Evaluation of Ionospheric Earthquake Precursor Signatures : Statistical and Tomographic Approaches over Japan Area

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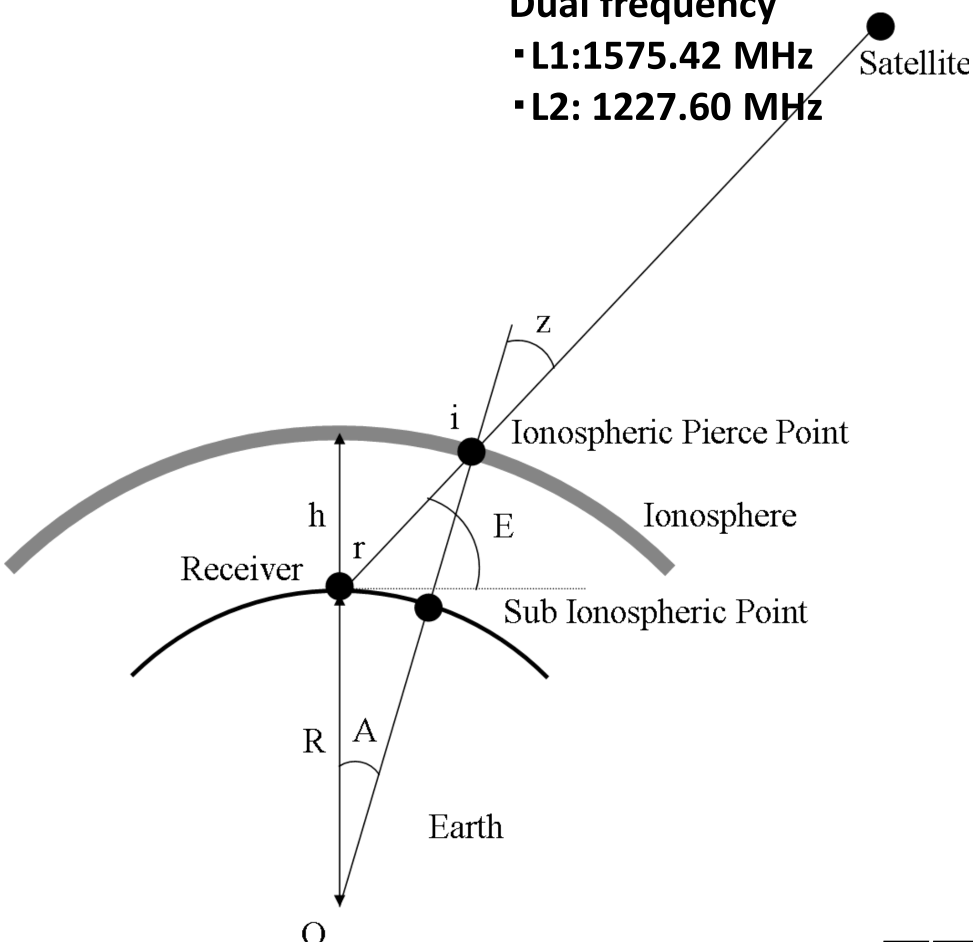
content

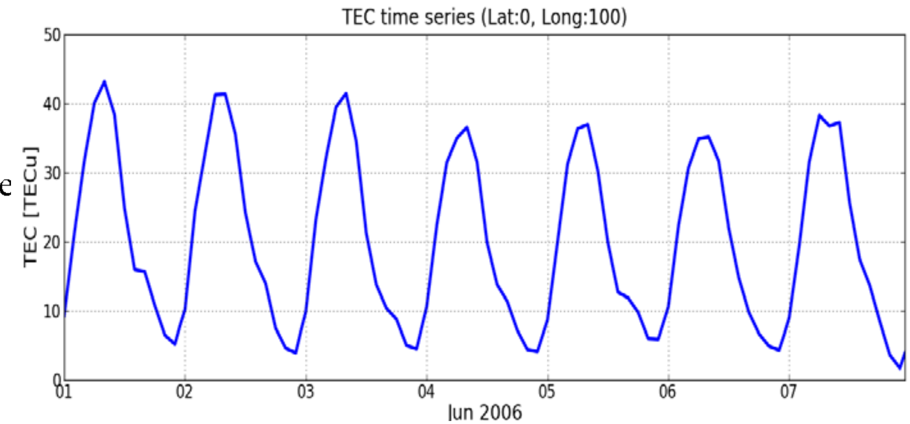
- Introduction
- Case study and statistical study for TEC analysis
- Evaluation of precursors
- Case study for tomographic analysis

Introduction
How to identify Ionospheric anomalies

Dual frequency

- **L1:1575.42 MHz**
- **L2: 1227.60 MHz**





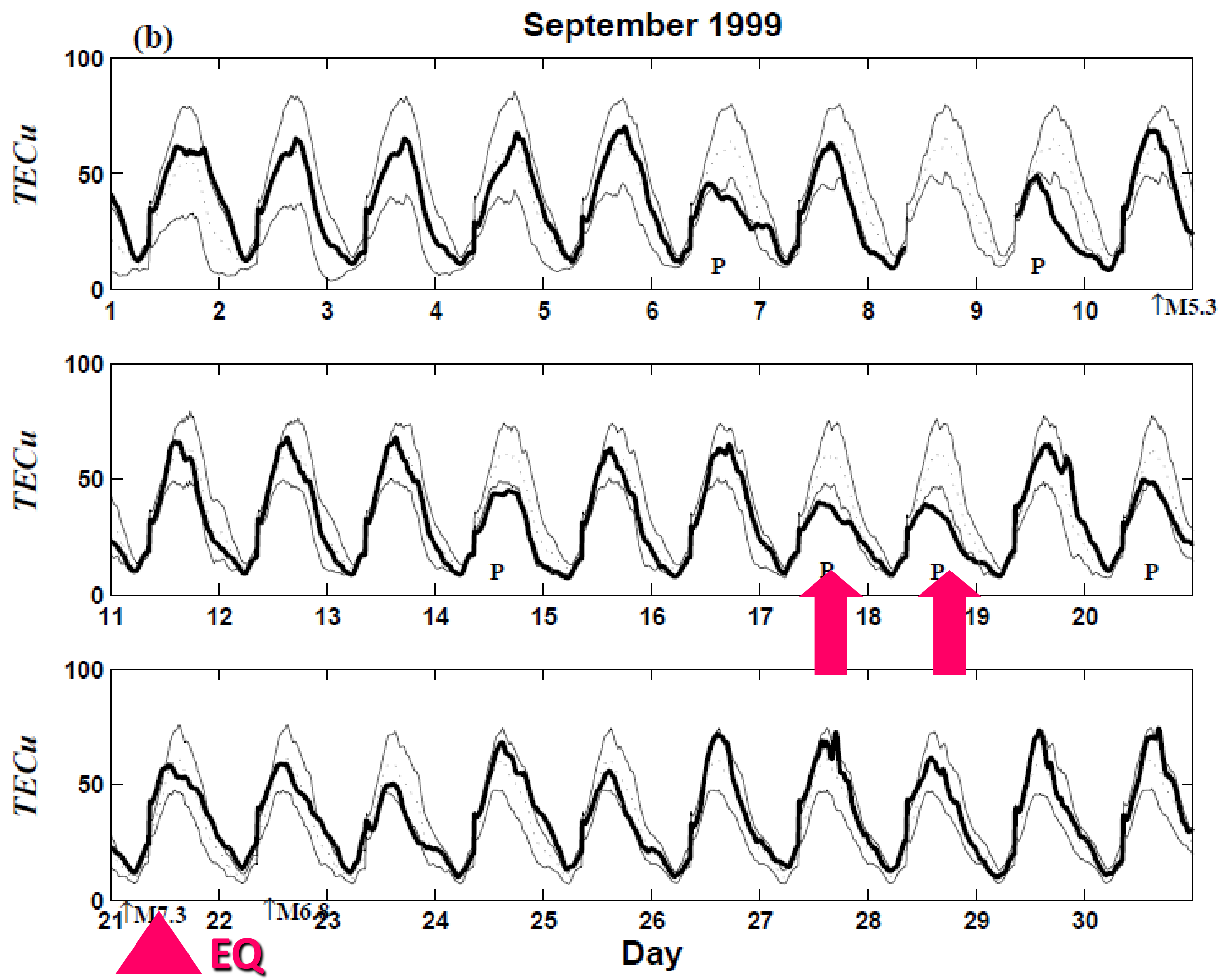
$$STEC = \frac{(f_{L1} f_{L2})^2}{40.3(f_{L1}^2 - f_{L2}^2)}(S_{L1} - S_{L2})$$

$$z = \arcsin \frac{R \cos E}{R + h}$$

$$\mathrm{VTEC} = \mathrm{STEC} \times \cos z$$

h= 350 km , R= 6370 km

$$TEC : 1TECU : 10^{16}[el / m^2]$$



Taiwan ChiChi EQ

(Liu et al, 2000, 2001, 2004)

Computation of TEC* & GIM-TEC*

To remove daily variation of TEC
and identify abnormal signals associated with EQs

We computed the **15 days backward mean values**, and the associated standard deviation (σ) as a reference at specific times.
Then, we derived the normalized ΔTEC (TEC*).

$$TEC^*(t) = \frac{TEC(t) - \overline{TEC(t)}}{\sigma(t)}$$

(computed using RINEX files)

$$GIM\text{-}TEC^*(t) = \frac{GIM\text{-}TEC(t) - \overline{GIM\text{-}TEC(t)}}{\sigma(t)}$$

Removal of geomagnetic storm effect

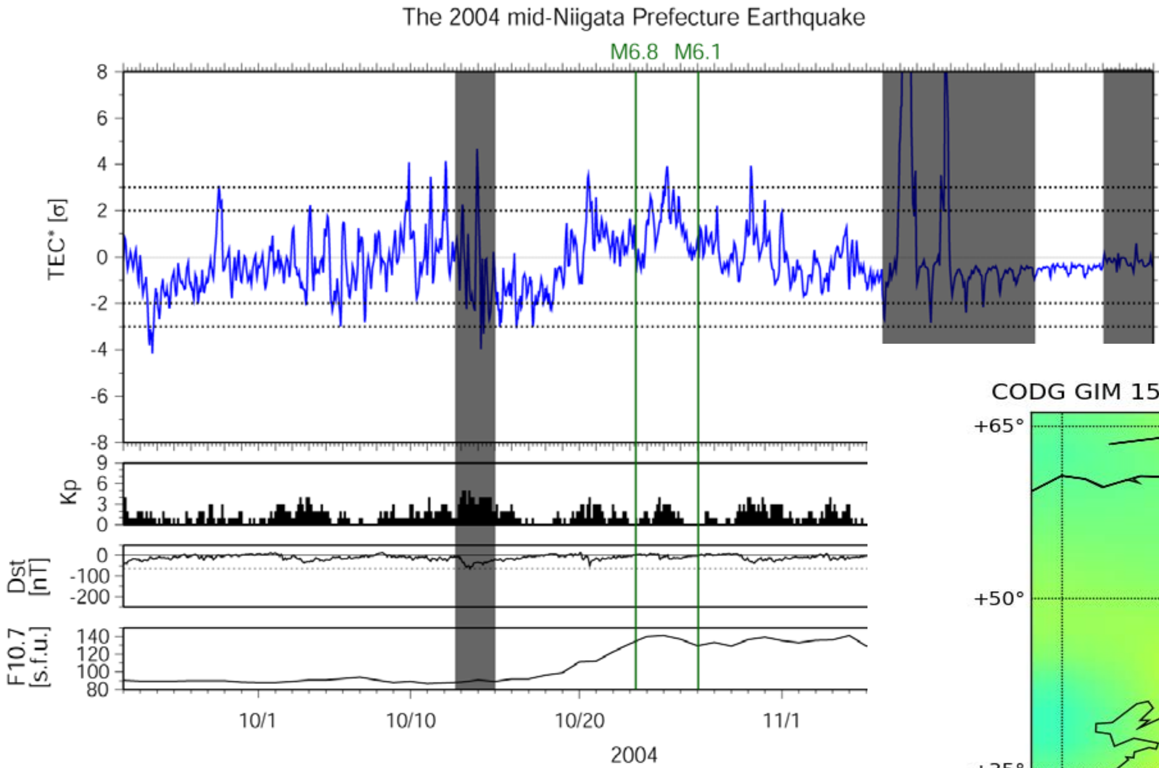
To remove geomagnetic storm effect,
we define a criterion as follows;

Dst index < -60 nT : geomagnetic storm

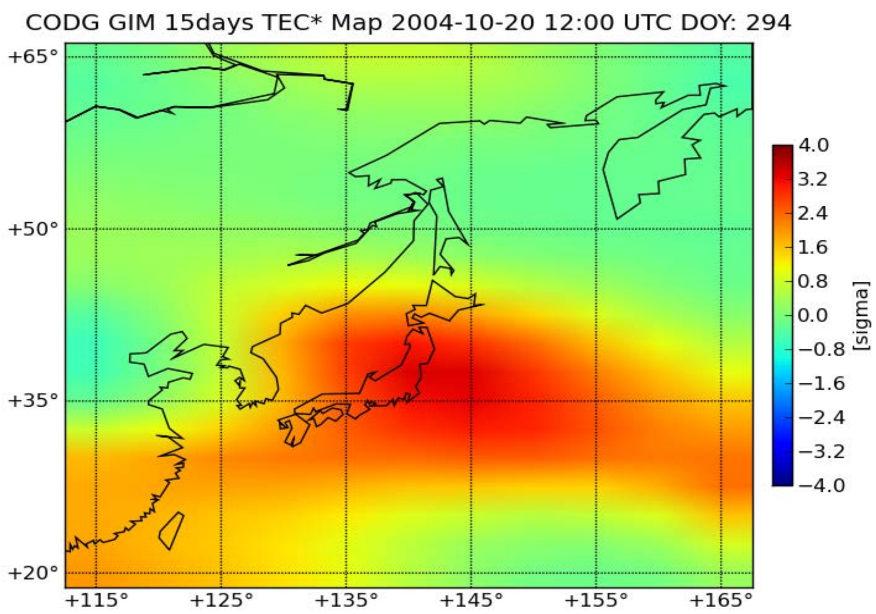
TEC could depress about a few hours
to 2 days after geomagnetic storm onsets.
(Kelley, 1989; Davies, 1990)

We removed the TEC data of geomagnetic storm period for 2 days after storm onset.

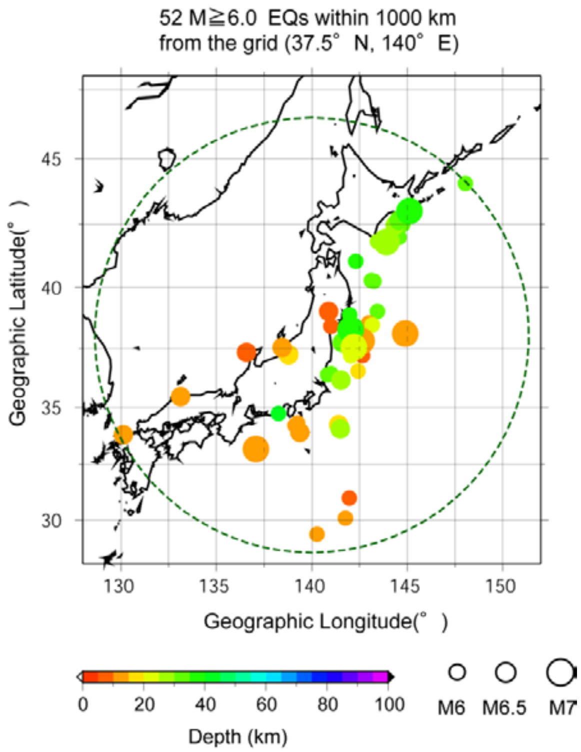
Case study for the 20041023 Chuetsu EQ(M6.8)
(Kon et al., JAES 2011)

