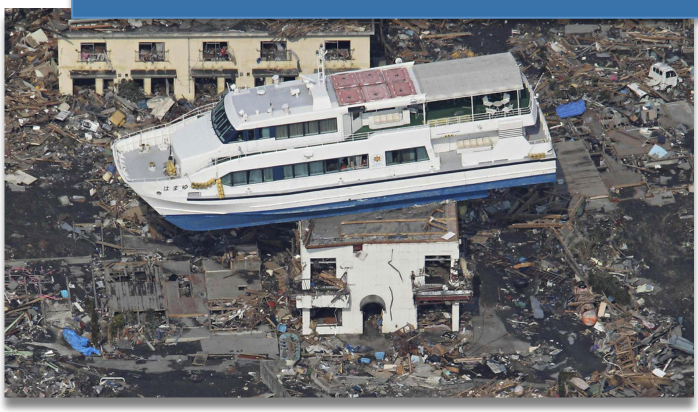
Natural Time Analysis of Seismicity

~ Can we introduce a new idea for seismic catalogue research ? ~



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Application of Natural Time Analysis

- Natural time analysis may be effective to predict a critical point in the time-series of critical phenomena.
  - 2D Ising spin systems
    - Varotsos et al., *Phys. Rev. E*, 2003
  - Superconducting flux avalanche
    - Sarlis et al., *Phys. Rev. B*, 2006
  - Rice pile model
    - Sarlis et al., *Phys. Rev. B*, 2006
  - Large earthquakes
    - Varotsos et al., *Phys. Rev. E*, 2002, 2003, 2006, 2007
    - Uyeda et al., *J. Geophys. Res.*, 2009
  - Heart attack
    - Varotsos et al., *Phys. Rev. E*, 2004, 2005

This week

Heartbeats warn of sudden death risk

DUNCAN GRAHAM-ROWE

HOW do you tell a healthy heart from one that could stop without warning? By measuring variations in the length of the heartbeat, according to a team of researchers in Greece.

The finding could provide a way to screen for people at risk of sudden cardiac death. Such people's heartbeat often looks perfectly healthy by conventional criteria. Yet a quarter of a million people die each year in the US alone when their heart suddenly stops and, like the soccer player Marc-Vivien Foé who collapsed and died last year while playing for Cameroon, many of them have had no history of heart problems.

Even a person's ECG, or electrocardiogram, can look normal for much of the time. In patients with Brugada syndrome, for example, abnormal electrical signals sporadically stop their hearts from pumping properly. Long QT syndrome is a similar condition, which can strike young, fit adults, and has also been linked to cot death.

Standard approaches to analysing ECGs tend to focus on the peaks and troughs of the trace. Instead, Panayiotis Varotsos of the University of Athens has been studying the variation in the length of time it takes for the heart to complete one beat (see Graphic, below).

The amount of variation in the rate of heartbeats is already used to measure aerobic fitness, with more variation meaning a fitter heart. However, for Varotsos the crucial test is the variation in the length of each beat, and whether this variation is random. He adapted equations he had previously used to describe physical systems such as earthquakes to predict that, in a healthy heart, these variations will have some degree of order. But if there is something wrong with the heart, however subtle, it should disrupt that order, making the variation more random.

To test the theory, Varotsos and his colleagues analysed 95 sample ECGs taken from public databases of people with various heart conditions and 10 from healthy patients. He found that the beats of the diseased hearts did indeed vary more randomly and the results are to be published in a future issue of *Physical Review E*. Varotsos says the method could be used as an initial screen to flag up all types of heart problems. "In principle our method should be applied to all causes of cardiac arrest."

"The method could be particularly useful for screening those who have a family history of sudden cardiac death"

Footballer Marc-Vivien Foé died of a cardiac arrest on the pitch last year

A lot of research has gone into discovering ways to identify cardiac diseases from an ECG. Some have used data mining techniques – screening blind for any effect that comes up, while other studies have looked for chaotic signatures that might distinguish unhealthy hearts from healthy ones (*New Scientist*, 3 January 1998, p 20).

But so far no method has stood up to scrutiny in clinical trials, says Arun Holden, a computational biologist at the University of Leeds, UK. Varotsos believes his discovery has a better chance of turning out to be real because he used a physical model of how the heart works to predict a specific effect.

However, as Tim Bowker of the British Heart Foundation points out, there is no way of knowing more about the patients whose ECGs were used in the database. "Without knowing this, one doesn't know that it applies to any group other than these 105," he says. So the jury will remain out until the method is tested to see if it is able to predict cardiac health.

If it proves reliable, the method could be particularly useful for screening those who have a family history of sudden cardiac death. In the UK, about 3500 people die from this syndrome each year. This may not be enough to give rise to a nationwide screening programme.

Instead, Varotsos suggests that cardiologists could apply his method to Holter monitors – the portable ECG devices that are used to monitor patients thought to be at risk.

HEART ATTACK WARNING?

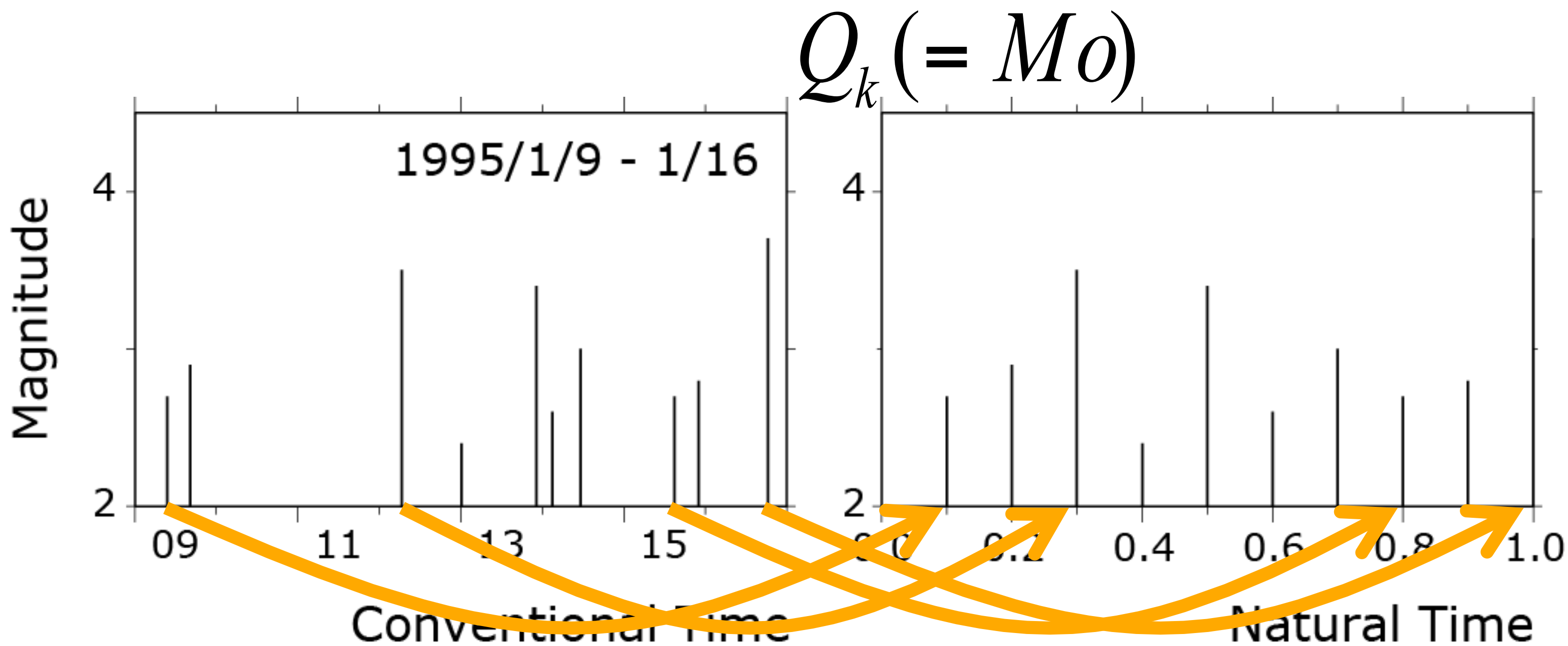
Varotsos and colleagues studied ECG traces and found that the more random the variation in Q-T interval, the higher the risk of sudden cardiac death

P – Atrial depolarisation: top chambers contract QRS – Ventricular depolarisation: larger, lower chambers contract
ST – Ventricular repolarisation: cells in the lower chambers recharge, in preparation for the next contraction

www.newscientist.com

(New Scientist, 2004)

Natural Time (NT)



$$\chi_k = \frac{k}{N}$$

k : k th event

N : total number of events

(Varotsos, Is time continuous ?, submitted to *Phys. Rev. Lett.*, 2011)

EOS VOLUME 89 NUMBER 39 23 SEPTEMBER 2008

NEWS

SES on Jan. 14, 2008

Greek Newspaper reported imminent M>6 EQ, on Feb. 10, based on Van's NT Criticality analysis on Seismic catalog.

Two EQs >6.9, 6.2 on Feb.14, 2008.

when a dynamic system (i.e., a system evolving with time) exhibits behavior similar to a phase change [*Varotsos et al.*, 2008, and references therein]. On the hypothesis that the main shock earthquake is a critical phenomenon, when SES activity is observed, natural time analysis is conducted on the seismicities of small earthquakes in the suspected future epicentral area solely by considering their order of occurrence and the energy emitted by each of them. The term natural time analysis stems from the disregard of the conventional time of the earthquakes' occurrence. It has been found that such an analysis enables the identification of the time of the main shock usually within a few days before it occurs (see P. Varotsos et al., Seismic electric signals and 1/f "noise" in natural time, at http://arxiv.org/abs/0711.3766).

On 14 February 2008, a large earthquake (U.S. Geological Survey M=6.9) and its probable aftershock (M=6.2) occurred in the Ionian Sea close to the region of southwest-

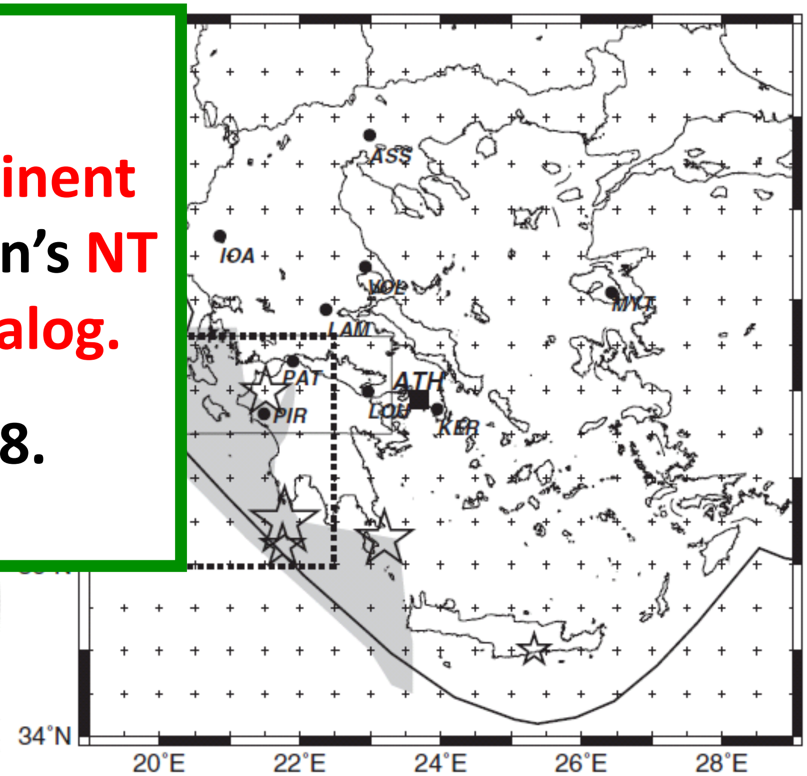
area. The first one, the largest in Greece since 1983, was also felt in some adjacent countries. This was a case where prediction by the VAN method was documented in a scientific publication as well as in the public media well before the main shock occurred.

References

Varotsos, P. (2005), *The Physics of Seismic Electric Signals*, TerraPub, Tokyo.

Varotsos, P. A., N. V. Sarlis, E. S. Skordas, and M. S. Lazaridou (2008), Fluctuations, under time reversal, of the natural time and the entropy distinguish similar looking electric signals of different dynamics, *J. Appl. Phys.*, *103*, 014906, doi:10.1063/1.2827363.

—SEIYA UYEDA, Earthquake Prediction Research Center, Tokai University, Tokyo, Japan; and MASASHI KAMOGAWA, Department of Physics, Tokyo Gakugei University, Tokyo, Japan; E-mail: kamogawa@u-gakugei.ac.jp



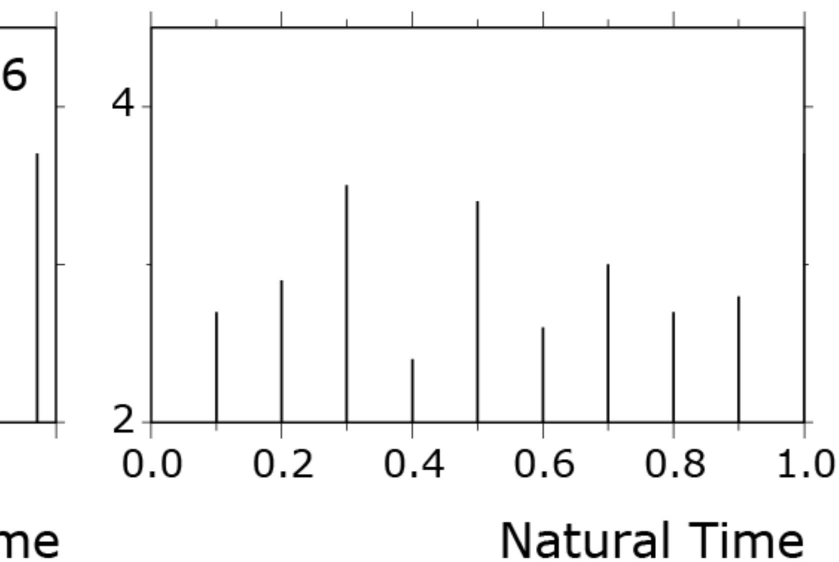
Uyeda & Kamogawa, Eos, 89, (2008)

Uyeda & Kamogawa, Eos, 91 (2010)

