



2016年熊本地震をめぐる地震活動および 余震活動に関する確率予測問題

Seismicity anomalies before and after the
2016 M6.5 and M7.3 Kumamoto earthquakes,
probability evaluations of the M7.3 earthquake,
and aftershock forecasts

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鶴岡 弘², 合原一幸³

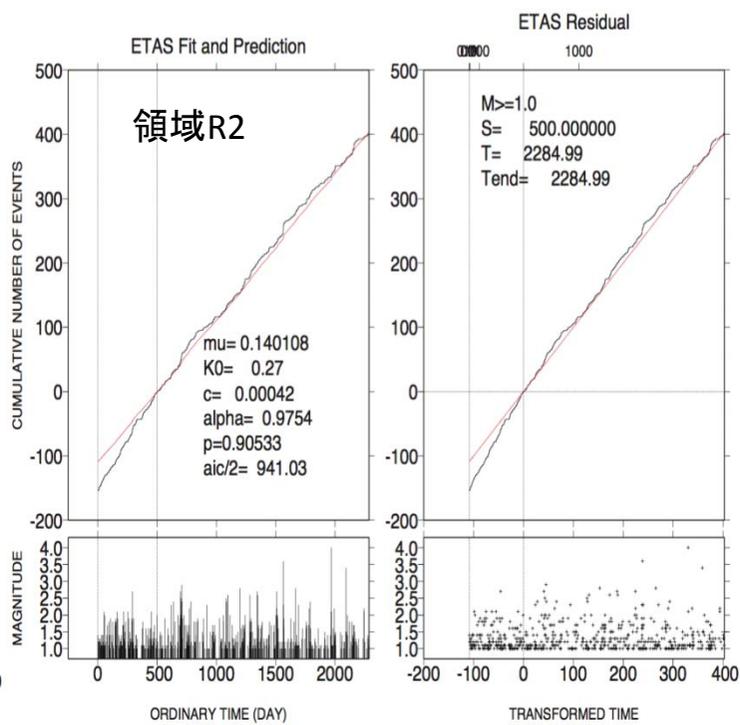
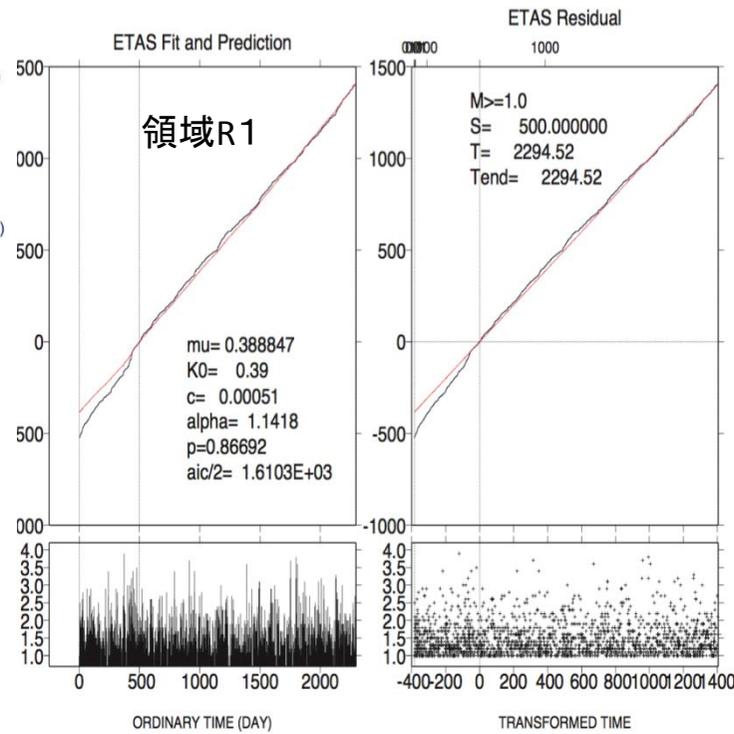
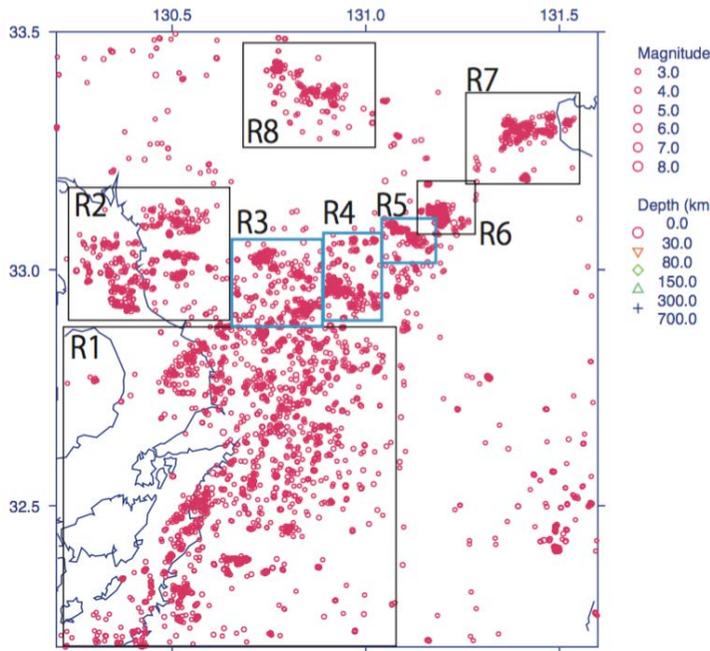
1. 統数研, 2. 東大地震研, 3. 東大生産研, 4. 東工大



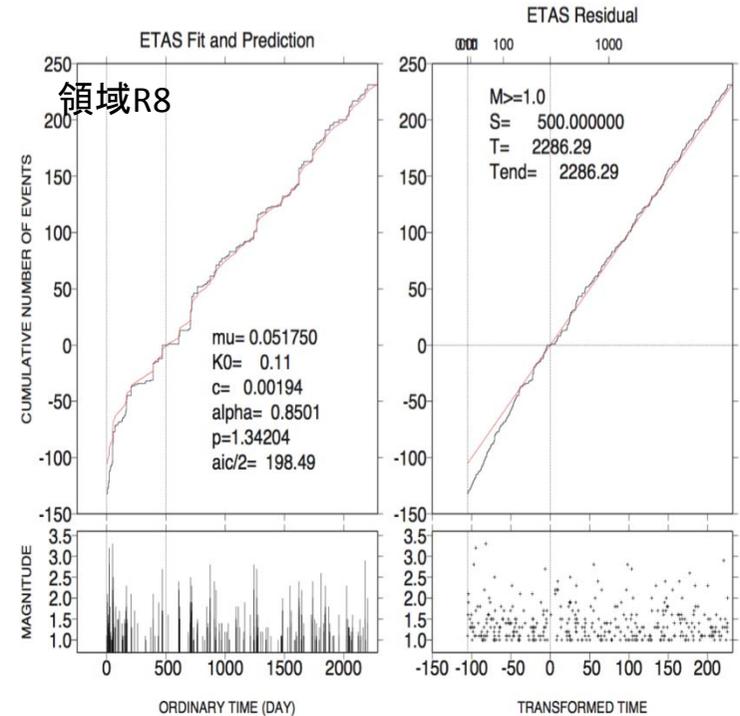
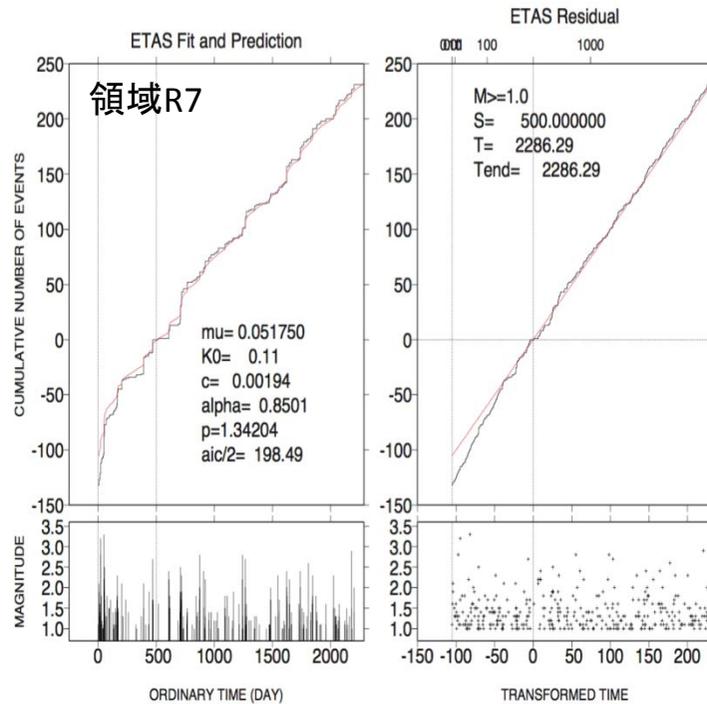
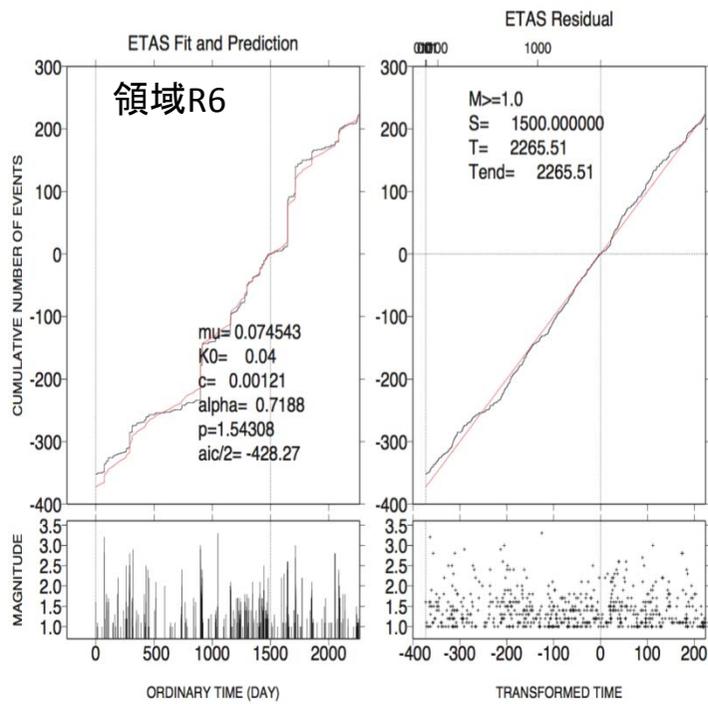
議題1

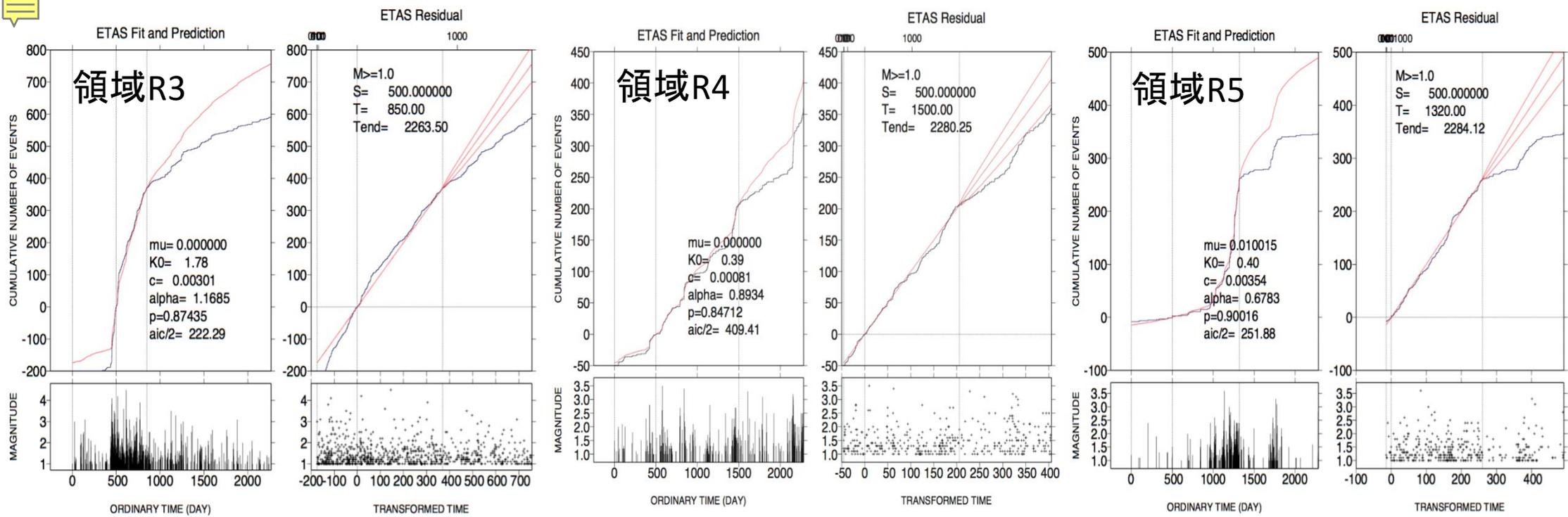
地震活動モニタリング

統数研, 東大地震研



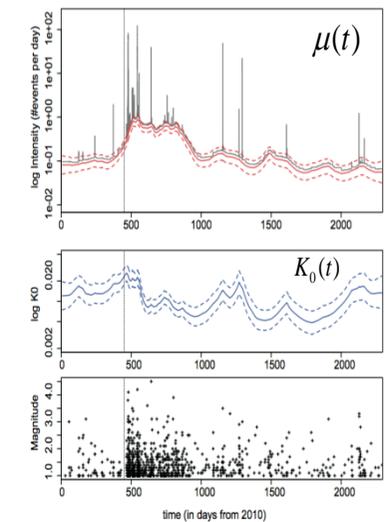
2010 ~ 2016.4.13



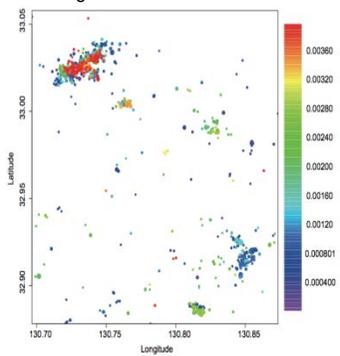


2010 ~ 2016.4.13

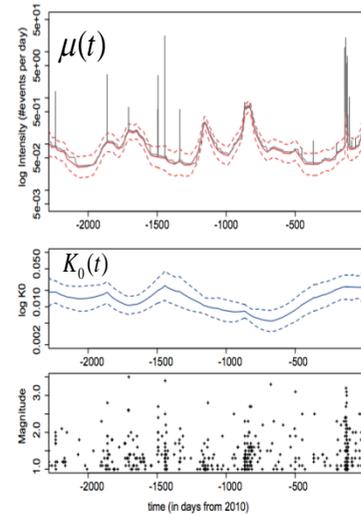
Non-stationary ETAS fit



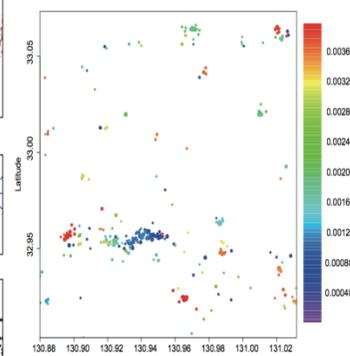
領域R3
 K_0 spatial distribution



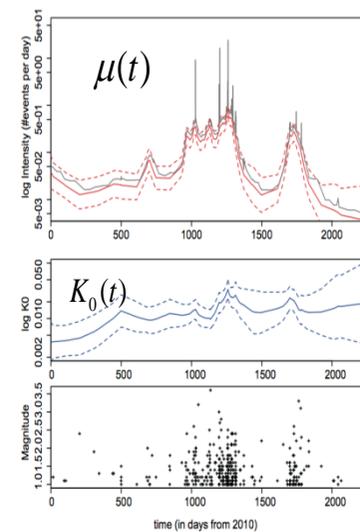
Non-stationary ETAS fit



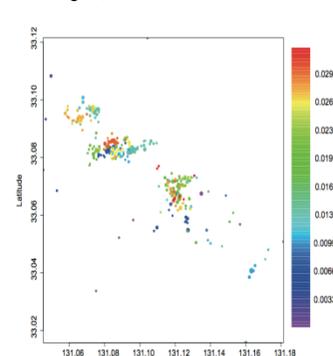
領域R4
 K_0 spatial distribution



Non-stationary ETAS fit

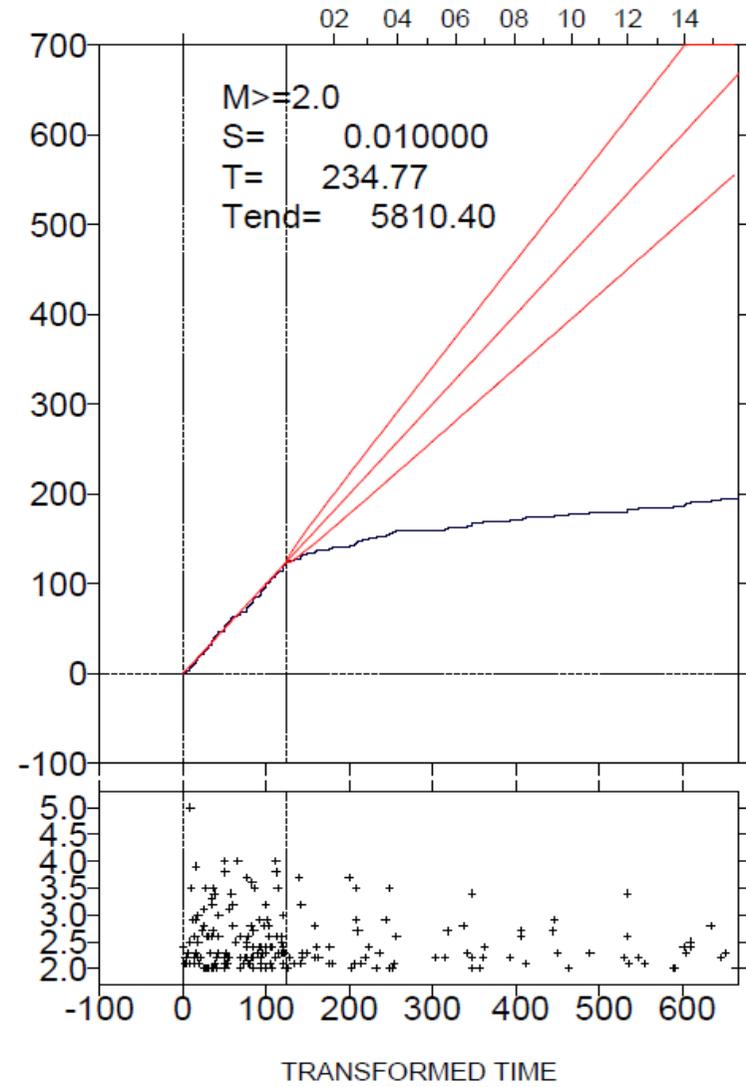
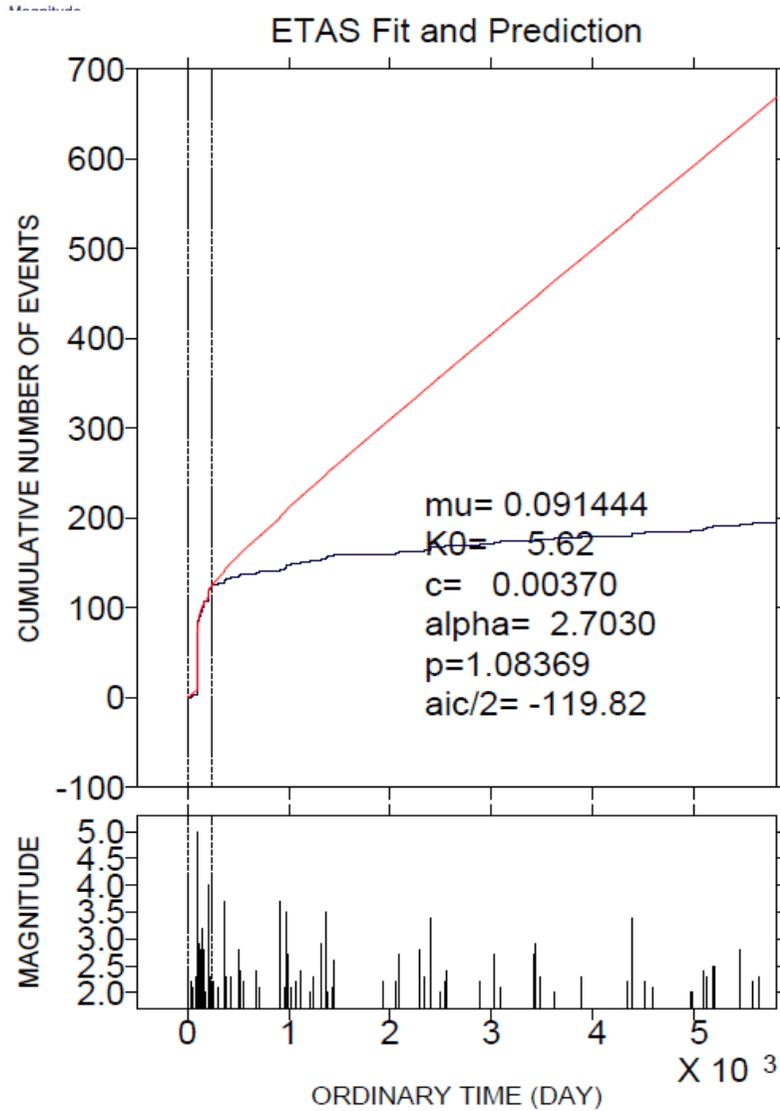
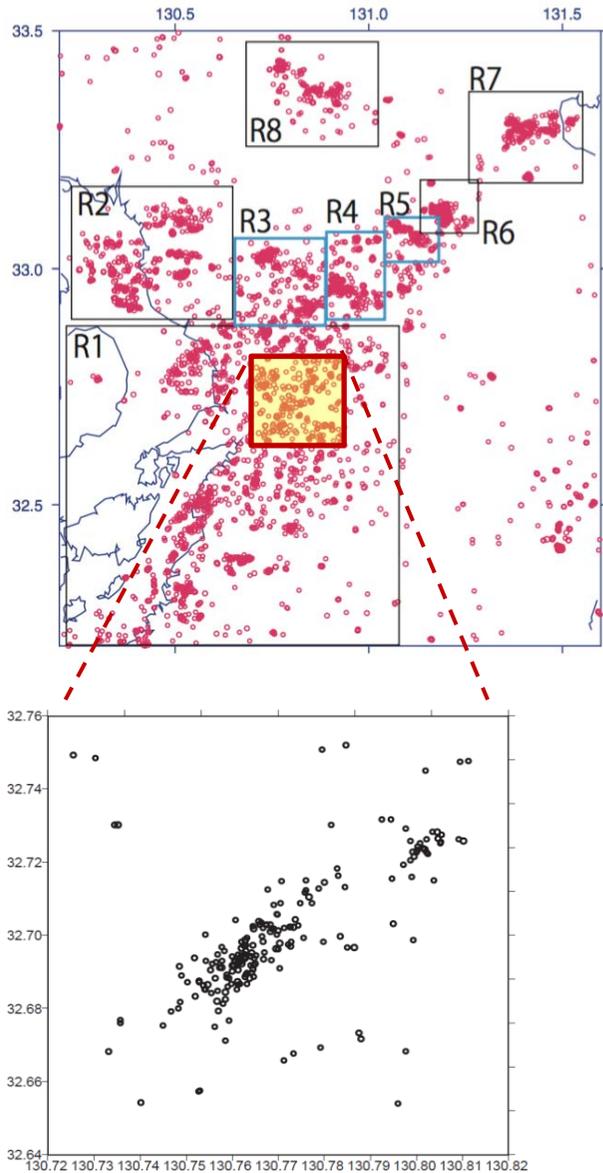


