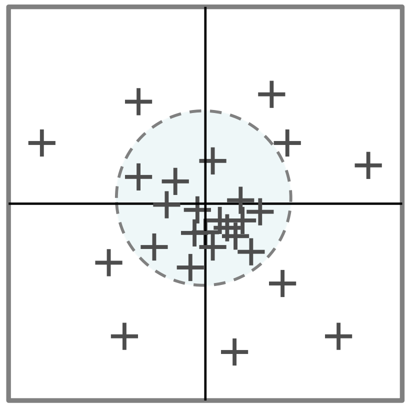
相対的静穏化無し(43例)



相対的静穏化有り(34例)







原点は最初の本震
＋は全ての後続地震

$$危険度拡大率 \propto \frac{\lambda_0(t-t_i, |r-r_i|)}{\mu(x,y)}, \quad r_i=(x_i, y_i)$$

where $\lambda_0(t, r)$ is estimated Palm intensity (smoothed)

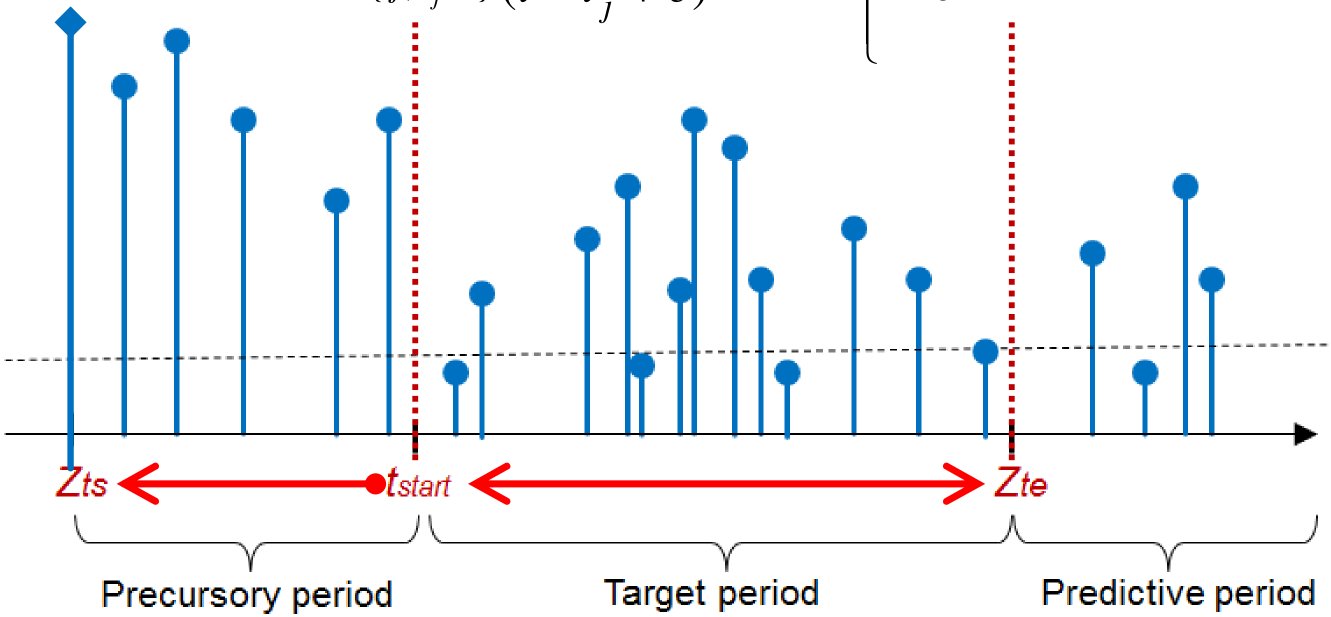
長期予測

Time-dependent long-term forecast

Earthquake occurrence data

$$\{(t_1,x_1,y_1,M_1),\ (t_2,x_2,y_2,M_2),\cdots,(t_n,x_n,y_n,M_n);\ \ M_i\ge M_c\}$$