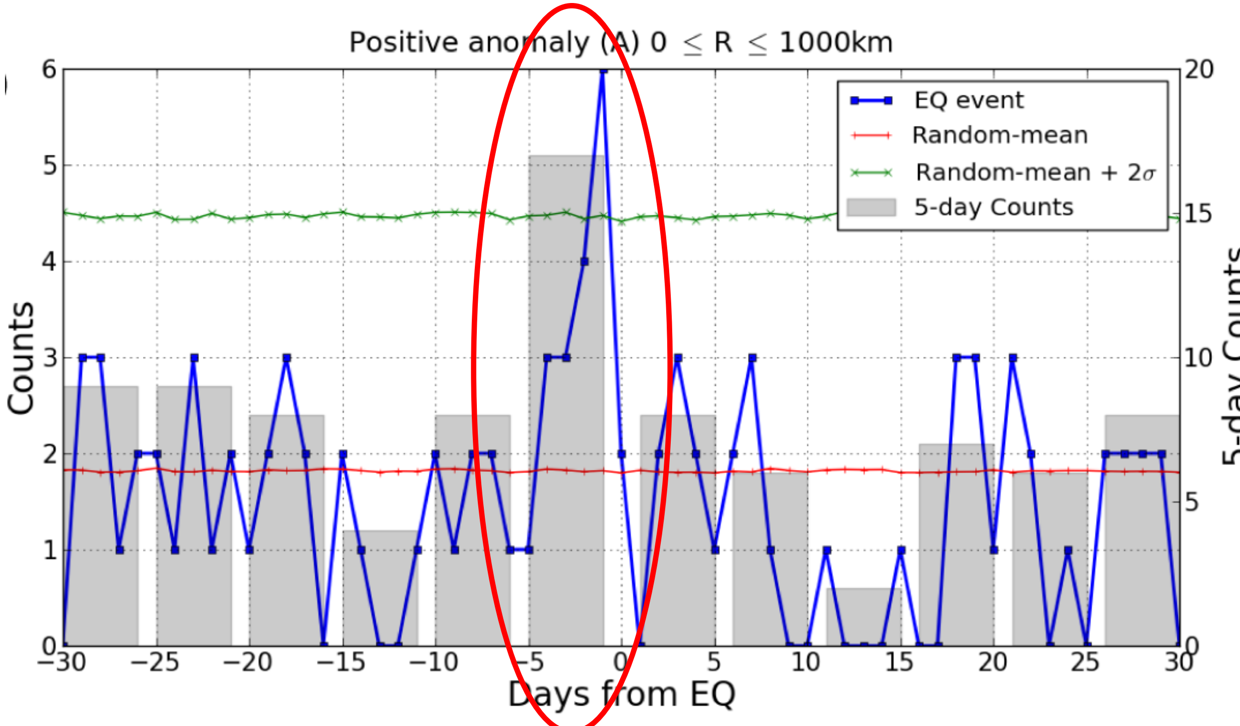


Spatial Distribution of anomalous TEC



Statistical Approach for 2D analysis

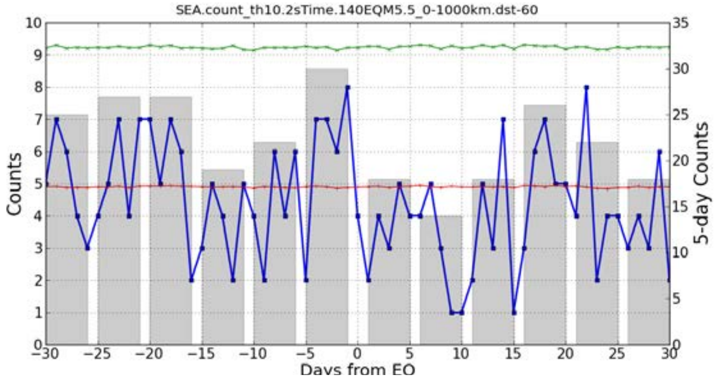




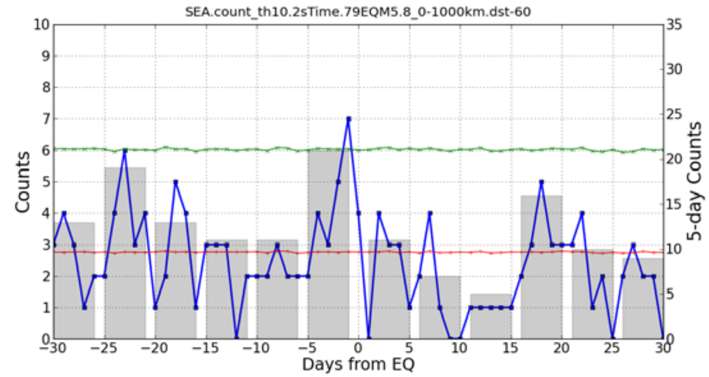
Kon et al, 2011

Kon et al., 2011 shows that the Positive TEC anomaly with duration > 10 hours 1-5 days before EQs with M>6 and D<40km is significant over Japan in 1998-2010 with magnitude and distance dependences

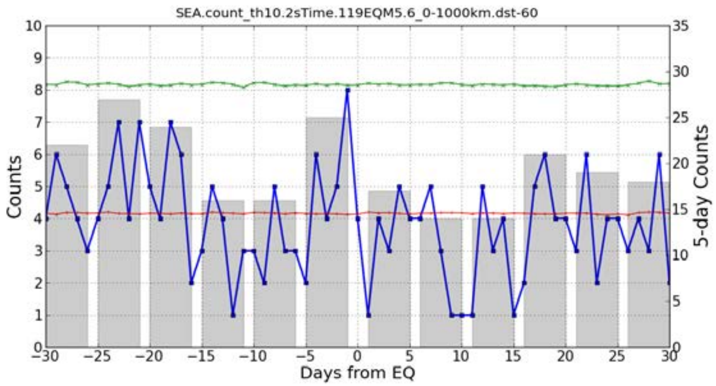
Statistical Investigation of GPS-TEC anomaly over 1998-2010 (Superposed Epoch Analysis Normalized GIM-TEC*) **Epidemiological approach**



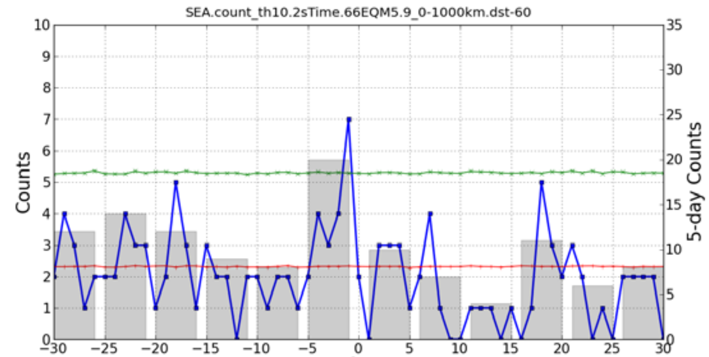
M>5.5
140 EQs



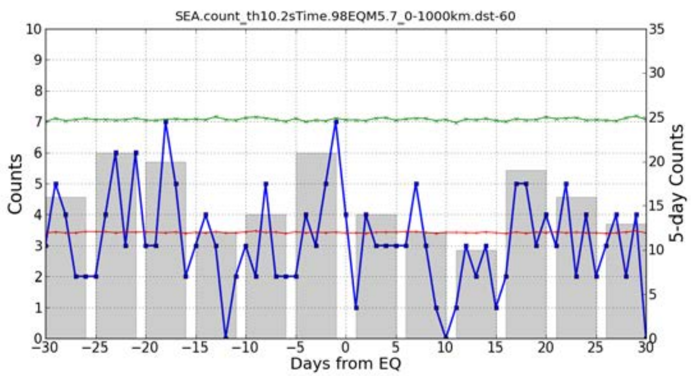
M>5.8
79 EQs



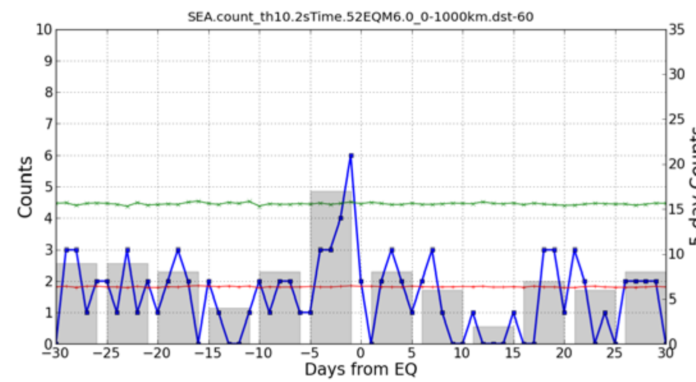
M>5.6
119 EQs



M>5.9
66 EQs



M>5.7
98 EQs



M>6.0
52 Eqs

(Kon et al
2011)

Definition of Anomaly: Positive, Intensity >2σ , Duration >10 hours/day

Removal of TEC anomaly related to magnetic storm

Removal of geomagnetic effects in Kon et al., 2011

- Definition of magnetic storm : Dst < -60 nT

  Remove 2 days data after onset of the storm

From a few hours to 2 days after the onset of the magnetic storm, TEC decreases in lower and mid latitudes. (Kelley, 1989; Davies, 1990)

Evaluate the duration of ionospheric disturbance due to geomagnetic storm statistically, based on the observed data.

Geomagnetic Storms

Definition of geomagnetic storm

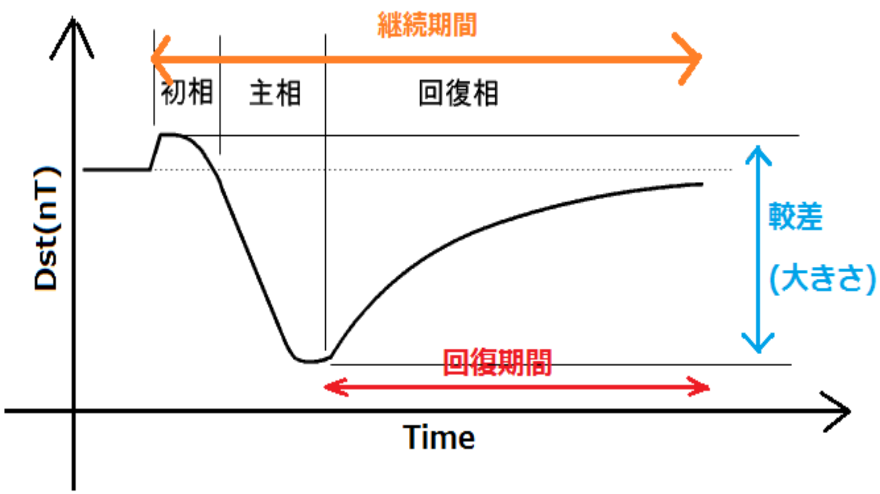
Dst index, WDC for Geomagnetism, Kyoto

Dst index (final report) (1998-2009)

Dst index (not final report) (2010-2012)

Dst index (first report) (2013)

Magnetic storm



Number of magnetic storm over 1998-2013

	Intensity (1) 60～79nT	Intensity (2) 80~99nT	Intesity (3) 100nT~	Total
Period 1 0000-0559LT	28	21	28	77
Period 2 0600-1159LT	31	22	27	80
Period 3 1200-1759LT	34	14	21	69
Period 4 1800-2359LT	25	15	28	68
Total	118	72	104	**294**

Ionospheric perturbation after the onset of magnetic storm

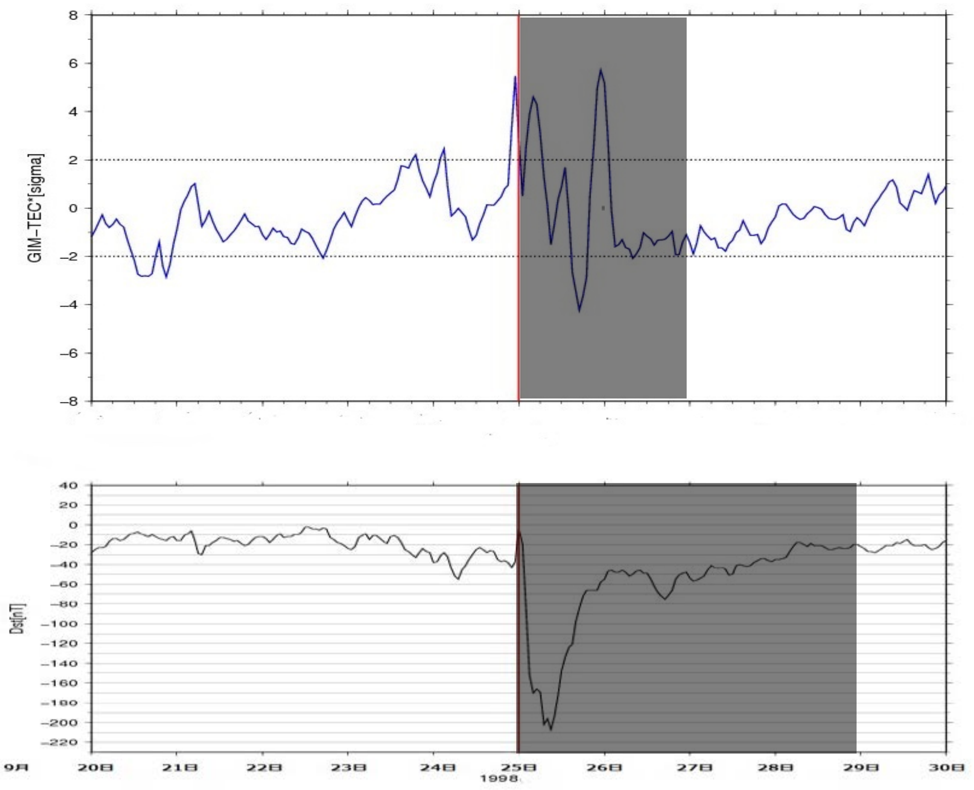
Geomagnetic storm and Ionospheric changes

Ionospheric response of GIM-TEC*

GIM-TEC*

$$GIM\text{-}TEC^*(t) = \frac{TEC(t) - \overline{TEC(t)}}{\sigma(t)}$$

Definition of anomaly of GIM-TEC*: ±2σ



Geomagnetic storm at 0:00 on September 25, 1998 (UT)
Storm class Intensity (3) and Period 1

Statistical Analysis for Ionospheric variations

Reduction of geomagnetic storm effects

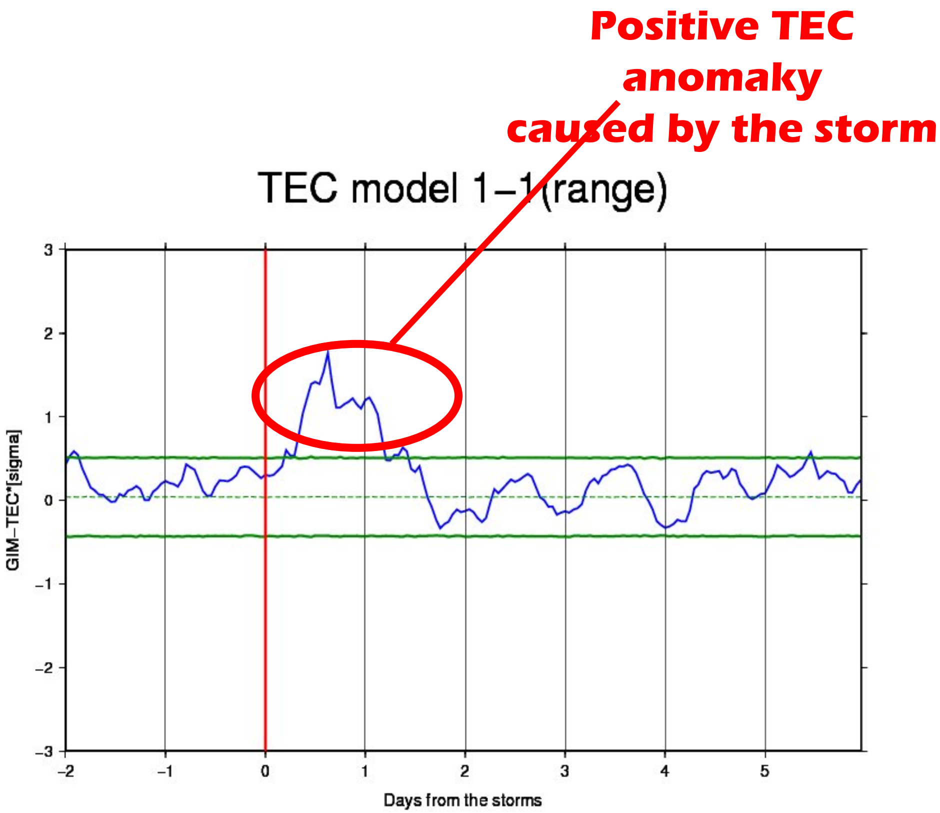
【Procedure】
Extract -2 and + 5 days GIM-TEC* data after the onset of the magnetic storm for each class of the storm.

↓

Apply the bootstrap method to increase number of data and take average.
Compute range of normal variation of GIM-TEC*.

↓

Determine the removal period of data due to geomagnetic storms for each group.