Critical Point of EQs

$$\kappa_1 = \sum_{k=1}^{N} p_k \chi_k{}^2 - \left(\sum_{k=1}^{N} p_k \chi_k \right)^2 \equiv \langle \chi^2 \rangle - \langle \chi \rangle^2$$

where, $p_k = Q_k \Big/ \sum_{n=1}^{N} Q_n$



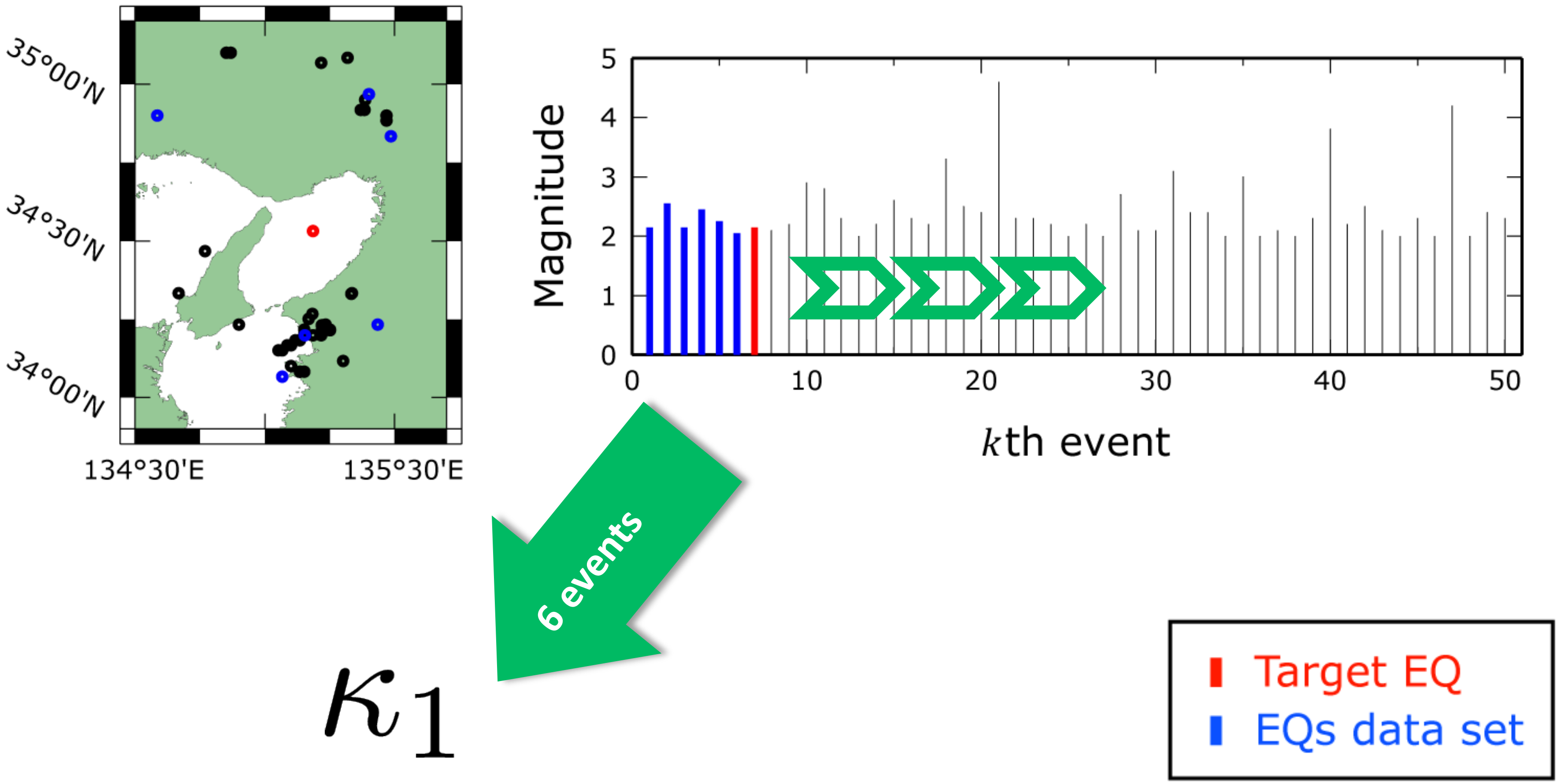
At criticality:

$$\kappa_1 \Rightarrow 0.07$$

(see Varotsos et al., PNAS, 2011)

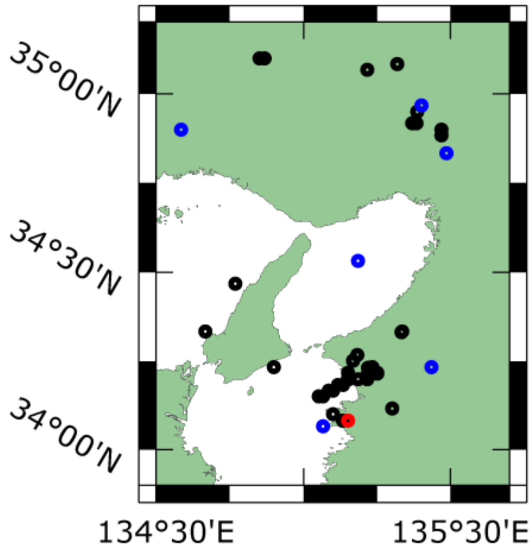
Statistical property of seismicity in NT

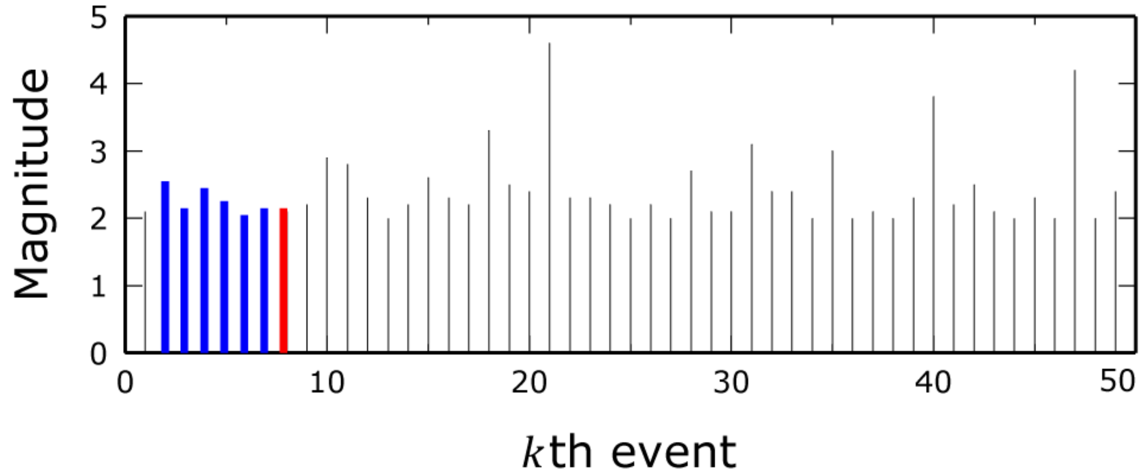
Distribution of κ_1 in seismicity



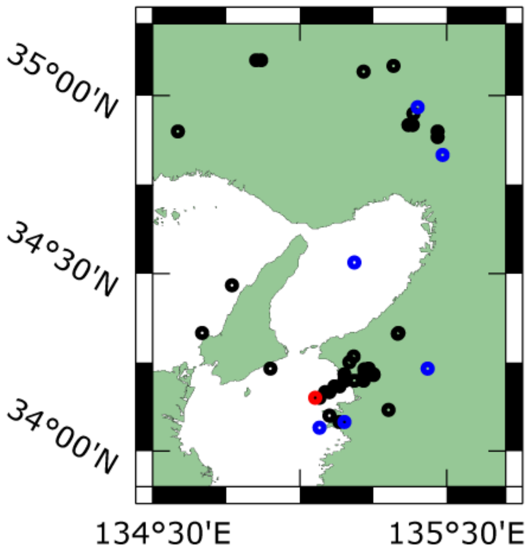
(See Varotsos et al., *PRE.*, 2005)

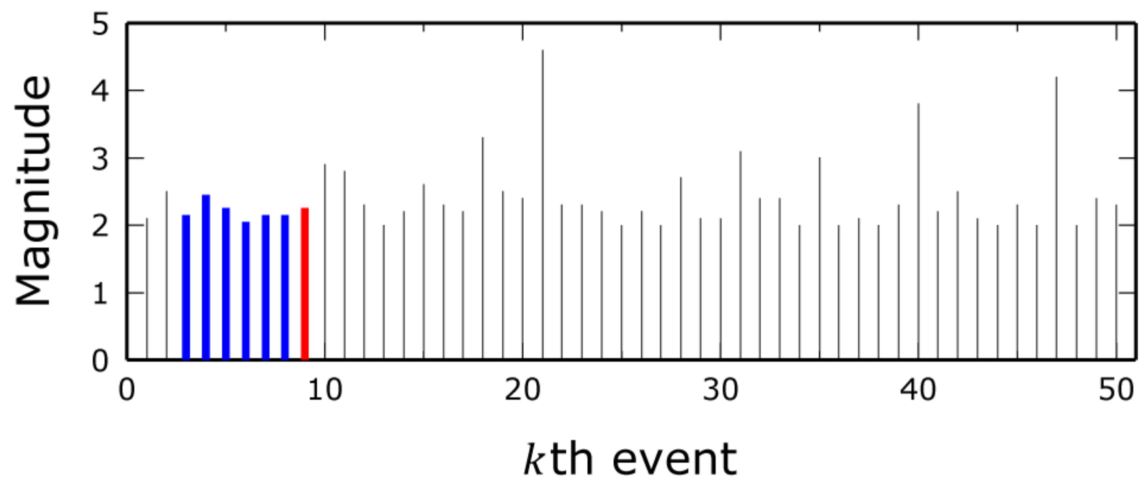
Next data set



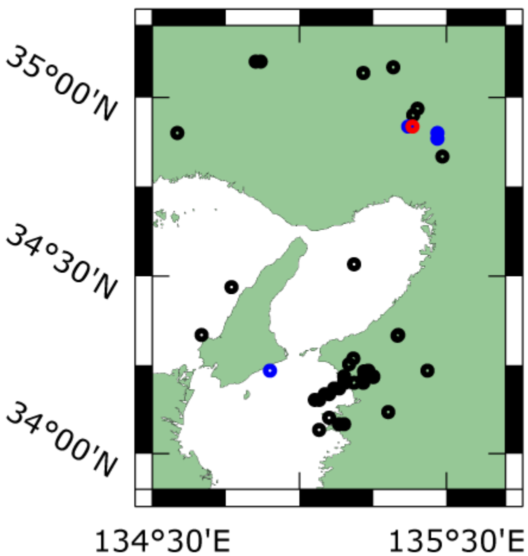


Running

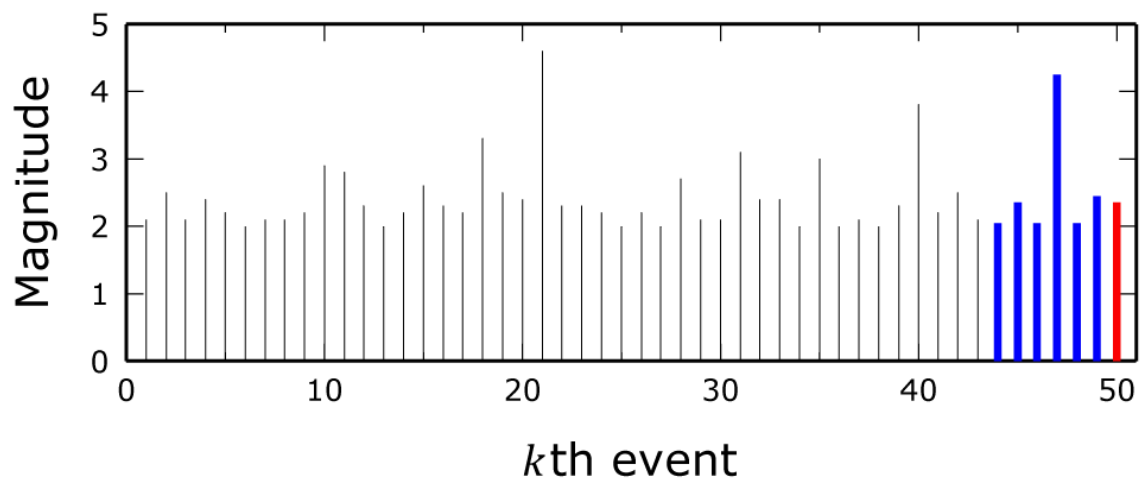

35°00'N
34°30'N
34°00'N
134°30'E
135°30'E


Magnitude
kth event
0
1
2
3
4
5
10
20
30
40
50

Last one



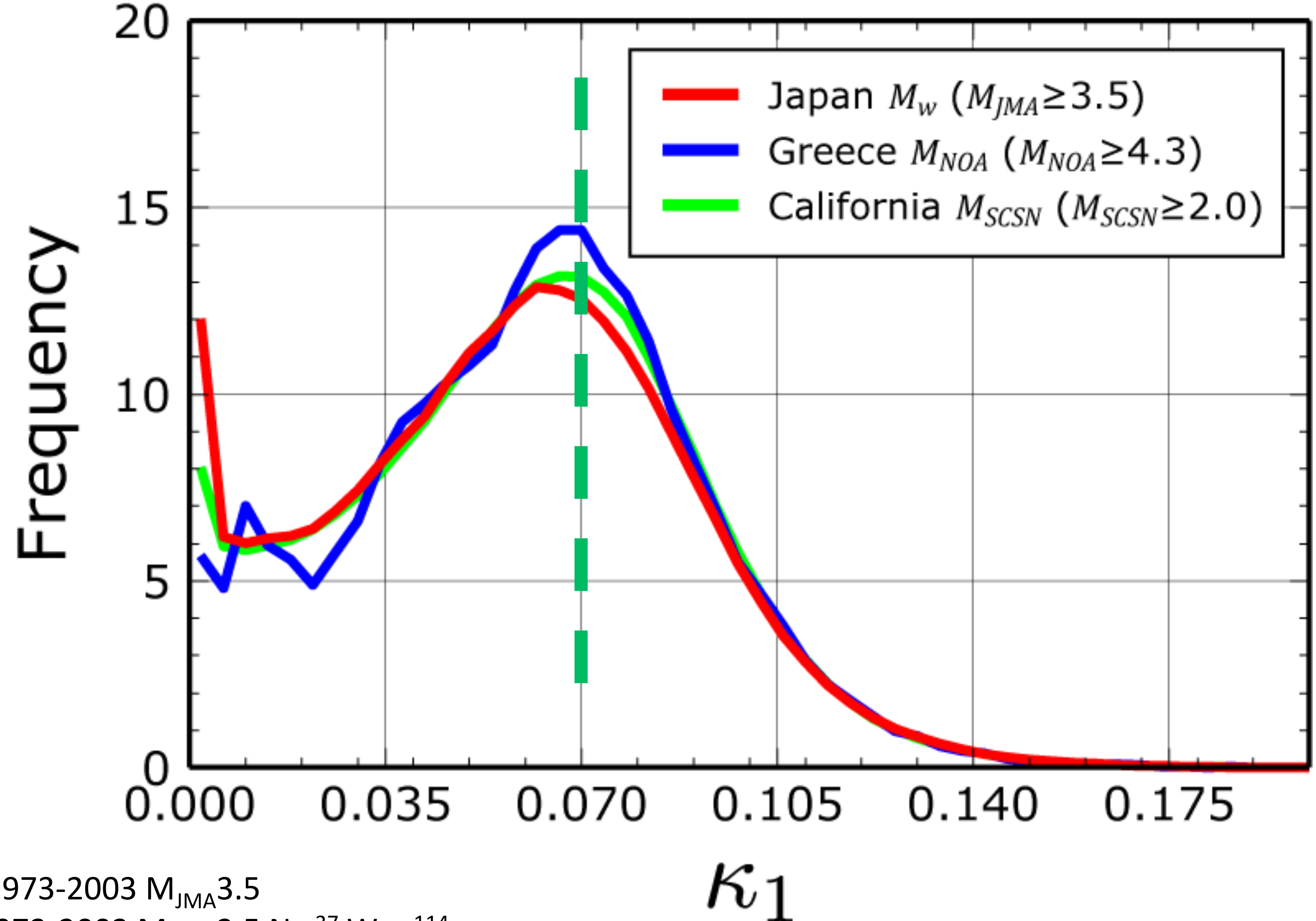
35°00'N
34°30'N
34°00'N
134°30'E
135°30'E