領域R5
 K_0 spatial distribution



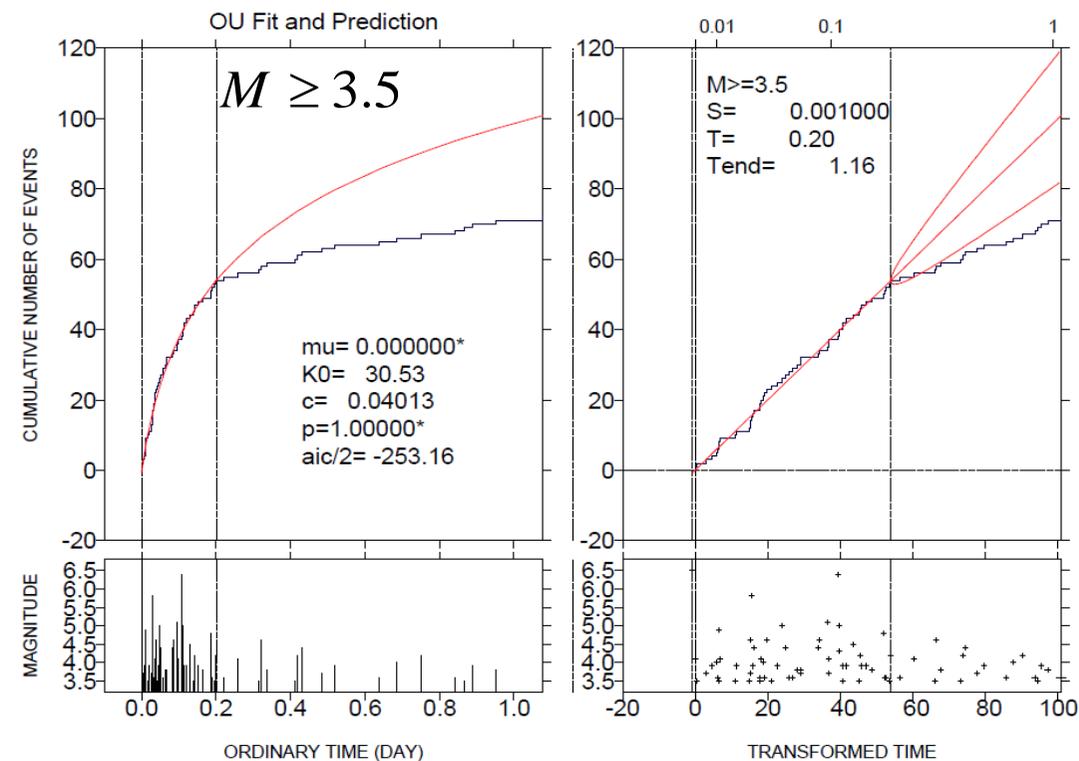
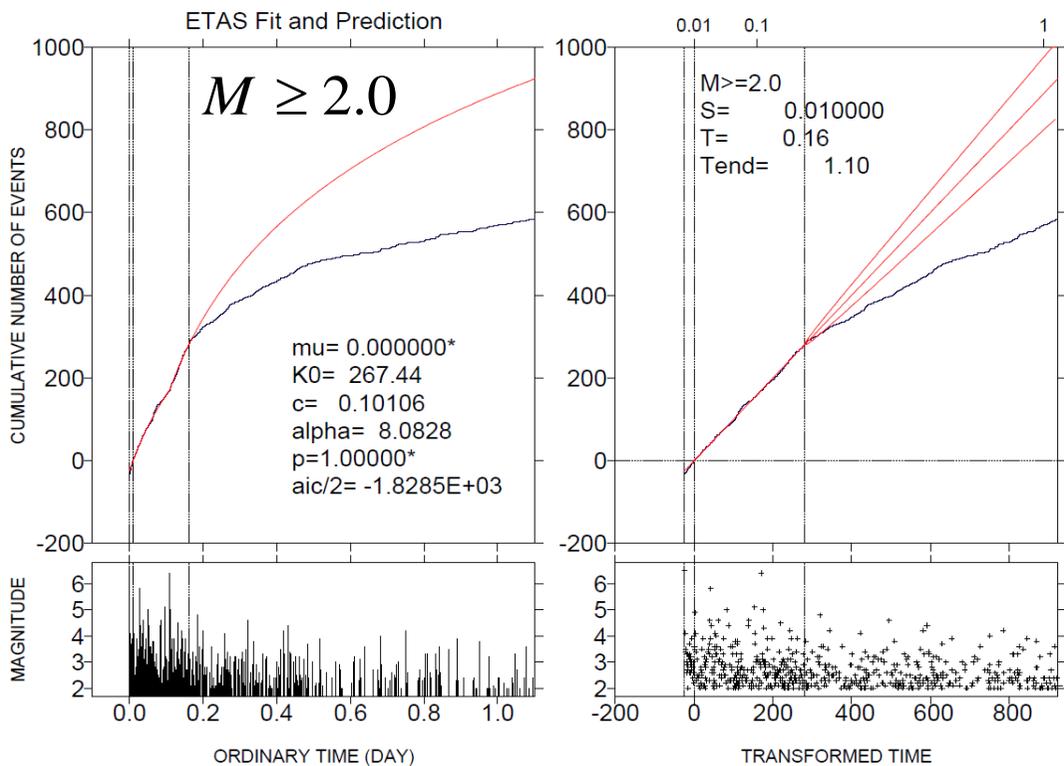
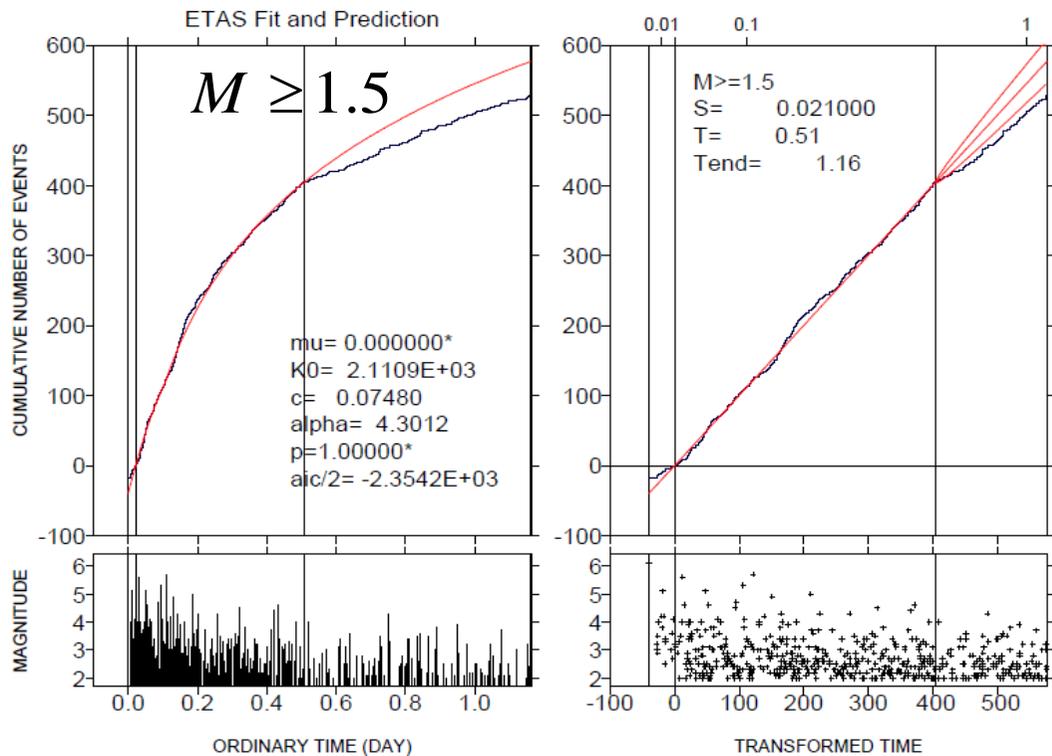
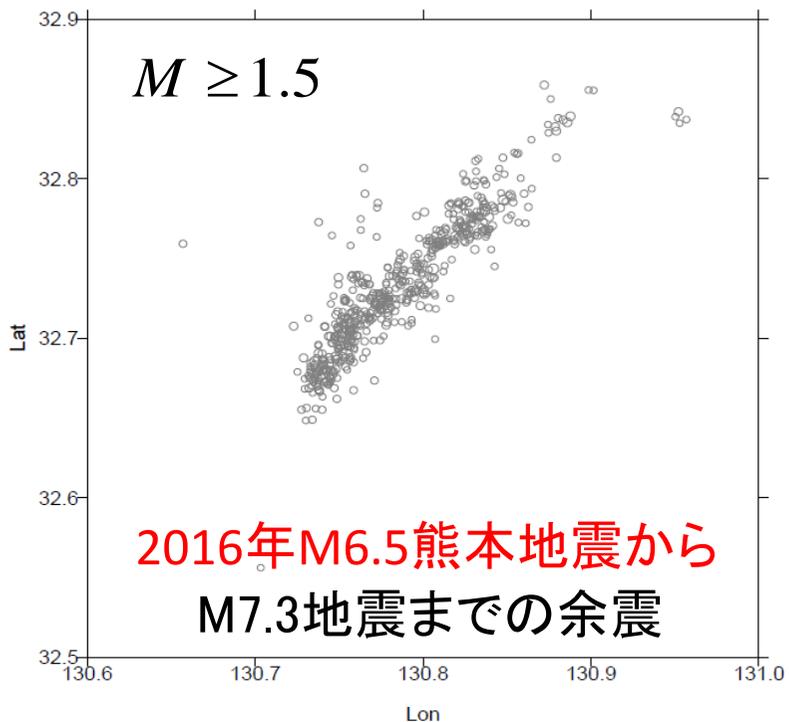
下段。非定常ETASモデルを当てはめ常時地震活動度 μ の時間変化と連鎖地震強度(余震生産性) K_0 の時間変化と空間変化

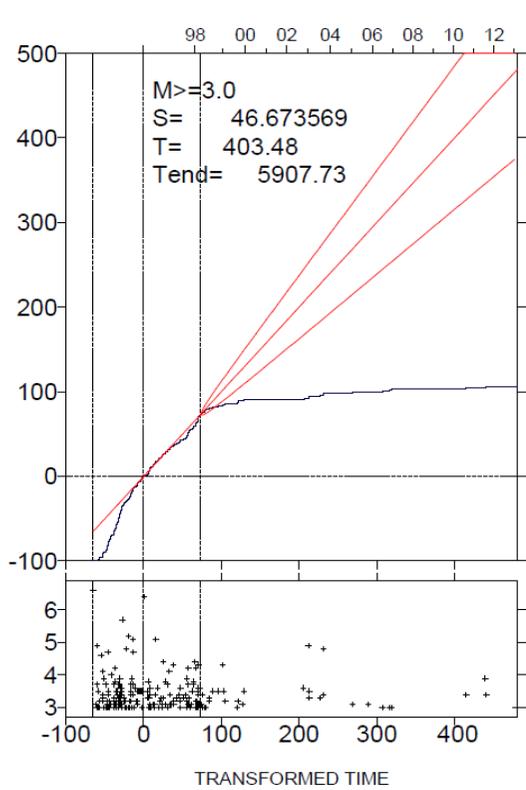
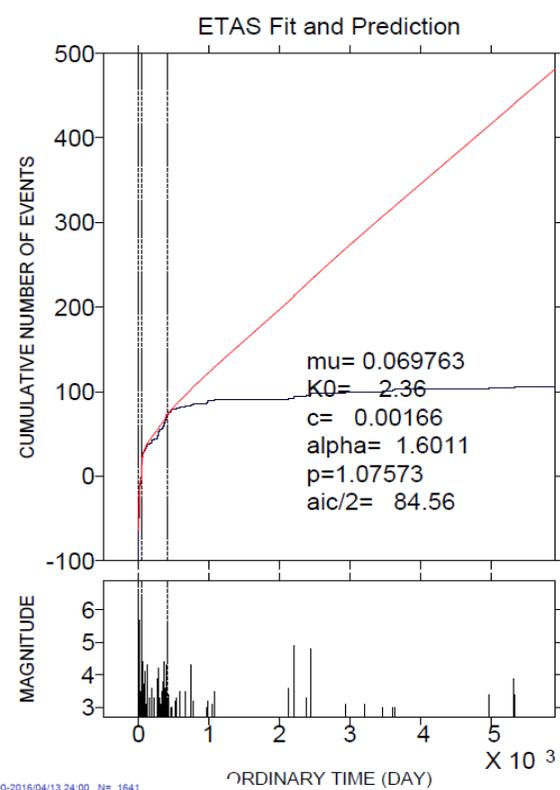
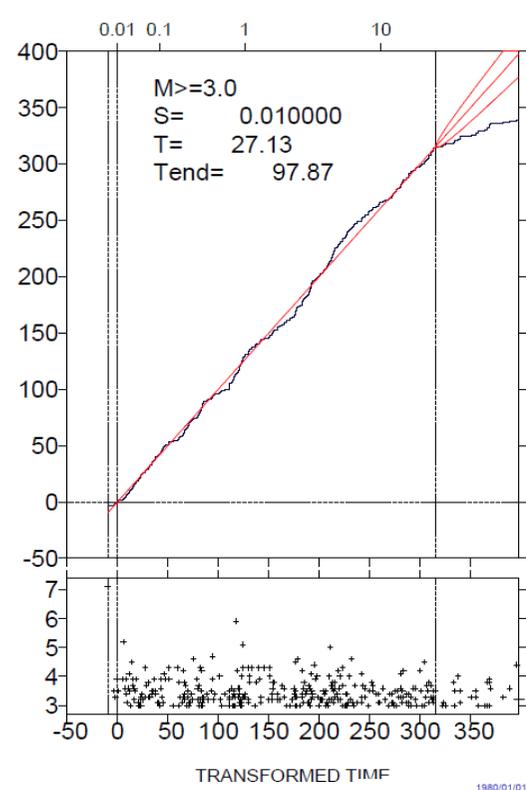
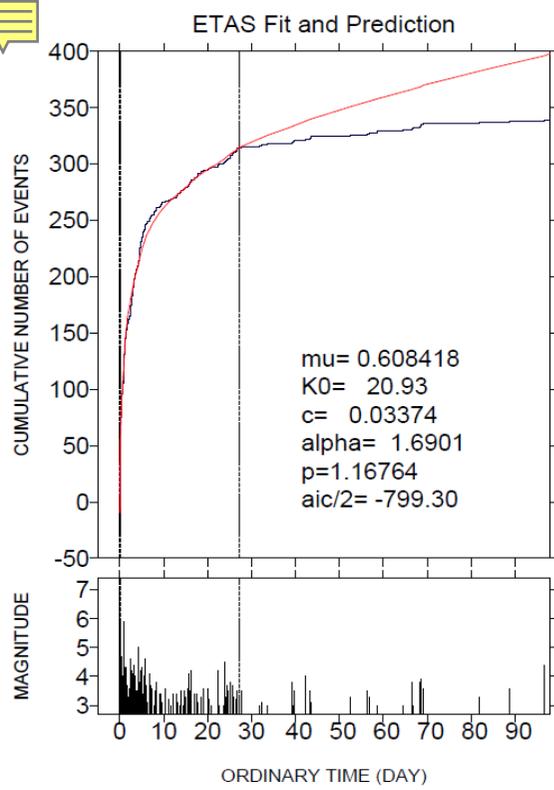
2000 ~ 2016.4.13



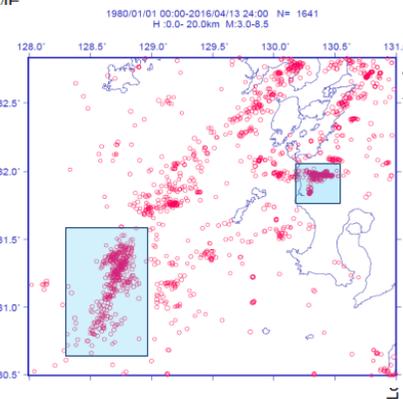
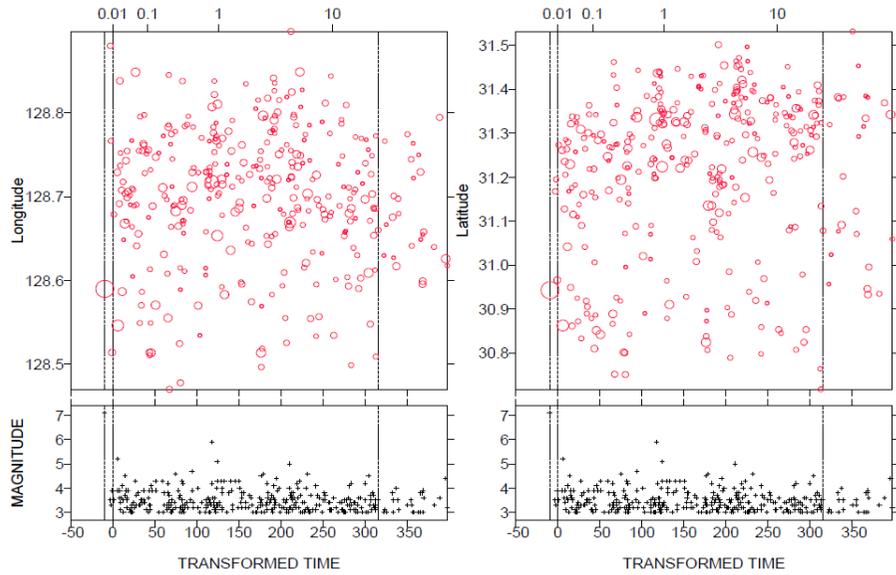
現震源域と同じ地域に起きた2000年6月8日M5.0地震の余震活動は4ヶ月後から2016年4月1日M6.5熊本地震まで静穏化している。