GIM-TEC* variation model derived by statistical
Computation for period 1 and intensity 1

Statistical models of Ionospheric responses caused by geomagnetic storms

Intensity (1)（60-79nT)

Intensity (2) (80-99nT)

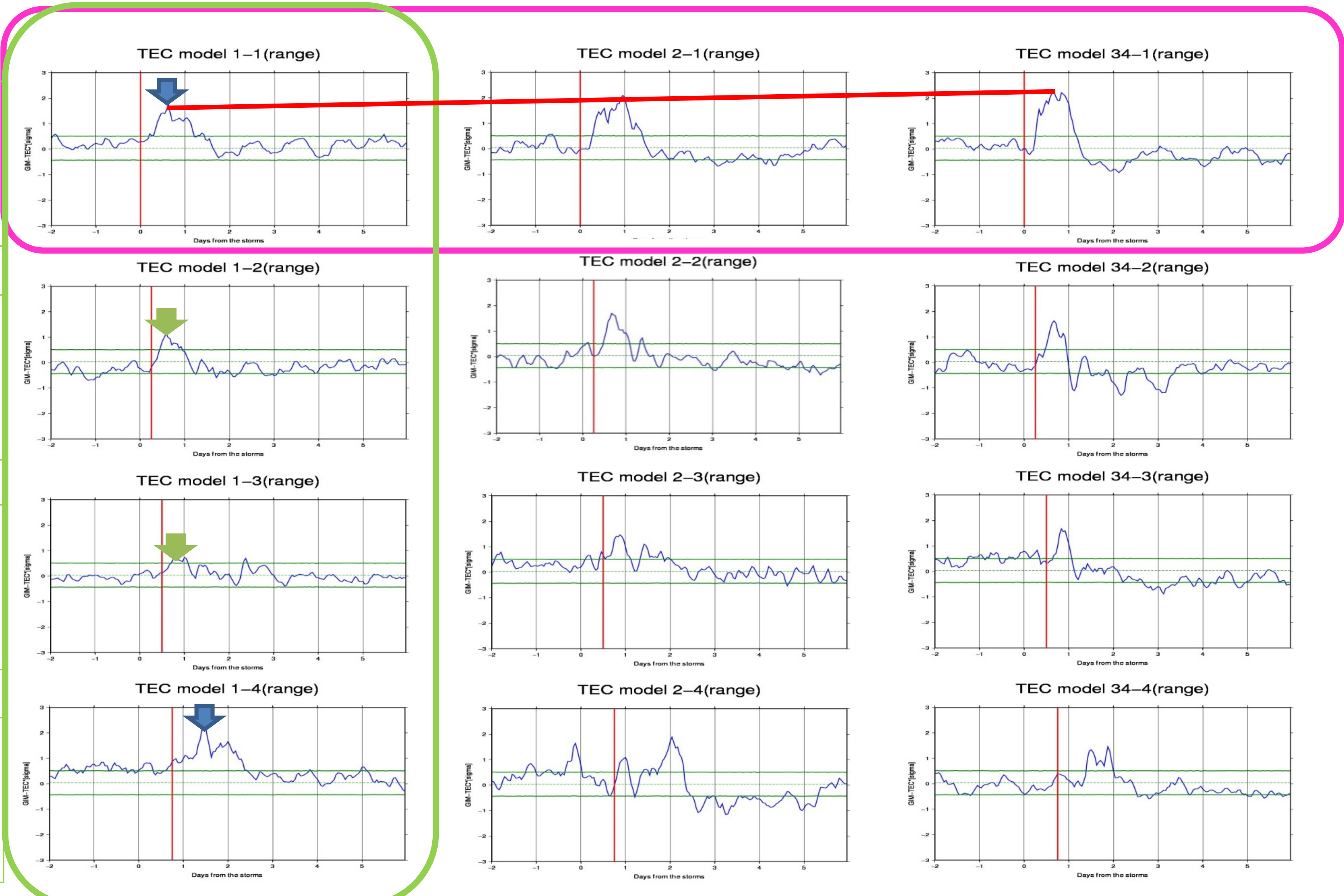
Intensity (3) (100nT-)

Period 1 0000-0559LT

Period 2 0600-1159LT

Period 3 1200-1759LT

Period 4 1800-2359LT



Summary of Ionosheric responses

・ Dependence of intensity of storm in that of Ionospheric perturbation

・ For the onset time of period 4(1800-2359LT), there is a tendency that a positive anomaly seems to last so long.

・ Positive anomalies occur just after the onset of magnetic storm for daytime (Periods 2 & 3), and a few hours after for nighttime (Periods 1 & 4).

Duration of magnetic storm（boot strap）

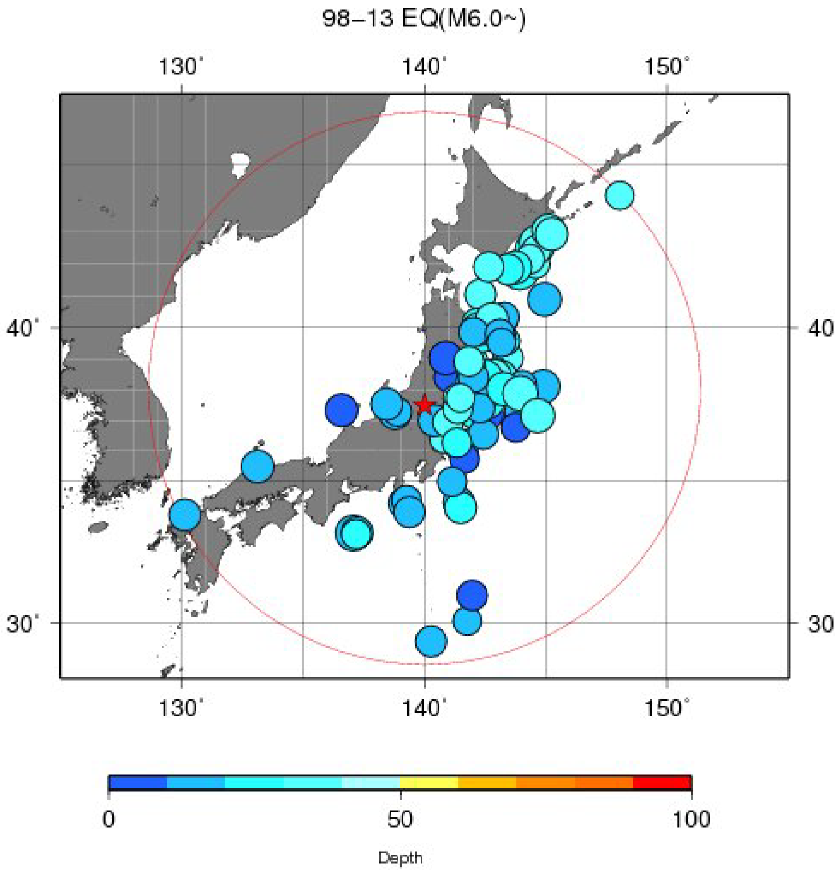
	Intens. (1)	Intens.(2)	Intens.(3)
Per.1	3 days	4 days	4 days
Per.2	2 days	3 days	4 days
Per.3	3 days	3 days	4 days
Per.4	3 days	3 days	4 days

Appearance of positive anomalies

	Intens.(1)	Intens.(2)	Intens.(3)
Per.1	2 days	2 days	2 days
Per.2	1 day	2 days	1 day
Per.3	3 days	2 days	2 days
Per.4	5 days	3 days	3 days

⇨ Duration of magnetic storm and timing for appearance of positive anomalies is different.

Significance check using Superposed Epoch Analysis (SEA) for 1998-2013



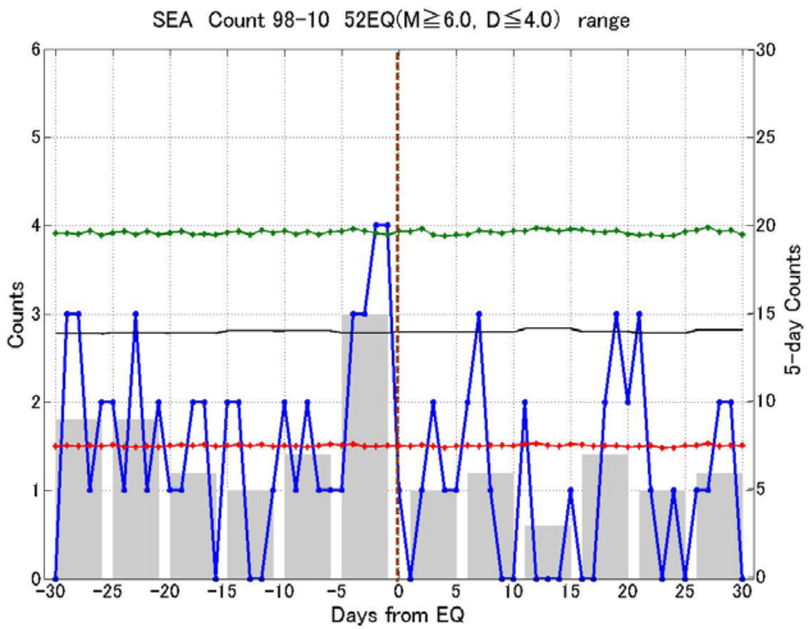
[EQ]
Period 1998/05 – 2013/12
R< 1000km from（37.5° N, 140° E）
M≧6.0, D≦40 km
87 EQ

USGS EQ catalog

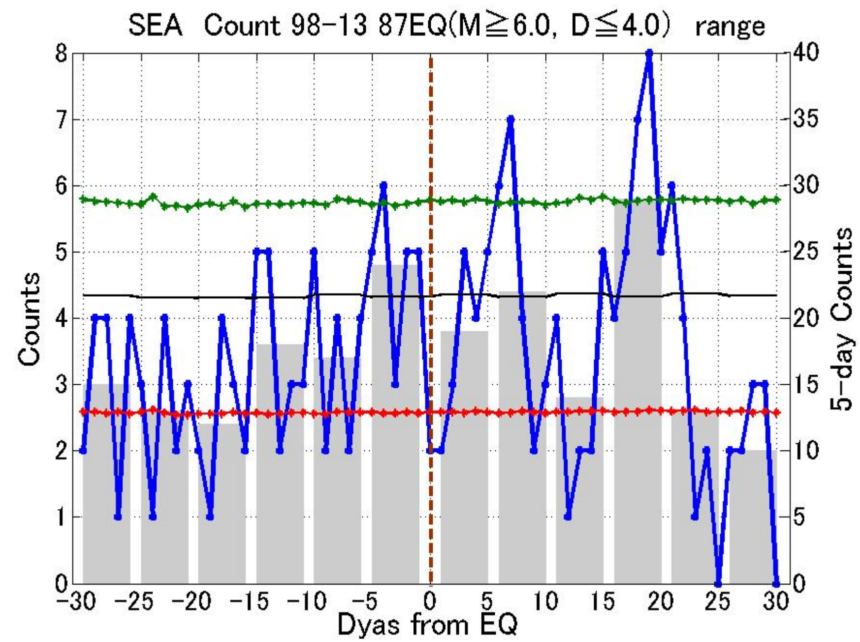
Superposed Epoch Analysis

Results of SEA

52 EQ for 1998－2010

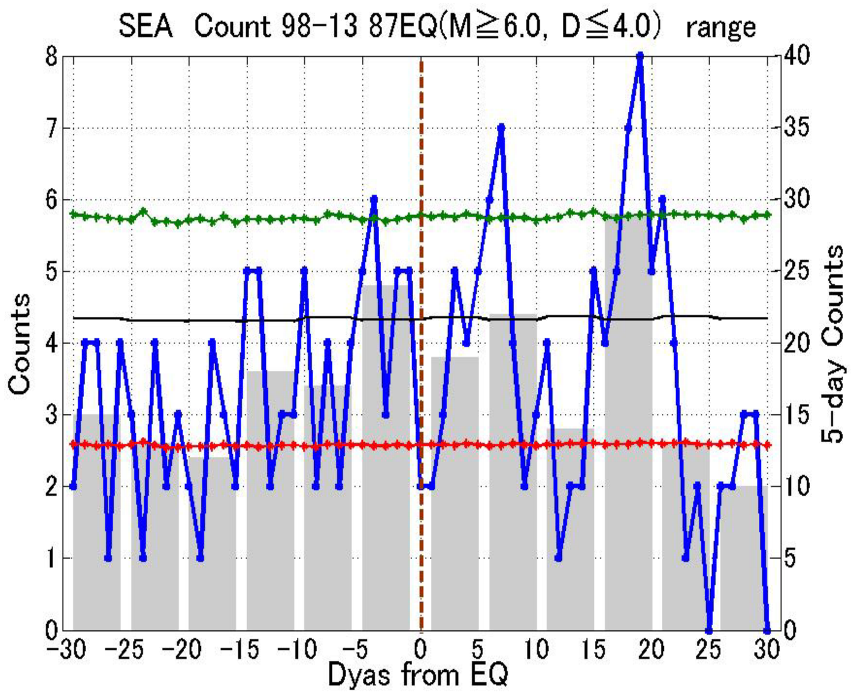


87 EQ during 1998-2013



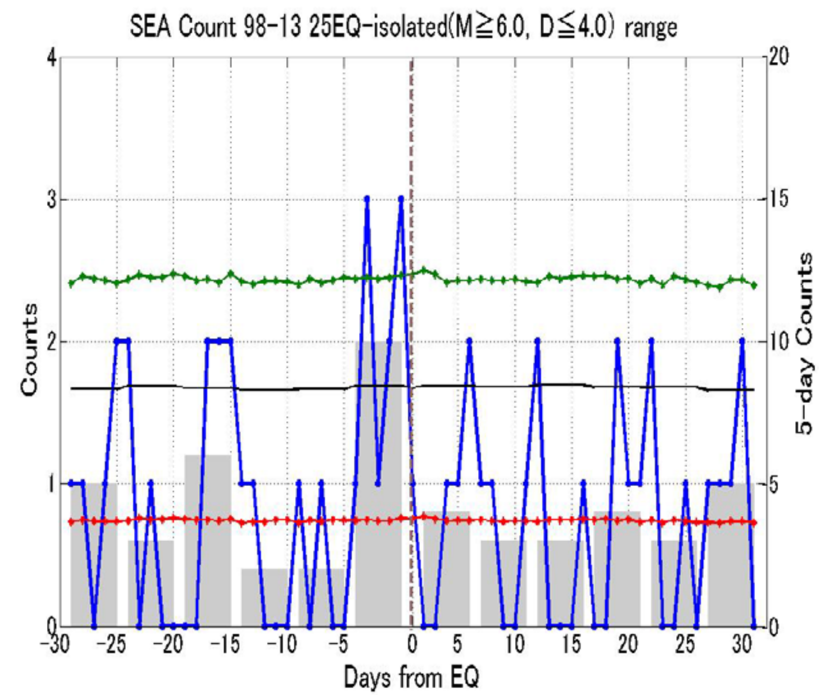
SEA resultremove EQs

Result for 87 EQ over 1998-2013.



Result for 25 isolated EQ s only over 1998-2013.

Isolated EQ; there are no EQ 30 days before and after the EQ.



Evaluation of efficiency of short-term forecast using Molchan's error diagram

a: the number of successful predictions of EQs

b: the number of false alarms

c: the number of successful predictions of non-occurrence

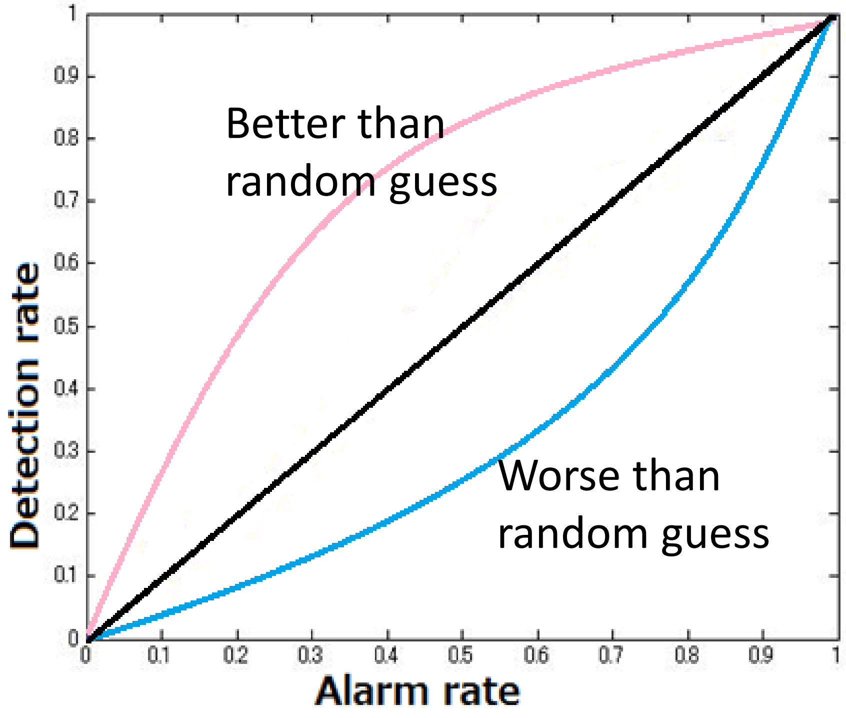
d: the number of missed EQ

The proportion of predicted EQs,

$$\nu = \mathrm{a} / (a + d)$$

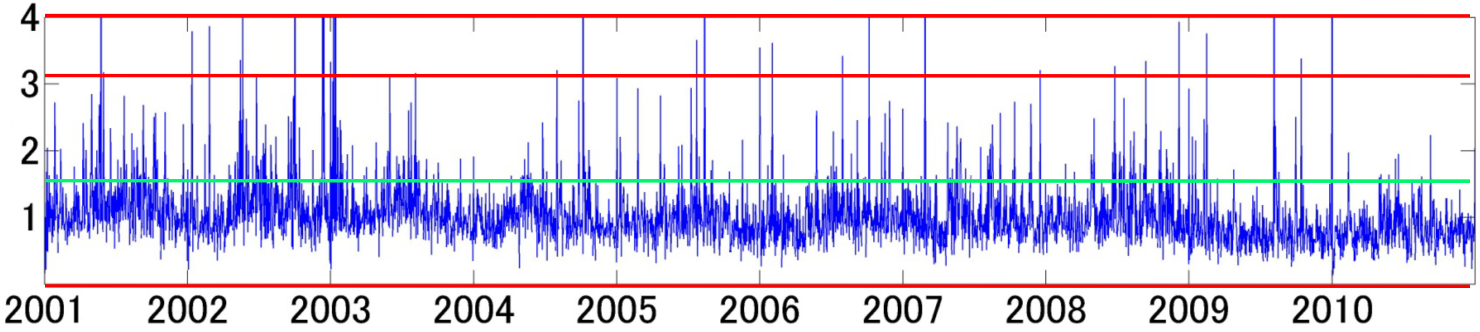
The proportion of alarmed cells,

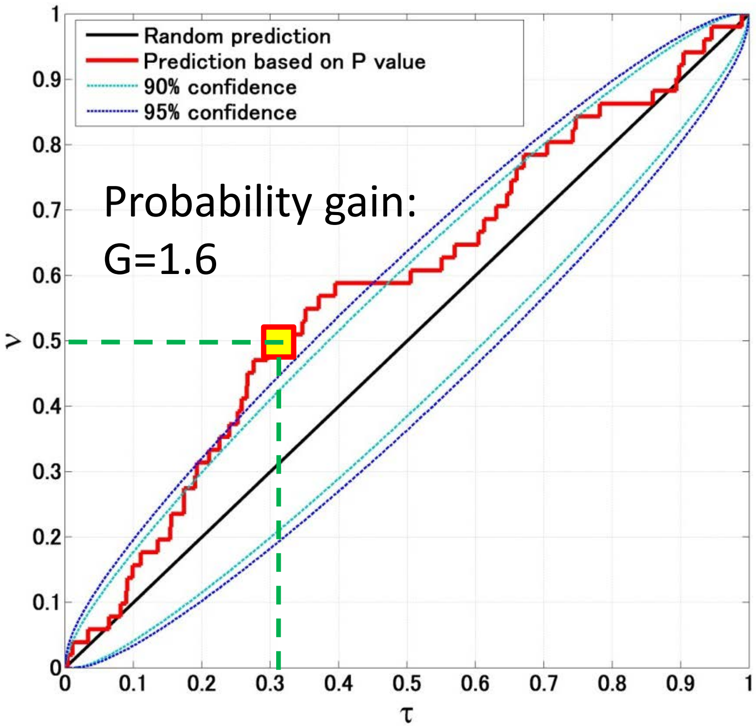
$$\tau = (a + b) / (a + b + c + d)$$



Molchan, 1990; Zechar and Jordan, 2008

Concept of the evaluation of the efficiency of ionospheric TEC phenomena for earthquake forecasting