Magnitude
5
4
3
2
1
0
0
10
20
30
40
50
kth event

Spatial comparison

(modified analysis of Tanaka, et al., JA, 2005)



Japan: 1973-2003 M_{JMA}3.5
SCSN: 1973-2003 M_{SCSN}2.5 N_{32}^{37} W_{122}^{114}

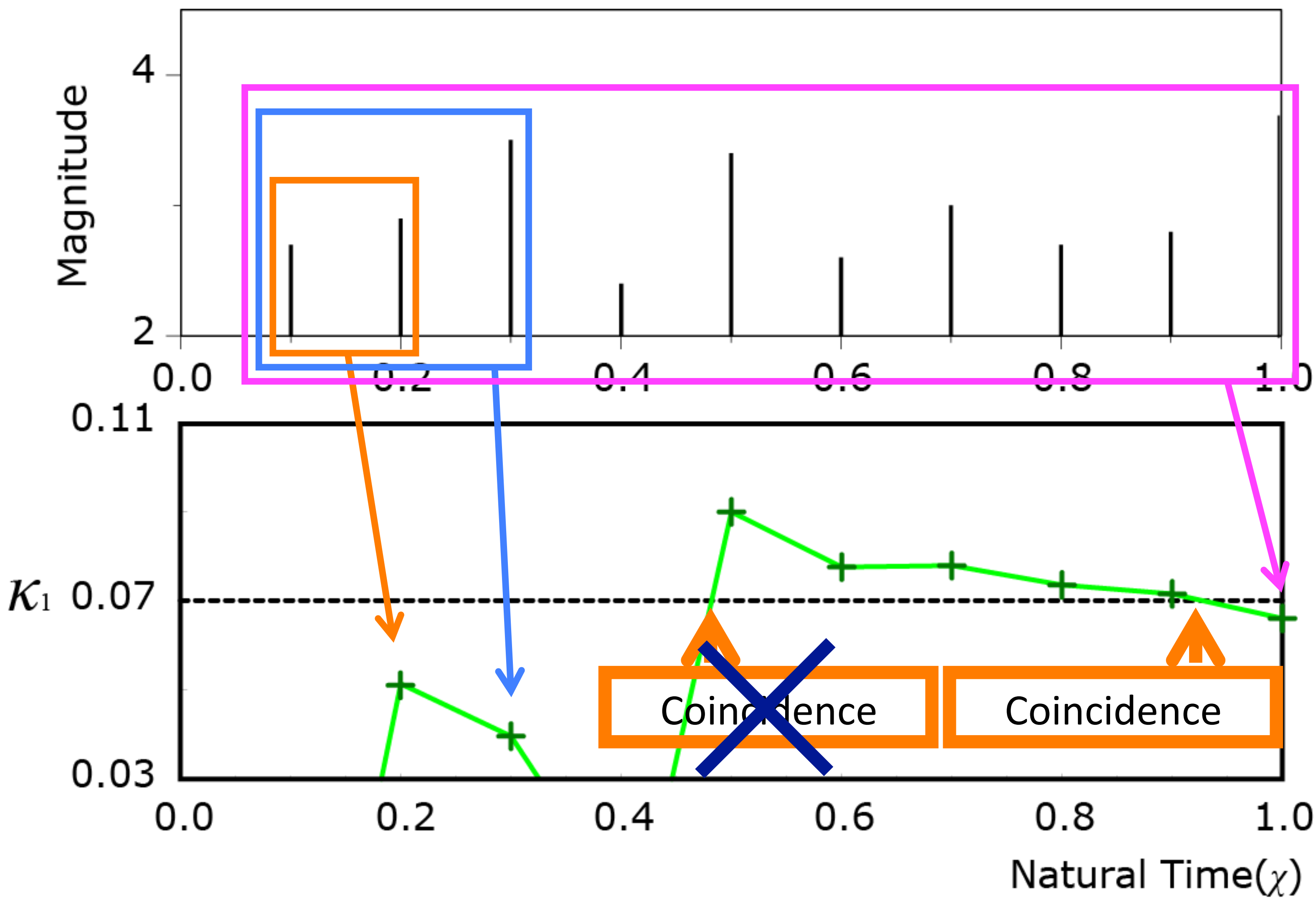
Ansatz for detection of critical point in NT analysis

- Quantity considered must have power-law distribution (e.g. Freq. vs. Mag.).

- Variance of normalized time weighted by normalized quantity of events converge to 0.07.

- Natural time-series indicating 0.07 must be scale free in time and space.

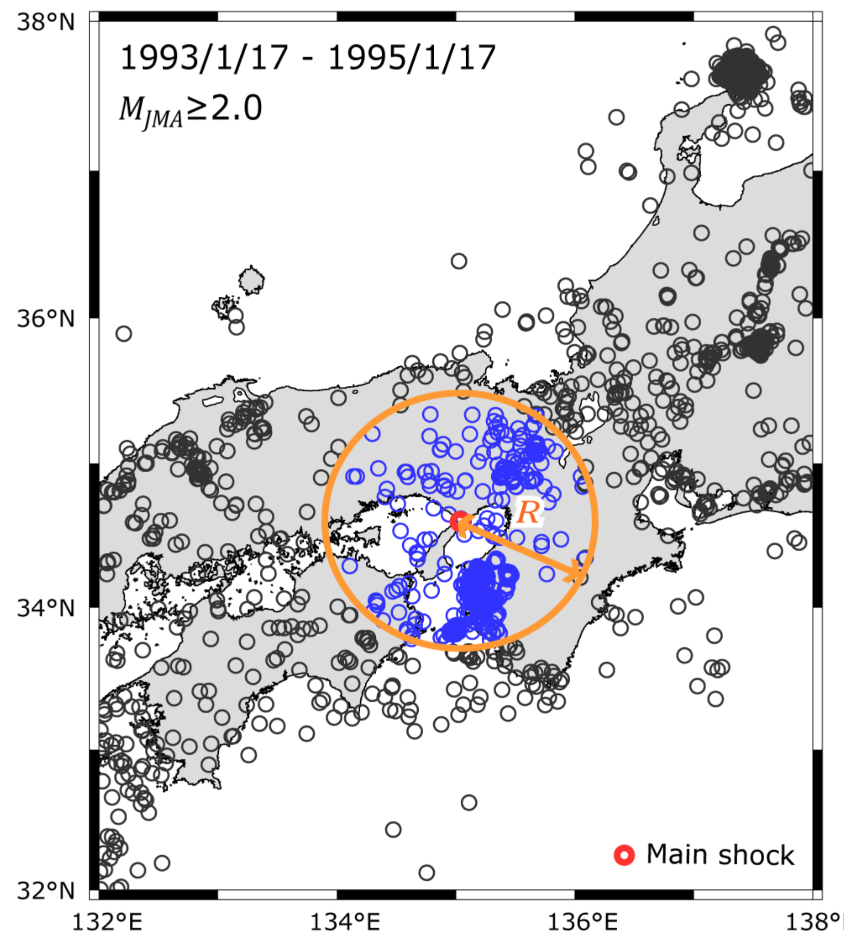
Time-series of κ_1

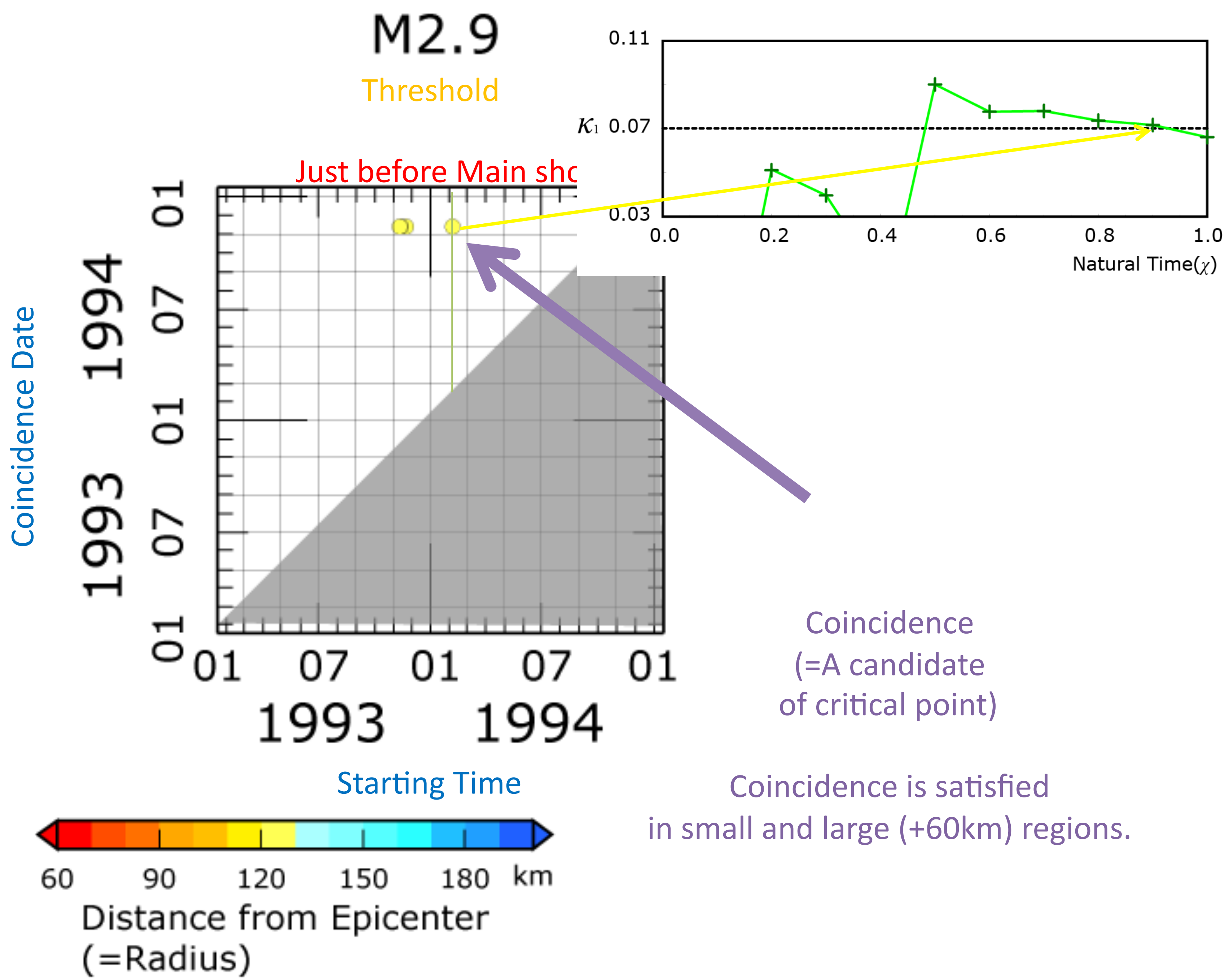


Natural time analysis for Large EQs

- Starting date
  - » From 2 years before Large EQs
- Thresholds magnitude
  - » M0.1 step
- Area
  - » 60km → 200km (10km step)