2016.4.14 ~ 4.15

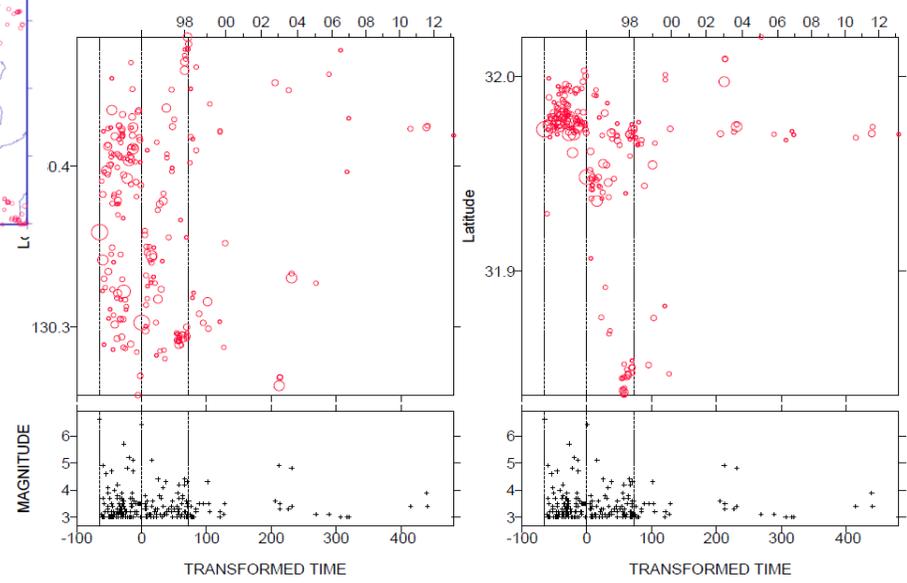


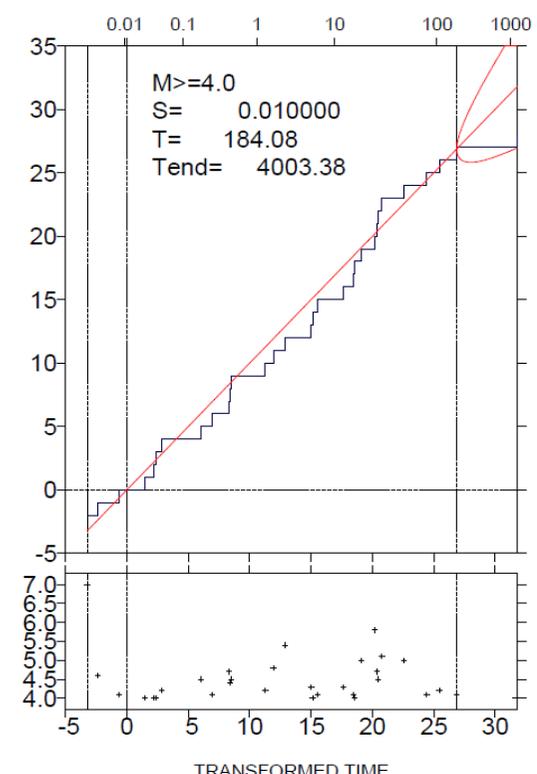
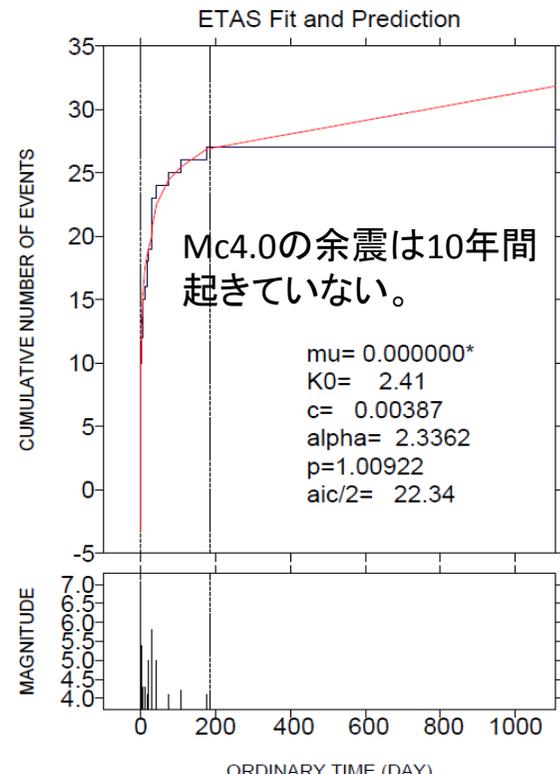
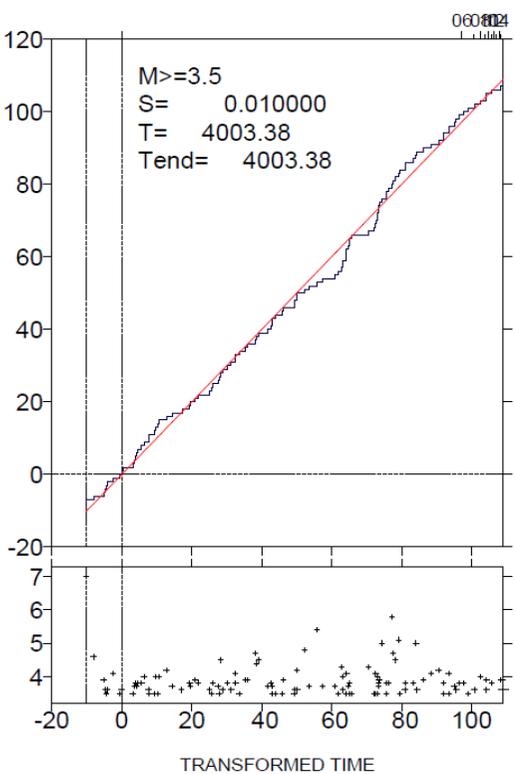
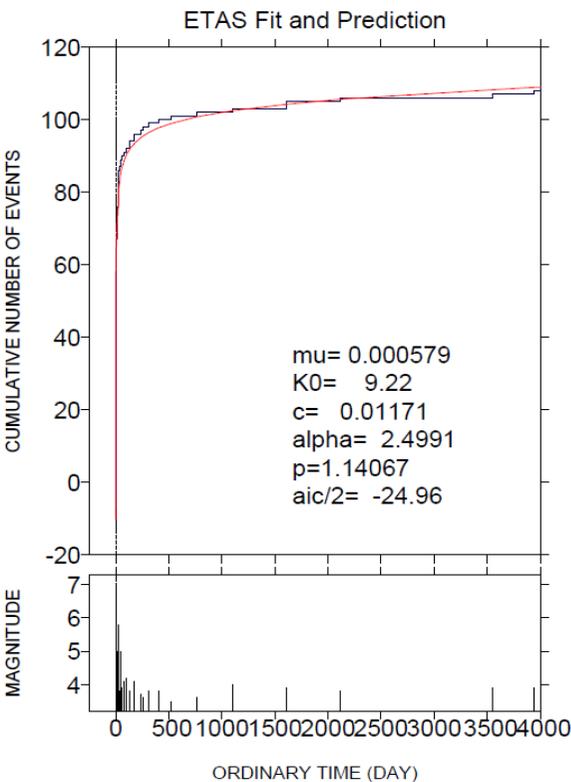
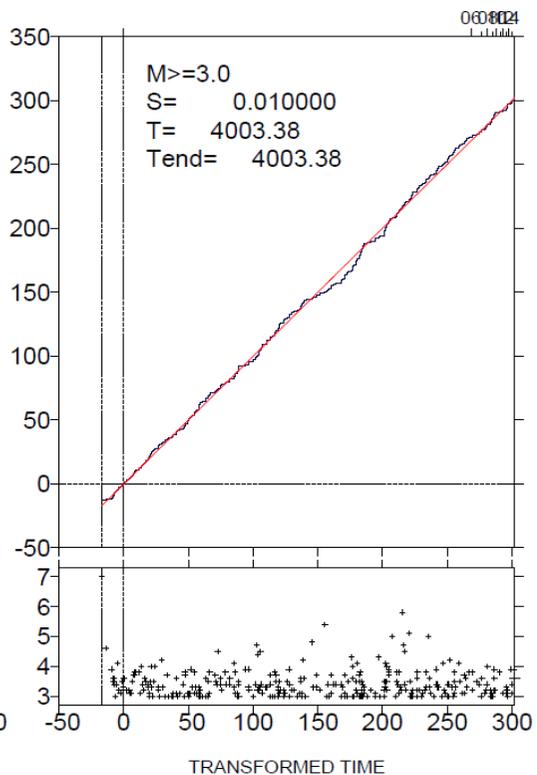
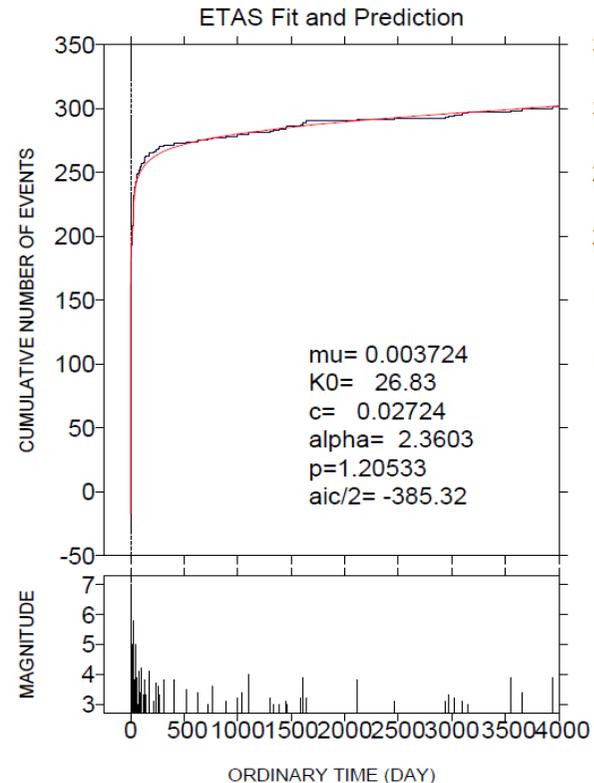
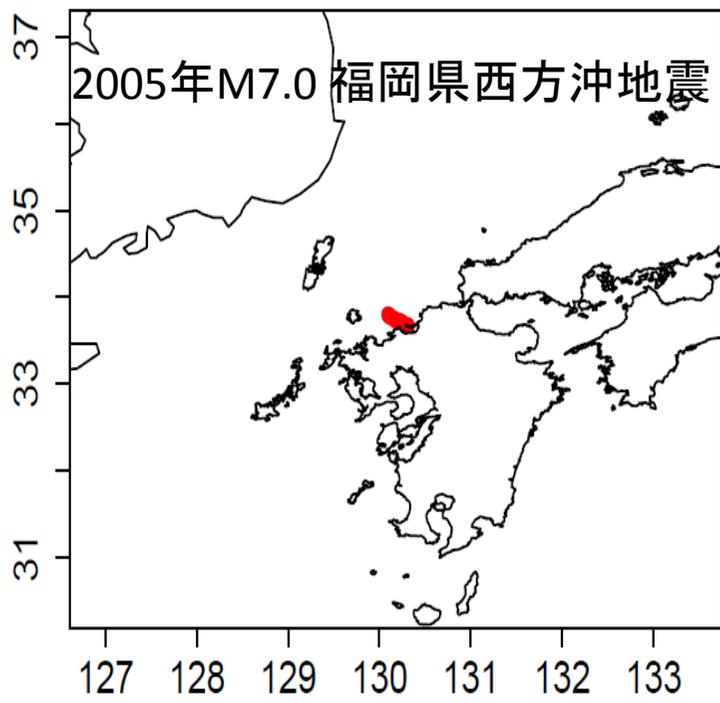


2015年M7.1鹿児島県西方沖の地震



1997年3月M6.6鹿児島県西北部の地震



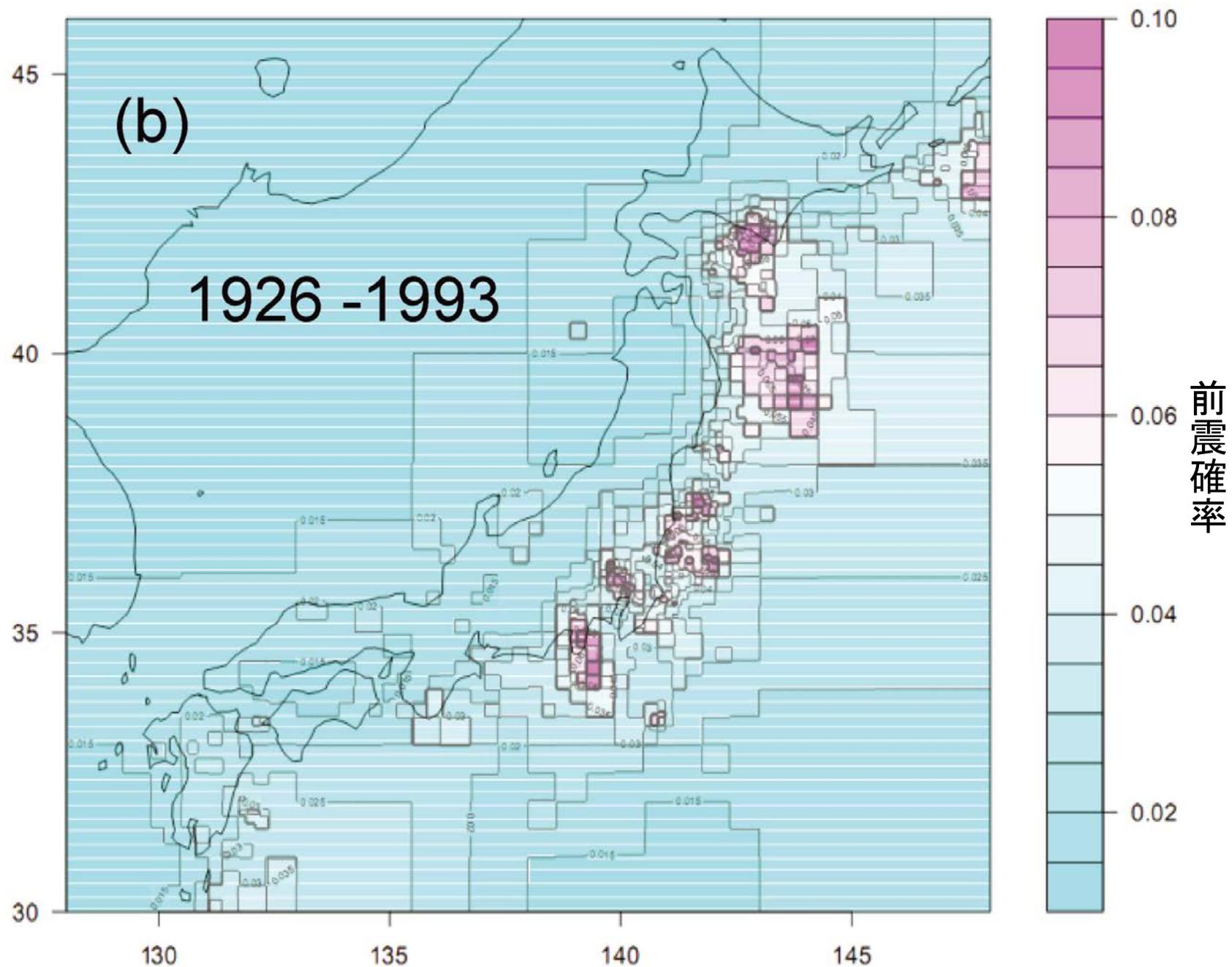




議題2

前震確率予測

東工大, 統数研



最初の $M \geq 4.0$ の地震（結果的に孤立した地震や群れの先頭の地震）が前震である予測確率。熊本地方は2%前後。

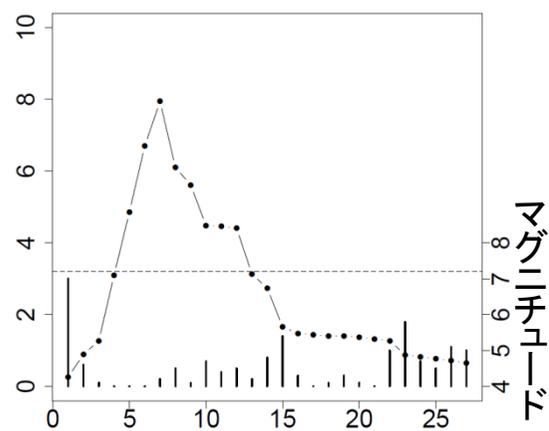
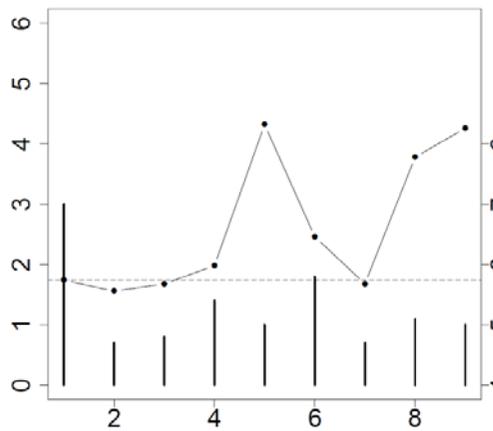
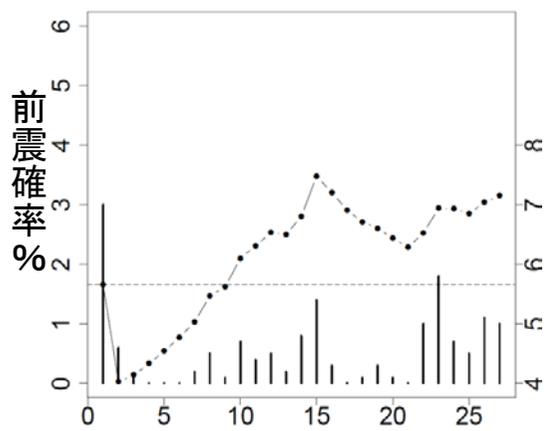
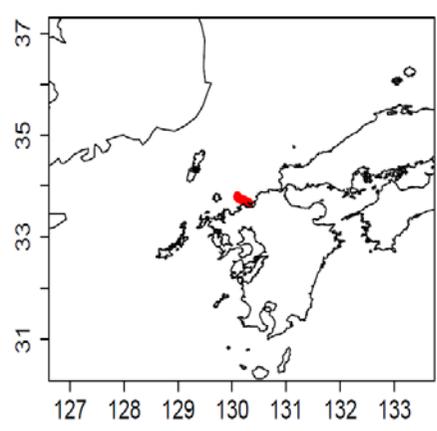
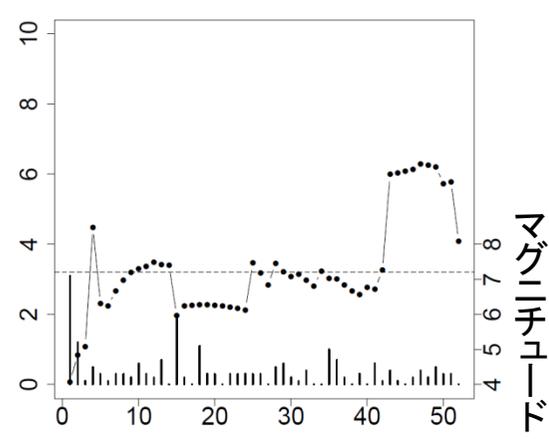
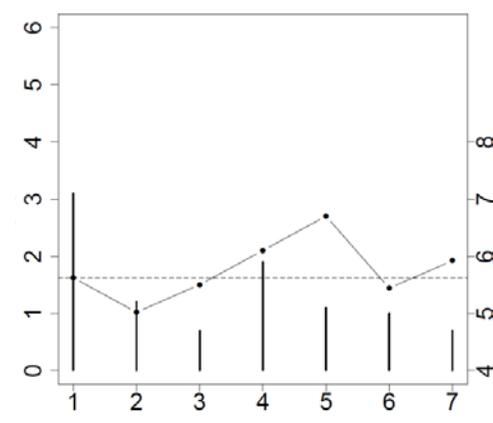
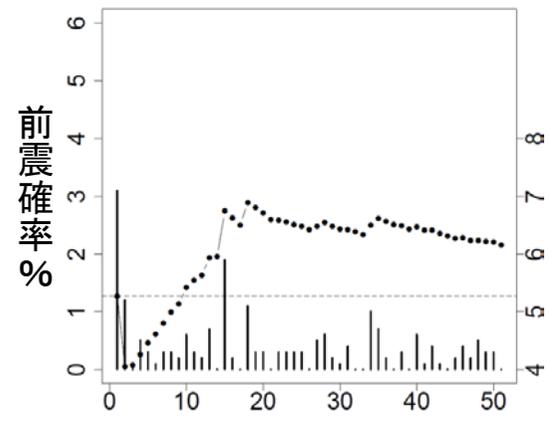
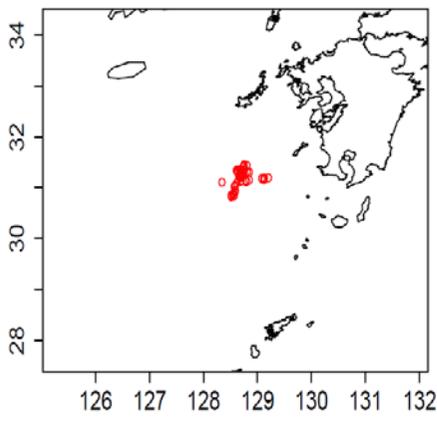
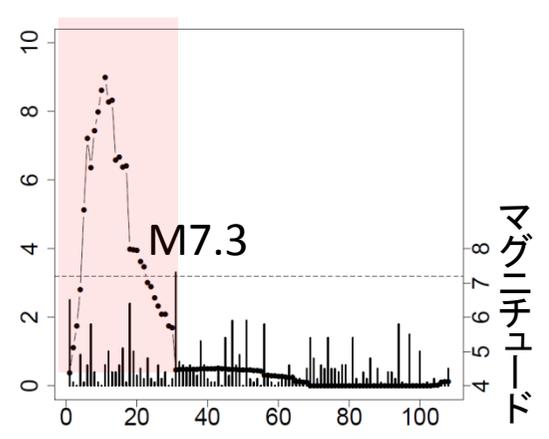
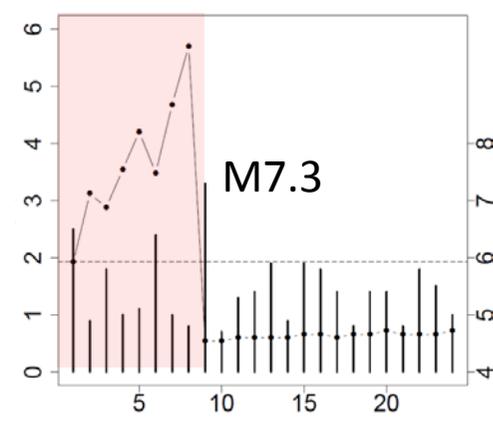
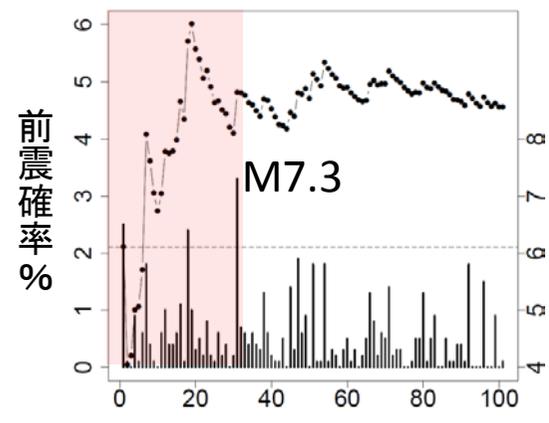
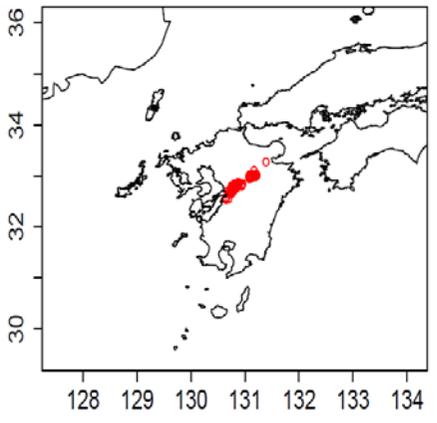


前震確率の推移

Ogata et al. (1997, GJI) model

Nomura global model

Nomura & Ogata model



先頭からの地震数

先頭からの地震数

先頭からの地震数

マグニチュード

マグニチュード

マグニチュード



議題3

多重確率予測試算

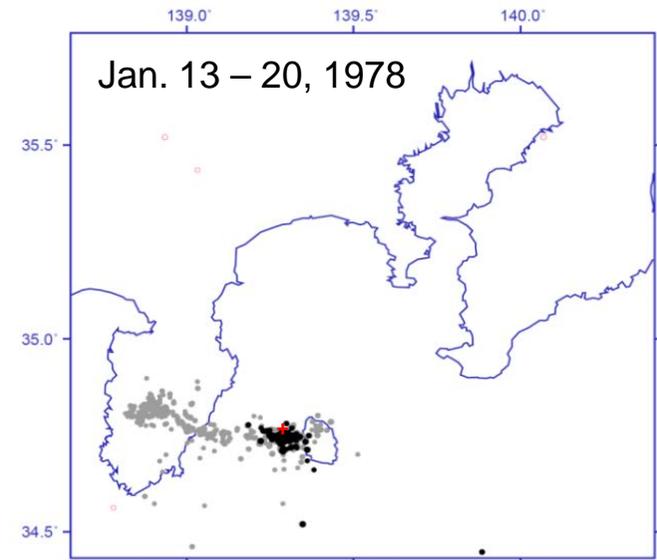
統数研

1978年1月14日12時24分 伊豆大島近海の地震 (M7.0)

宇津 (1978予知連会報)