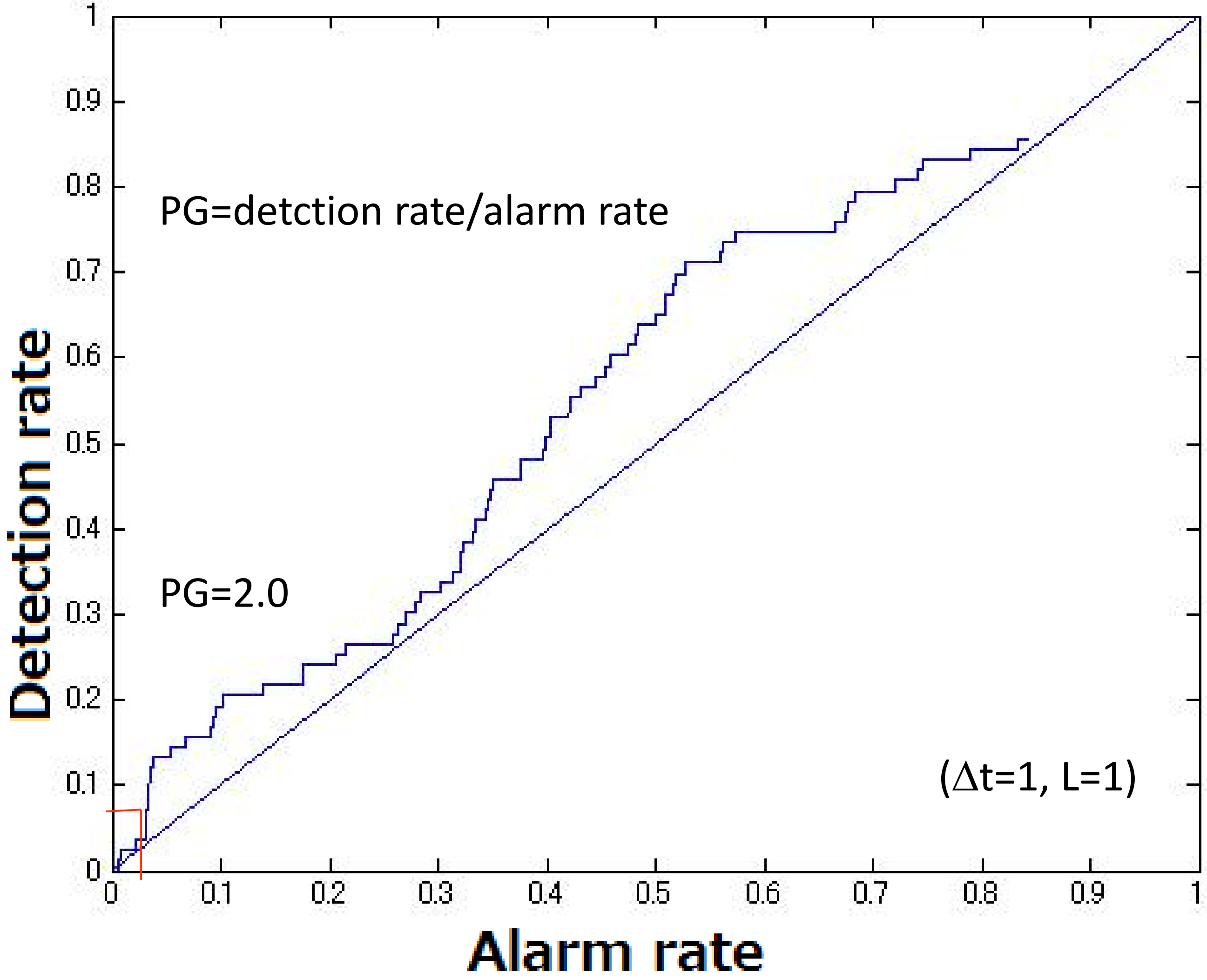




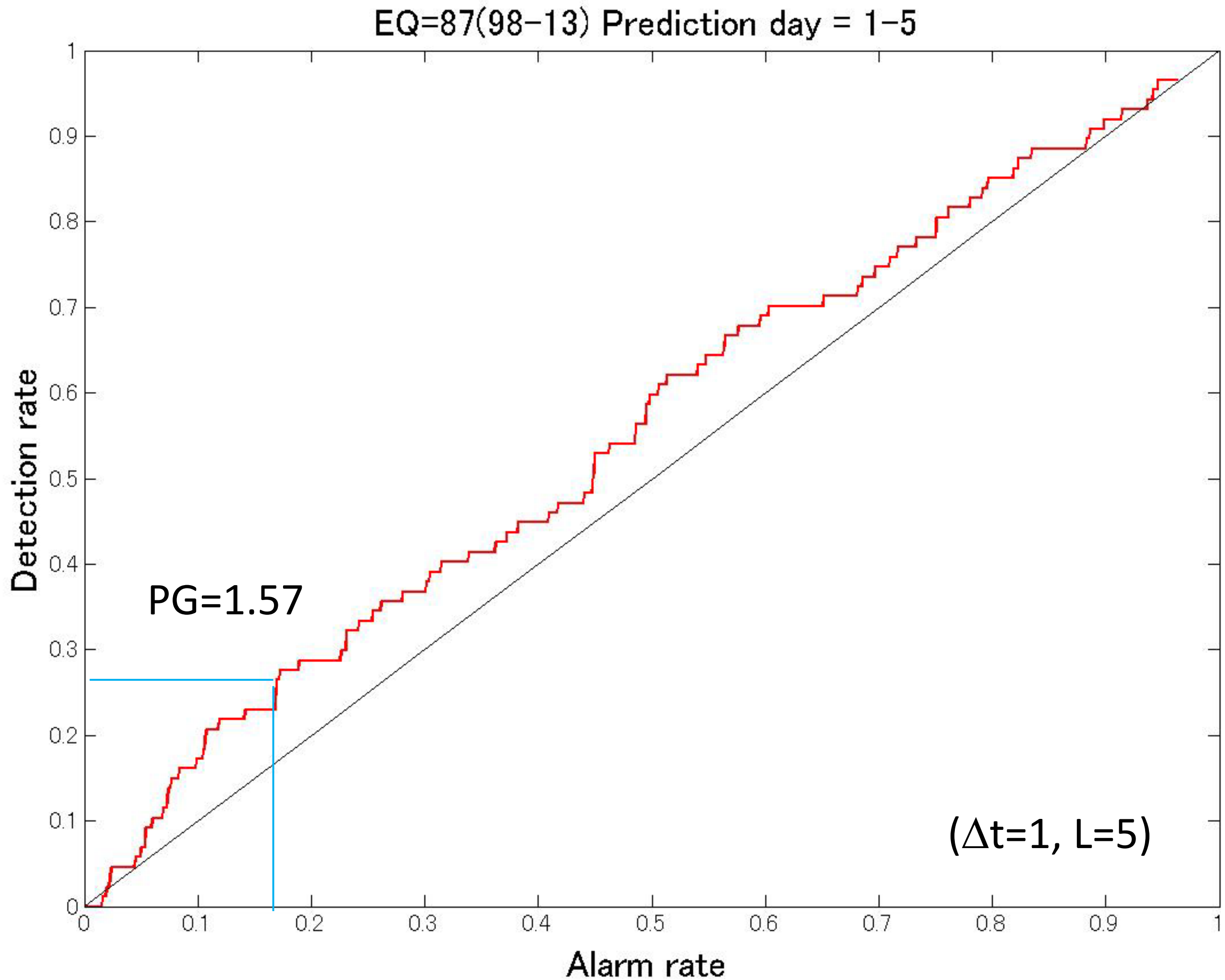
For example,
Δ (lead time) = 1 day
L (alarm window) = 5 days
and change threshold of the anomaly.

Molchan's error diagram for earthquake predictions using "anomalies in the Data set A" as precursors.

Results of Molchans' Error Diagram Analysis during 1998-2013 (EQ M≧6.0, D≦40km)



Result Molchan's Error Diagram



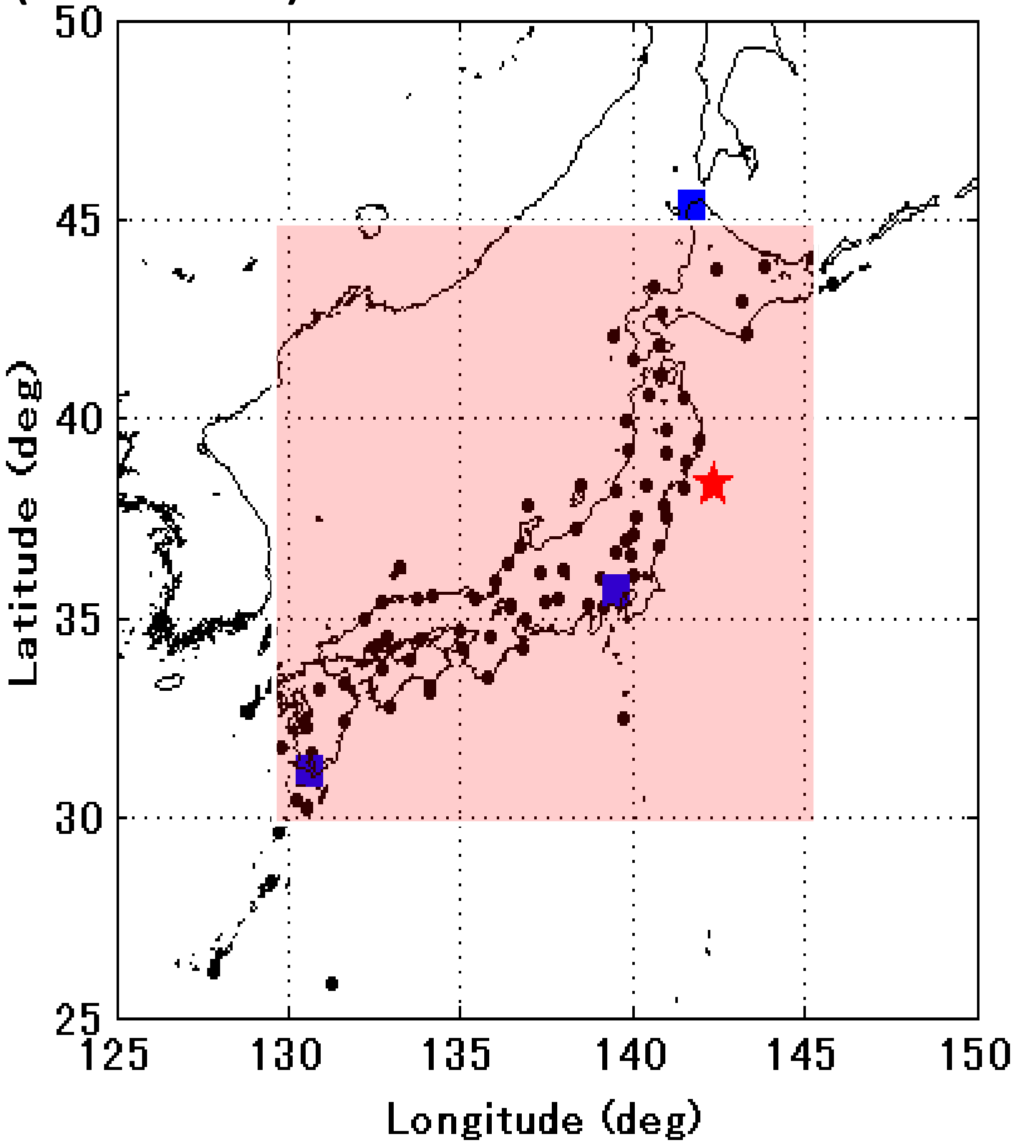
Ionospheric Tomography using local GPS network (GEONET)

- Data
  - 80 GPS stations
  - 3 Ionosonde stations
    （NmF2, hmF2）
    Wakkanai,
    Kokubunji,
    Yamakawa

- reconstructed area
  Lat. 30 – 45°　N,
  Long.130 – 145°　E
  height：100 – 700 km

- spatial resolution　：
  0.5°　× 0.5°　× 30 km

(Hirooka et al., Radio Sci., 2011,
Hirooka et al., NHESS, 2011)



Residual Minimization Training Neural Network (RMTNN)

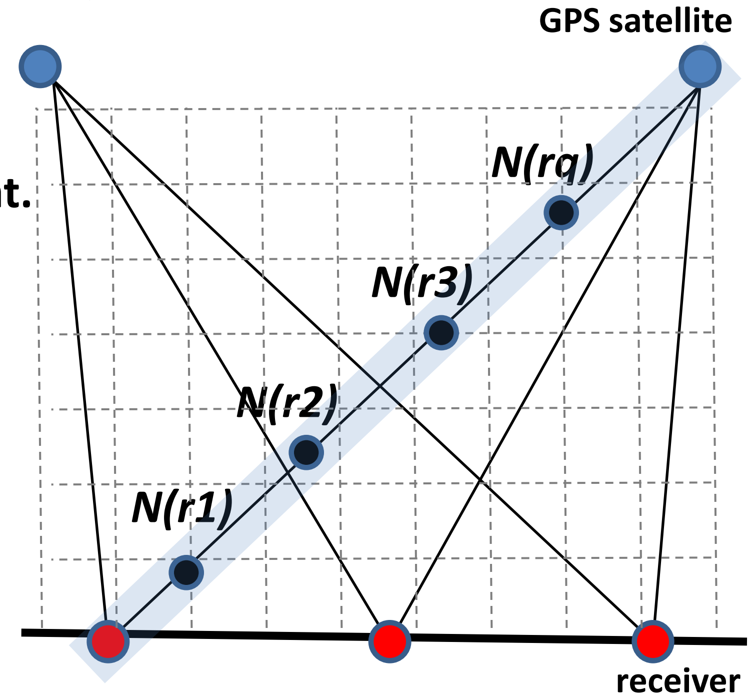
（Ma's approach (Ma et al., 2005)）

Ionospheric Tomography

Observation : TEC along the line between rec. and sat.

No Info. for inputs (lat., long., alt.)