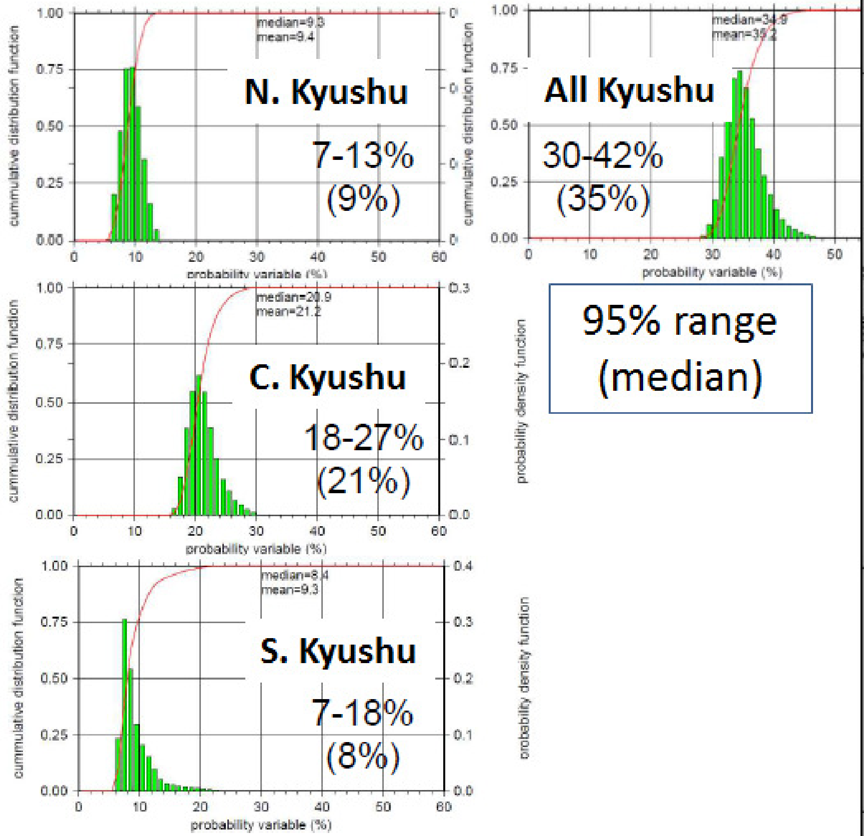
$$\lambda_{ETAS(M_c)}(t,x,y\mid H_t)=\ \mu_{M_c}(x,y)\ +\sum_{\{j;t_j<t\}}\frac{K(x_j,y_j)}{(t-t_j+c)^{p(x_j,y_j)}}\left\{\frac{(x-x_j,\ y-y_j)\,S_j\begin{pmatrix}x-x_j\\ y-y_j\end{pmatrix}}{e^{\alpha(x_j,y_j)(M_j-M_c)}}+d\right\}^{-q(x_j,y_j)}$$

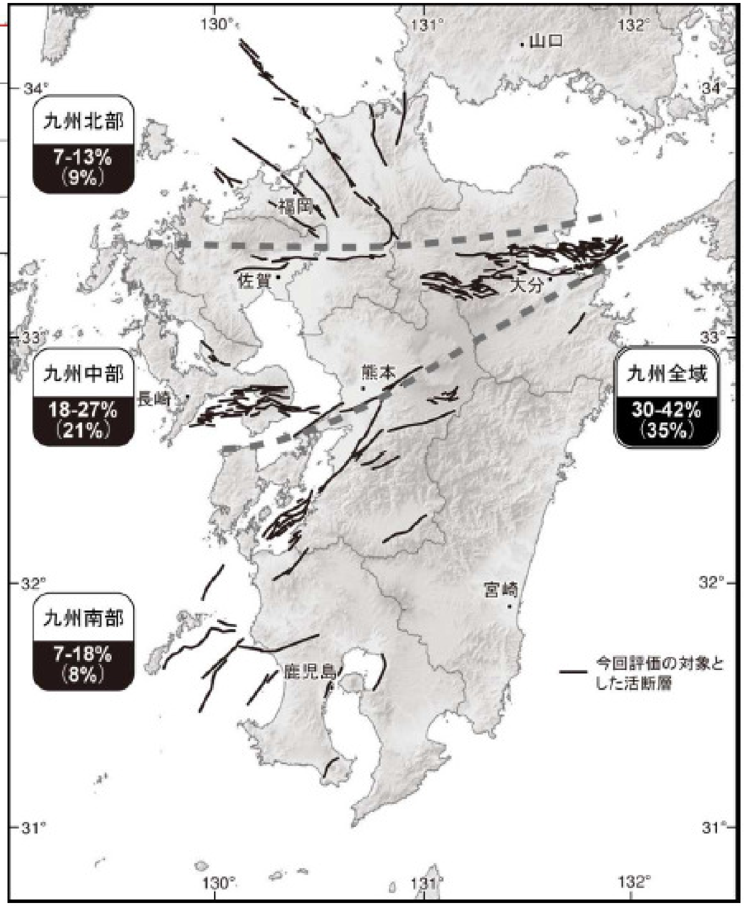


Log likelihood

$$\log L(\theta;Tstart,Z_{te})=\sum_{tstart<t_i<Z_{te}}\log\lambda_\theta(t_i,x_i,y_i\mid H_{t_i})-\int_{Tstart}^{Z_{te}}\iint_{Area}\lambda_\theta(t,x,y\mid H_t)\,dx\,dy\,dt$$