予測地震を $M6\frac{1}{2}$ 以上としての
前兆確率の試算



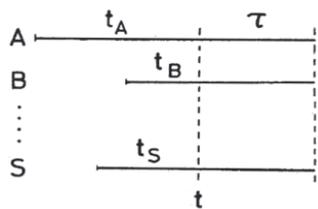
項目A: 1976年初からの隆起域の広がり等から考えて、
隆起が始ってから5年以内にかかる確率 $1/3$ (0.02% per day)

項目B: 石廊崎と網代の埋込式体積ひずみ計に現れた異常や伊豆半島でのラドン、井戸水位等の異常、前年の12月中旬から1か月以内にかかる確率 $1/10$ (0.3% per day)

項目C: 1月14日午前大島西方の地震活動、前震確率 $1/10$ 。
始ってから3日以内にかかる確率 $1/35$ (1% per day)

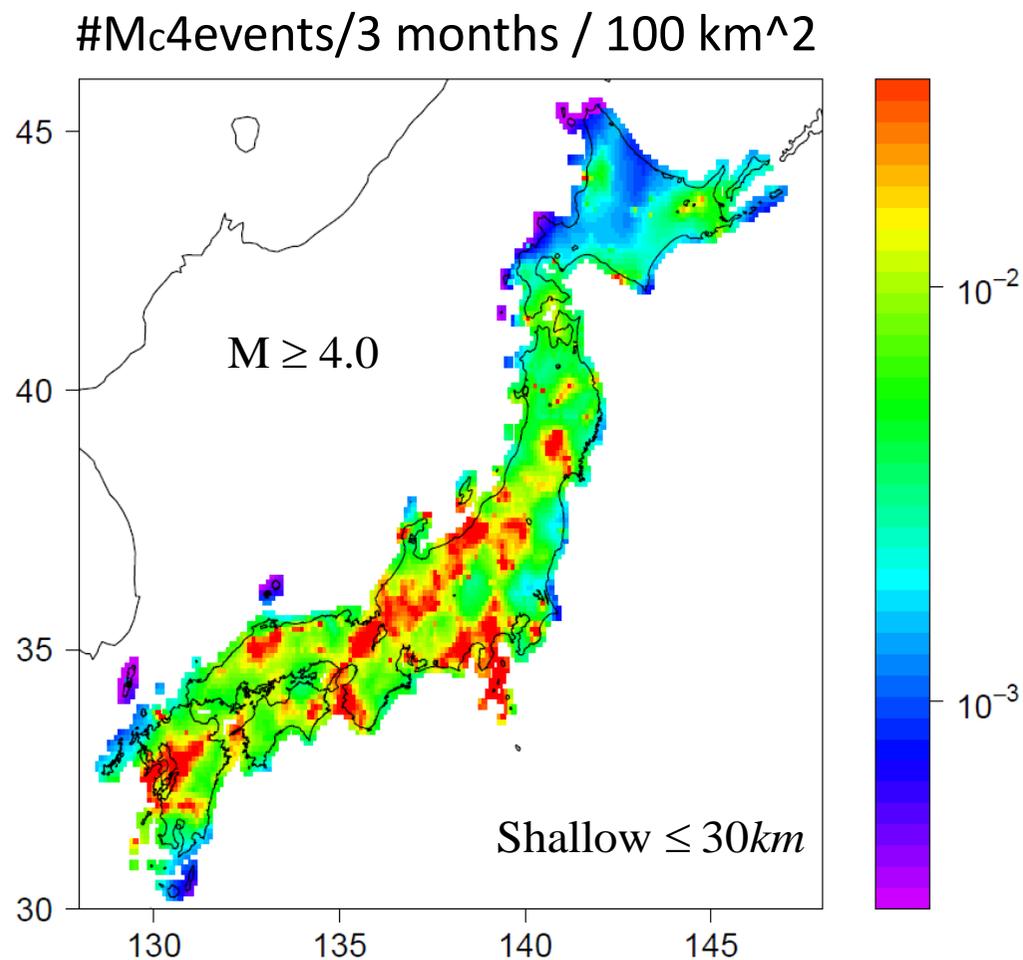
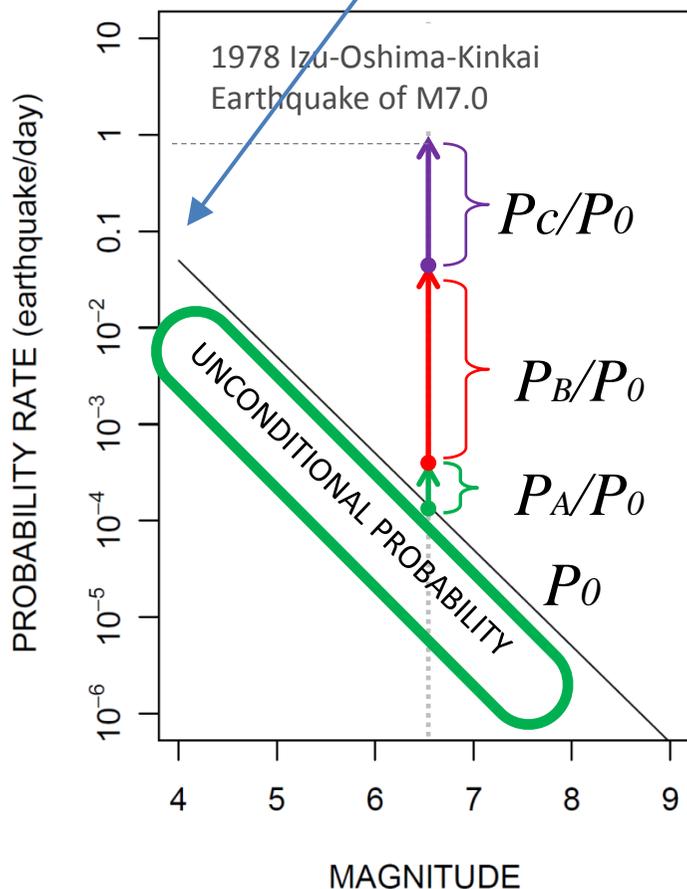
項目O: 大地震の基礎確率 P_0 : 対象地域内で
30年に1回の割合で起っている場合 (Case I) (0.009% per day)
100年に1回の割合で起っている場合 (Case II) (0.003% per day)

多重確率予測公式 (宇津, 1977「地震」)



$$P = \frac{1}{1 + \left(\frac{1}{P_A} - 1\right) \left(\frac{1}{P_B} - 1\right) \left(\frac{1}{P_C} - 1\right) \cdots \left(\frac{1}{P_S} - 1\right) / \left(\frac{1}{P_0} - 1\right)^{N-1}}$$

地震活動度 (seismicity rates)



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

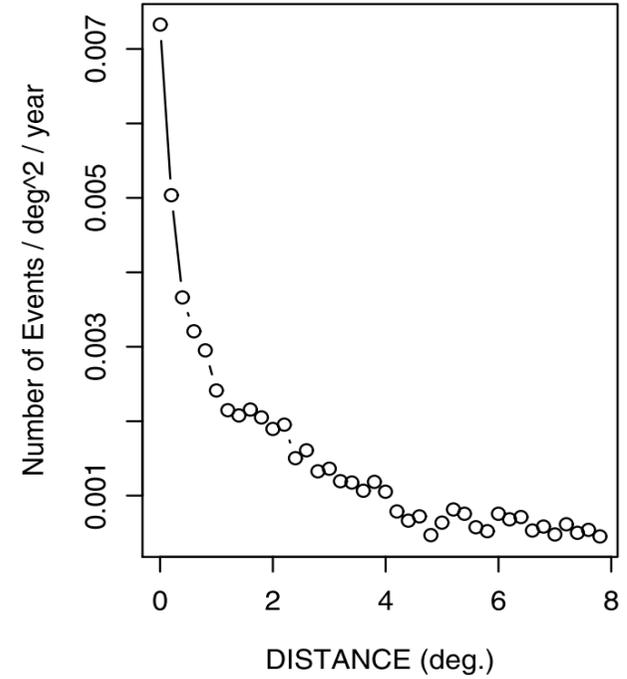
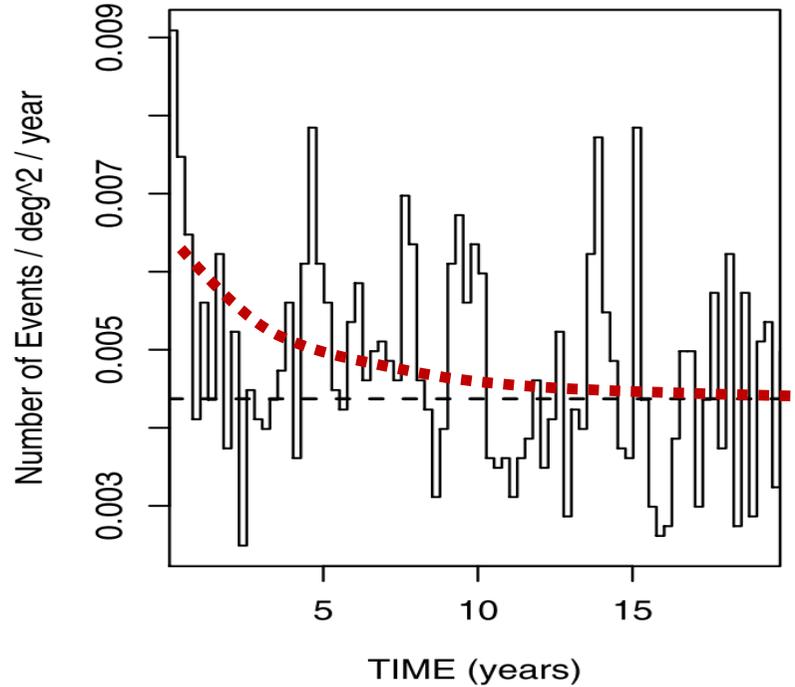
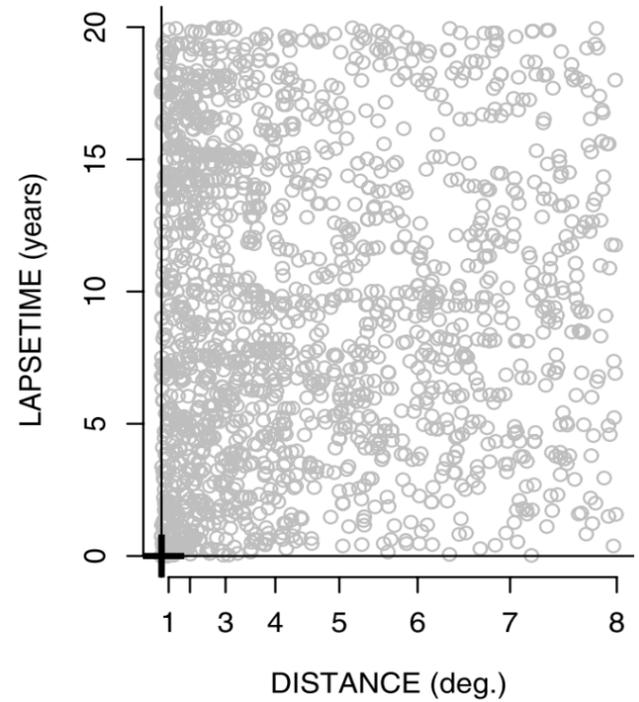
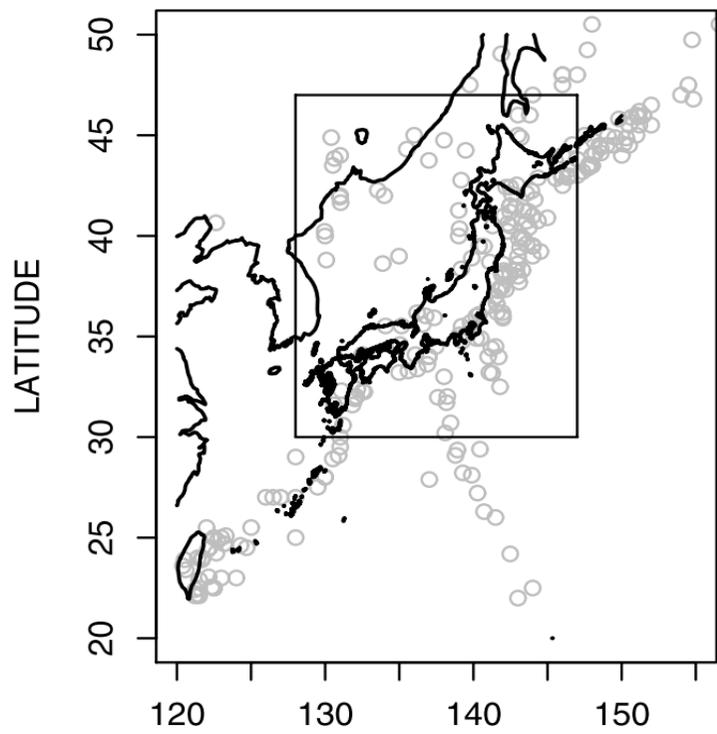
階層的時空間ETASモデル

常時地震活動度 (Background seismicity rates)

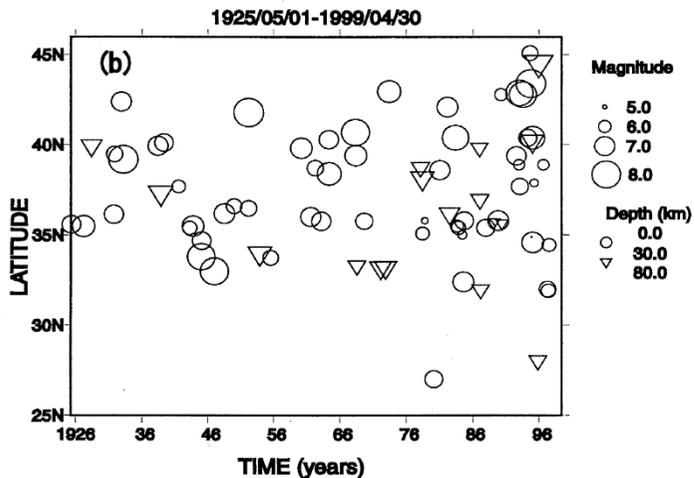
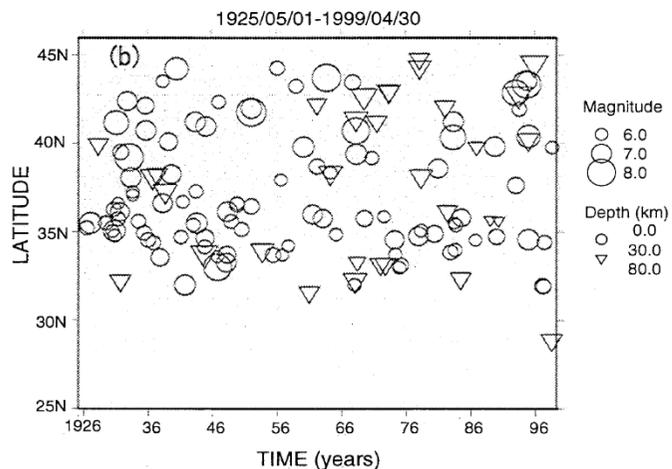
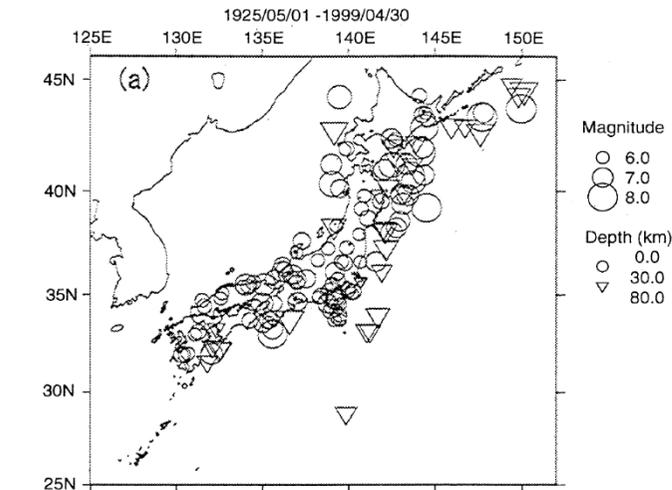


1885 ~ 2003, $M \geq 7.0$

地震誘発 (triggering) の統計

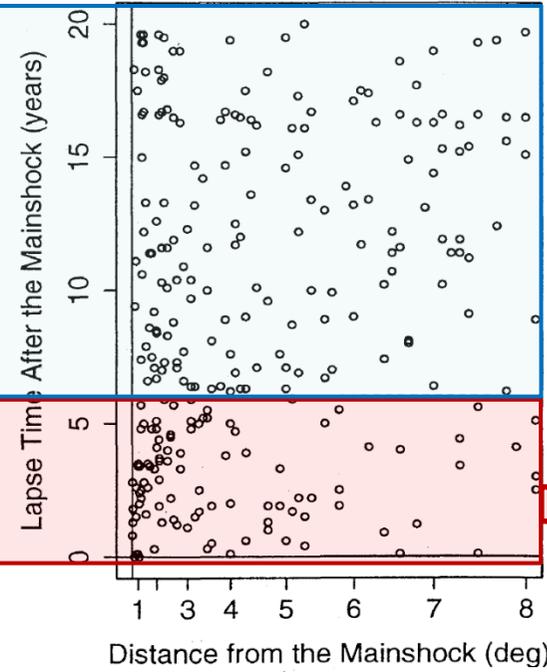
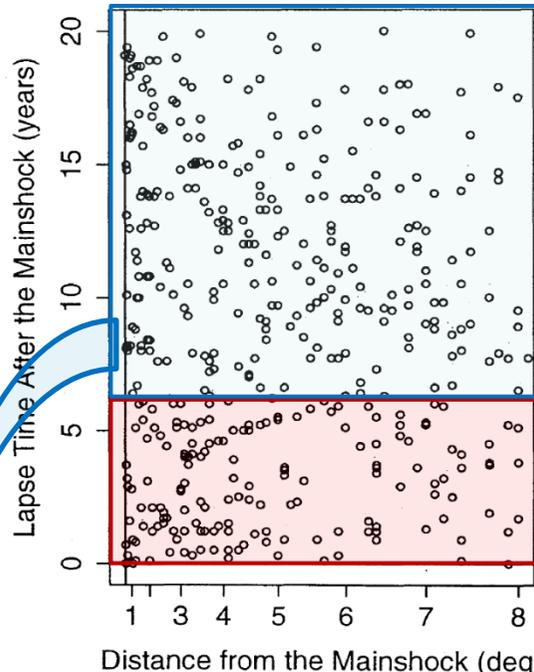


余震の相対的静穏化と近辺での大地震の統計 JGR 2001



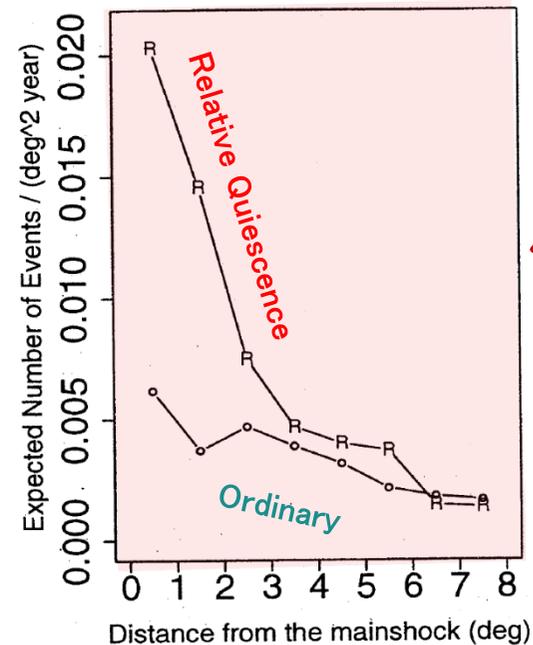
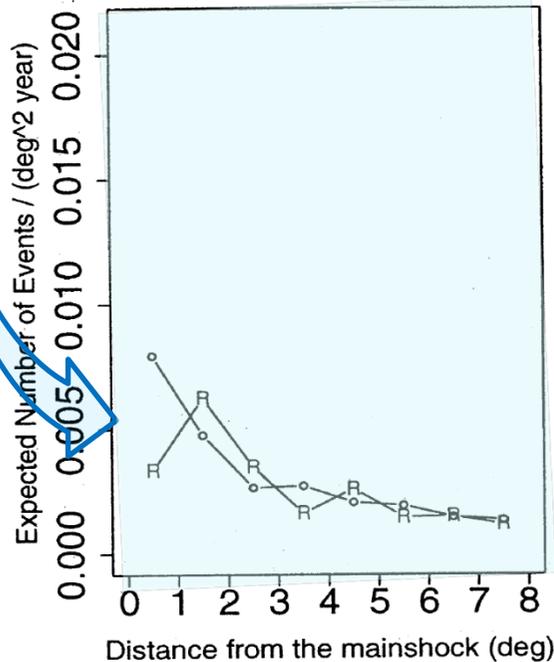
(a) No change-point

(b) Relative quiescence



(b) next 14 years span

(a) first 6 years span



2016年4月16日1時25分 熊本地震 (M7.3)

ターゲット予測地震をM7.0以上としての前兆確率の試算(1平方度・1日当り)

余震域を含む長方形は概ね 1 deg²

- 項目A:** A1. 布田川断層帯の30年確率0.9% (**0.000082% per day**)
A2. 九州中部の断層帯の30年確率21% (**0.0019% per day**)

- 項目B:** B1. 誘発(トリガリング)の地震確率, 1年当り0.5% (**0.0014% per day**)
B2. 余震活動の静穏化の地震確率, 1年当り2% (**0.0055% per day**)

- 項目C:** 4月14日M6.5地震の余震列(M4+) **30日以内**に起る**前震確率5%** (**0.17% per day**)

- 項目O:** 大地震の**基礎確率** P_0 : 対象地域内で**90年に1回以上**の割で起きる確率
(Case I) M_c4 地震数とGR則 $b \sim 1.0$ (**0.00058% per day**)
(Case II) M_c4 ETAS model BG率とGR則 $b \sim 1.0$ (**0.0027% per day**)

多重確率予測公式(multiple elements prediction formula, 宇津, 1977「地震」)

$$P = \frac{1}{1 + \left(\frac{1}{P_A} - 1\right) \left(\frac{1}{P_B} - 1\right) \left(\frac{1}{P_C} - 1\right) \cdots \left(\frac{1}{P_S} - 1\right) / \left(\frac{1}{P_0} - 1\right)^{N-1}}$$