1995 South Hyogo Prefecture EQ (M_{JMA}7.3)

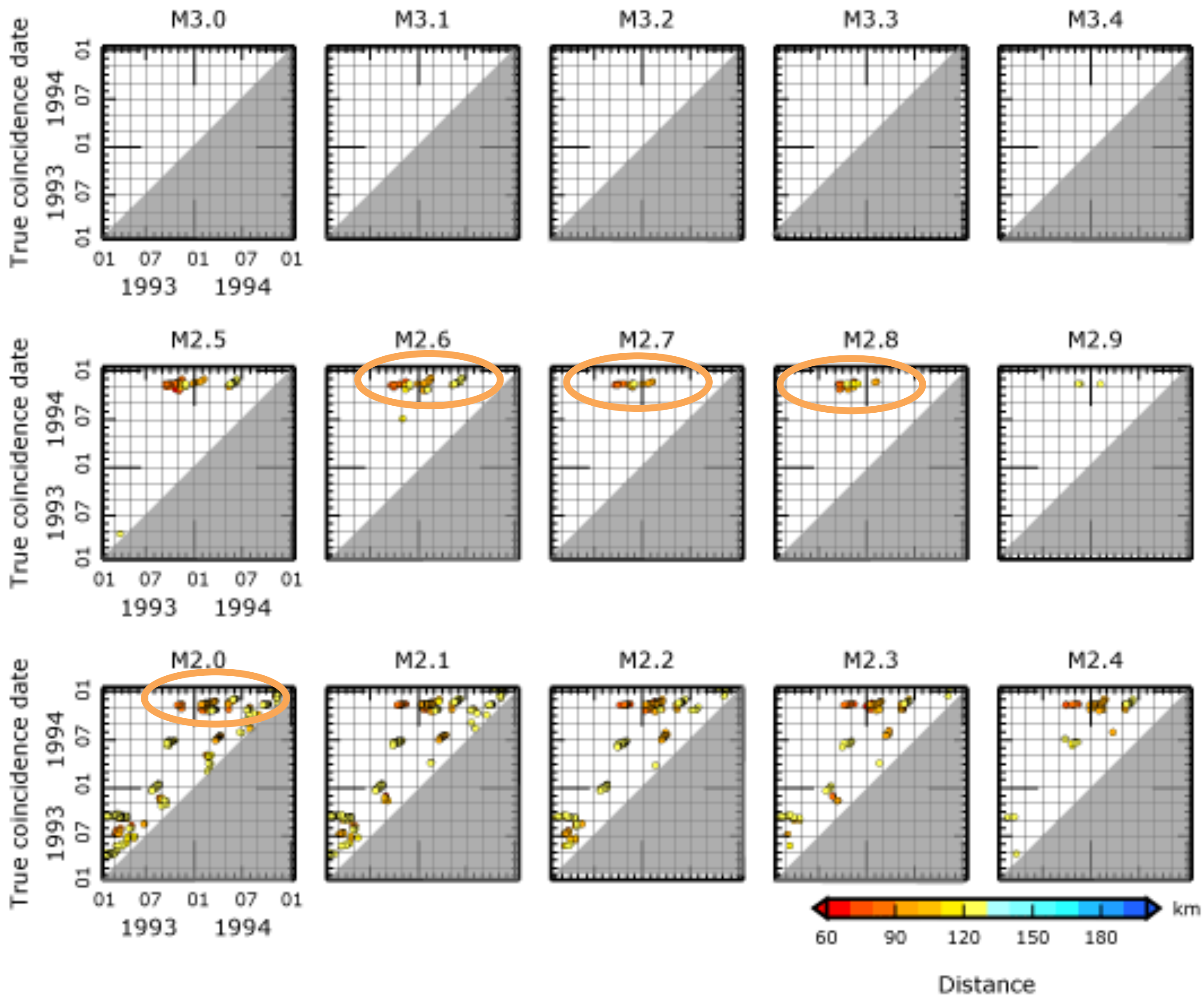




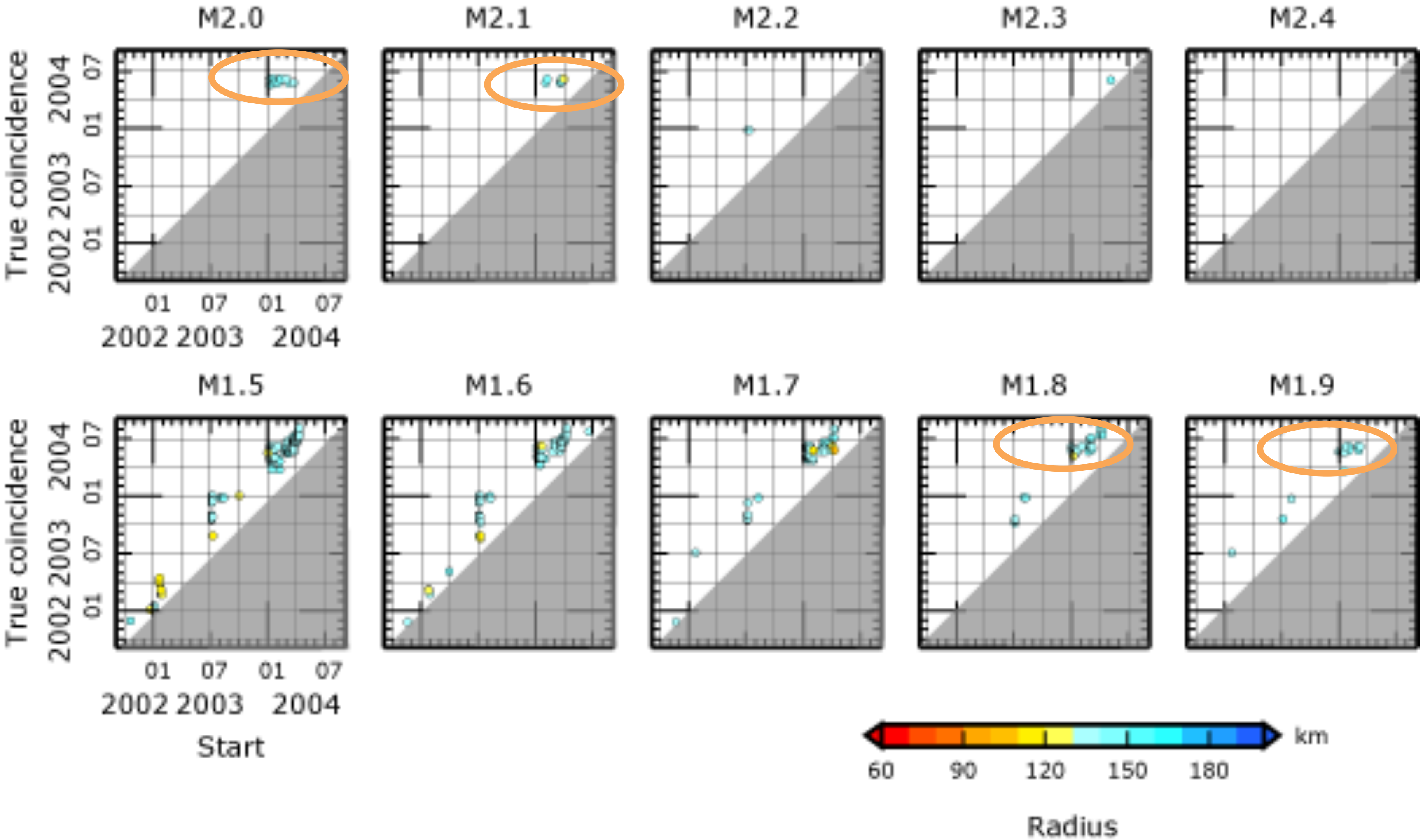
Coincidence
(=A candidate
of critical point)

Coincidence is satisfied
in small and large (+60km) regions.

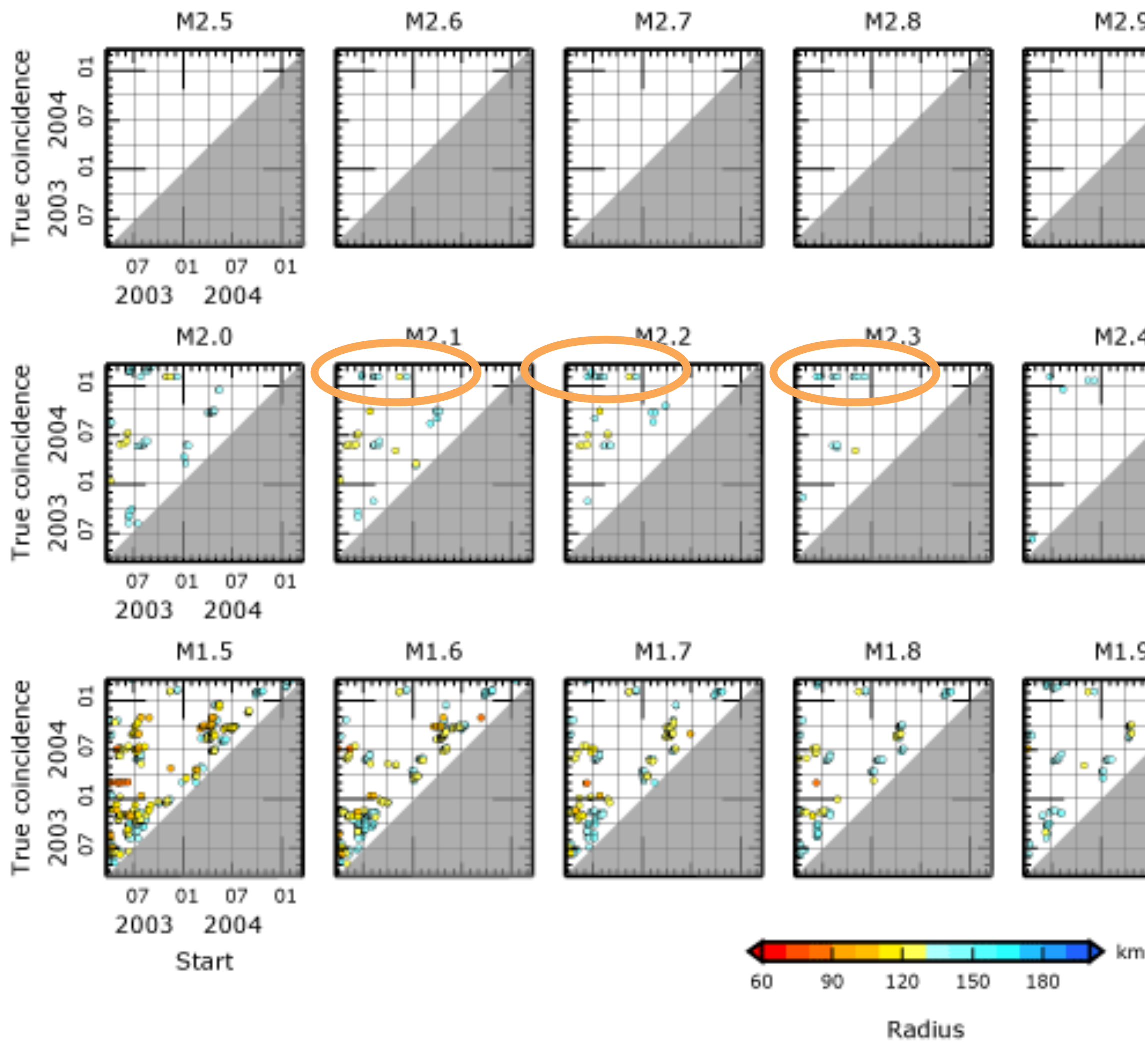
1995 M7.3 Kobe



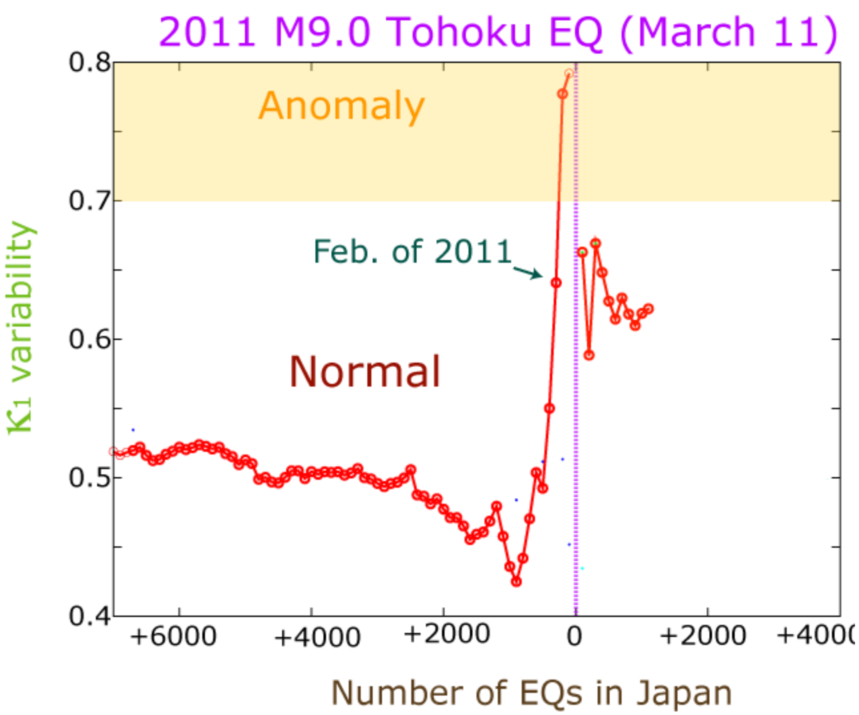
2004 M7.1 Off Kii Peninsula

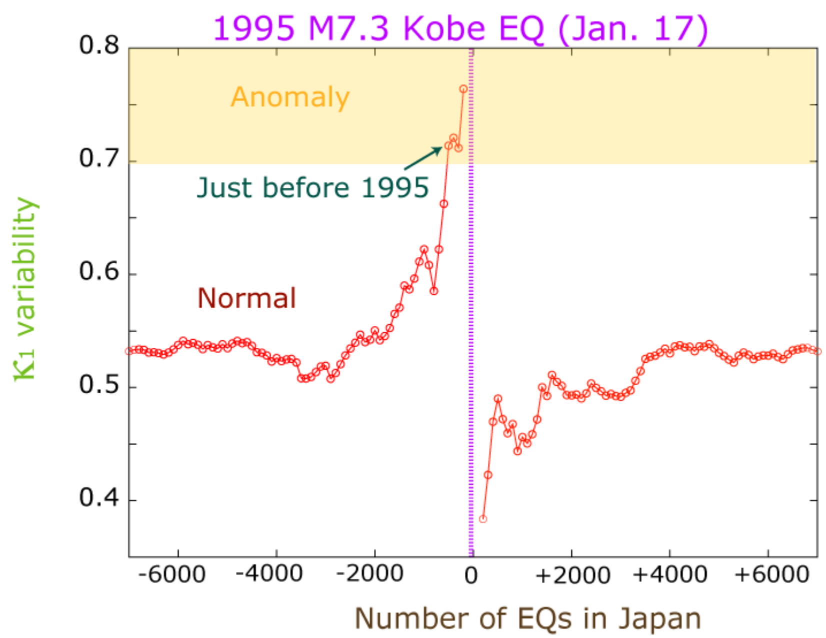


2005 M7.0 West-off Fukuoka



Fluctuation of k1 distribution before large EQs





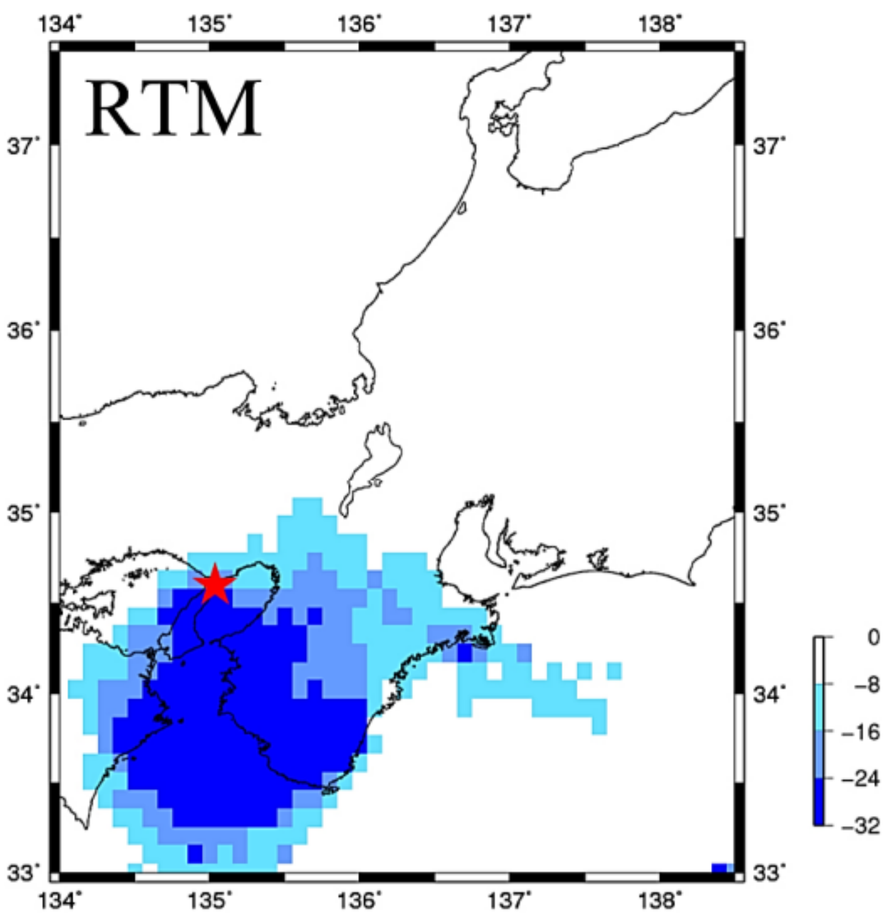
Varotsos et al.,
submitted to Phys. Rev. Lett. (2011)