Minimize the residual of objective function



◆**Objective Function**

$$E_{gps} = \sum_{p=1}^{P} \left(\sum_{q=1}^{Q} \alpha_q N(\vec{r}) + B_i + B_j + P_i^j - I_i^j \right)^2$$

$I_j^i = SlantTEC$

$B_i = Bias\ of\ \ ith\ receiver$

$B_j = Bias\ of\ \ jth\ GPS\ \ satellite$

$\alpha : weight$

$P : TEC\ \ in\ \ plasmasphere$

NeQuick Model

$$P_i^j \approx \frac{1}{\cos\theta} n_0 H_s$$

$n_0 : ElectronDensity(700km)$

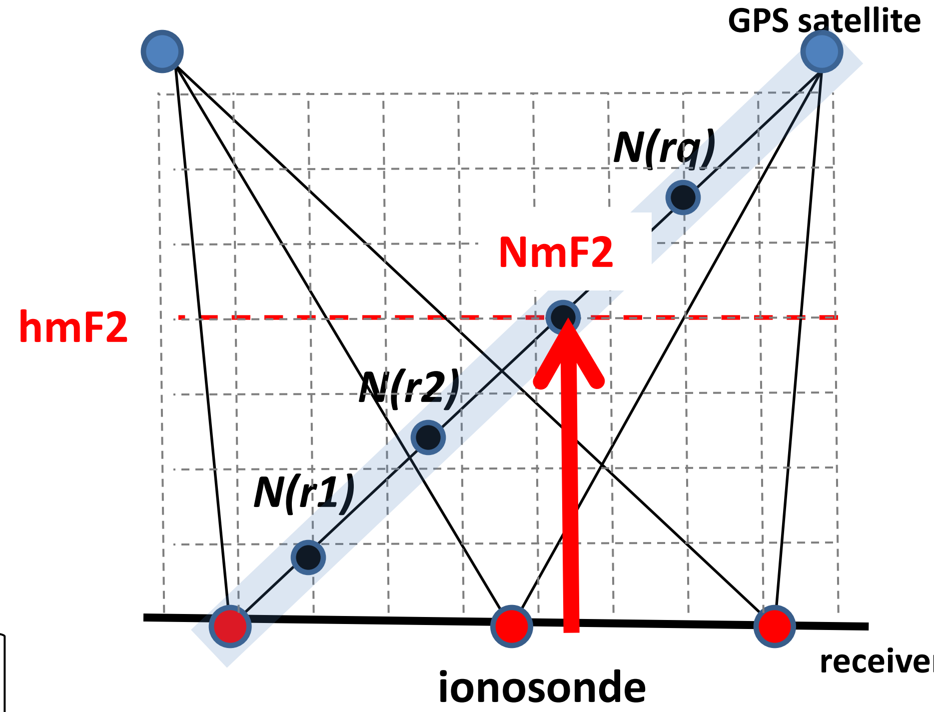
$H_s : ScaleHeight(const)$

$\theta : Zenith\ Angle$

Restriction for reconstruction

Lack of vertical information

Using Ionosonde data (density NmF2 and height hmF2) as a restriction



- cost function for Ionosonde data

$$E_{ionosonde} = \sum_{s=1}^{S} (N_s - N_s^{ion})^2$$

$S : Number of\ Ionosonde$

- cost function for system

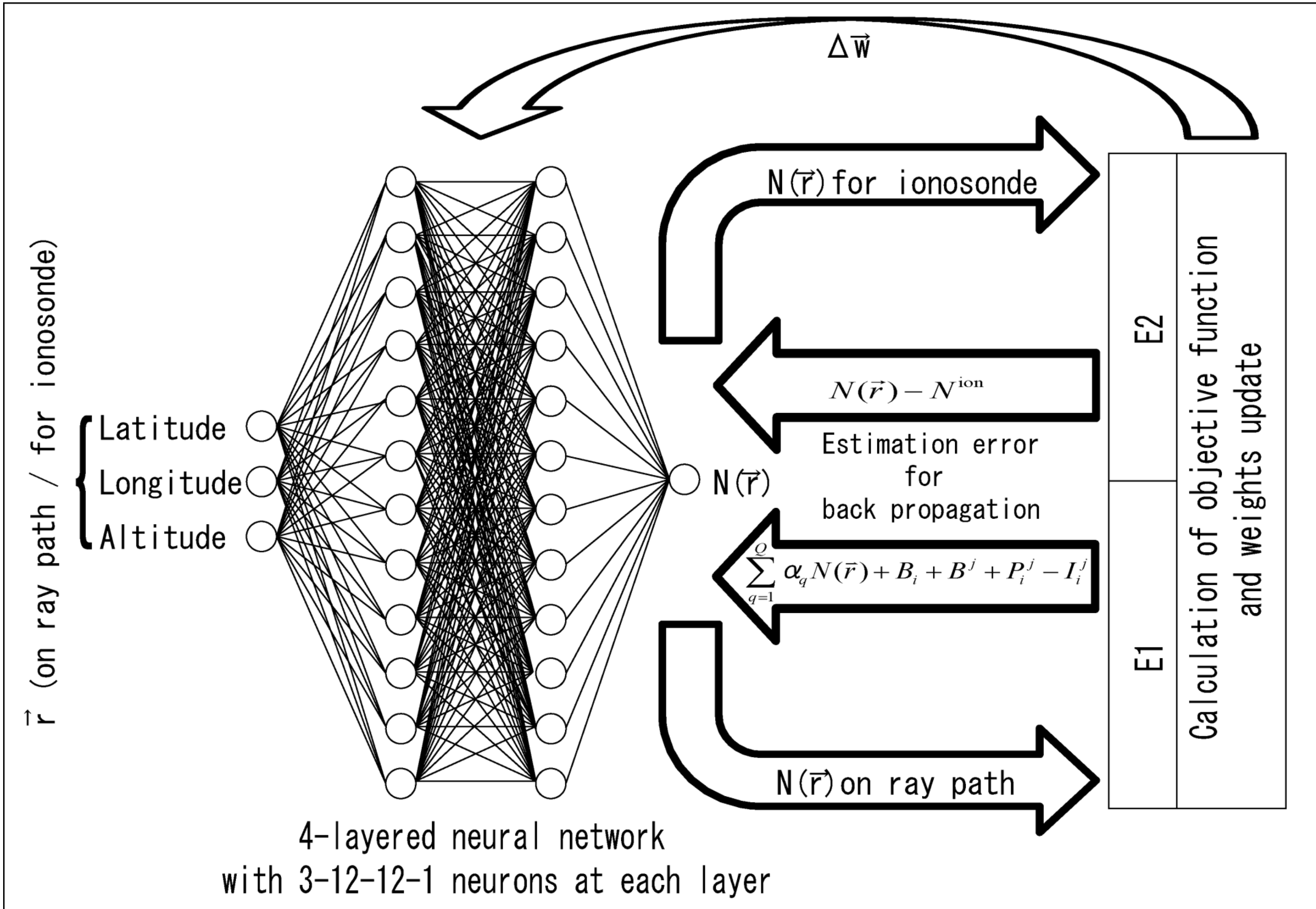
$$E = gE_{gps} + E_{ionosonde}$$

$g : Lagrange's\ coefficient$

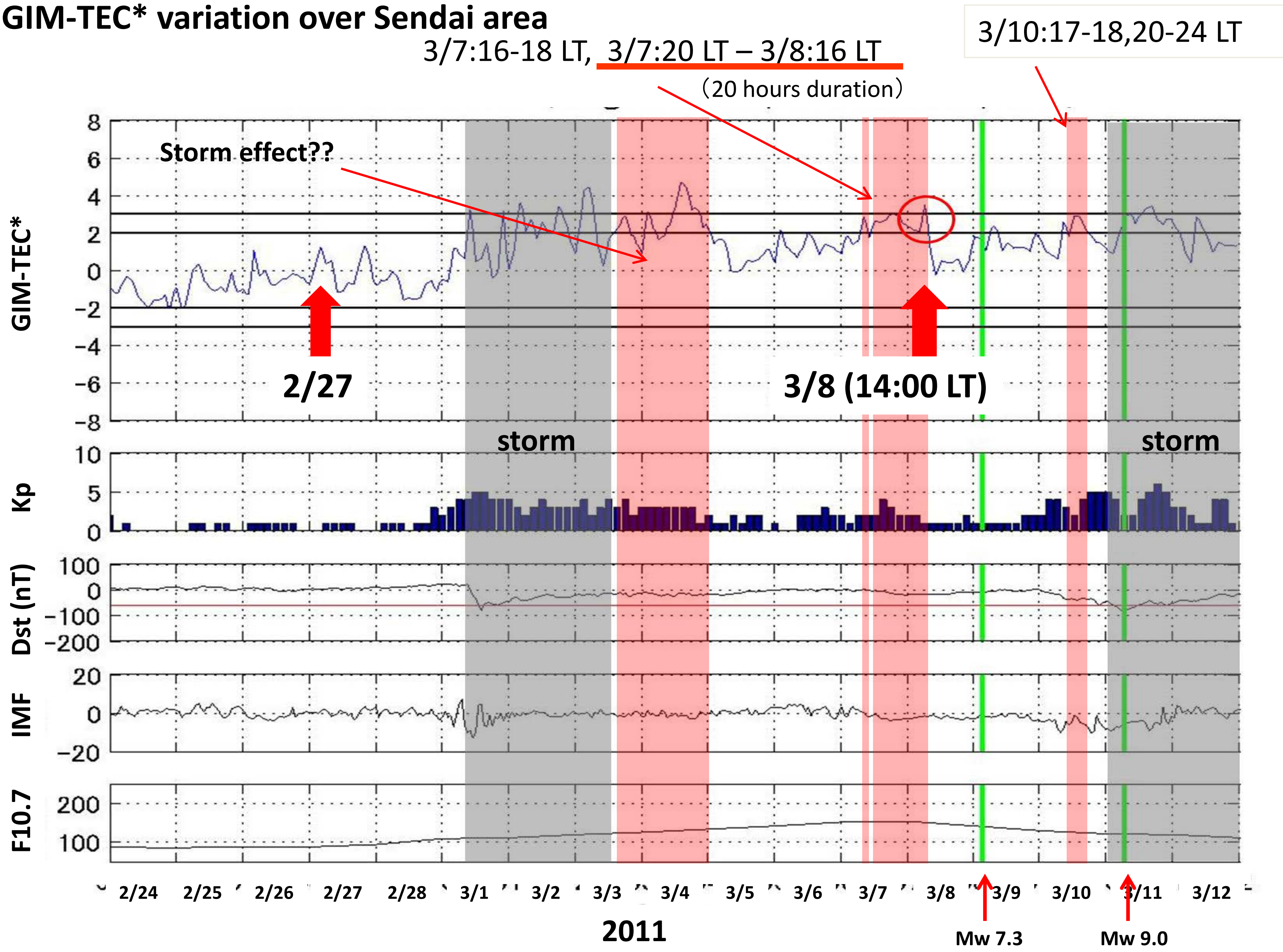
Supervise to minimize function E

Restriction of Ionosonde and other Data make improve reconstruction results.

System design of NN based Ionospheric tomography

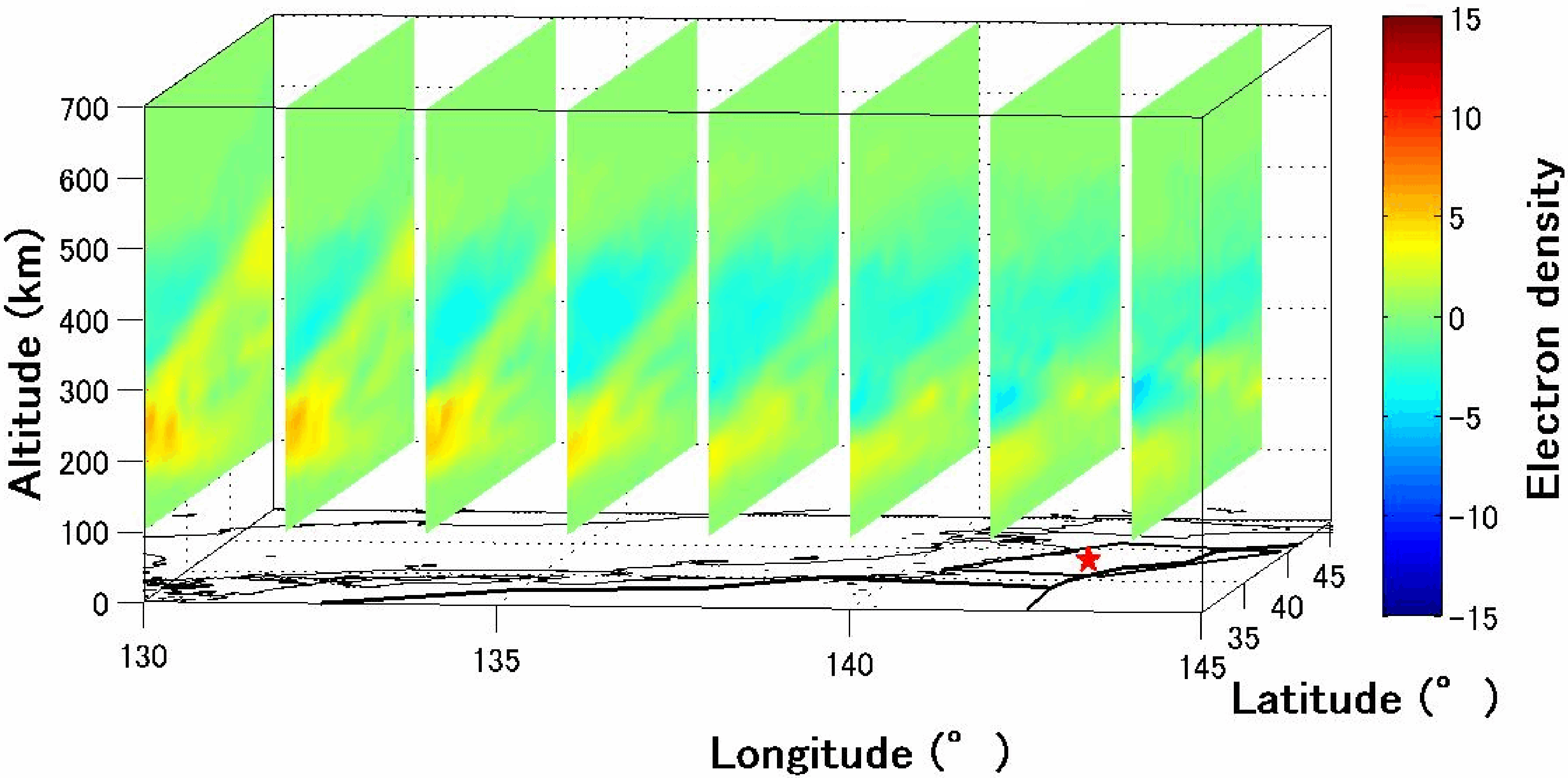


GIM-TEC* variation over Sendai area



GIM-TEC* : No anomaly（13:00 LT on Feb. 27）

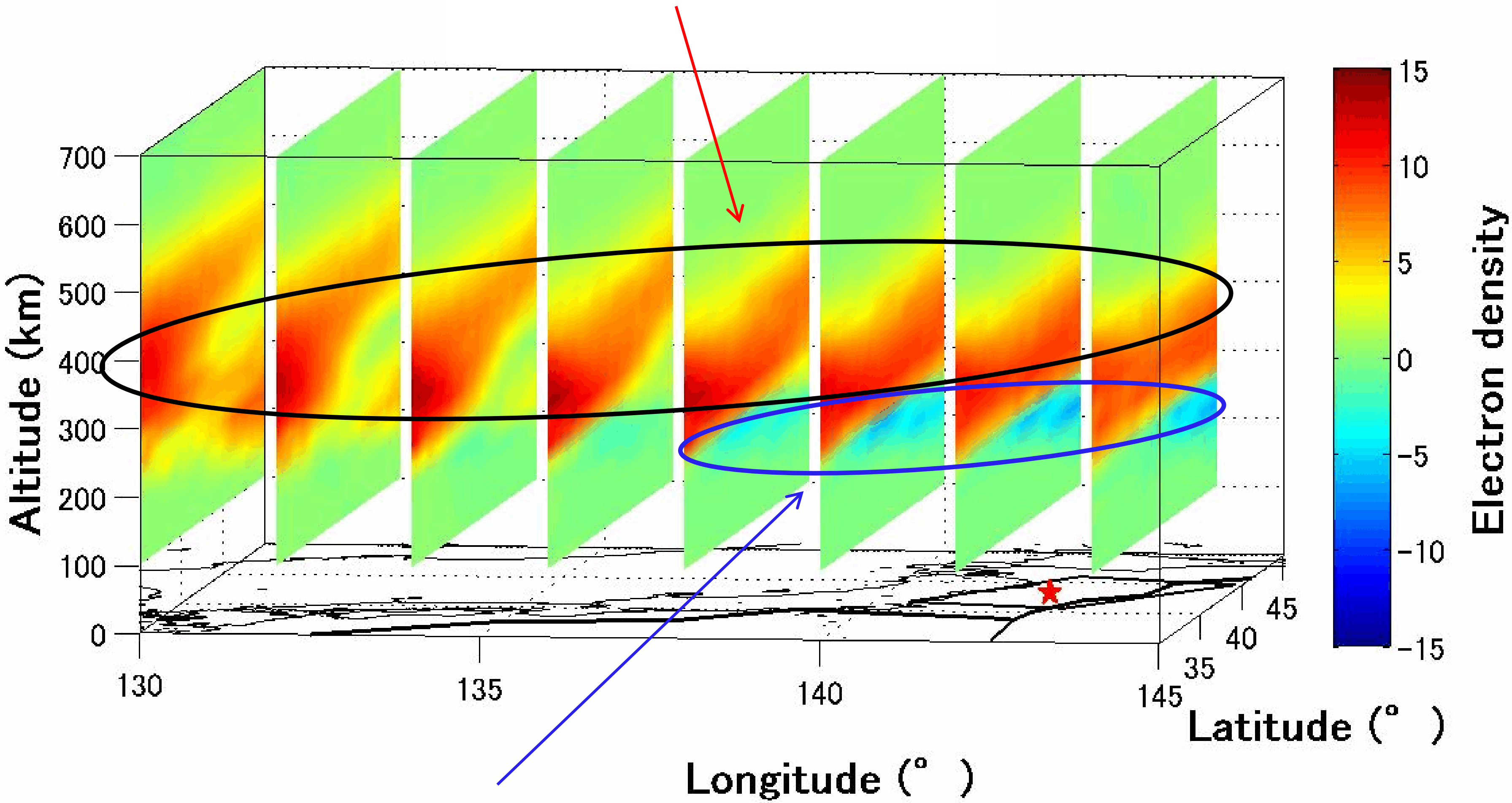
Differential Image



GIM-TEC* : Anomalous day (13:00 LT on March 8)