項目BとCについては, さらに半分の確率を設定して多重予測確率の幅を見る。

計算結果

活断層情報有。1日確率 0.007%~20%, 3日 0.016%~41%, 7日 0.03%~62%, 1月 0.2%~88%
活断層情報無。1日確率 0.1%~3%, 3日 0.04%~9%, 7日 0.06%~19%, 1月 3%~51%

多重確率予測 (multiple element prediction)

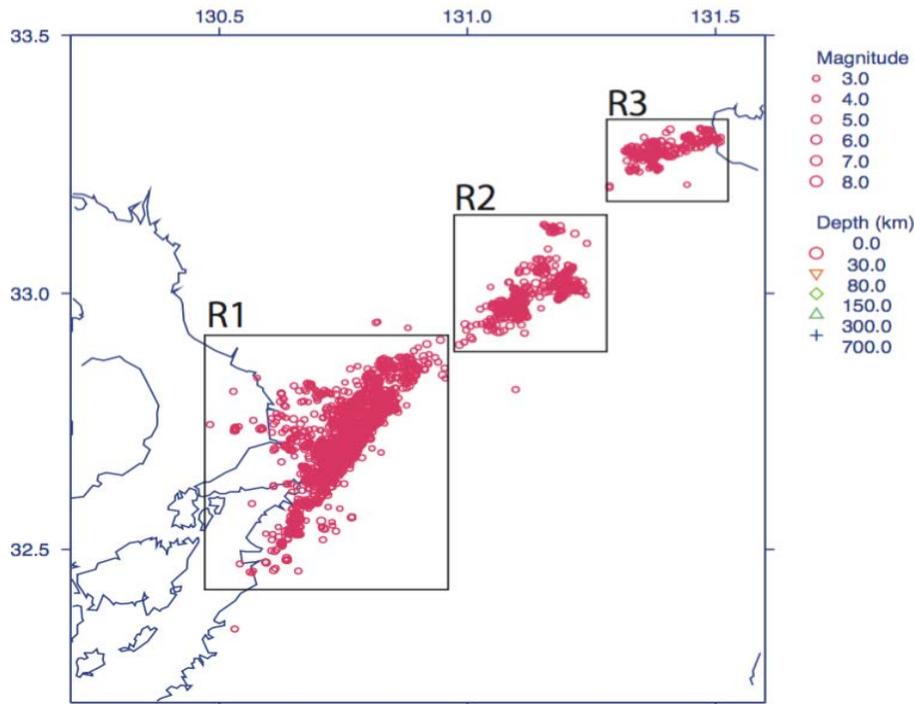
単位面積	1 平方度							
単位時間		30年	1年	30日	1日	3日	1週間	30日
永年確率 P_0	ETAS常時活動度GR				0.000002747			
長期確率 P_{A_1}	布田川断層帯	0.009	0.0003		0.00000082			
P_{A_2}	九州中部	0.210	0.007		0.00001917			
中期確率 P_{B_1}	誘発		0.005		0.00001369			
P_{B_2}	静穏化		0.02		0.00005476			
短期確率 P_C	前震			0.05	0.00166667			
多重確率予測								
$P(A_1 \cap B_1 \cap C)$					0.002482	0.00743	0.0173	0.0727
$P(B_1 \cap C)$					0.00825	0.0244	0.0556	0.208
$P(A_1 \cap B_2 \cap C)$					0.009853	0.291	0.0658	0.239
$P(B_2 \cap C)$					0.0322	0.0911	0.191	0.512
$P(A_1 \cap B_2 \cap C)$					0.0549	0.149	0.291	0.647
$P(A_2 \cap B_2 \cap C)$					0.188	0.411	0.622	0.88
単位時間		30年	1年	30日	1日	3日	1週間	30日
永年確率 P_0	地震数とGR				0.000005821			
長期確率 P_{A_1}	布田川断層帯	0.0045	0.0002		0.00000041			
P_{A_2}	日奈久断層近辺	0.105	0.0035		0.00000958			
中期確率 P_{B_1}	誘発		0.0025		0.00000684			
P_{B_2}	静穏化		0.01		0.00002738			
短期確率 P_C	前震			0.025	0.00083333			
多重確率予測								
$P(A_1 \cap B_1 \cap C)$					0.000069	0.00016	0.000377	0.00165
$P(B_1 \cap C)$					0.00098	0.00259	0.0060	0.0259
$P(A_1 \cap B_2 \cap C)$					0.000277	0.00065	0.00151	0.00656
$P(B_2 \cap C)$					0.00391	0.0103	0.0237	0.0961
$P(A_1 \cap B_2 \cap C)$					0.00161	0.00375	0.00873	0.0371
$P(A_2 \cap B_2 \cap C)$					0.00642	0.0148	0.0340	0,134



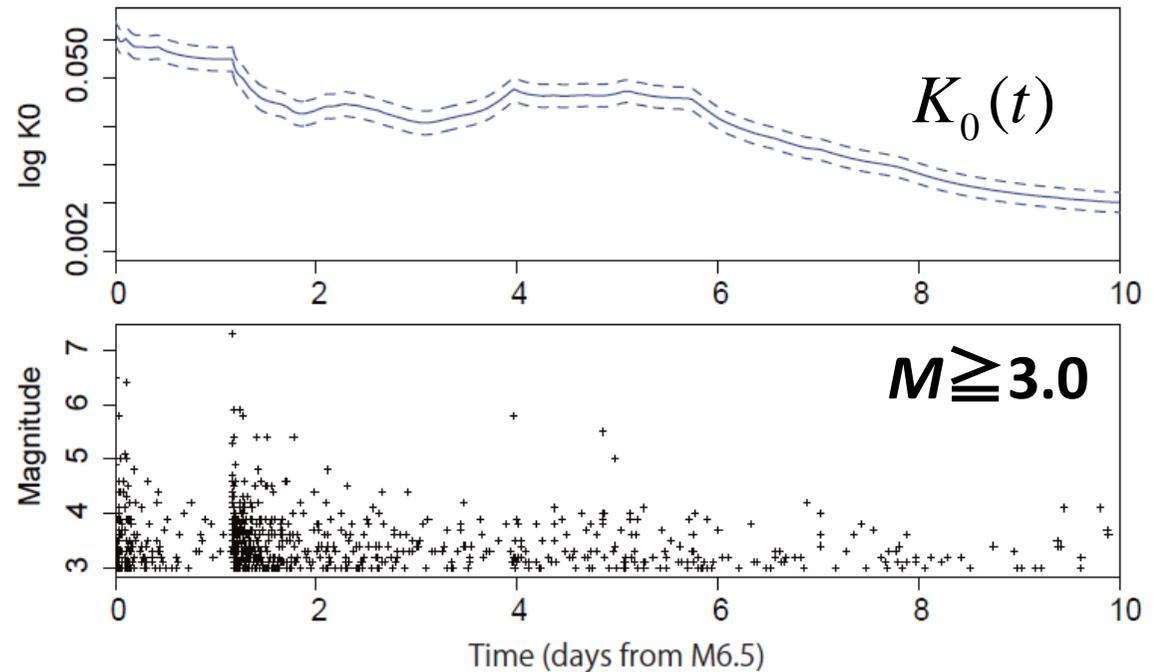
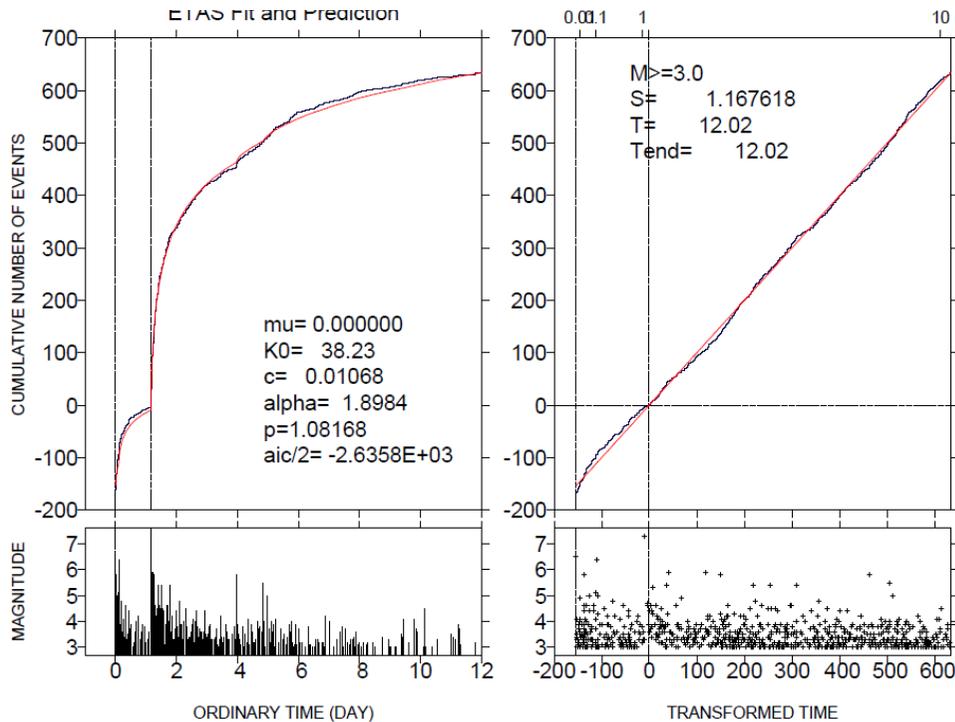
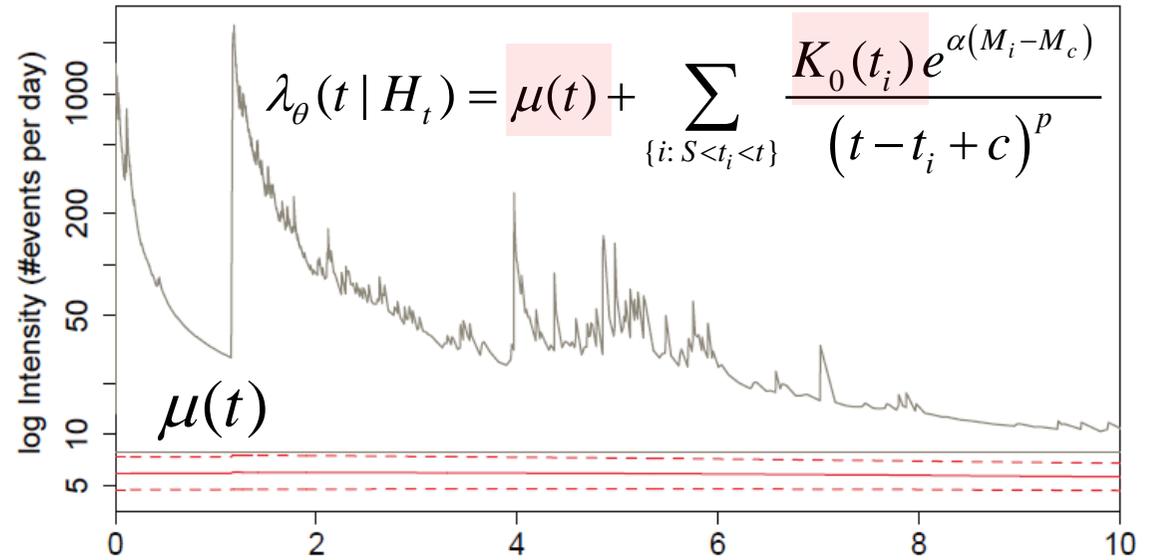
議題4

余震活動予測

東大生産研, 統数研, 東大地震研



Non-stationary ETAS fit



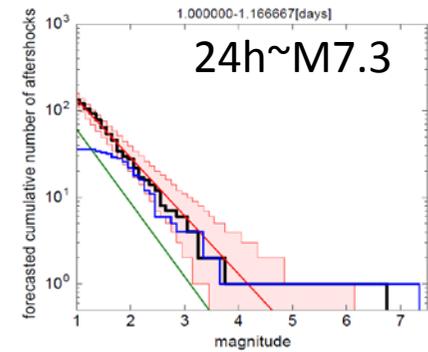
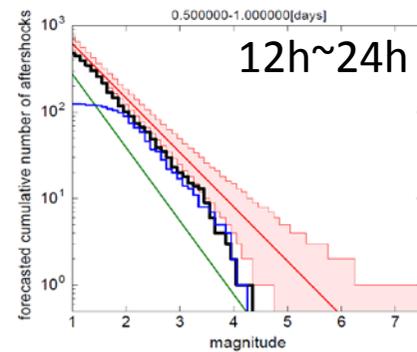
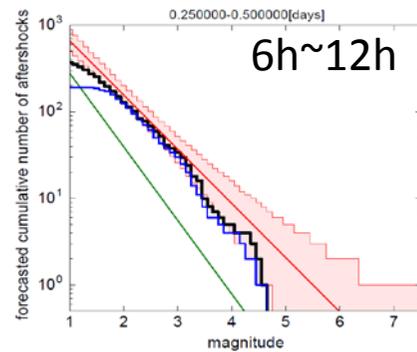
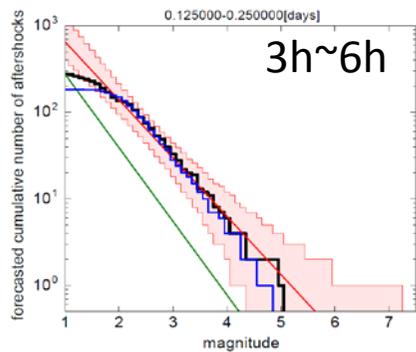
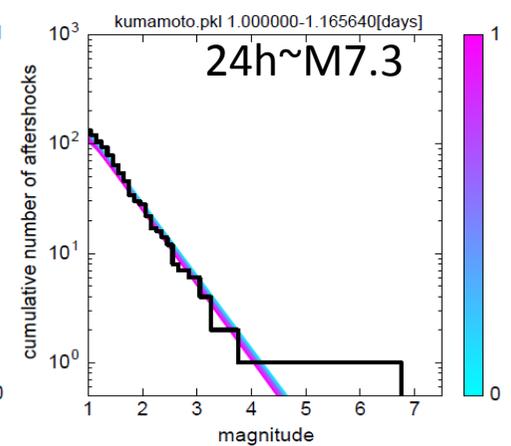
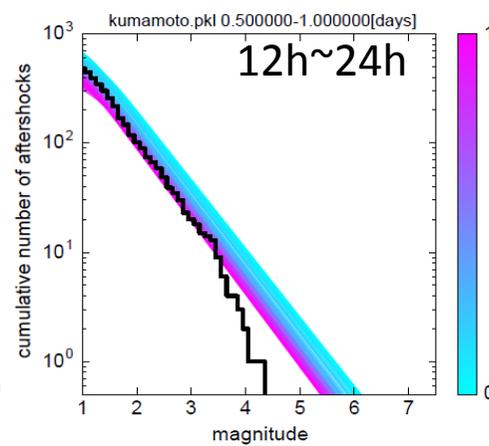
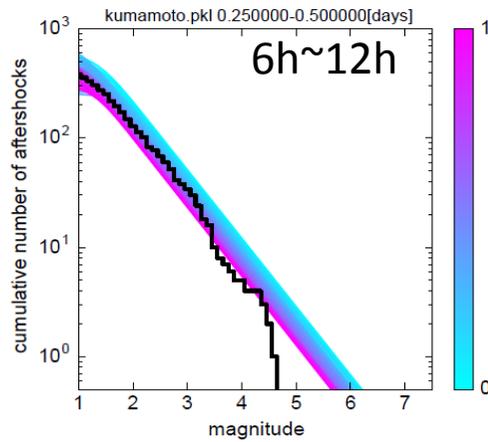
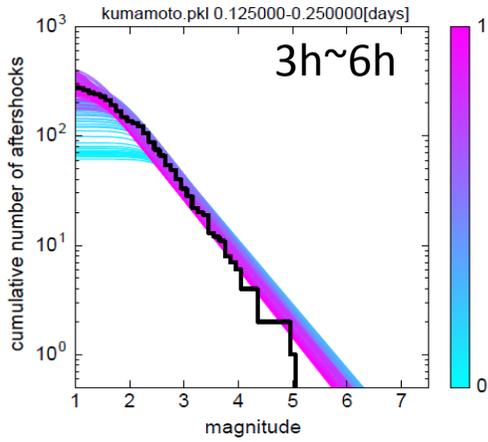
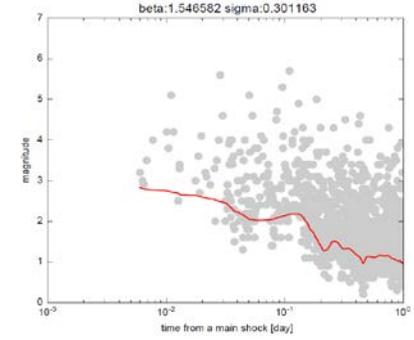
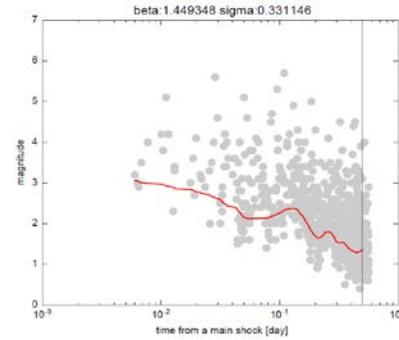
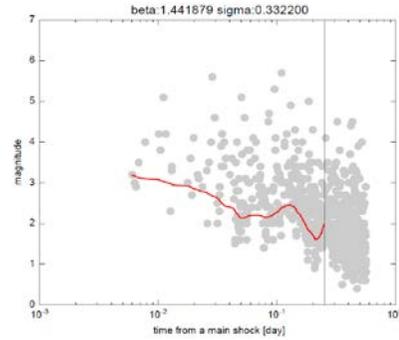
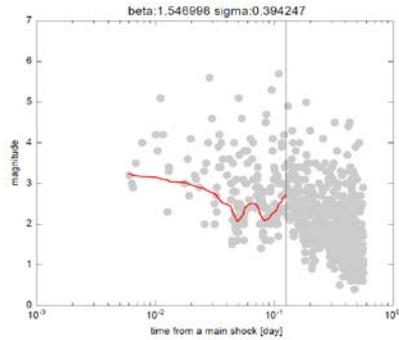
2016年M6.5熊本地震(前震)の余震確率予報

3h

6h

12h

24h



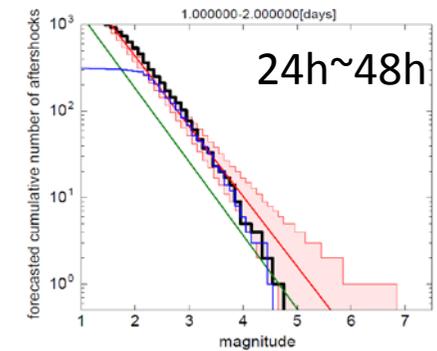
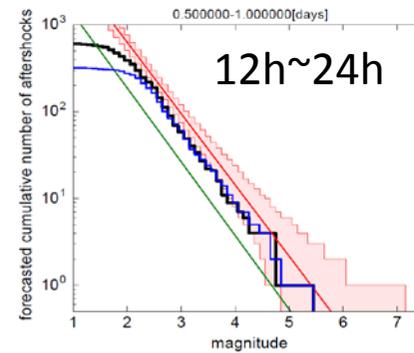
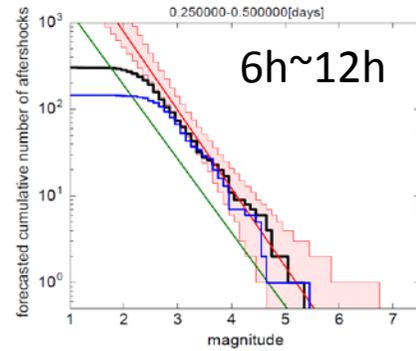
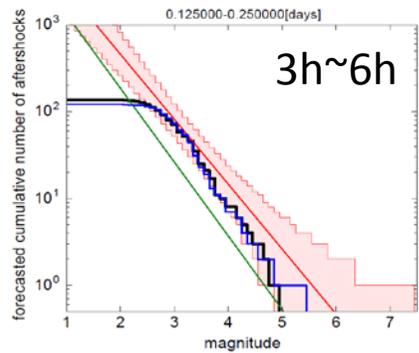
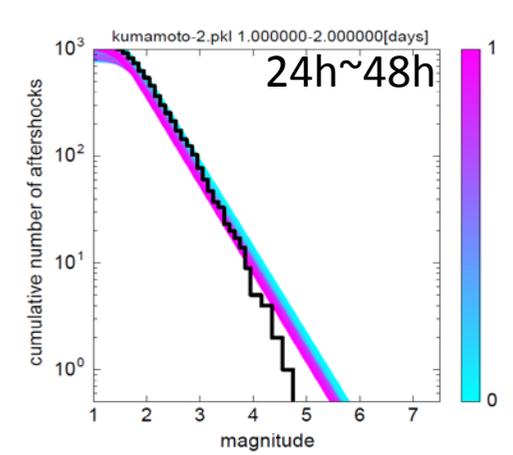
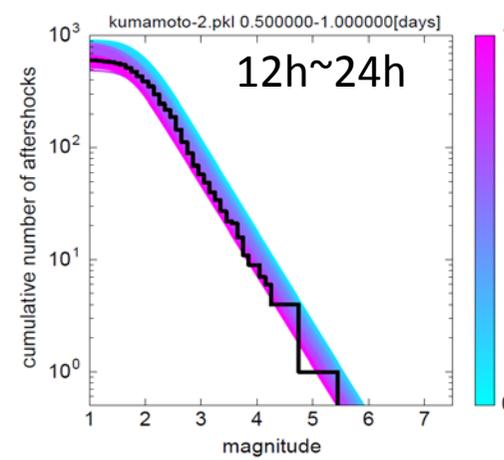
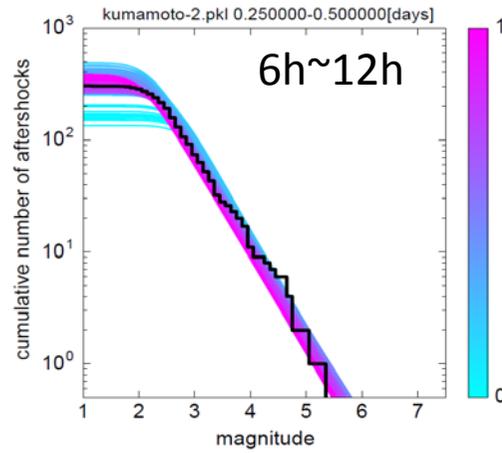
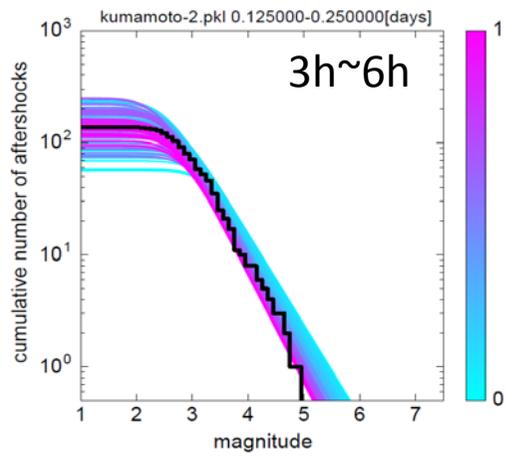
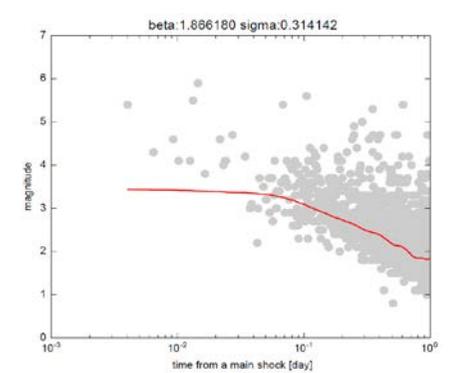
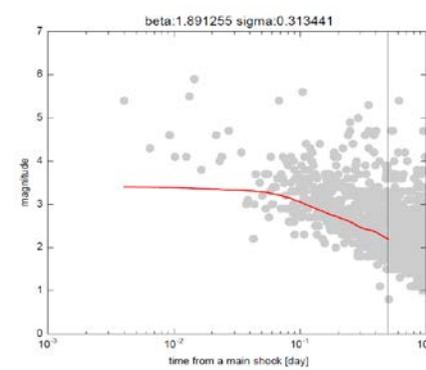
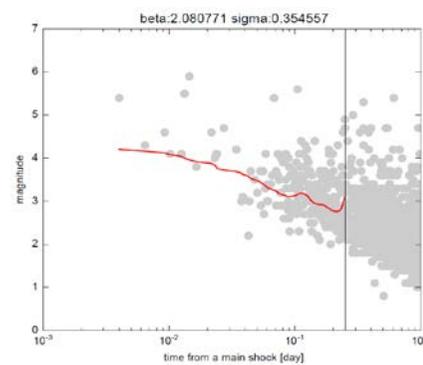
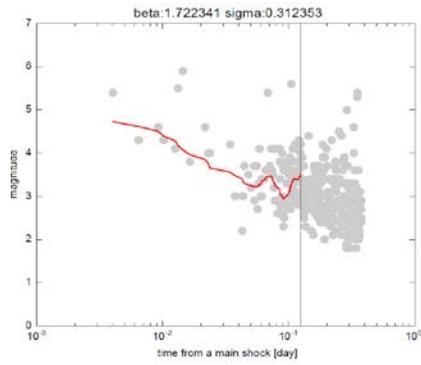
2016年M7.3 熊本地震の余震確率予報