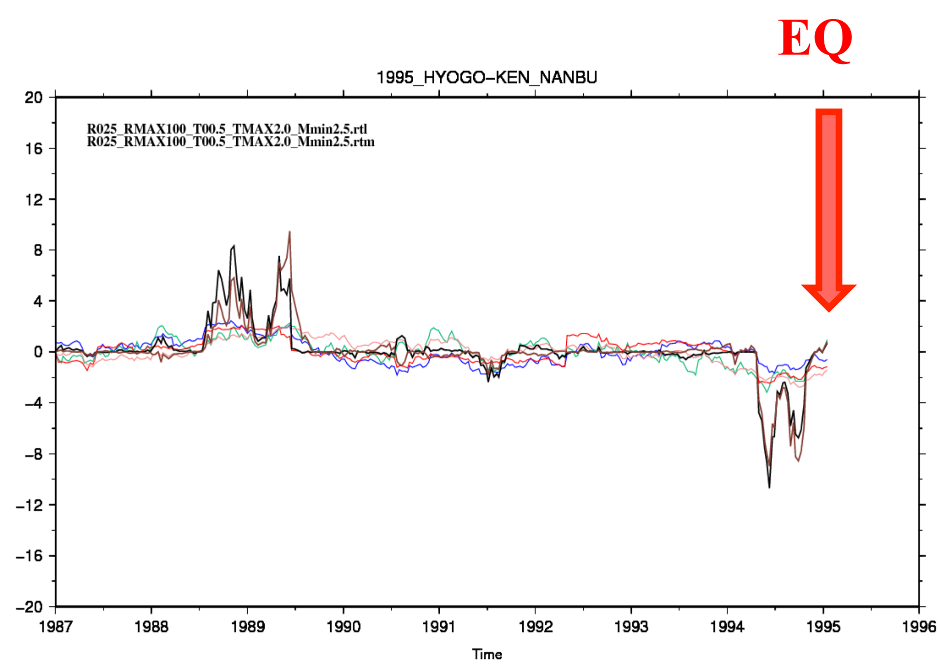
- What physical hypotheses about earthquake predictability have motivated your research?
- What evidence can be used to support or reject these hypotheses?
- What data are used? What is the spatial and temporal extent of the data? How often are there gaps in the data? What uncertainties exist in the data? Are there authoritative data sources and are they openly available?
- How is “noise” (ambient or sensor-generated) treated in the data collection and analysis process?
- Have earthquake-forecasting models that incorporate these hypotheses been formulated? Is the model under development or ready for retrospective or prospective testing? Are these models automated such that they could be submitted for independent evaluation? Are there parameters (e.g. time, space, and magnitude windows, thresholds when forecasts are made) that still need to be determined?
- Is there corroborating evidence within a forecast (e.g. Is this forecast made based on 1 indicator or multiple indicators)?
- Under which circumstances have the forecasting models been tested Retrospectively? Prospectively?
- What are the statistical results of formal testing (e.g., false-alarm and failure-to-predict error rates, skill scores, or relative information/probability gain)?
- Is currently significant information from this research ready for “operational” earthquake forecasting? What is the scale of the forecast elements (e.g. Time, Location, Magnitude, depth, probability) and what weight is placed on each.
- What are next steps for moving towards the use of this information in earthquake forecasting?
- What are the next steps for improving our understanding of the physical hypotheses?

RTM method

Toshiyasu Nagao
(Tokai Univ.)

RTM method in 1995 M7.2 Kobe EQ, Japan (see Nagao et al., EPS, 2010)

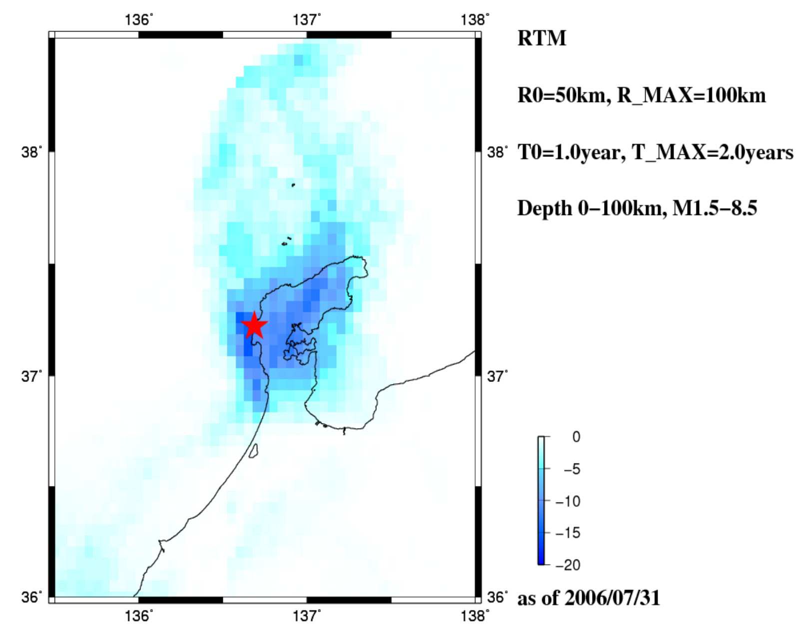


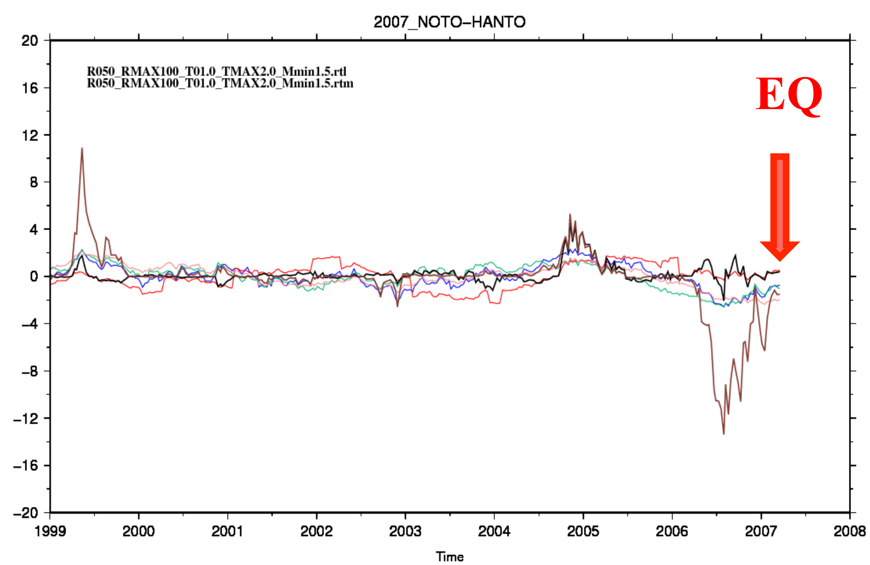


(Nagao et al, EPS, 2010)