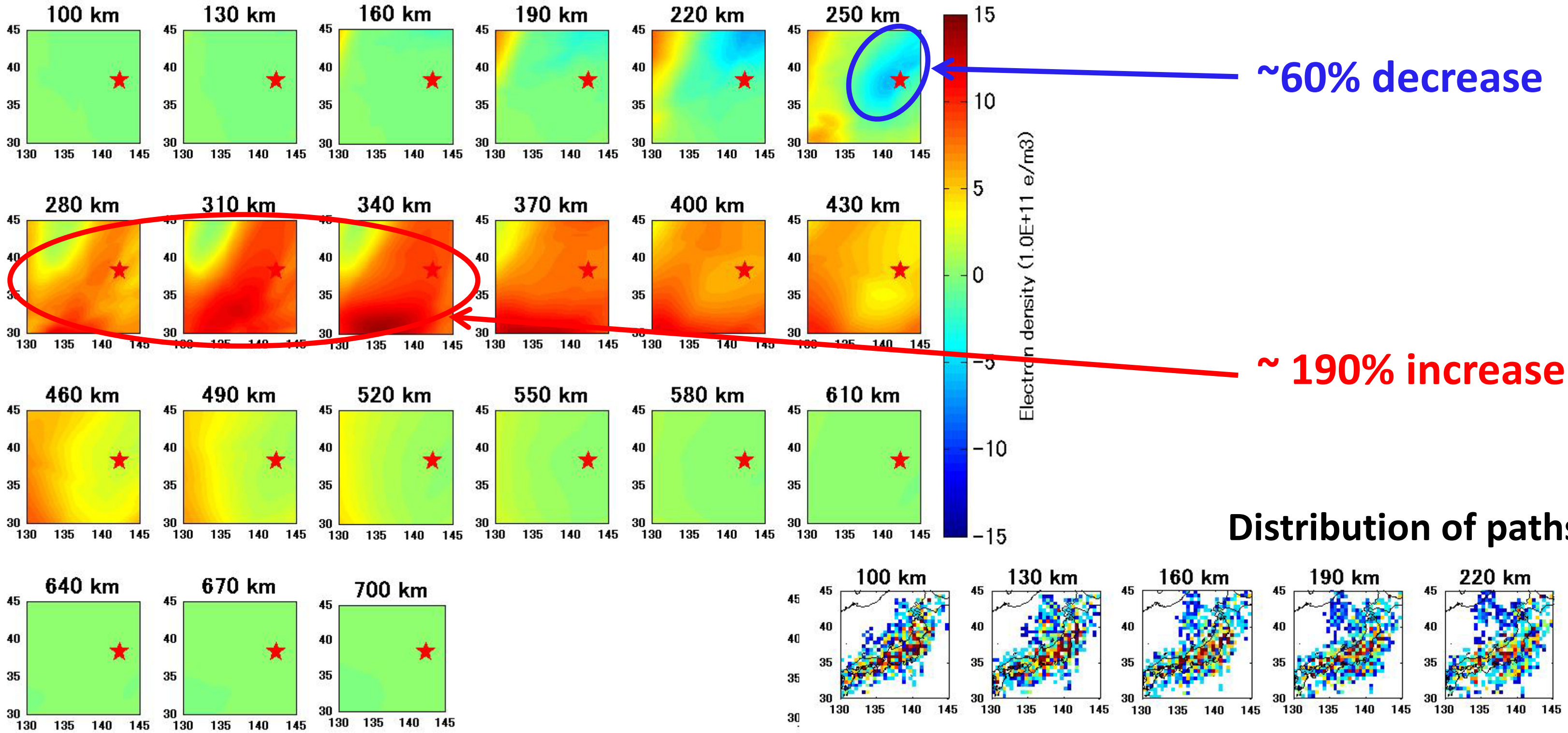
Differential Image

Positive enhancement of electron density（＋190%）

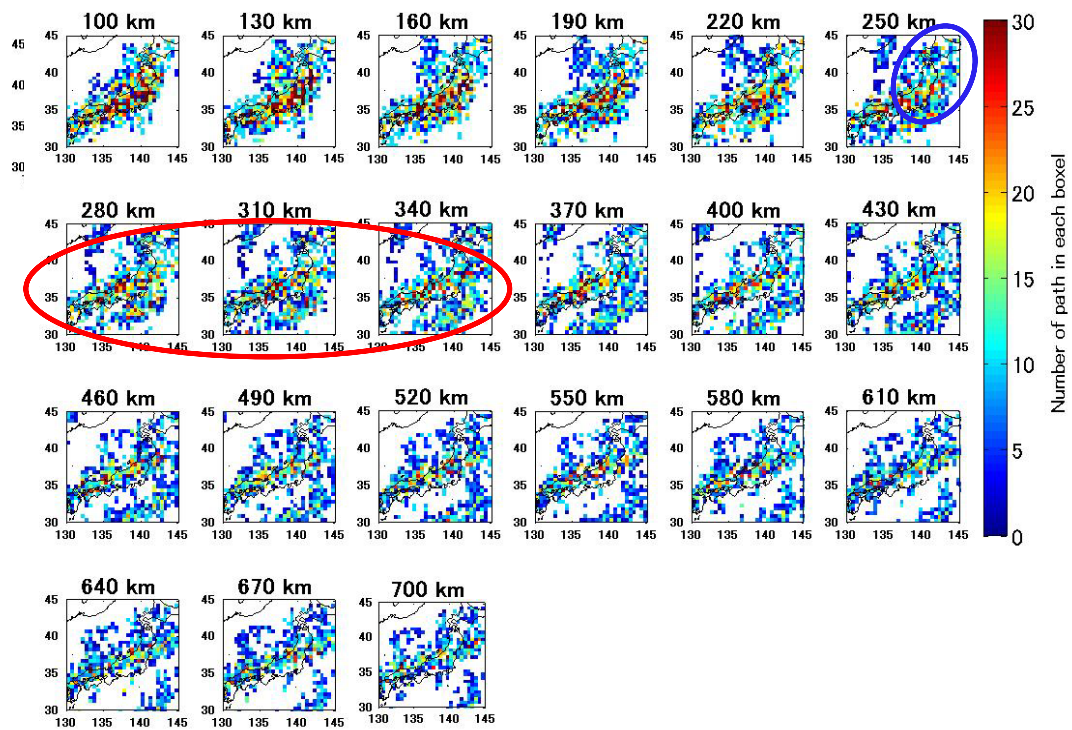


local decrease of electron density over epicenter（~60%）

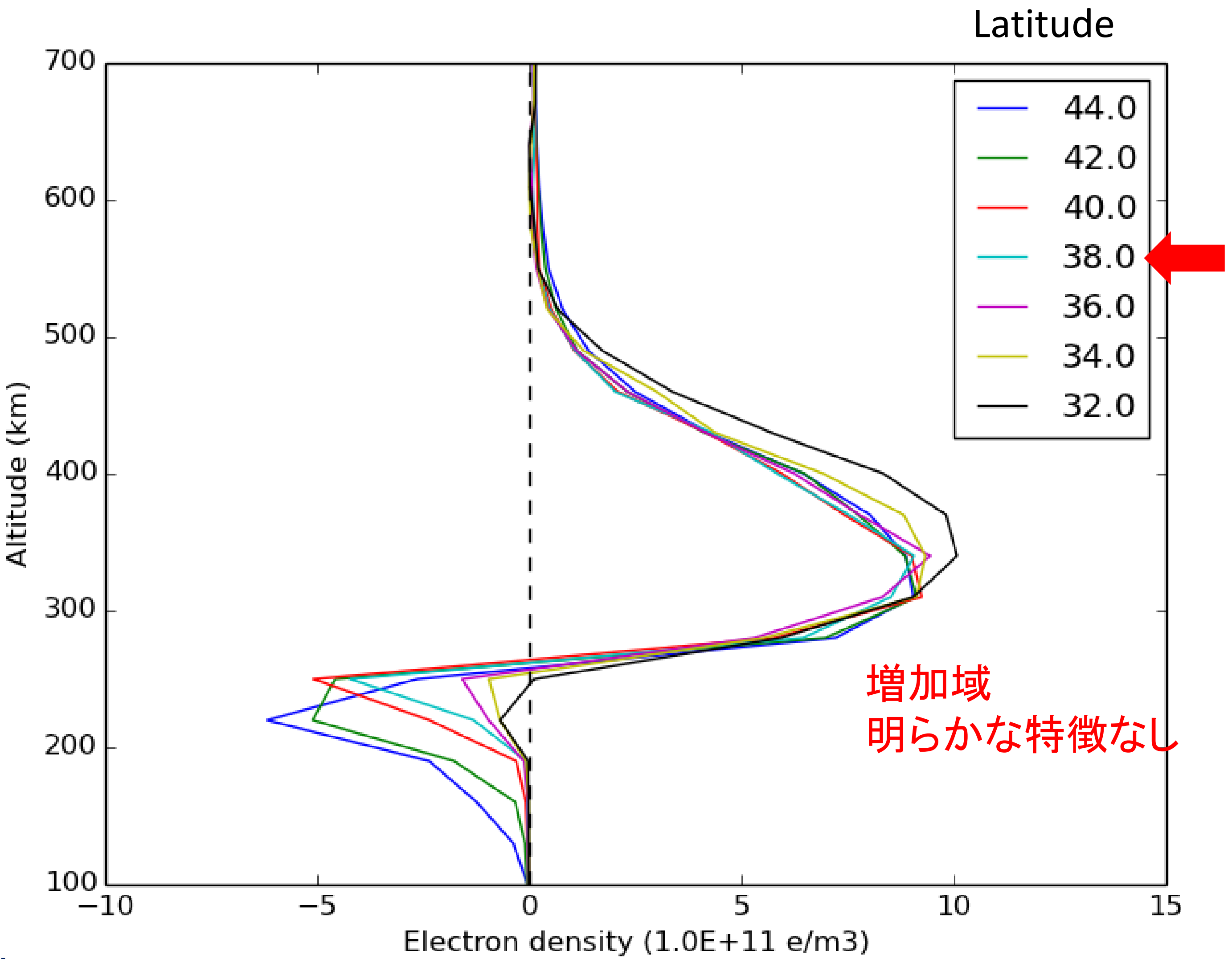
March 8, 13:00 LT



Distribution of paths



Electron density profile at different latitudes for the 20110311 M9 EQ (differential values from 15 days backward median)

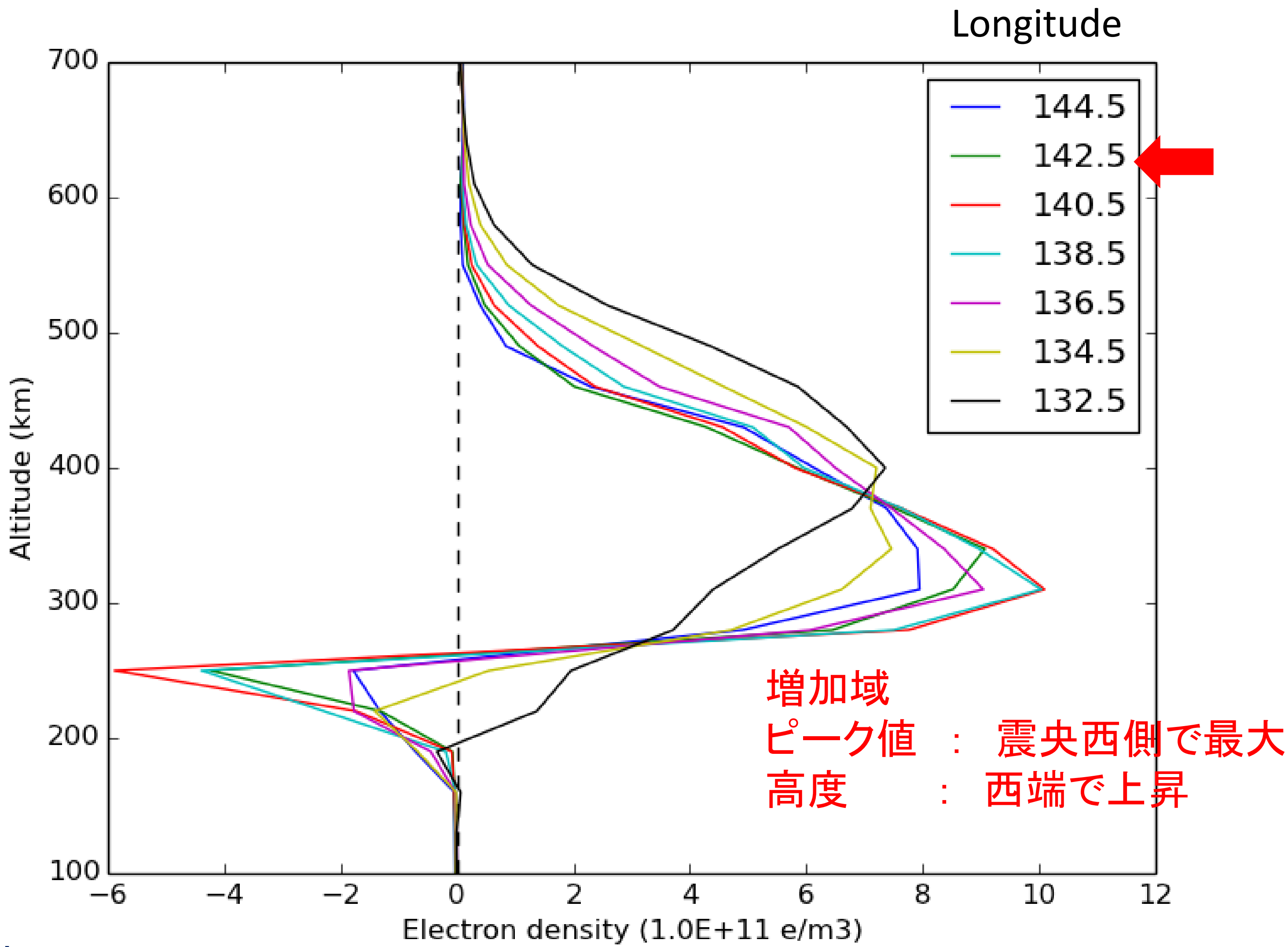


減少域

ピーク値　:　高緯度から低緯度へ徐々に低くなる

高度　　　:　震央付近で最も高くなる

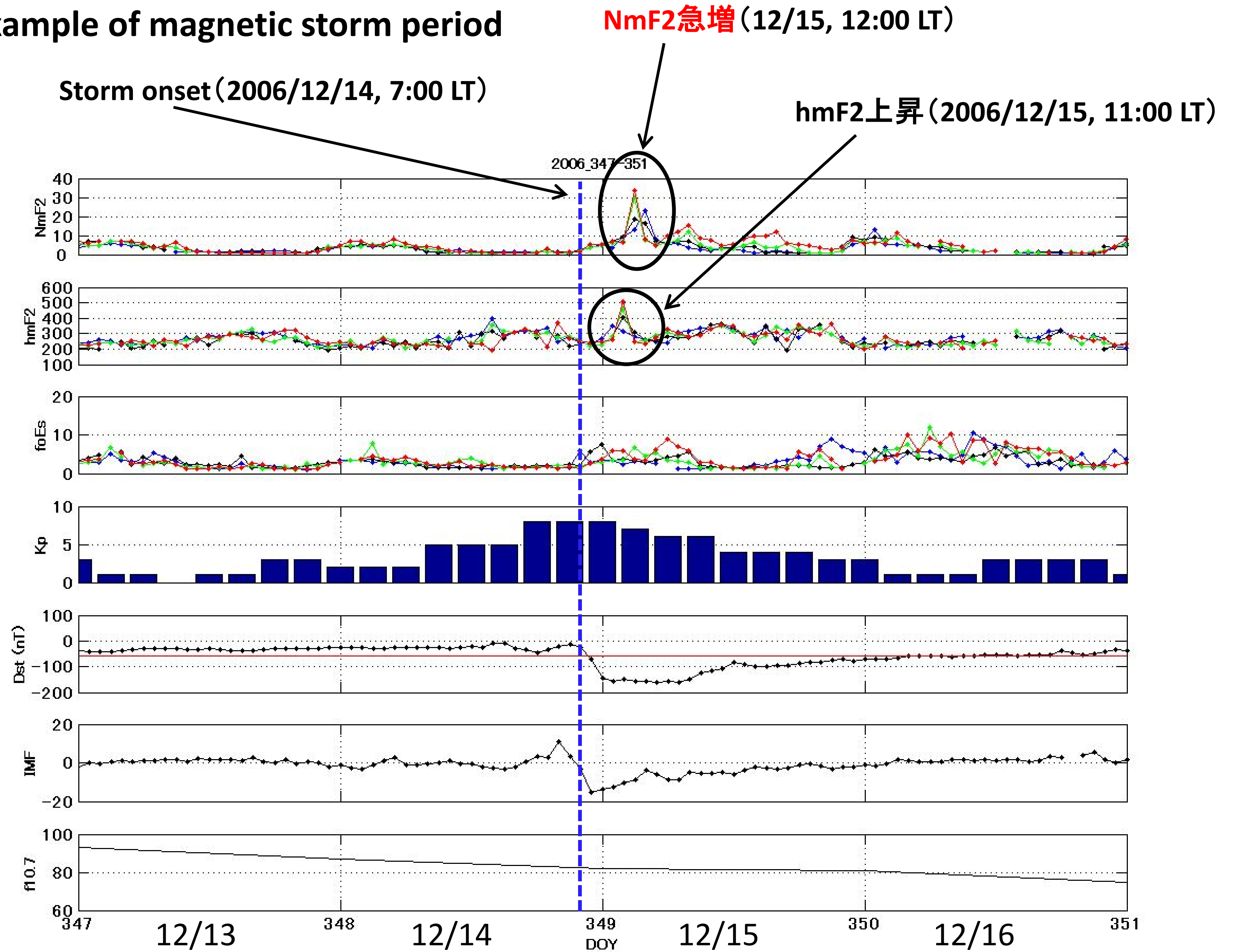
Electron density profile at different longitudes for the 20110311 M9 EQ (differential values from 15 days backward median)