3h

6h

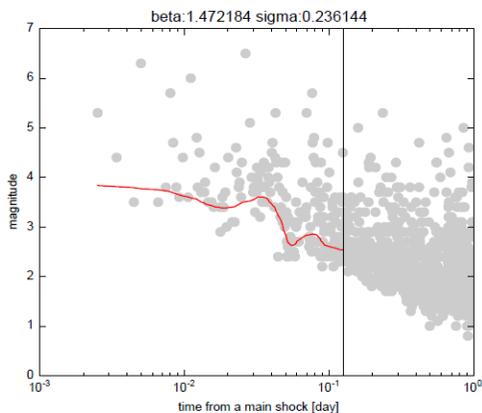
12h

24h

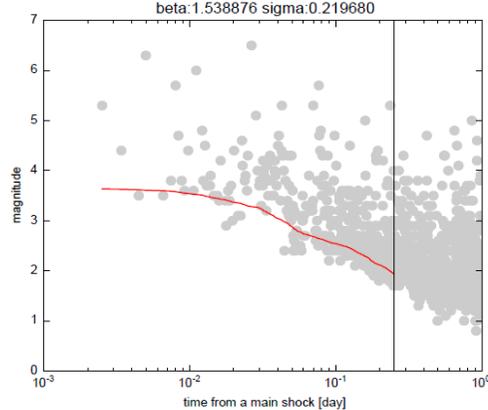


2004年M6.8中越地震の余震確率予報

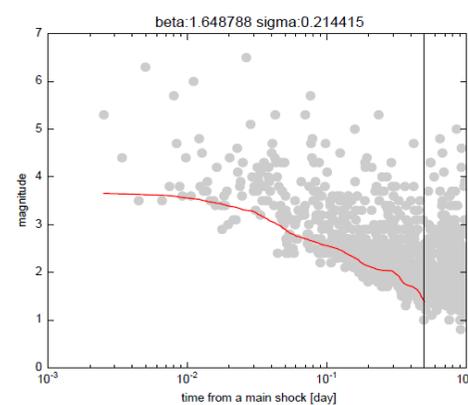
3h



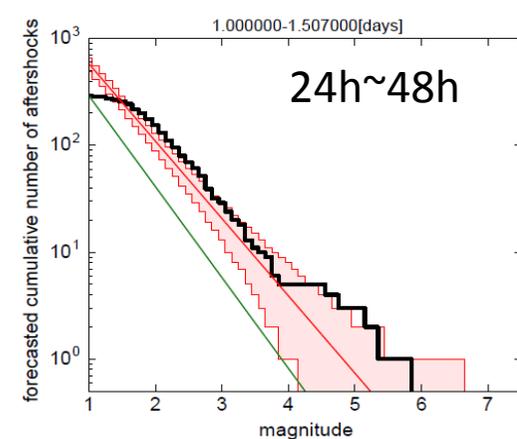
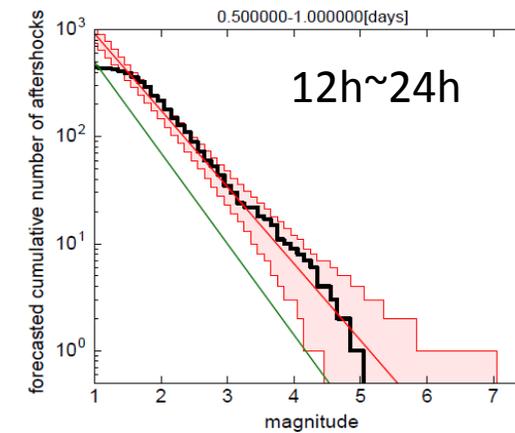
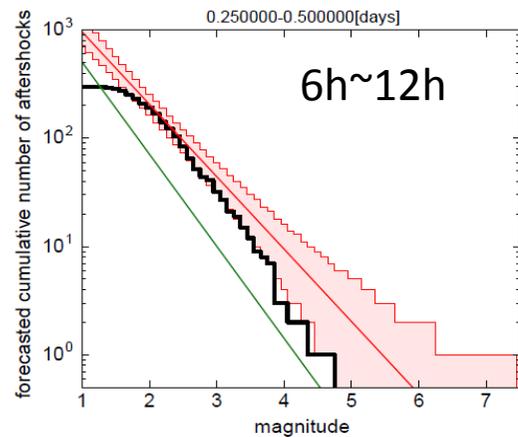
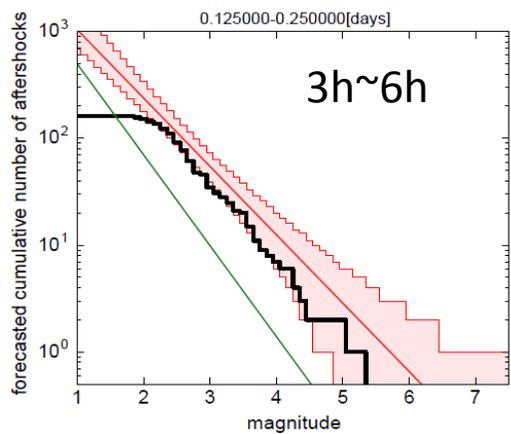
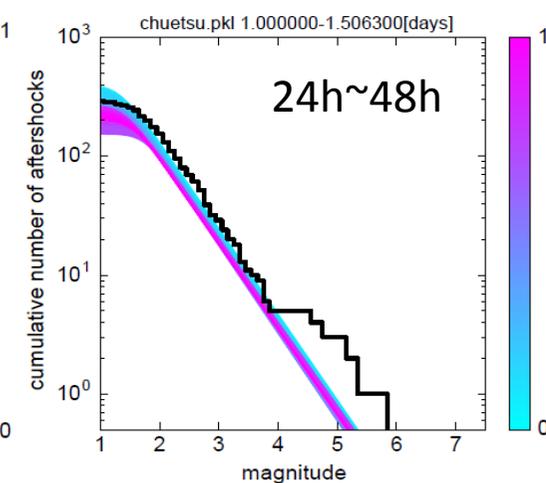
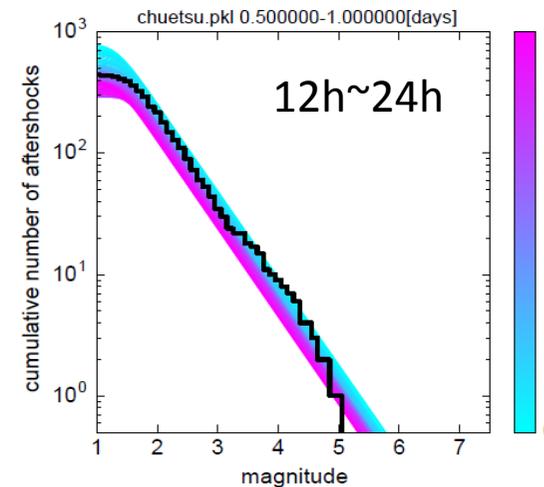
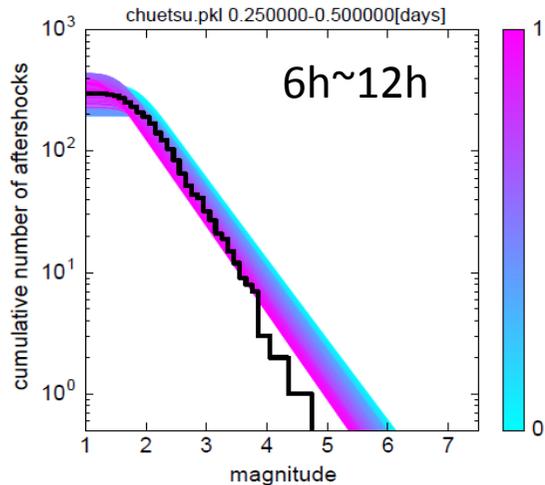
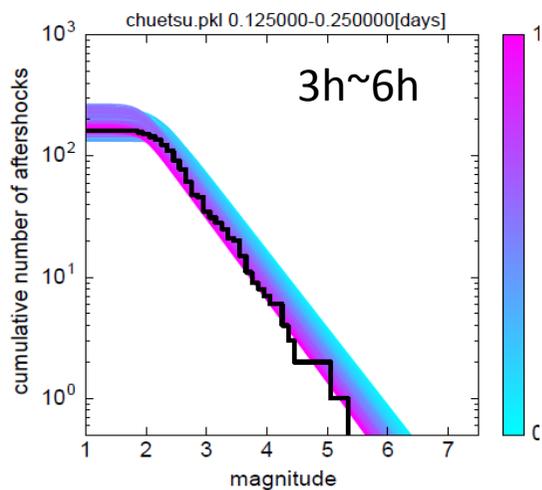
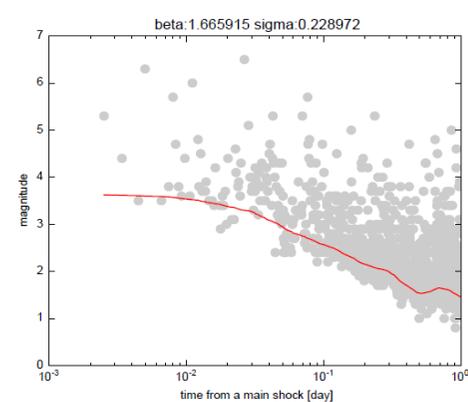
6h



12h



24h



2003年M6.4宮城県北部地震

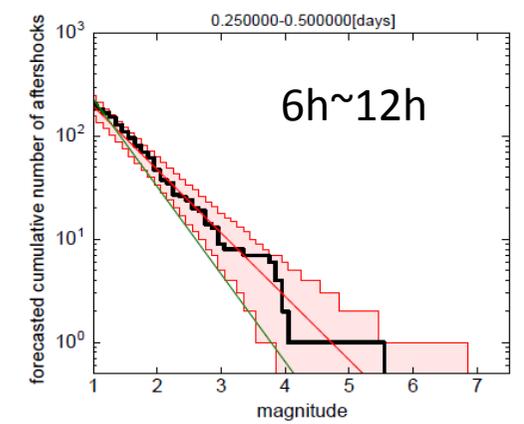
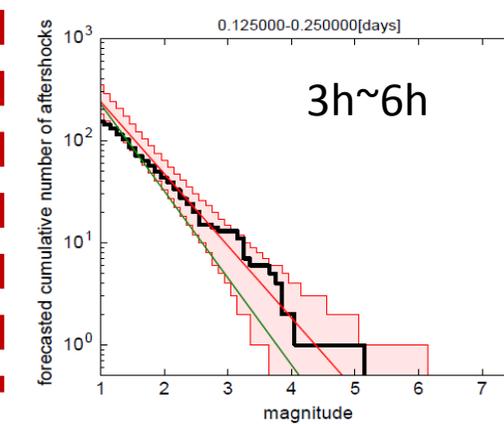
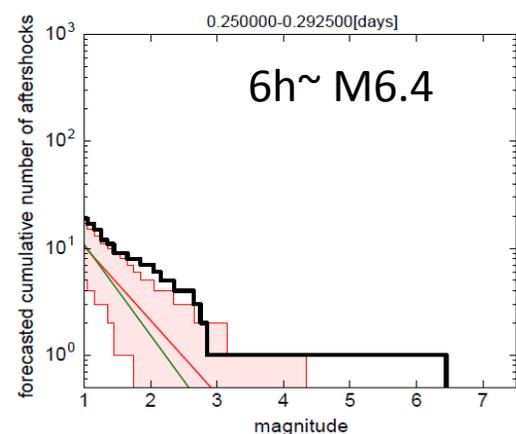
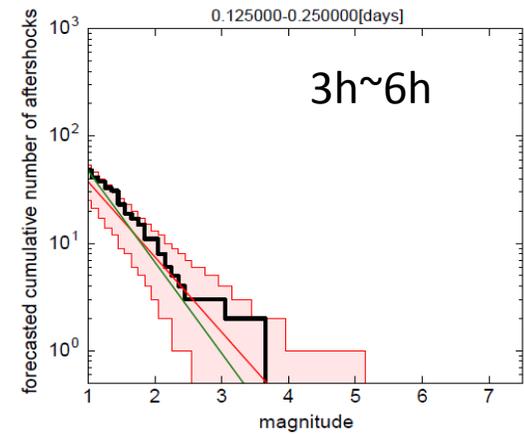
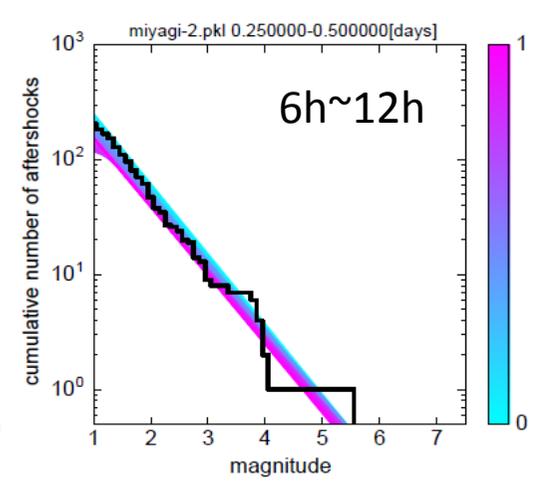
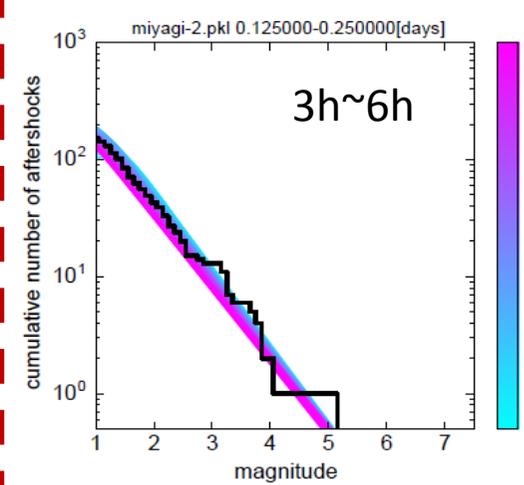
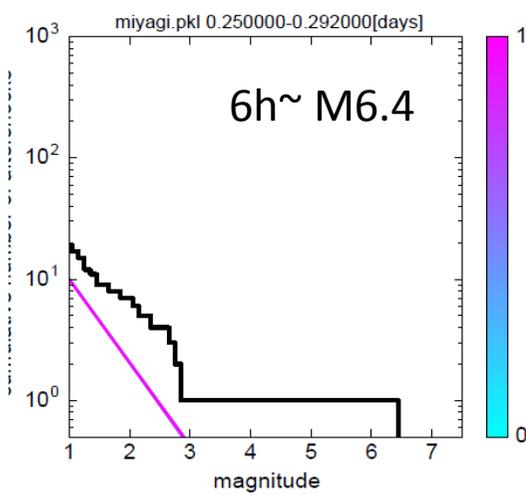
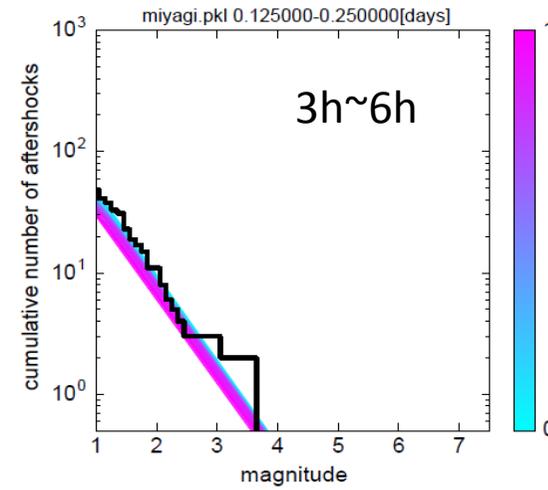
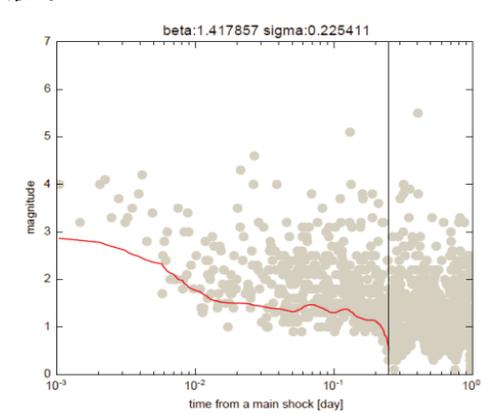
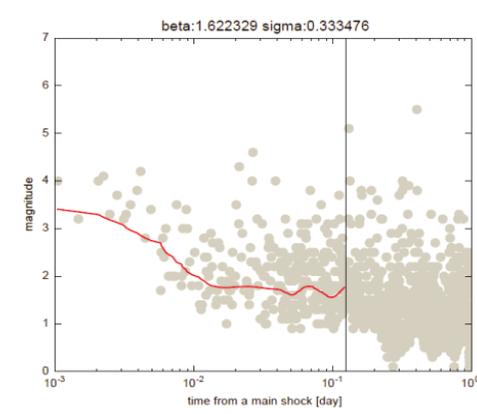
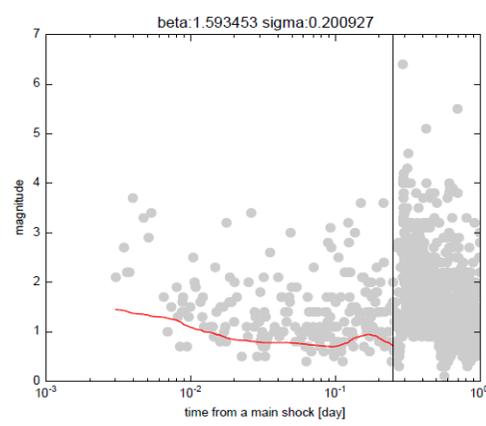
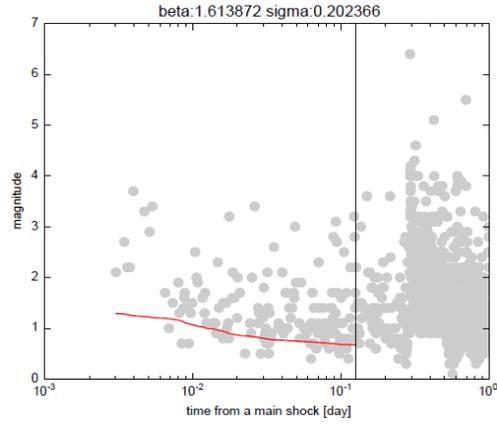
3h 前震(M5.6)