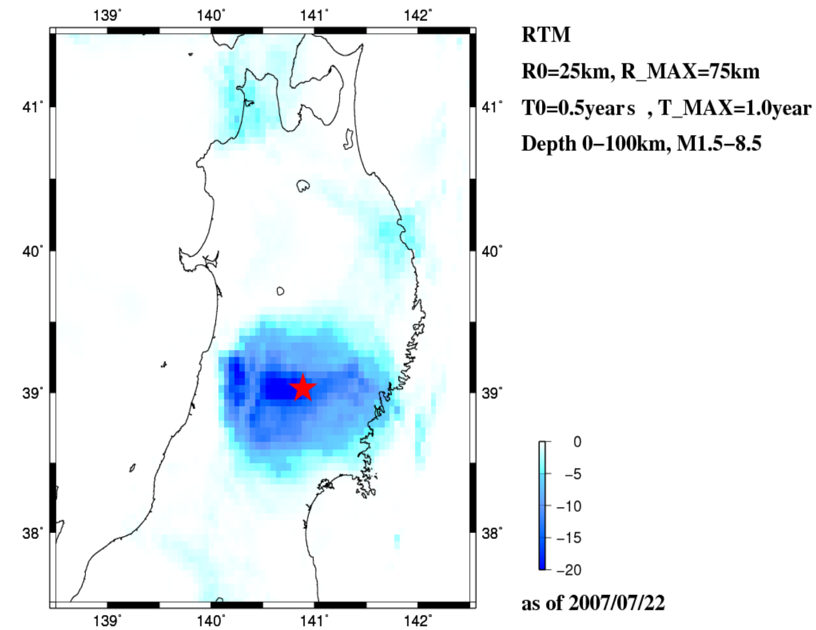
Other examples

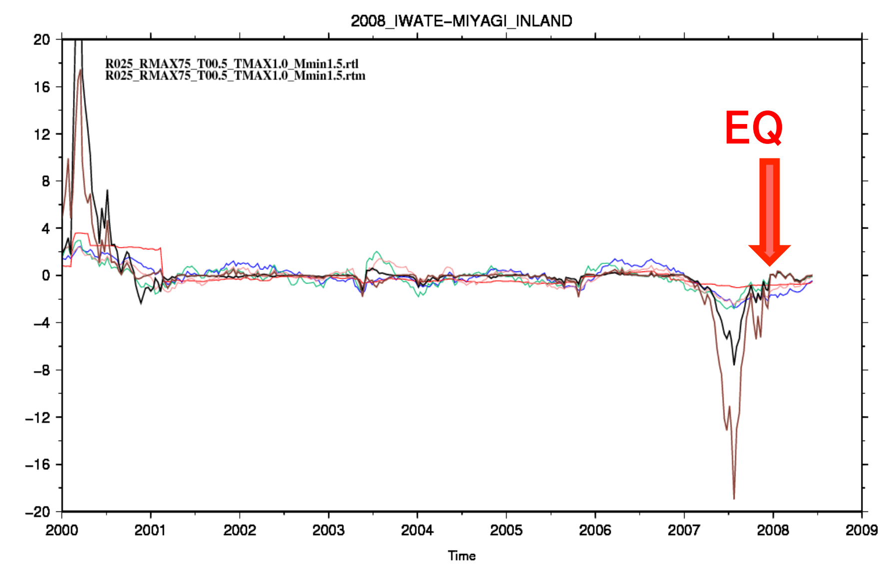
2007 M6.9 Noto peninsula in Japan

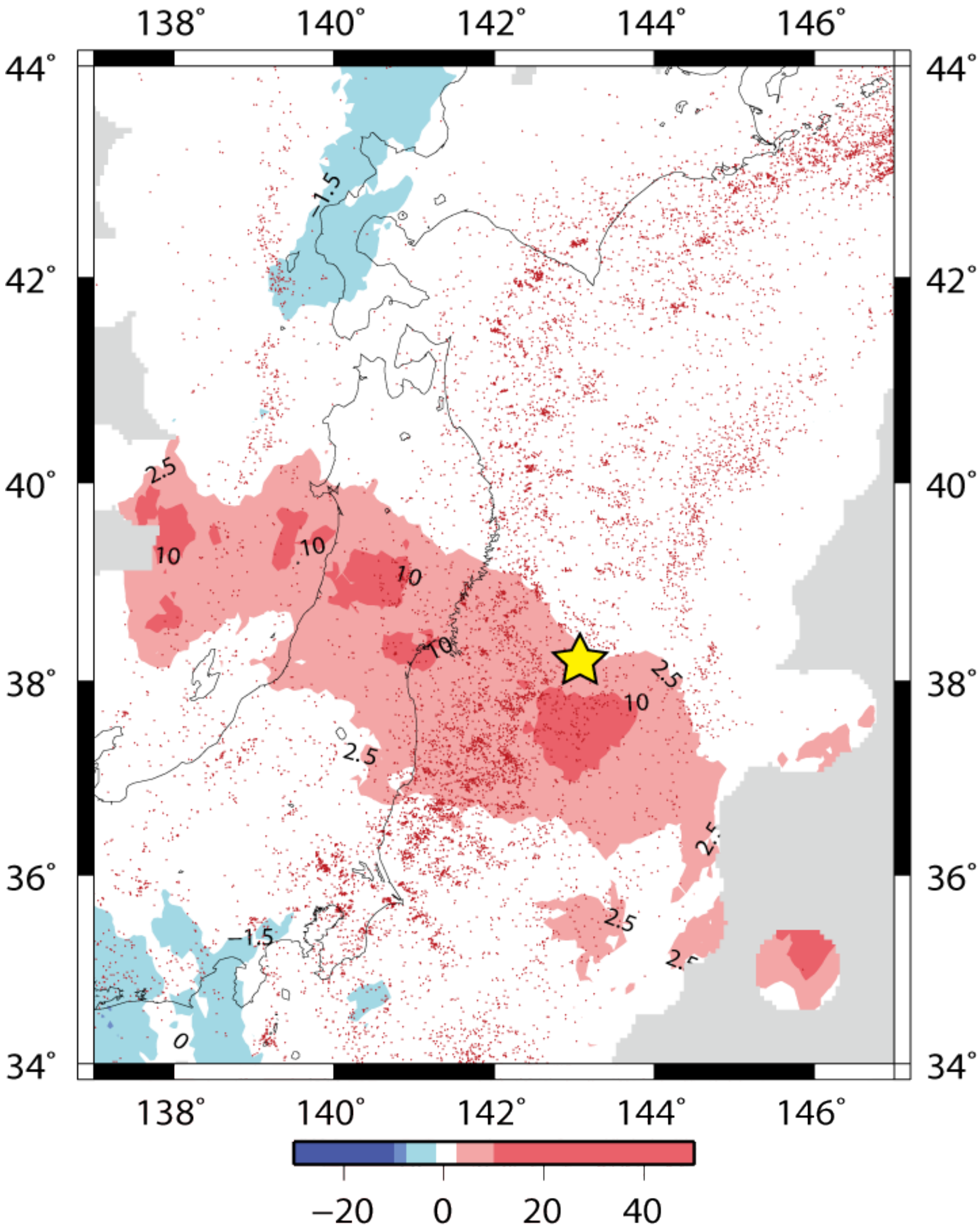




2008 M7.2 Iwate-Miyagi Inland EQ



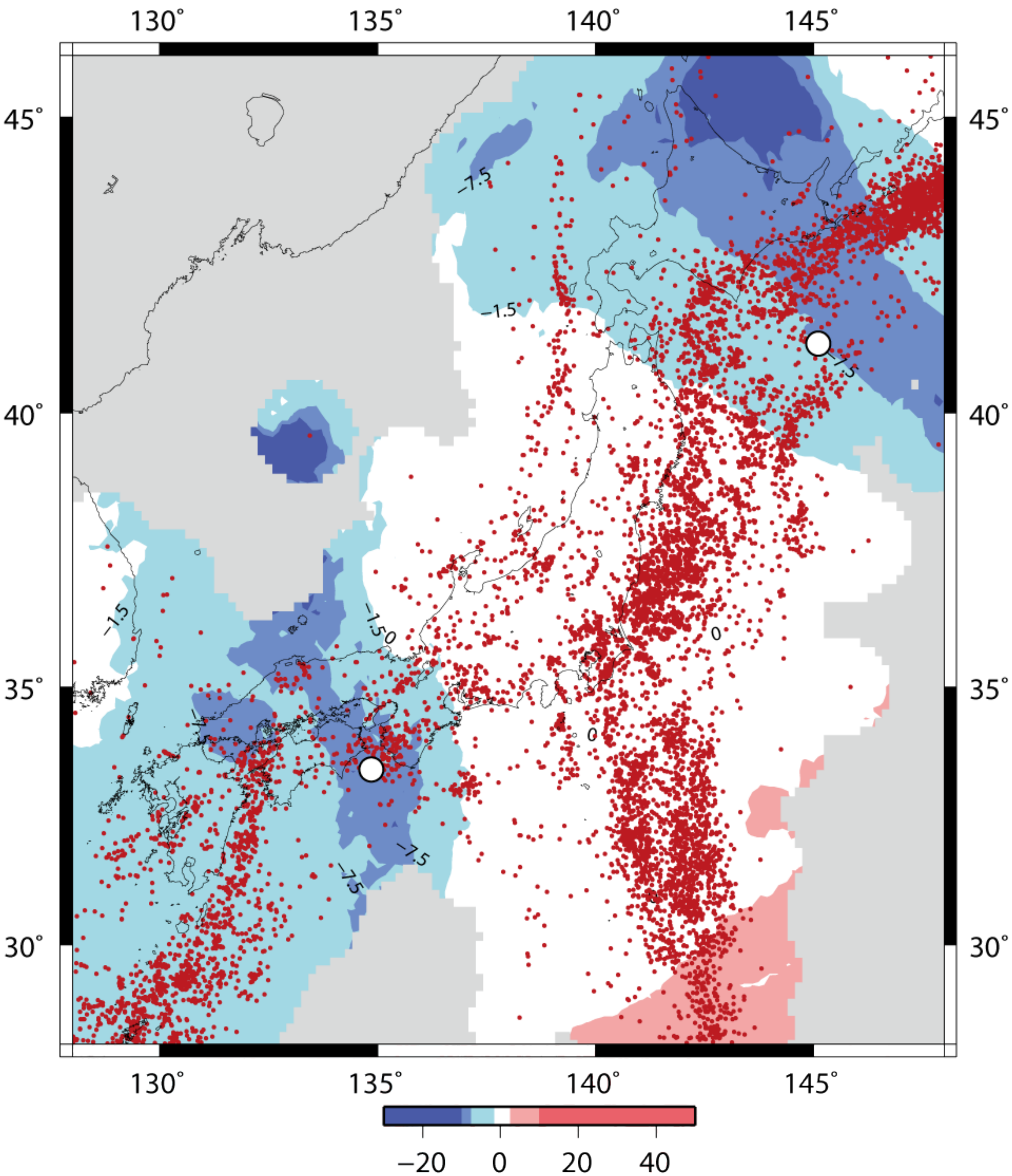




Anomalous RTM value before 2011 Tohoku EQ

(Activation near epicenter and quiescence around epicenter)

Gray: No evaluation region due to no seismic data

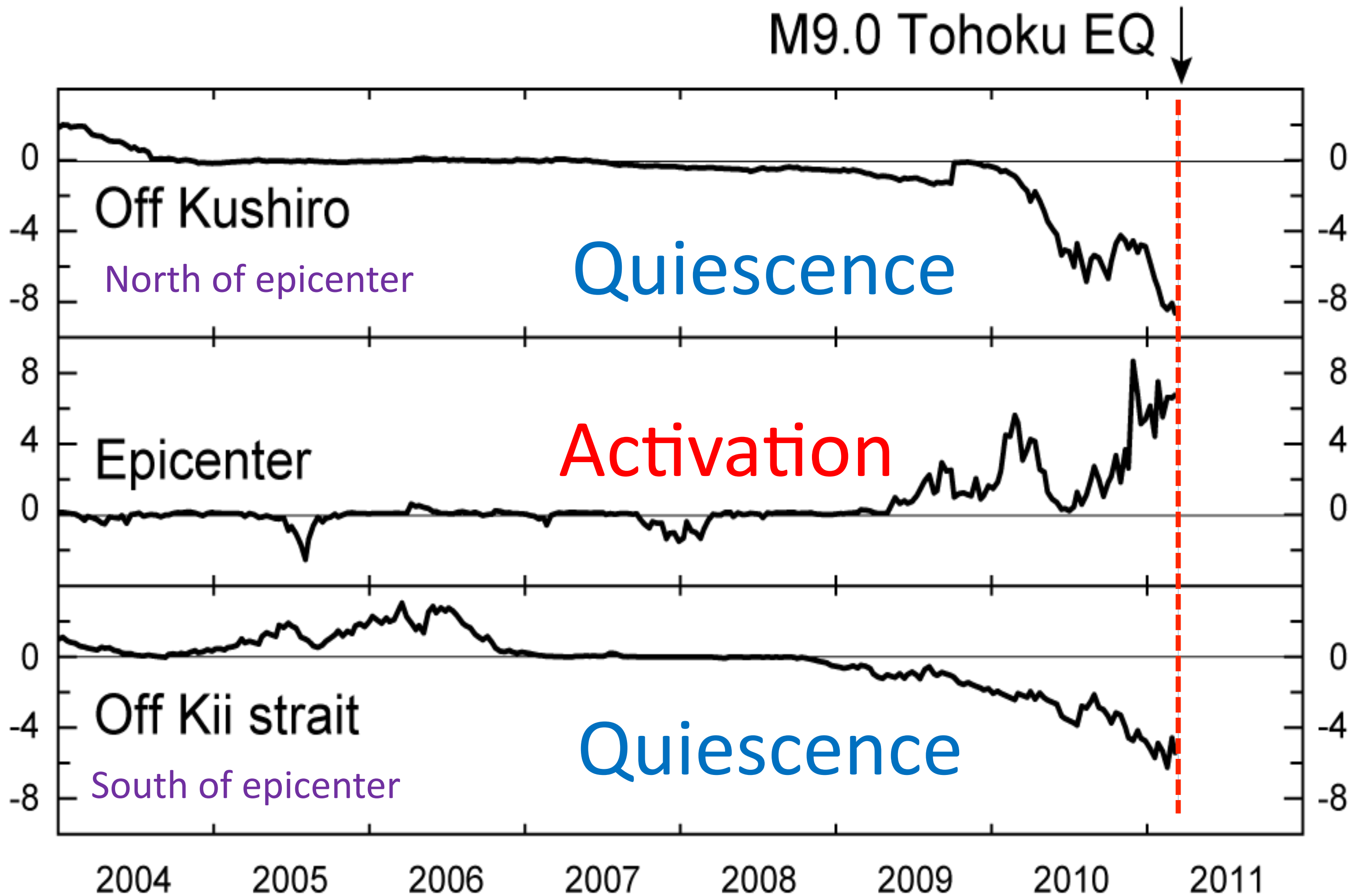


Anomalous RTM value before 2011 Tohoku EQ

(Activation near epicenter and quiescence around epicenter)

Gray: No evaluation region due to no seismic data

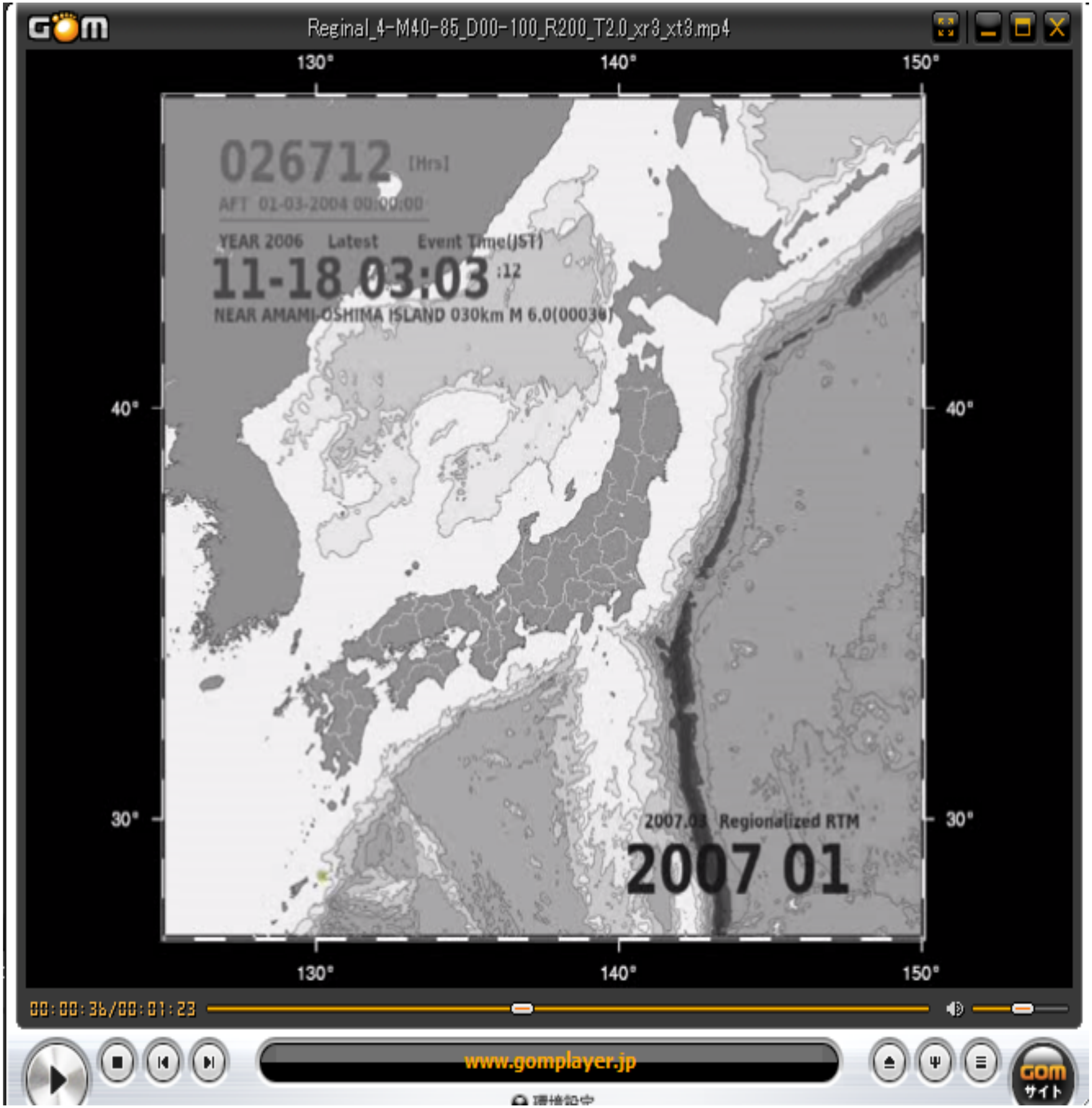
Time-series of RTM in 2011 M9.0 Tohoku EQ



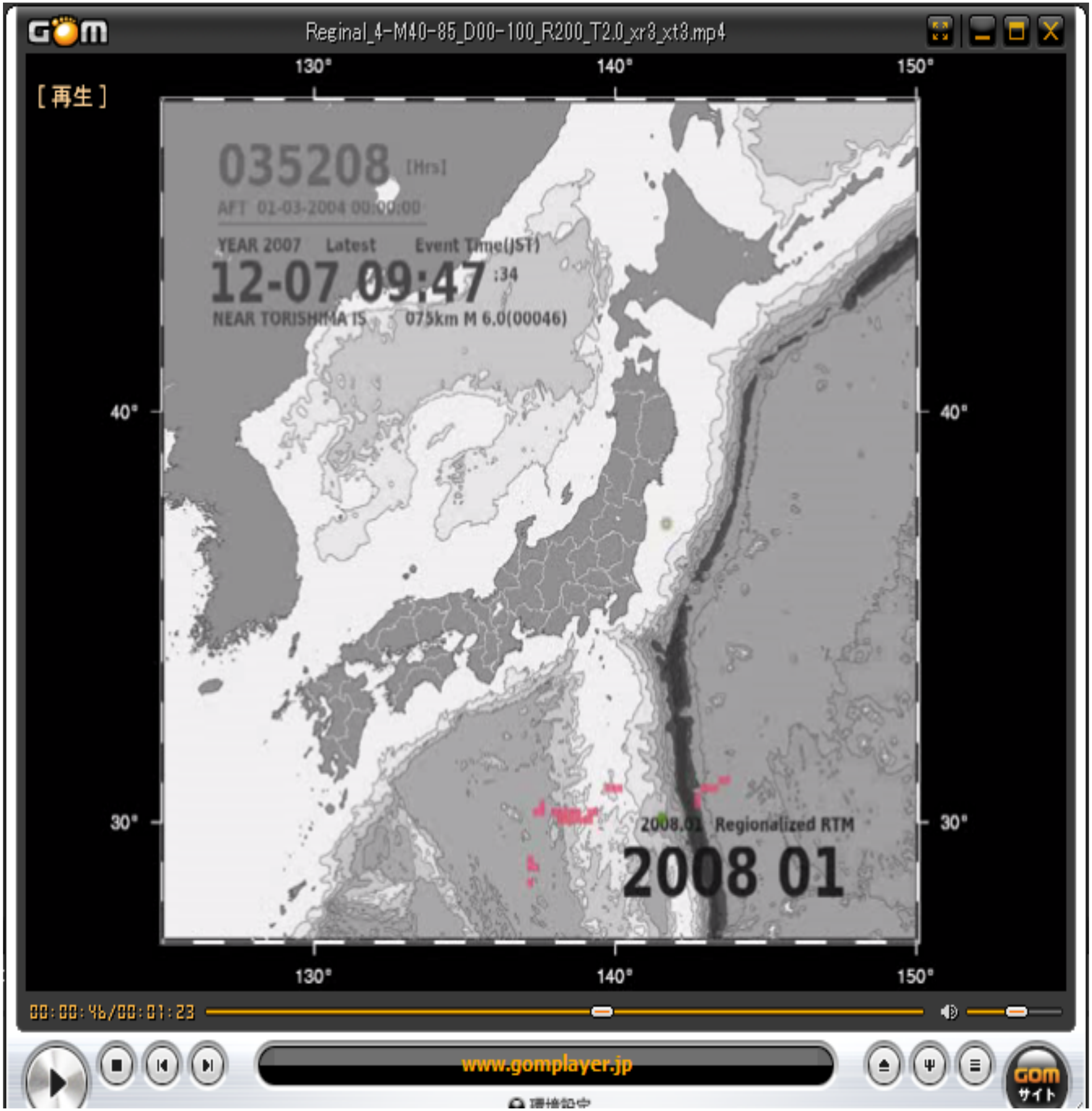
Concluding remarks

- Natural time analysis may be useful to predict a critical point before a large event. (NT itself does not have prediction ability.)
- RTM method is traditional EQ catalogue science. But, it can highly detect seismic quiescence before large EQs.