減少域
ピーク値　：　震央付近で最も高くなる
高度　　　：　大きな変化なし

2次元マップ作成

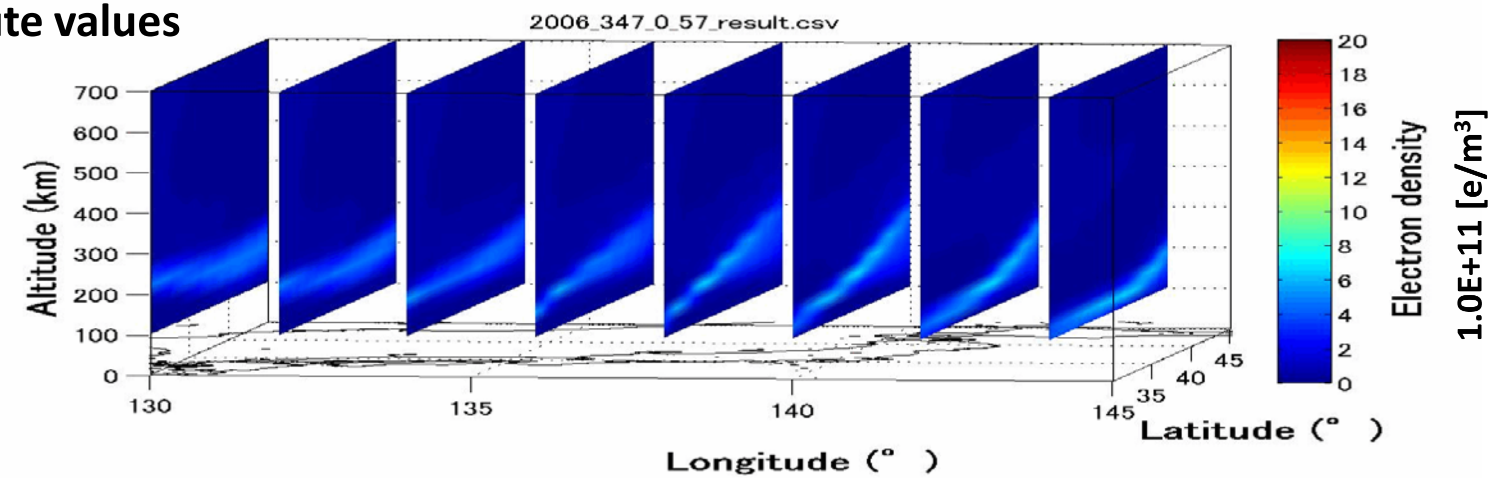
An example of magnetic storm period



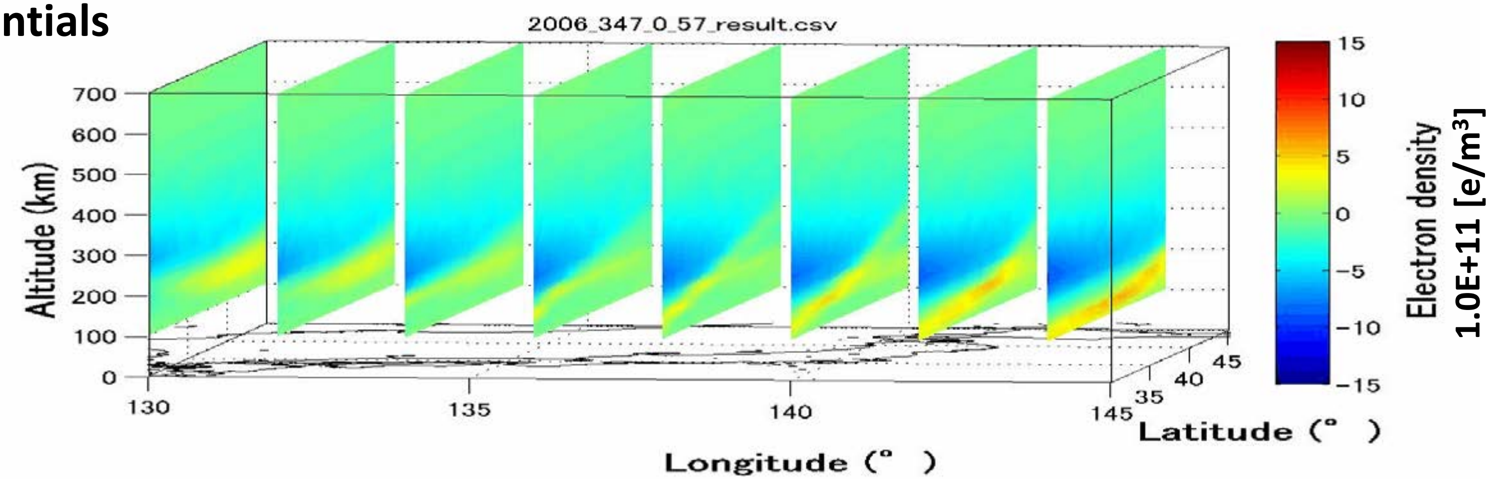
Blue : Wakkanai, Black : Kokubunji, Green : Yamagawa, Red : Okinawa

Storm発生前後の変化
（2006/12/13 – 12/15）

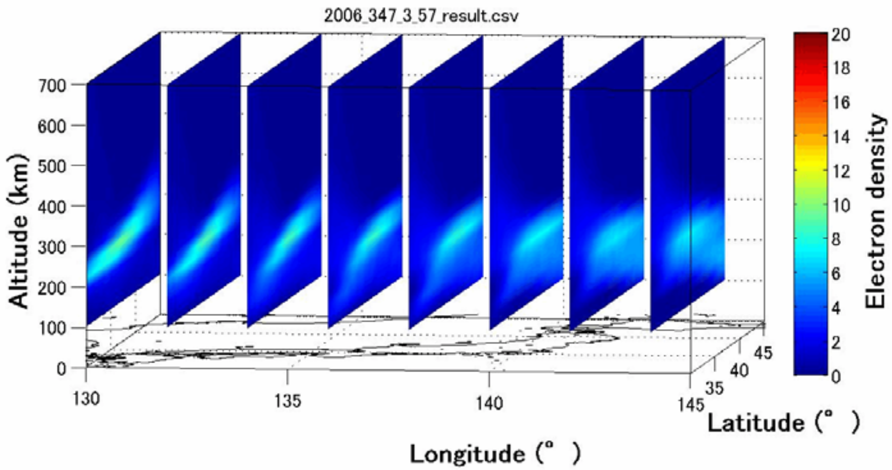
Absolute values

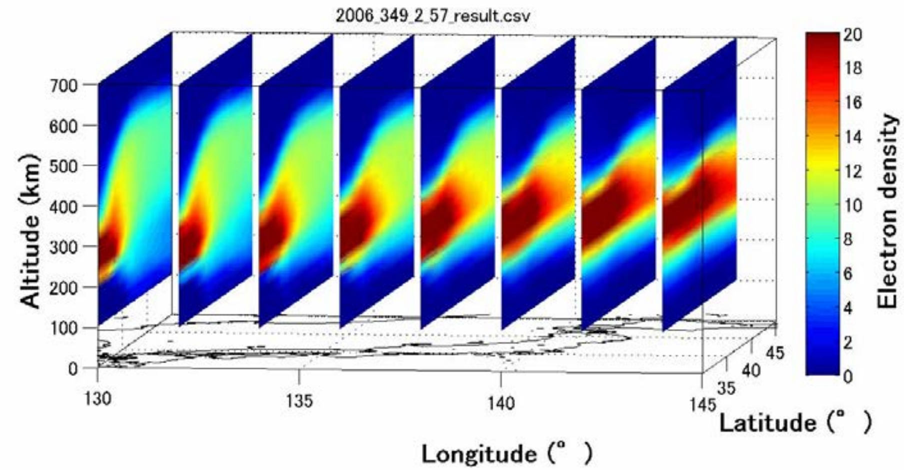


Differentials

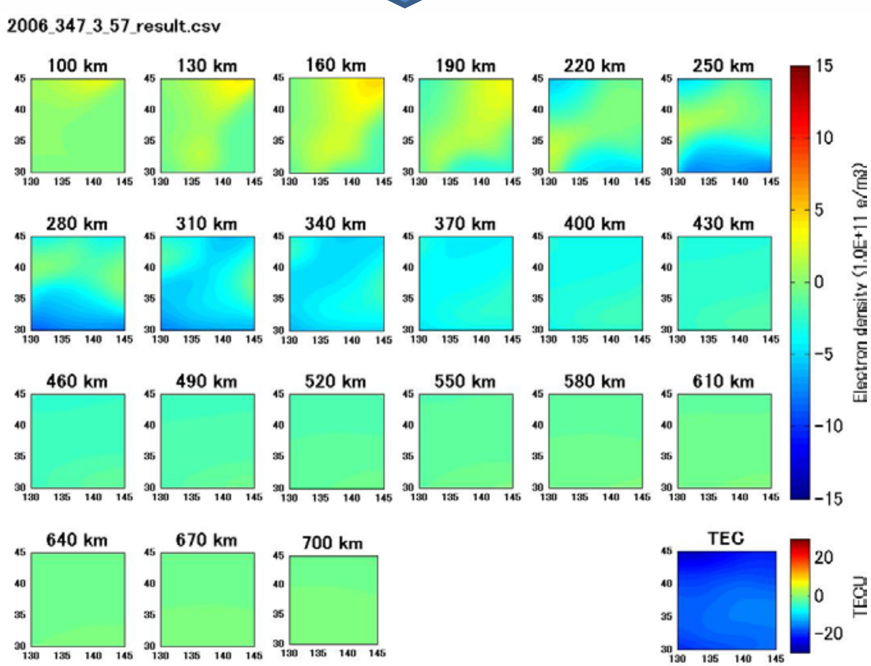


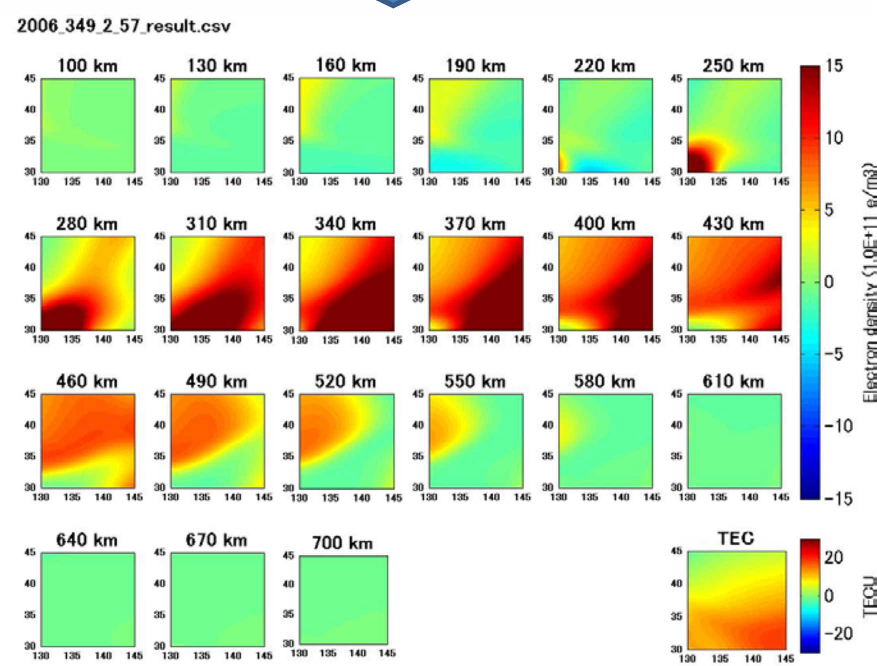
Before Storm（2006/12/13, 13 LT）5 hours after the main phase（2006/12/15, 12 LT）





高度別断面（差分値像）





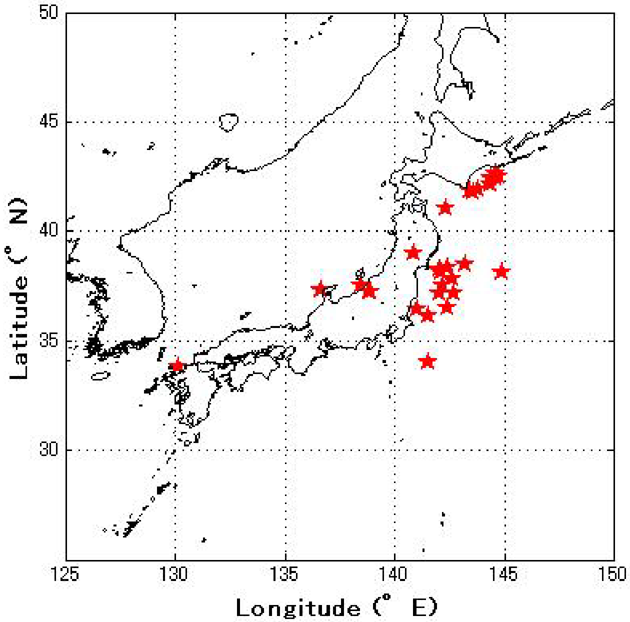
Tomographic results for other EQs（M≧6.0, D≦40 km around Japan）

EQ with M≧6.0, D≦40 km over 1998-2010 + The 2011 Tohoku EQ (M9.0)

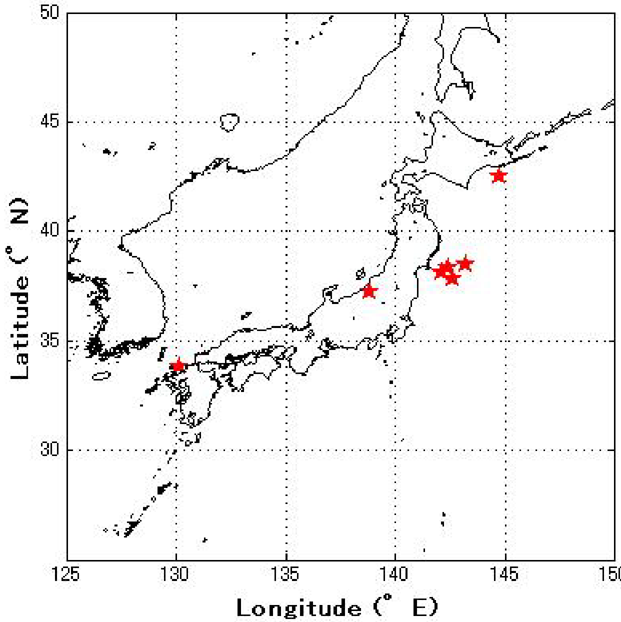
･･･Total 53

GIM-TEC* Anomaly	Number of EQ
① Number of EQ with GIM-TEC* anomalies within 7 days before the EQ satisfied the condition	28
② Number of EQ with duration more than 10 hours/day in the case of ①	7