6h

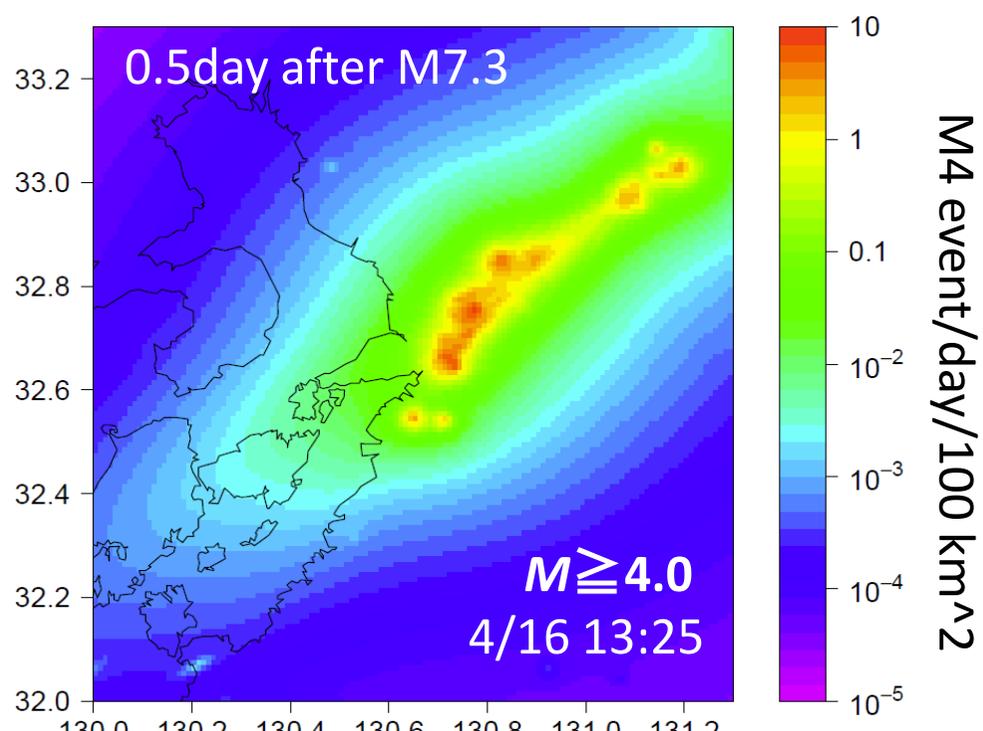
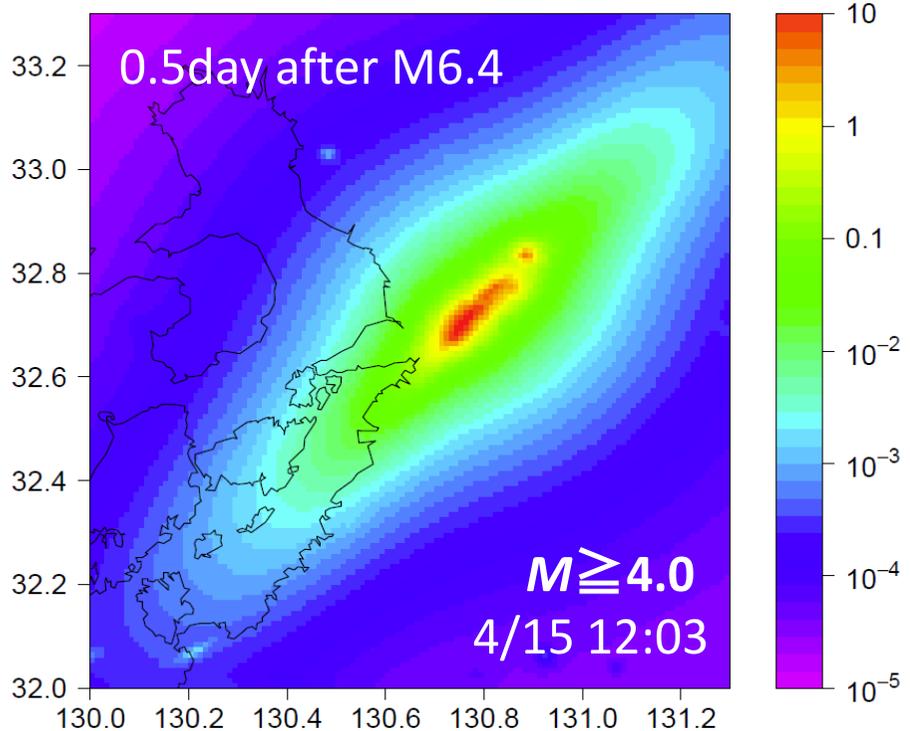
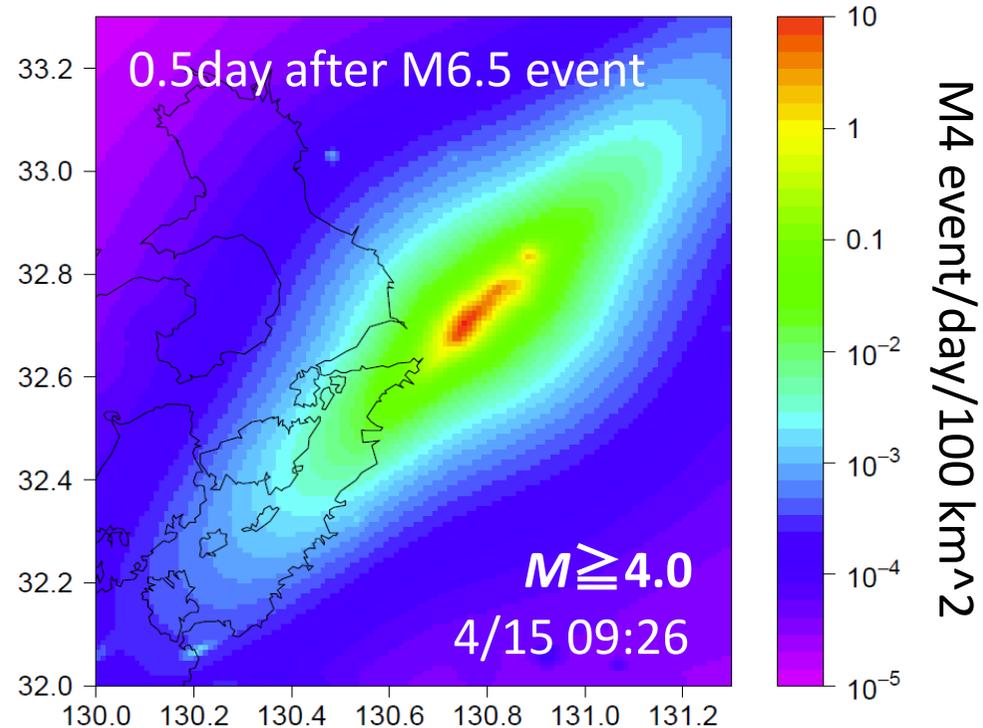
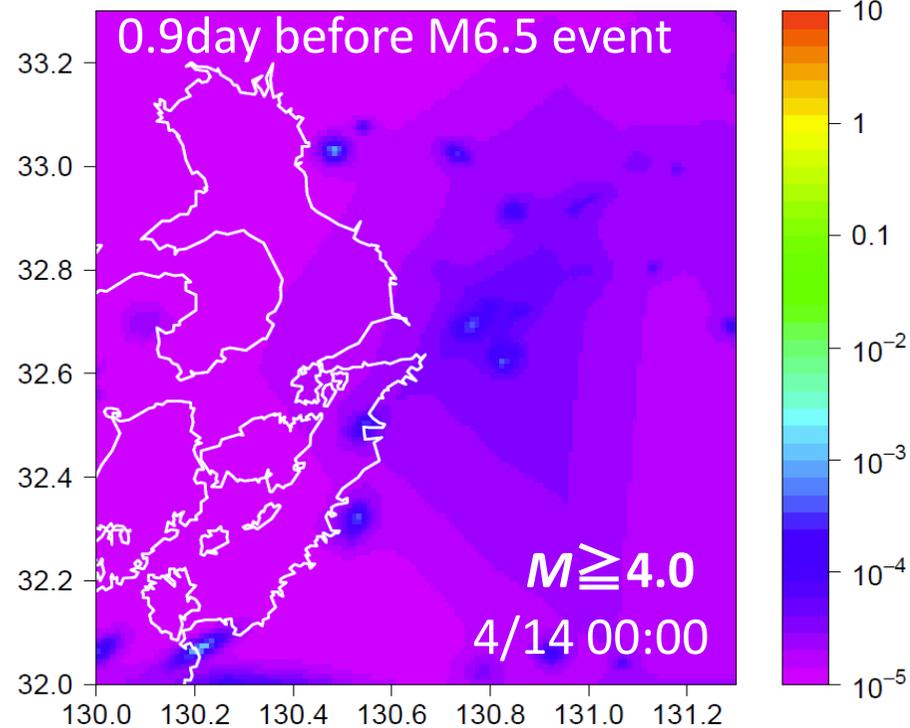
3h

余震

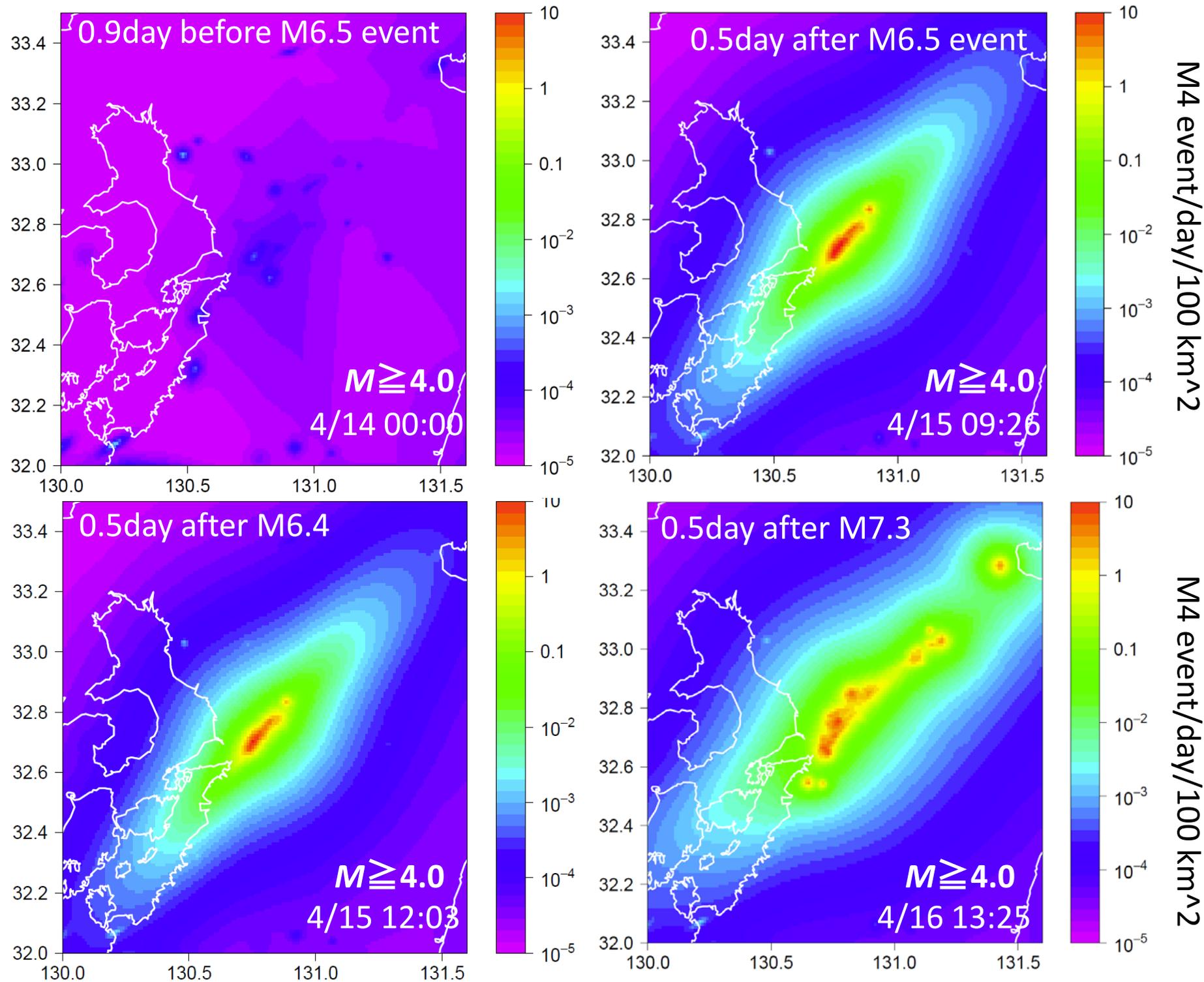
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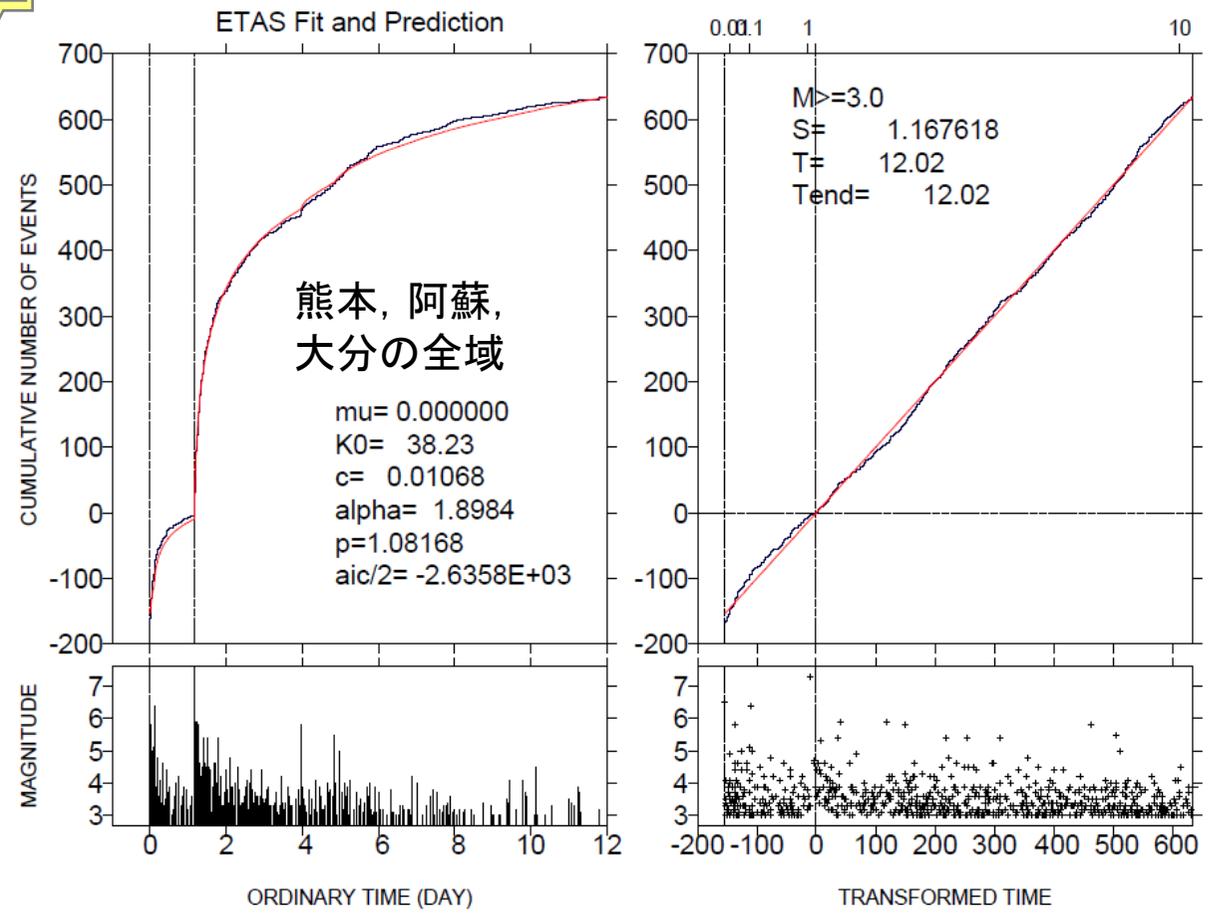


CSEP日本検証センターに提出した階層的時空間ETASモデルによる各記載時刻での発生予測確率

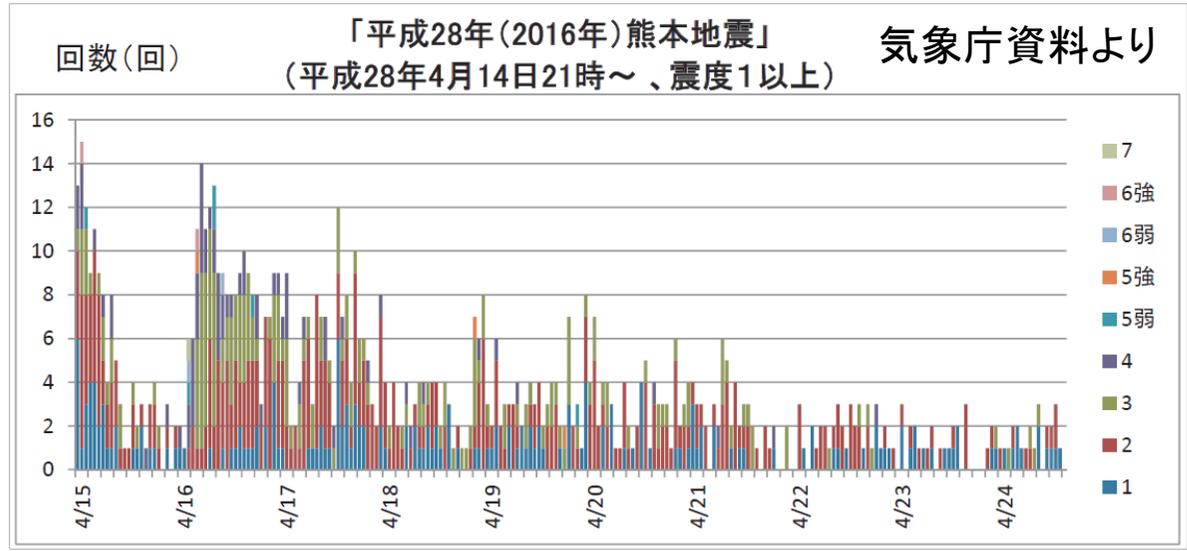
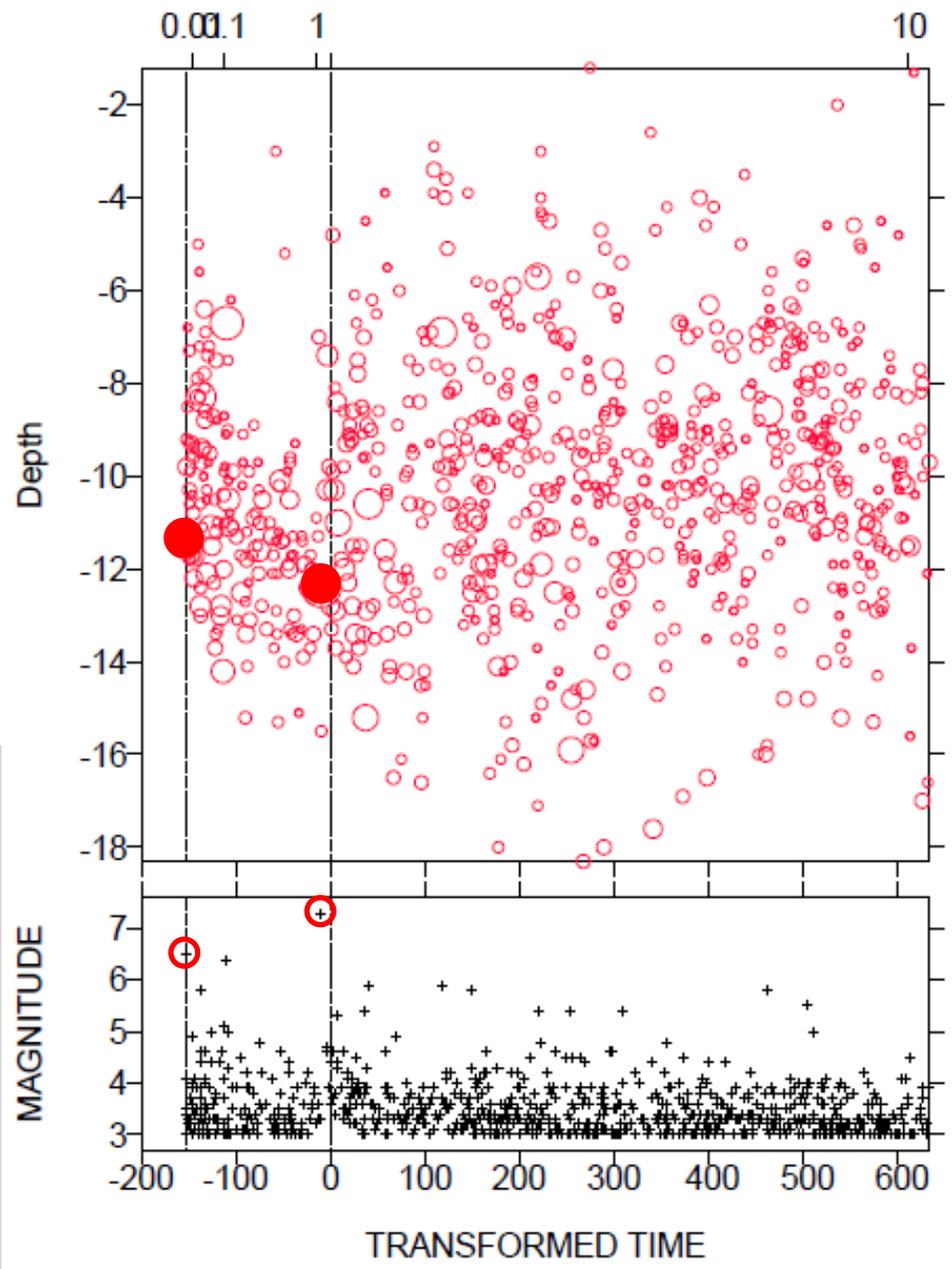