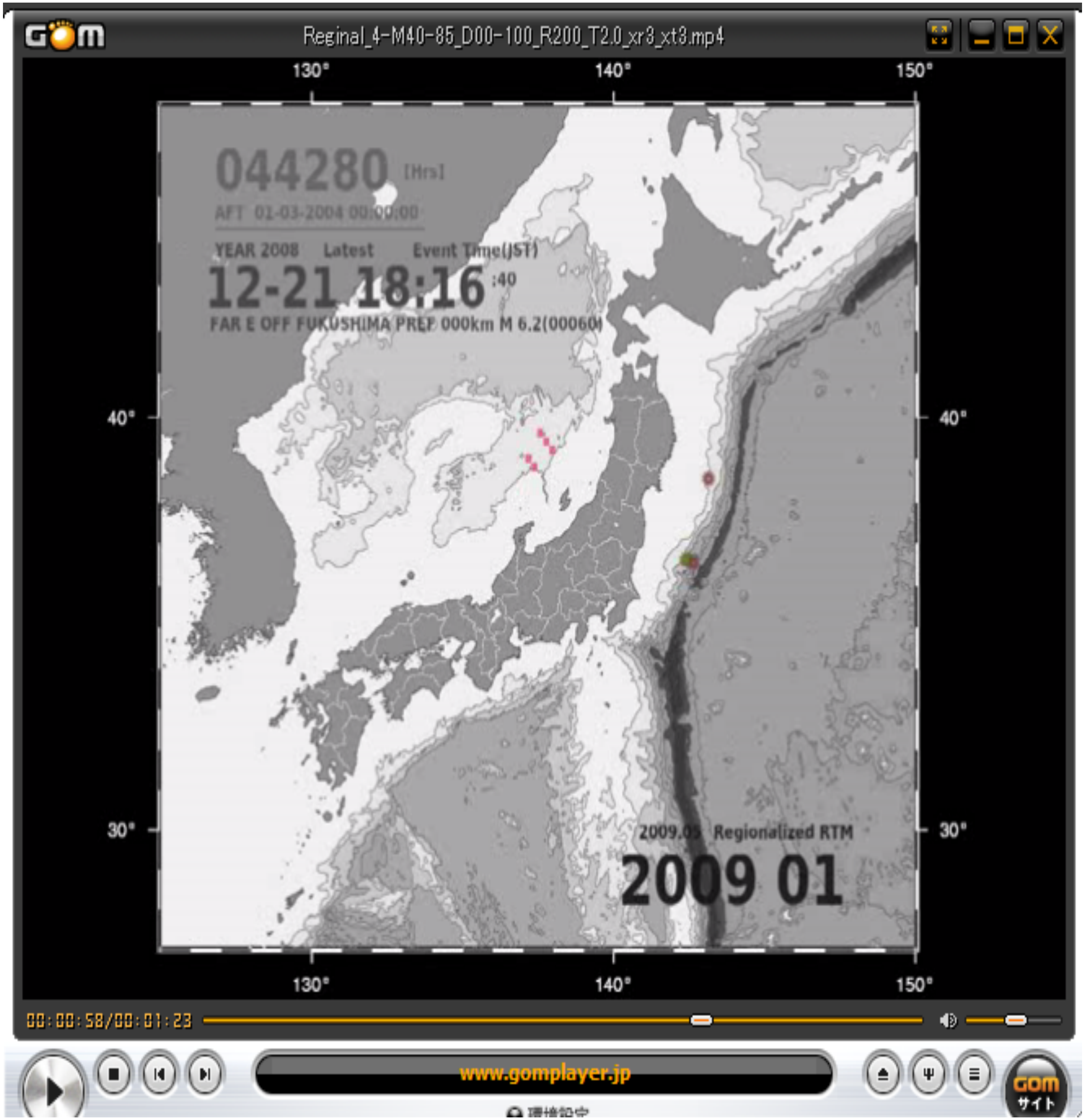
Temopral-spatial distribution of RTM value before 2011 M9.0 Tohoku EQ