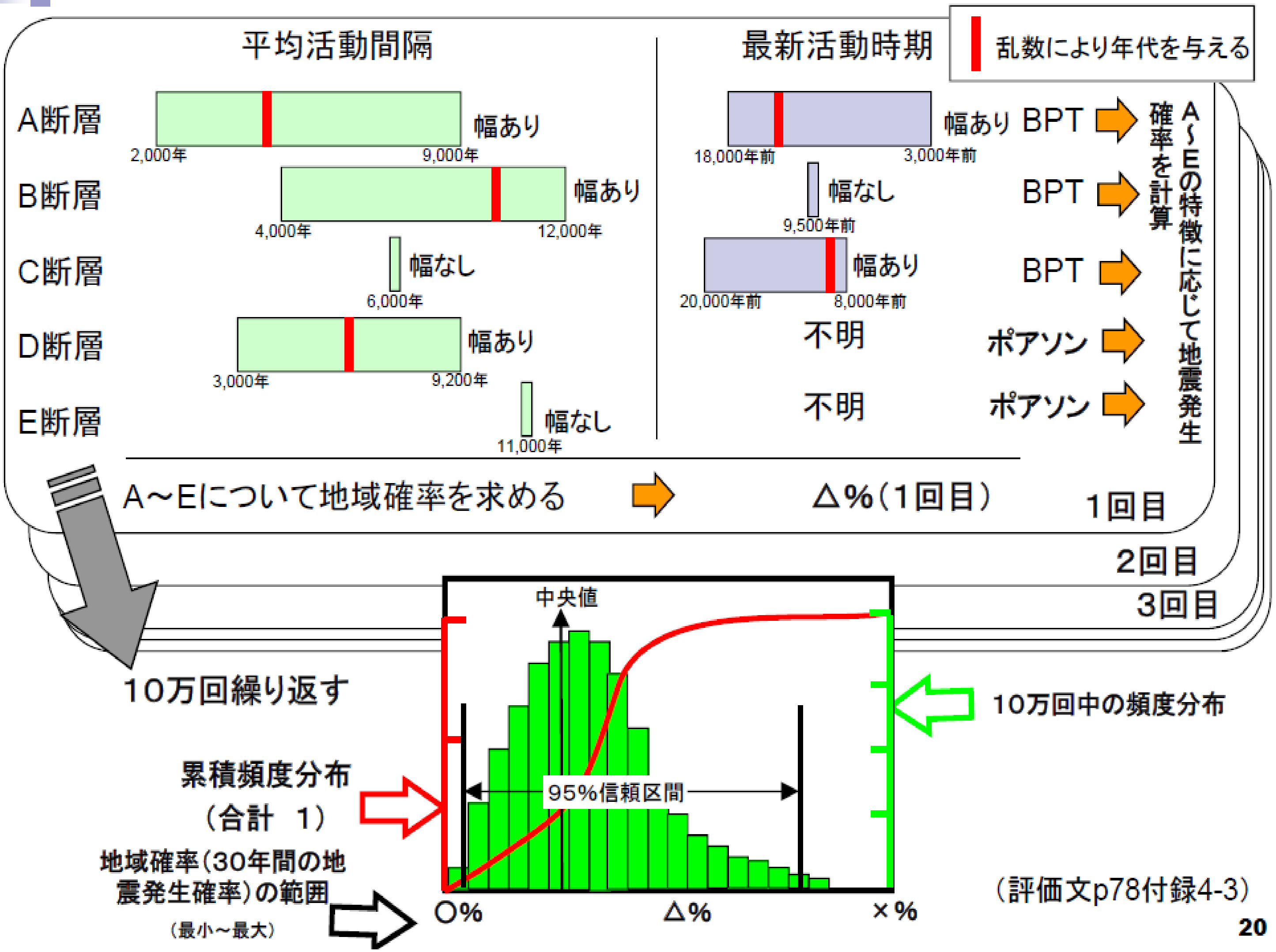
Earthquake occurrence probability of M≥6.8 occurring on active faults in each region (30 years from now) taking into account combinations of multiple active faults





Earthquake Research Committee (2013)

（参考） モンテカルロ法による、地震発生確率値の算出方法



（評価文p78付録4-3）

まとめ

① 予め永年確率や各異常現象の確率を準リアルタイムで与える準備・環境を整えることが必要。

② 広領域での多項目確率予測式を点過程の危険度拡大率の積で表現する。

③ 大中規模地震を予測する危険度拡大率は時間的切迫度や影響地域範囲のスケーリングを示す。

④ HIST-ETASモデルで自動的な時空間短期予測する。

⑤ 前震の統計的識別法は独立G-R分布のETASモデルより優れた短期予測を与える。

⑥ 初期の余震予報は前震の確率予測も与える。

⑦ データ欠測によるバイアスの補正ために時空間的検出率を準備する。

ETASモデル、デロネ型平滑化の階層ベイスモデル（HIST-ETAS モデルを含む）などのソフトウェアは統計数理研究所・地震予測解析プロジェクトのURL；
https://www.ism.ac.jp/~ogata/Ssg/ssg.html
を参照ください。