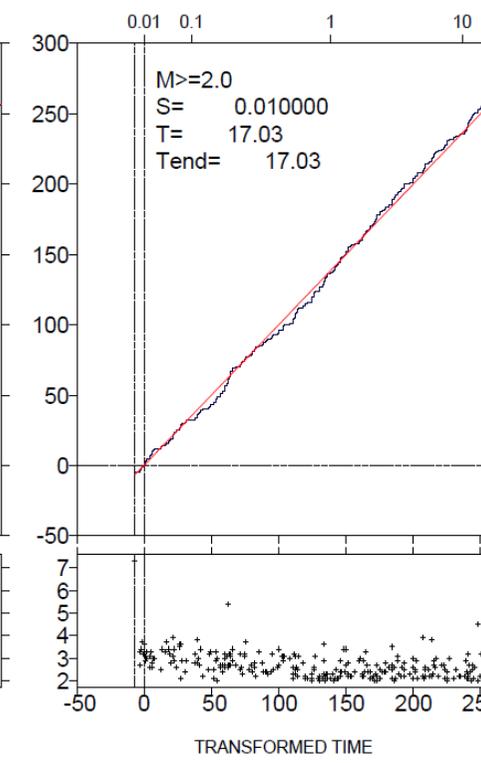
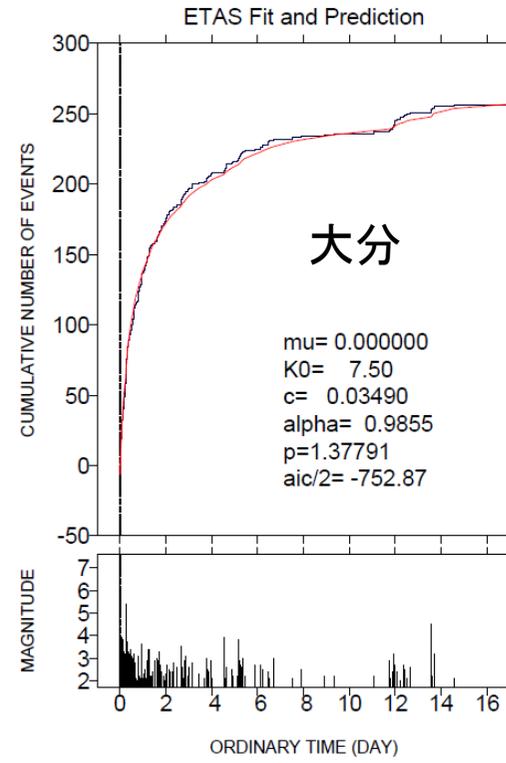
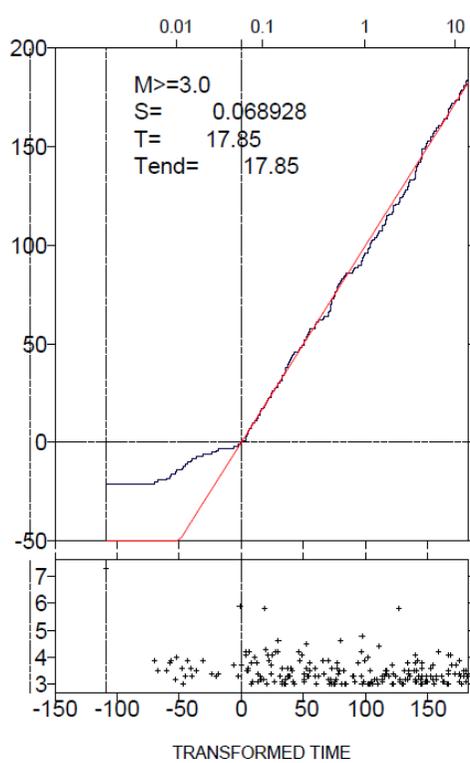
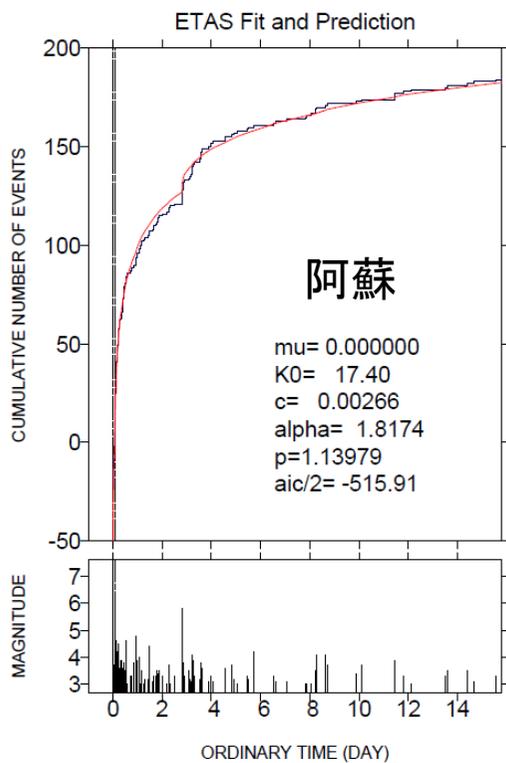
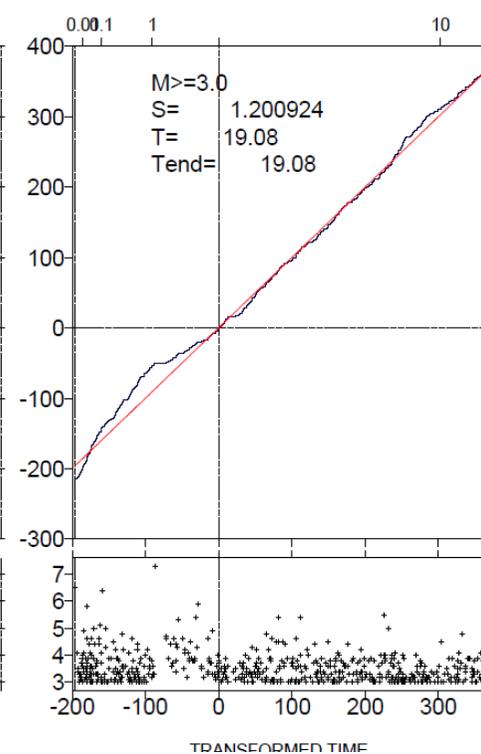
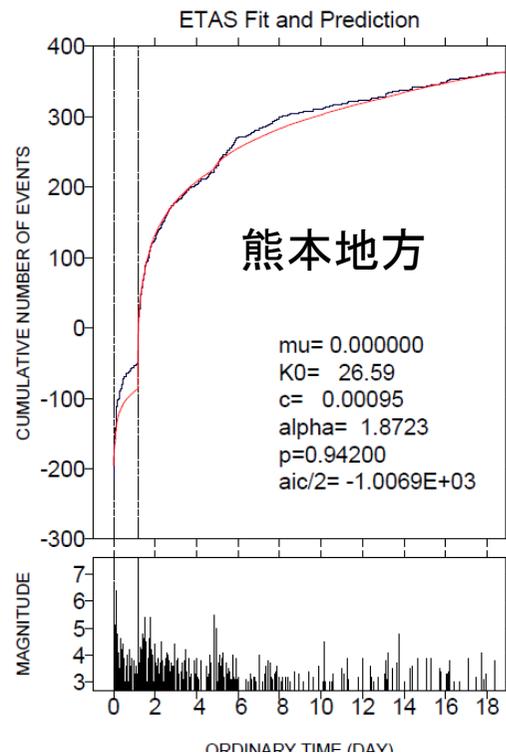
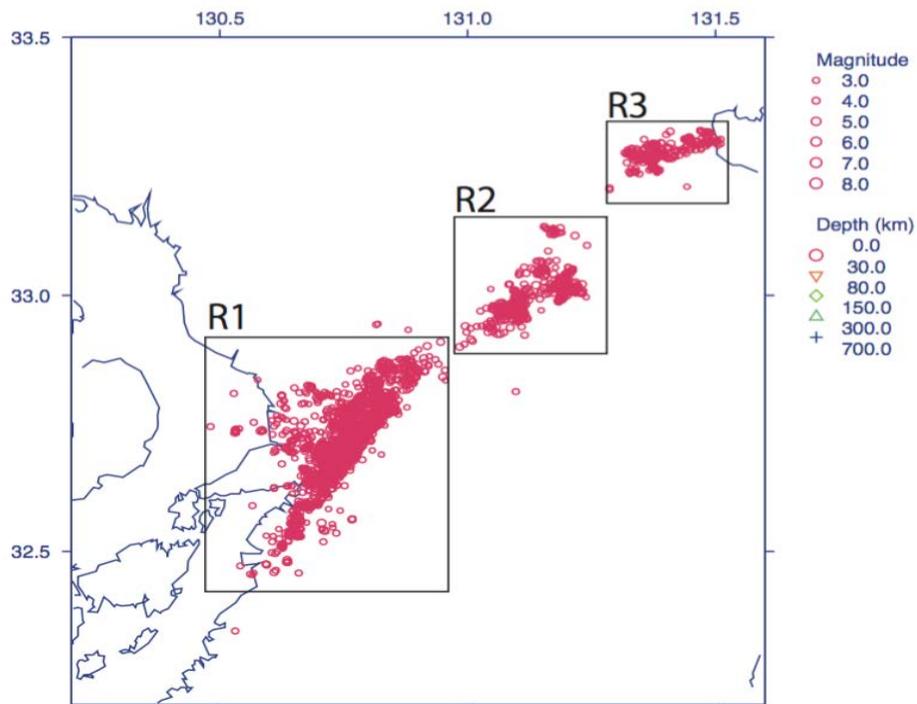
CSEP日本検証センターに提出した階層的時空間ETASモデルによる各記載時刻での発生予測確率



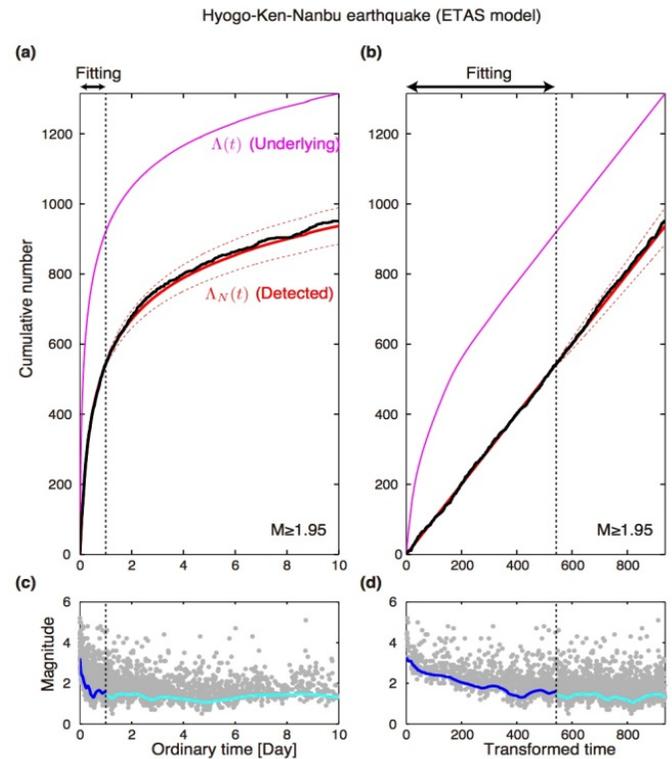
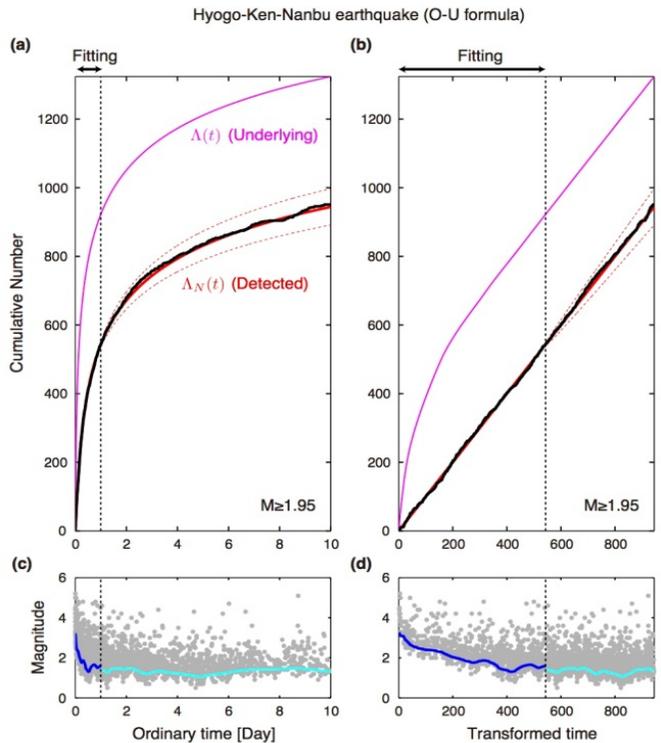
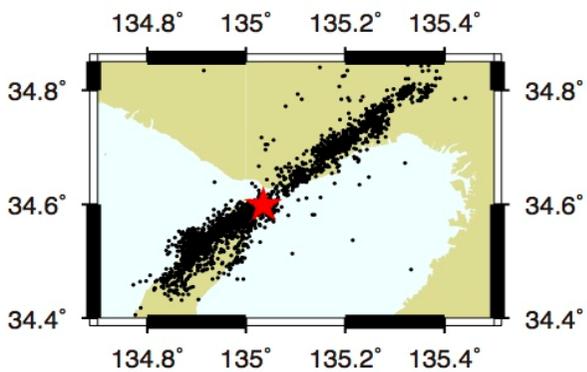


深さ対ETAS変換時間



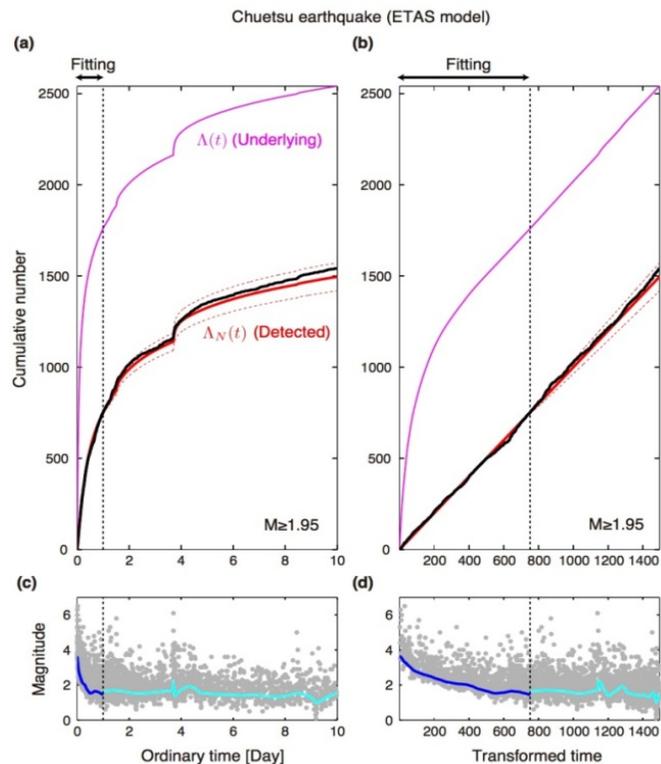
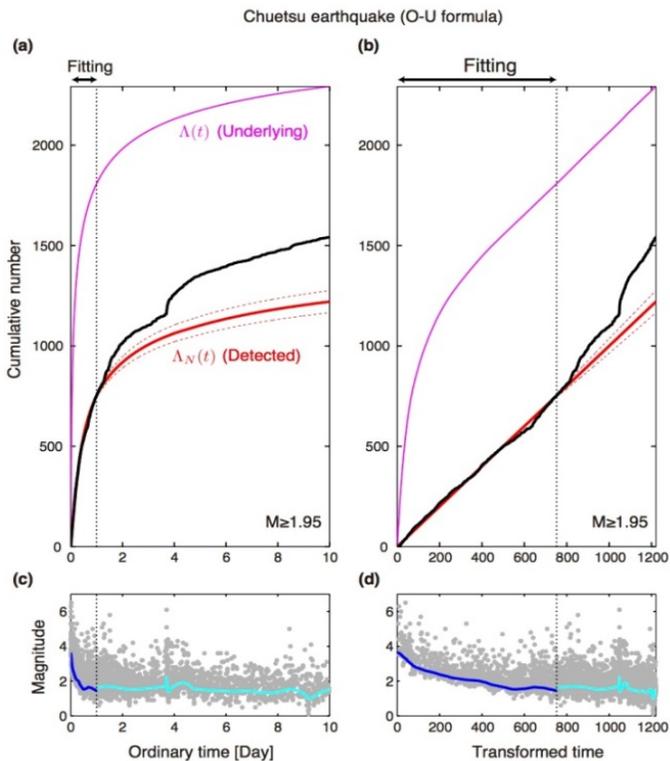
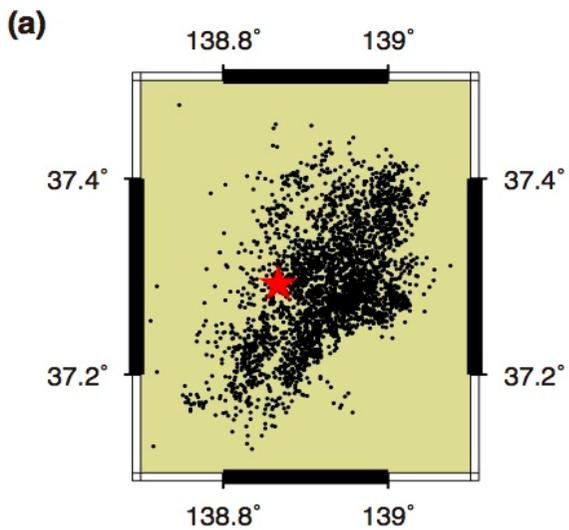


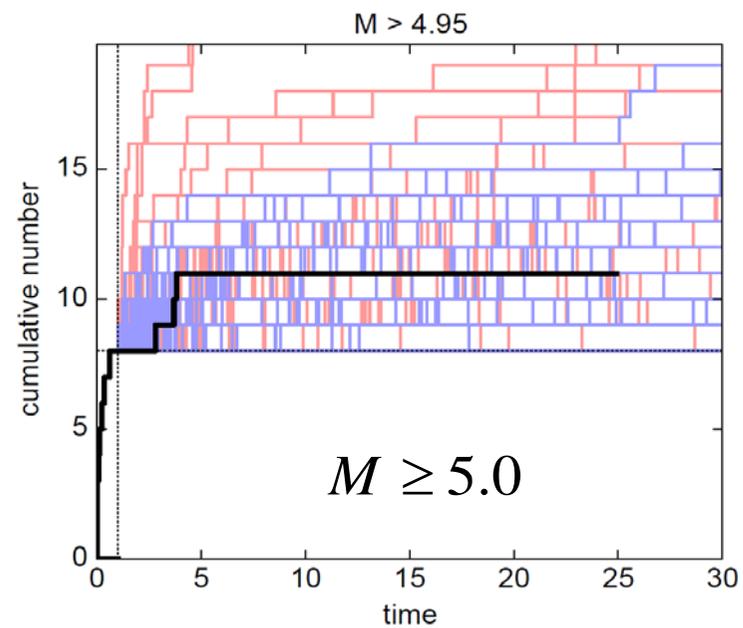
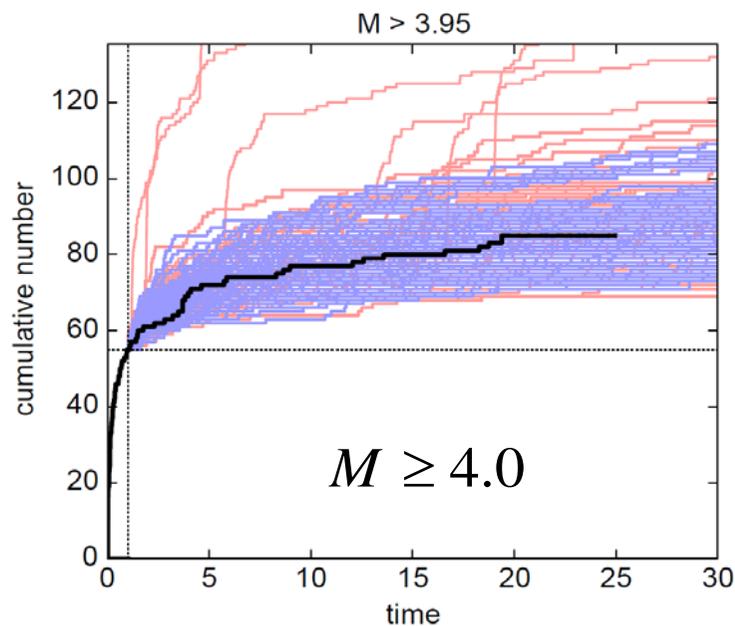
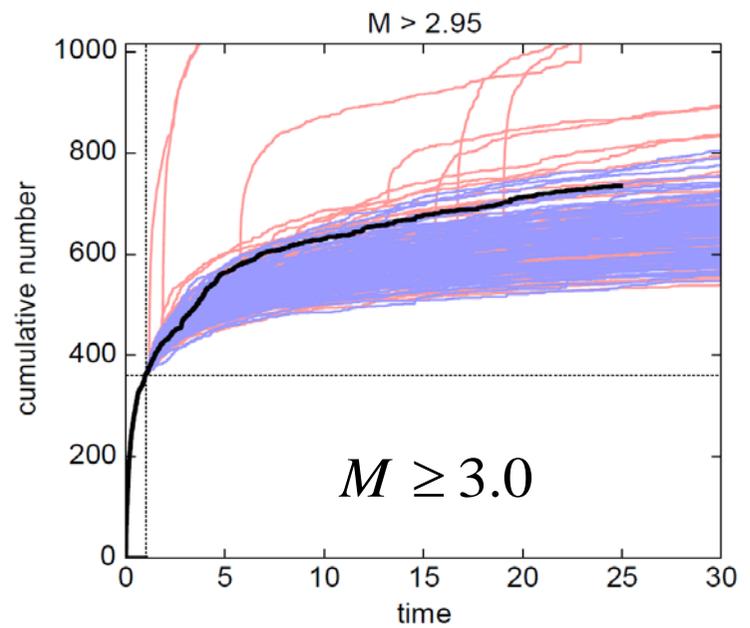
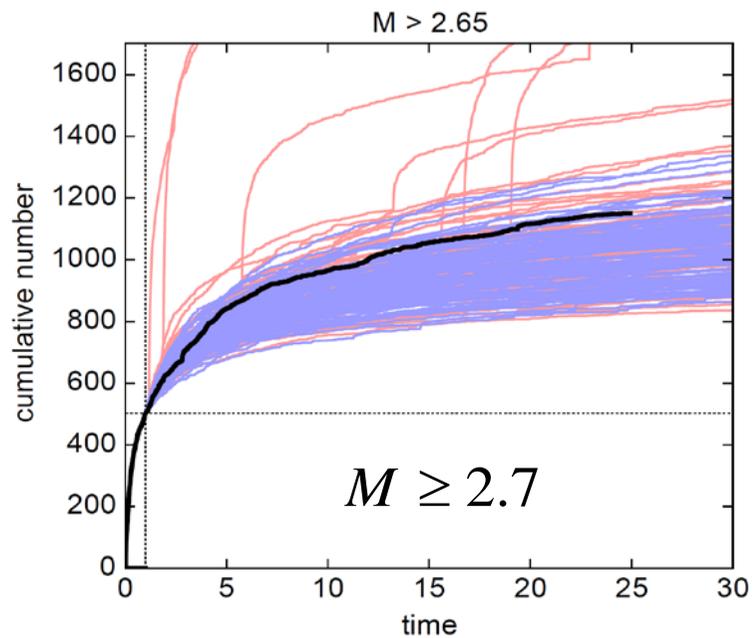
1995年兵庫県南部地震



2004年中越地震

2004 Chuetsu earthquake (M6.8)





M7.3熊本地震の余震頻度の中期予測

本震から1日間のデータを基に30日先までの予測。

右側の赤バーは、95%幅、50%幅、メディアン