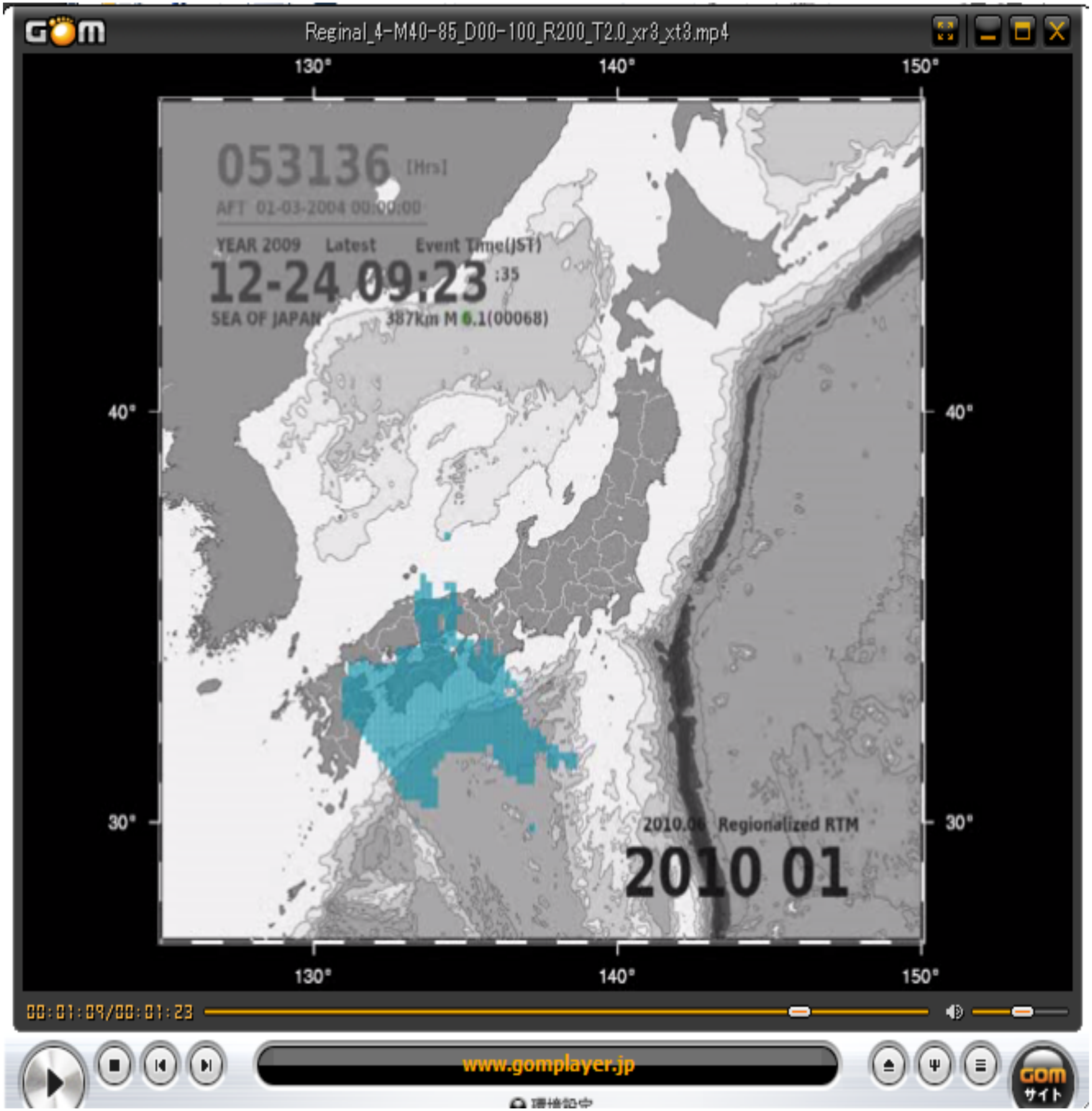
4 years before



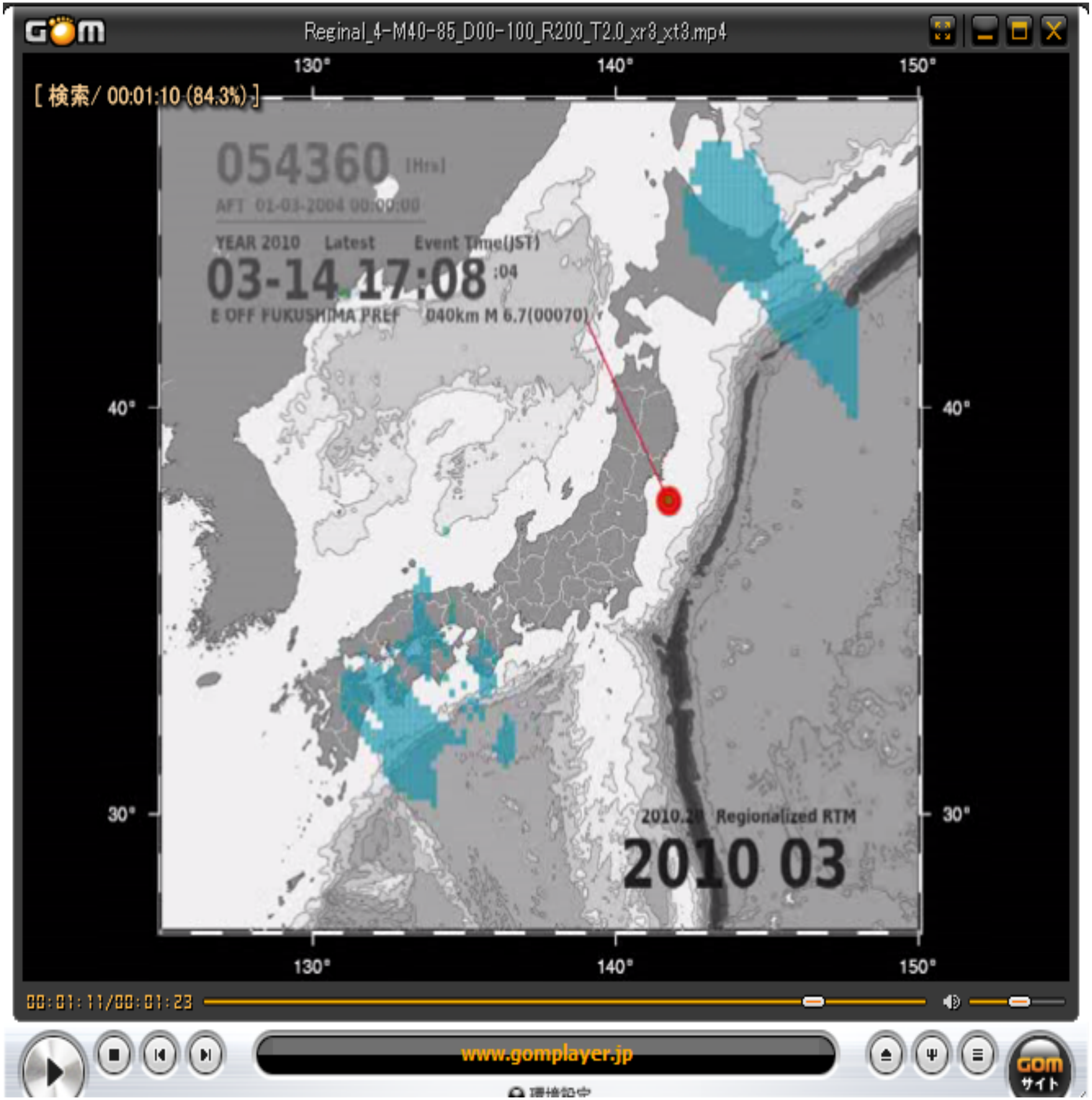
3 years before



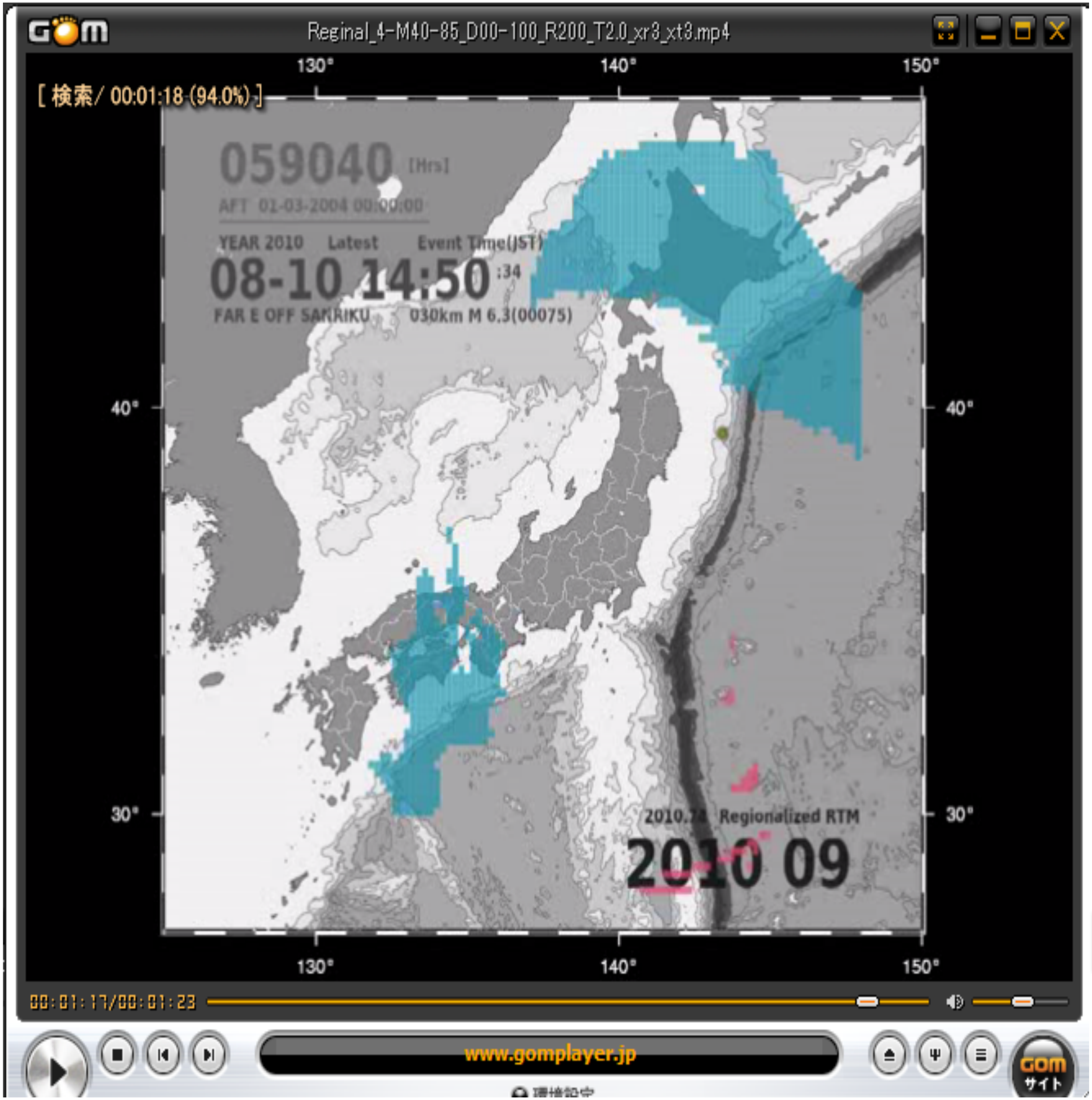
2 years before



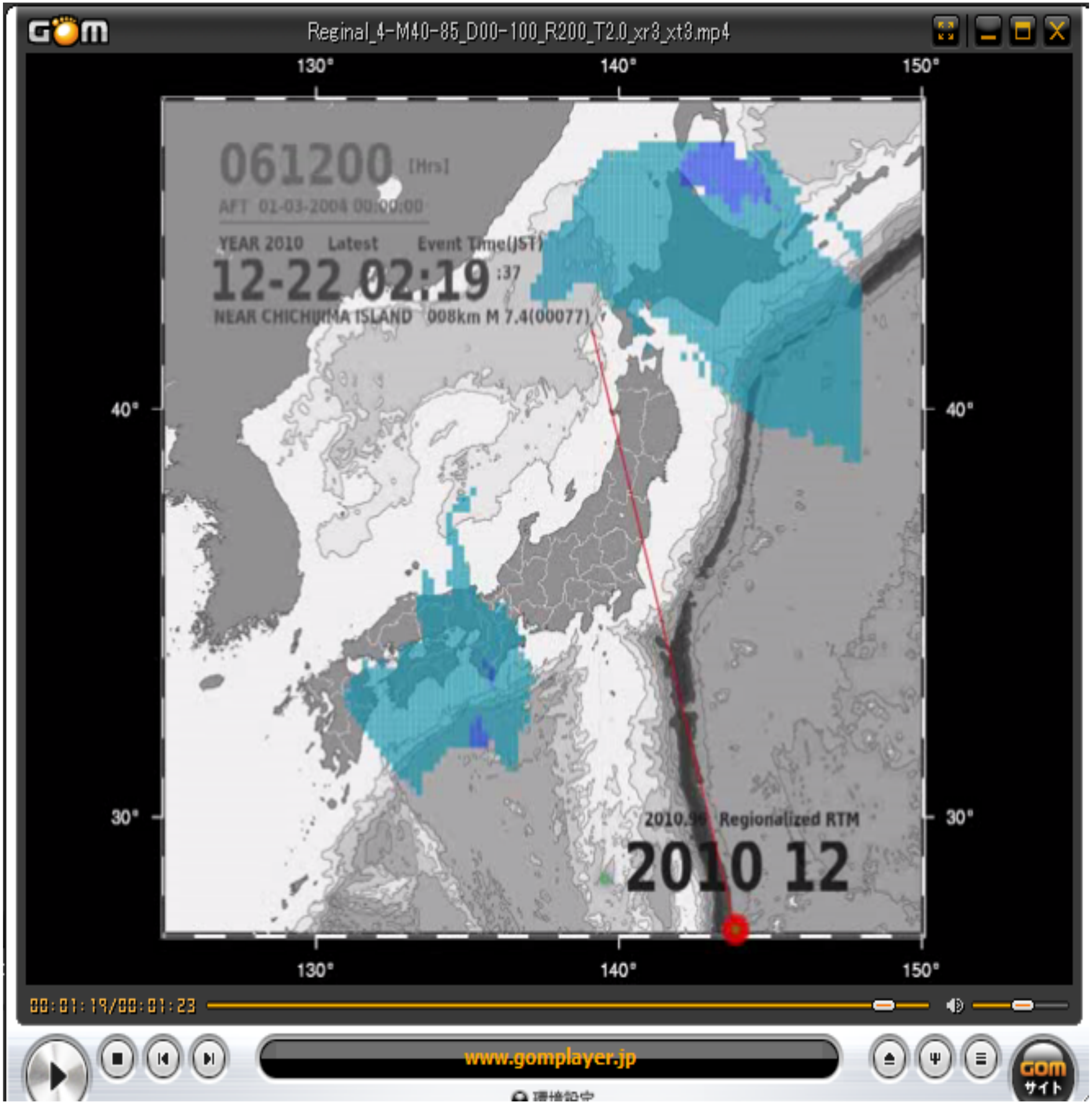
1 years before



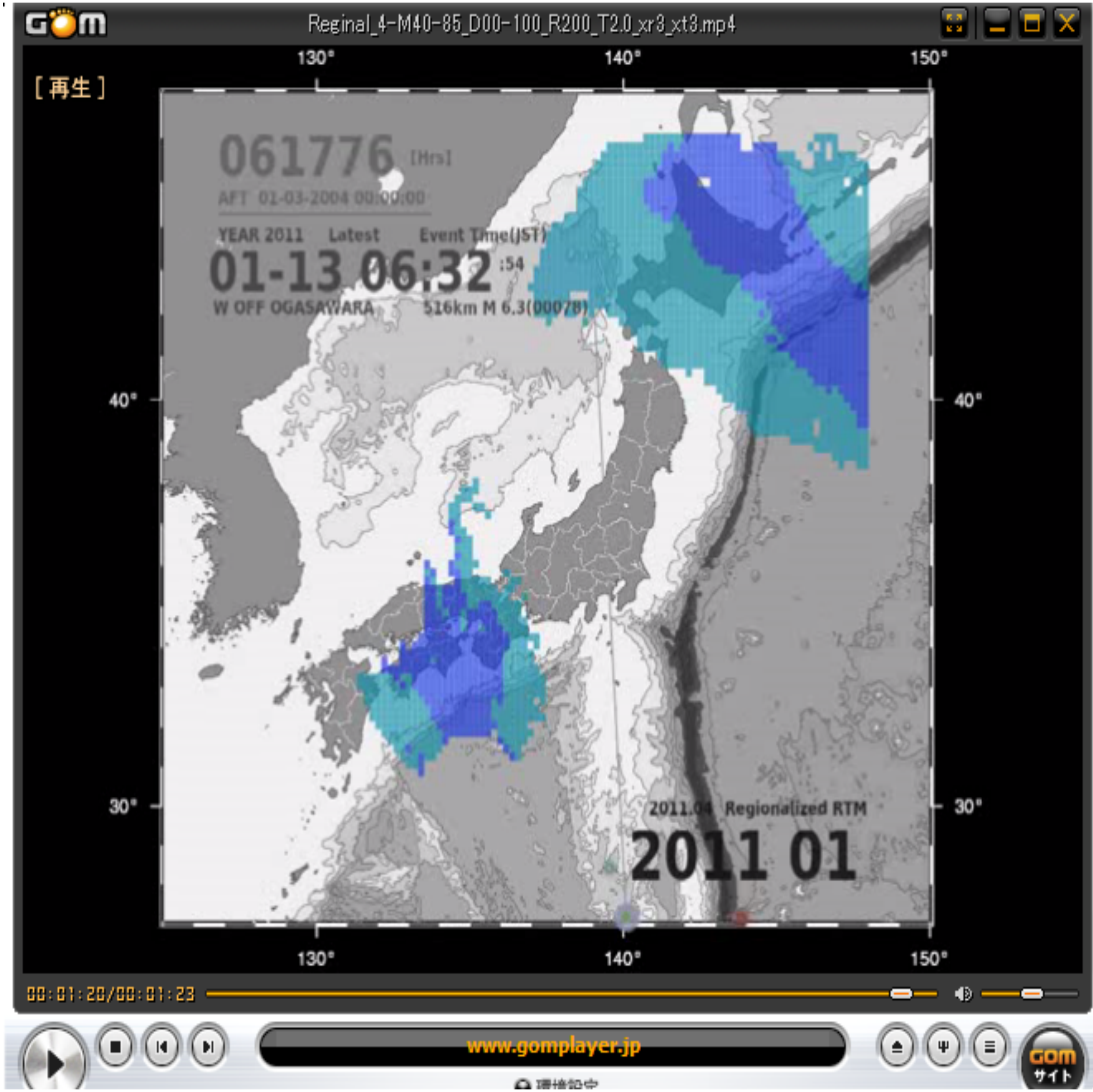
1 year before



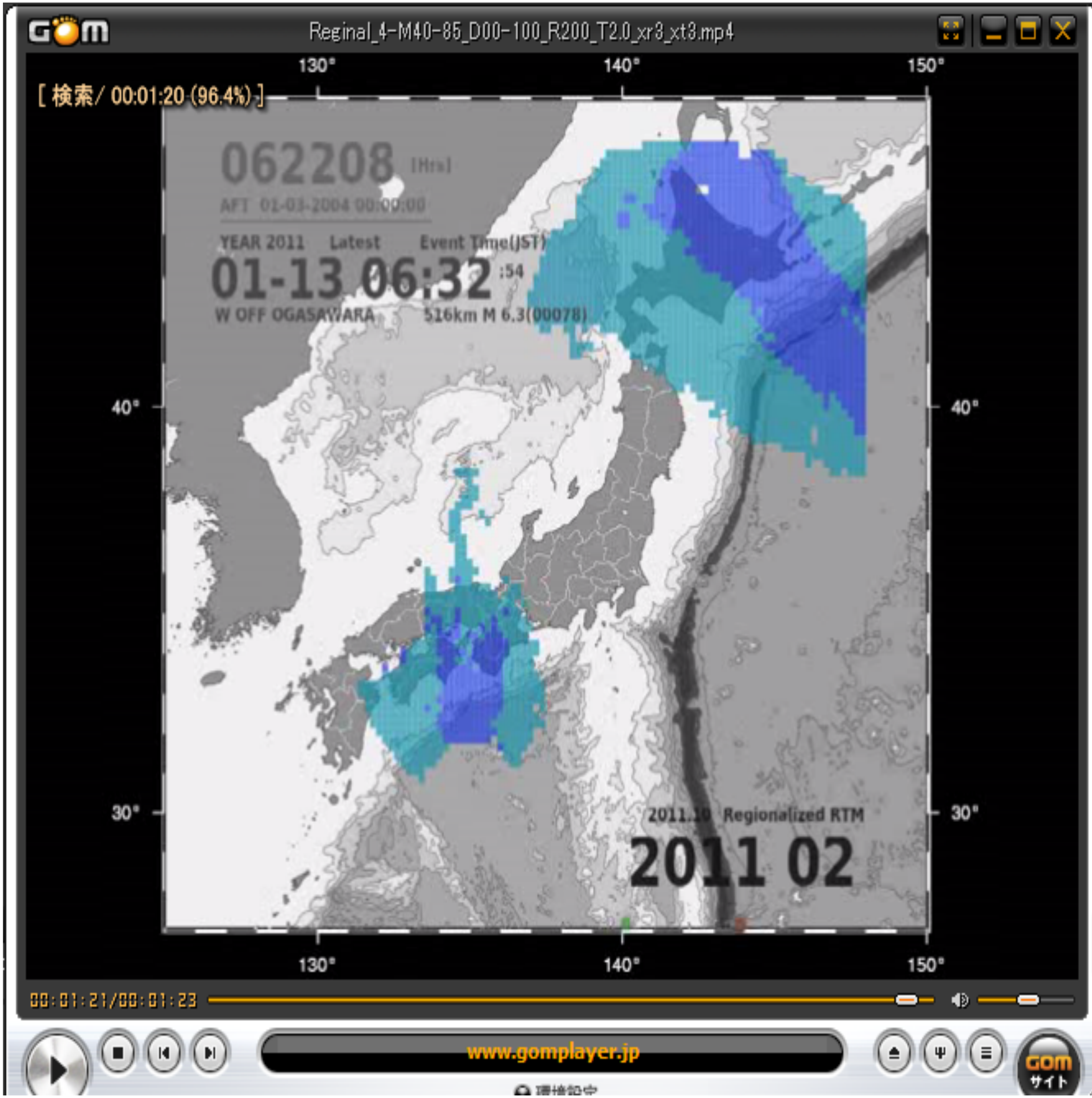
6 months before



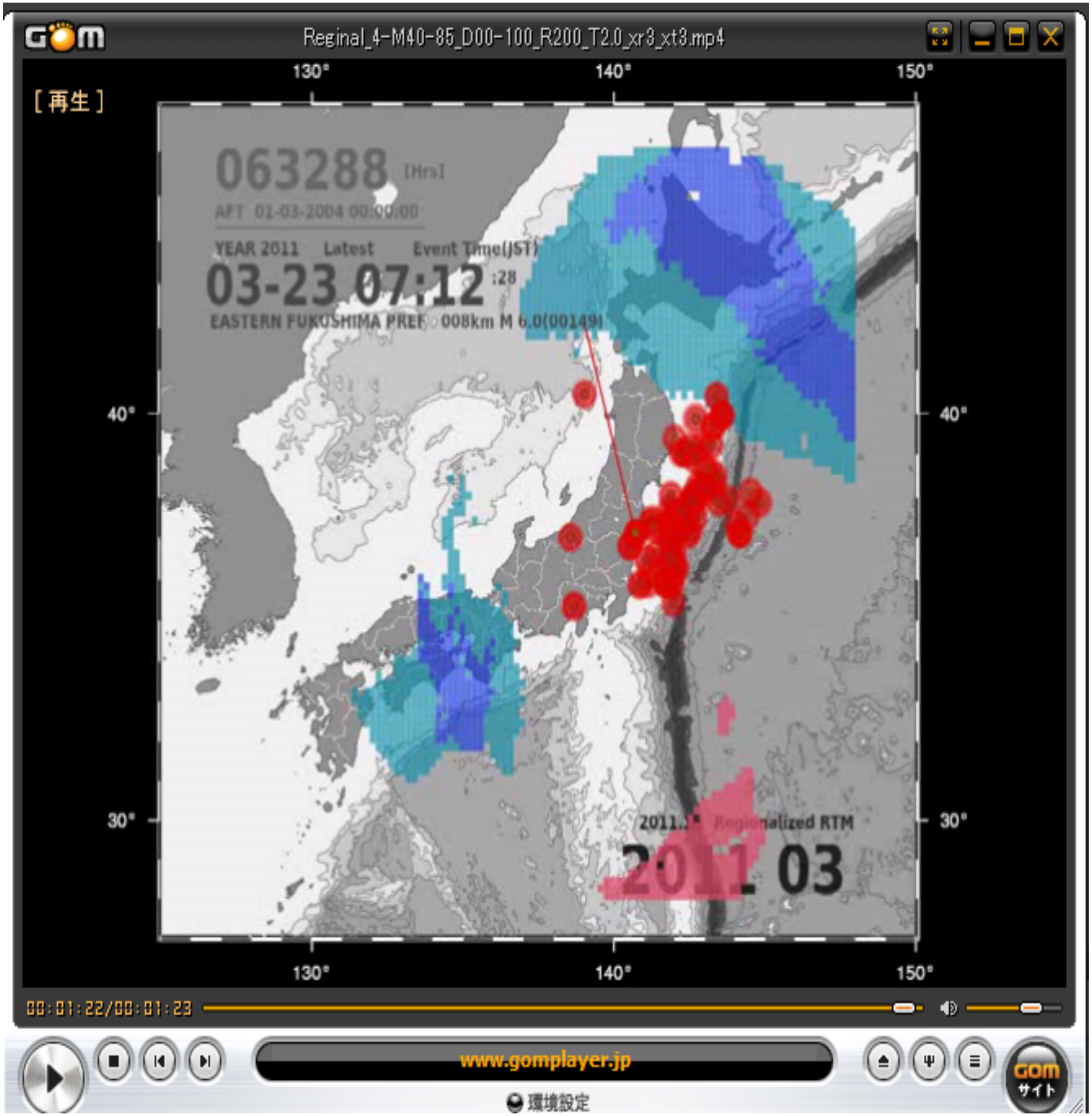
3 months before



2 month before



1 month before



Just after Tohoku EQ