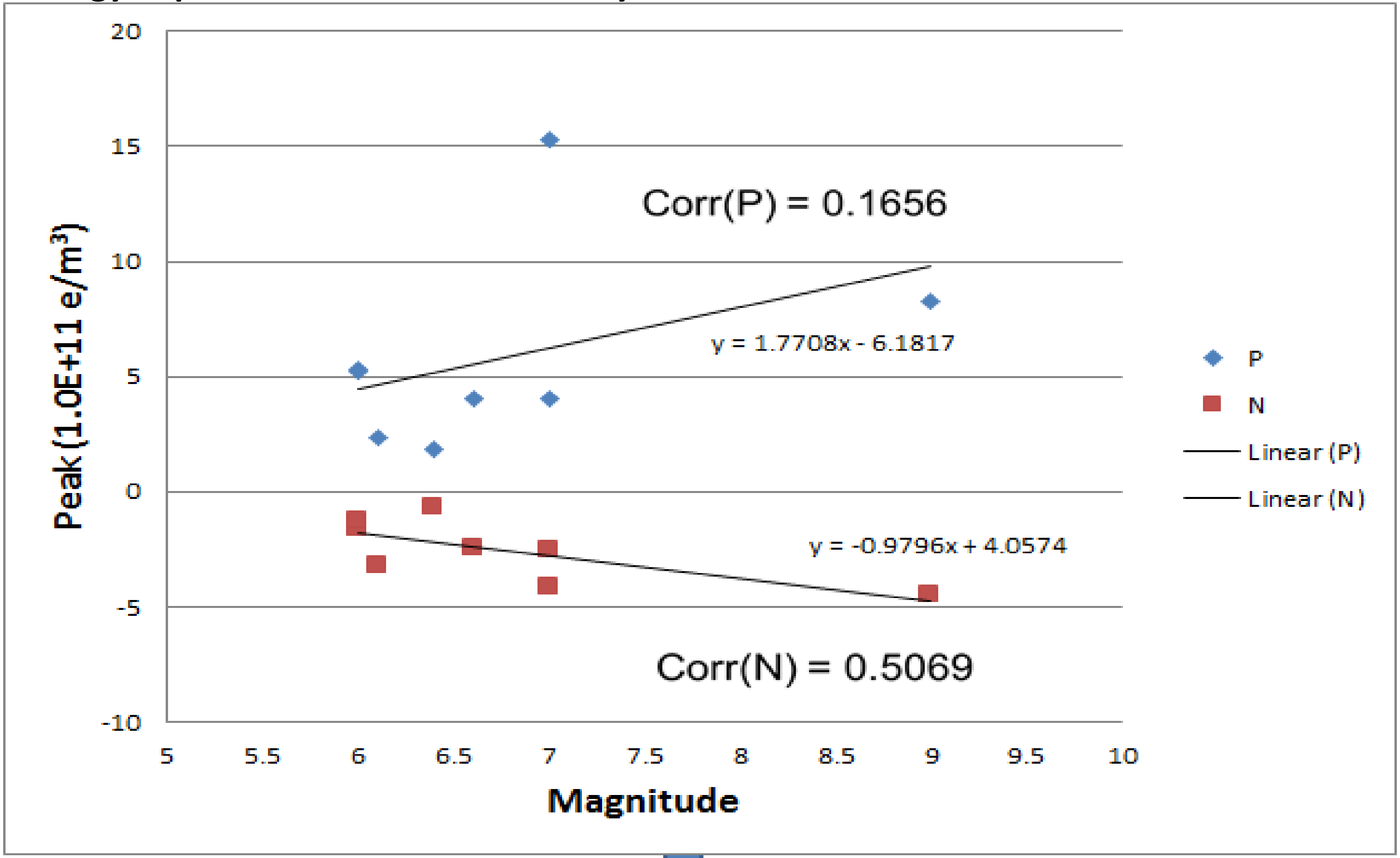
①Distribution on EQ of ①（28 EQ）



② Distribution on EQ of ②（7EQ）



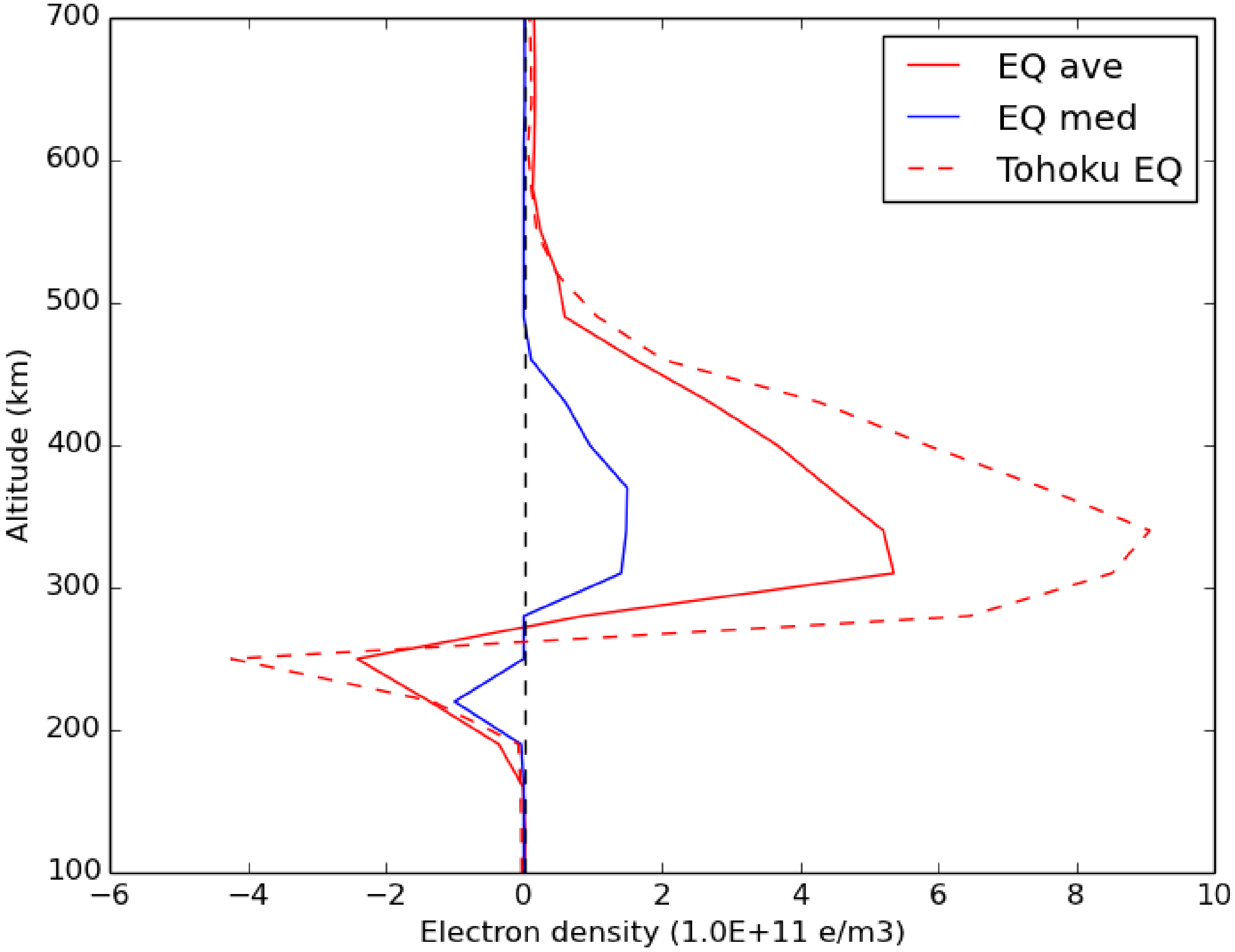
Energy dependence of electron density enhancement



$$E = \frac{10^{4.8+1.5M}}{Depth^2}$$

Energy at surface above the hypocenter

Difference of electron density profile from the 15 days backward median profile over epicenter

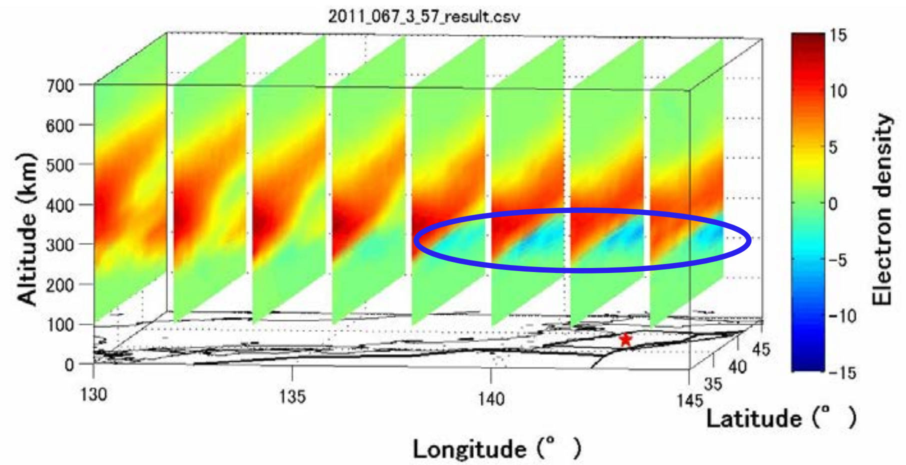


Summary for Tomographic approach

GIM-TEC* ⇒ Significant positive anomaly

Characteristics of 3 D structure

- Local decrease of electron density around 250 km height over the epicenter region.
- increase of electron density at the higher altitude.
- 6/7 of the EQ with a longer GIM-TEC* anomaly (10 hours/day) shows the typical 3D structure (see below) 1-7 days before the EQ.

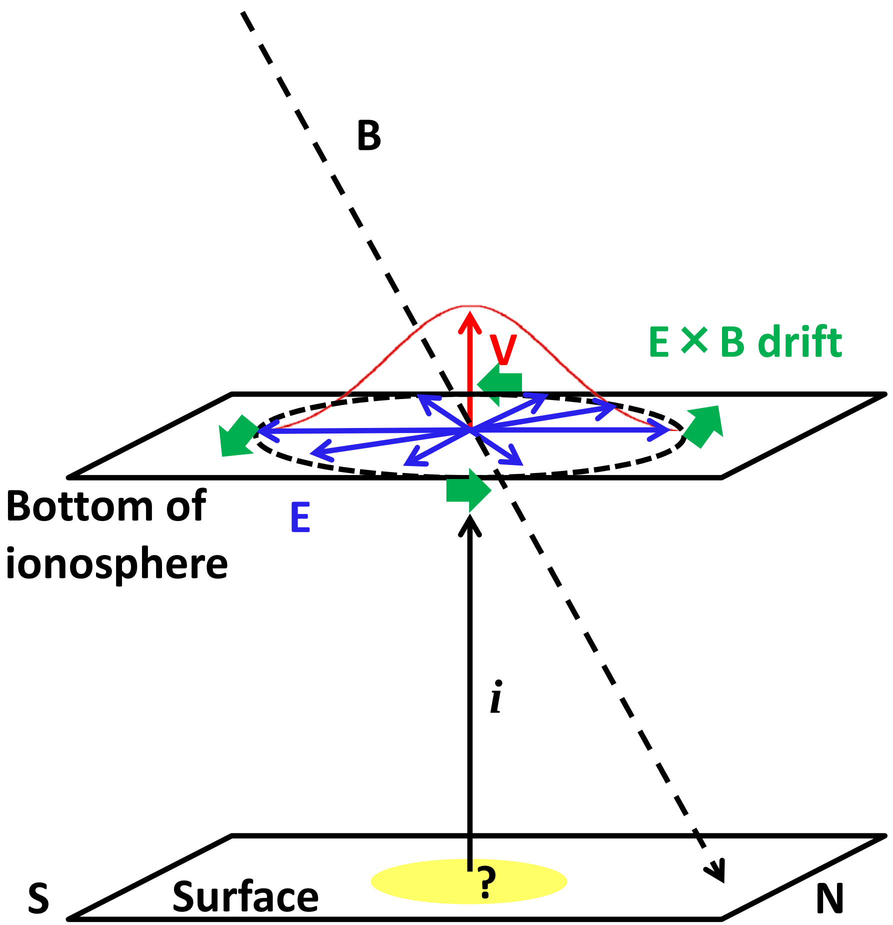


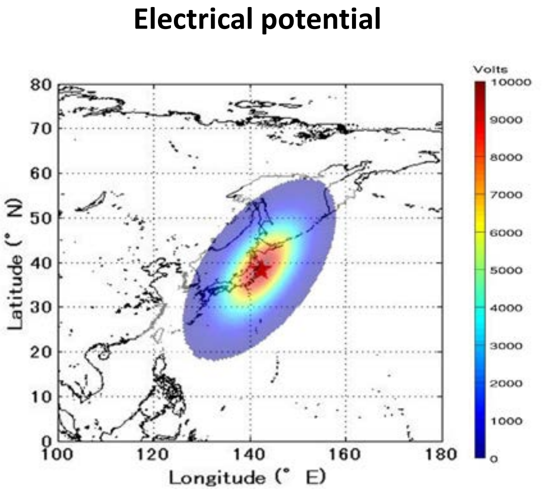
The typical 3 D structure preceding longer GIM-TEC* anomaly

Evaluation with numerical simulation for electron density changes before the EQ

- potential increase at the lower ionosphere

Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) : NCAR

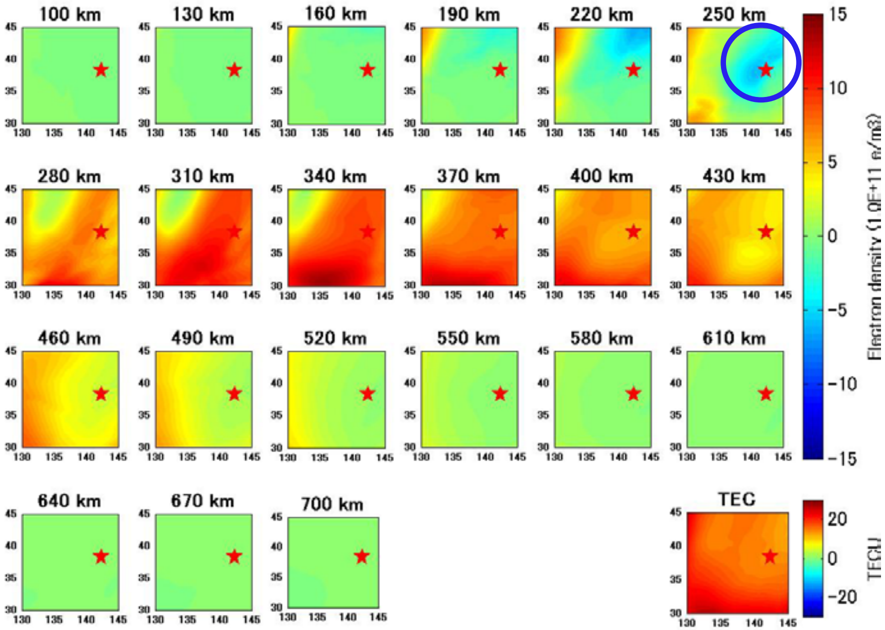


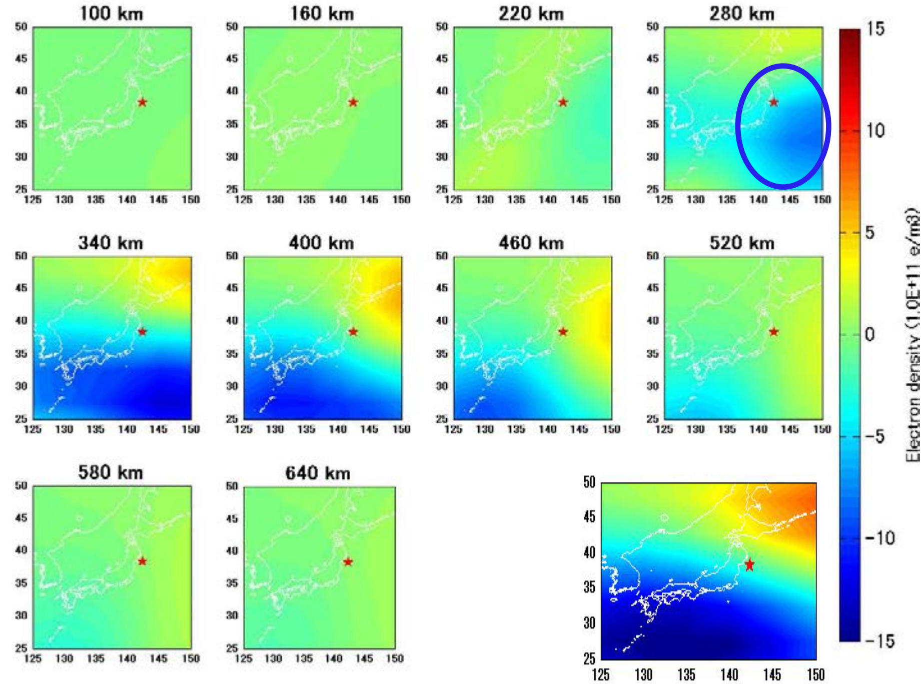


- march 8, 2011
- 10000 V at 97 km height（10 mV/m）
  - Onset of the additive potential is at 0:00 UT and the intensity does not change.

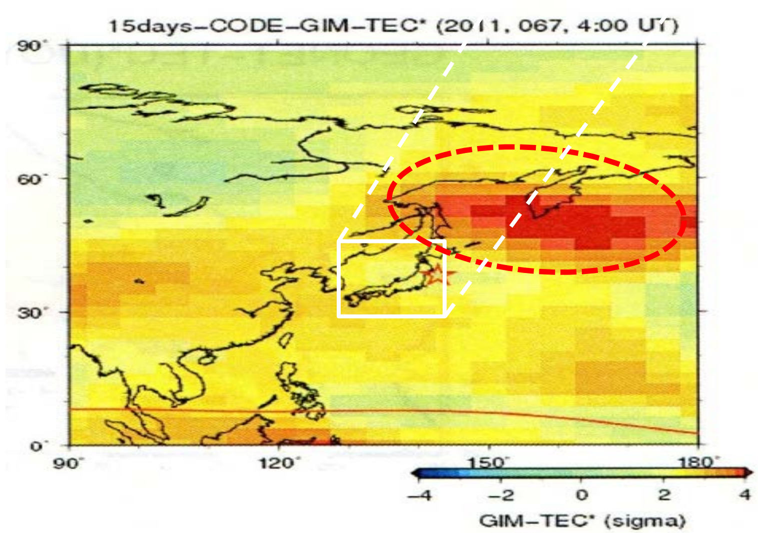
※ personal communication : I-T. Lee, NCU, NCAR

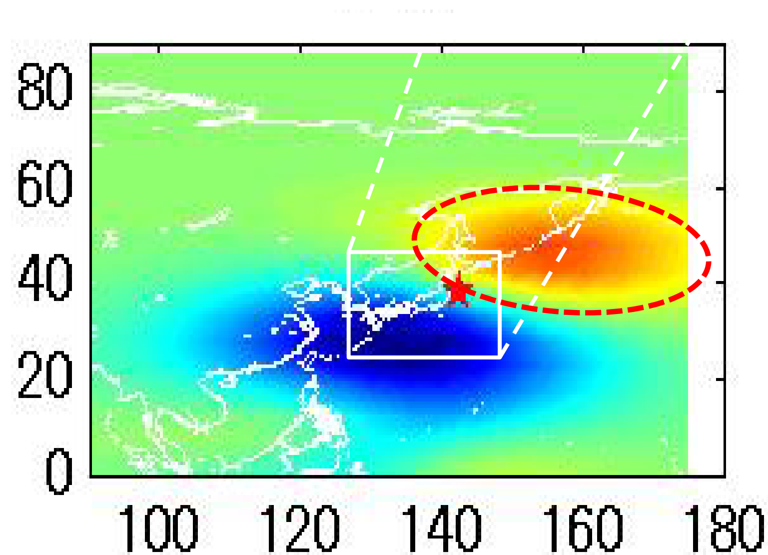
04:00 UT **Observation** **Simulation**





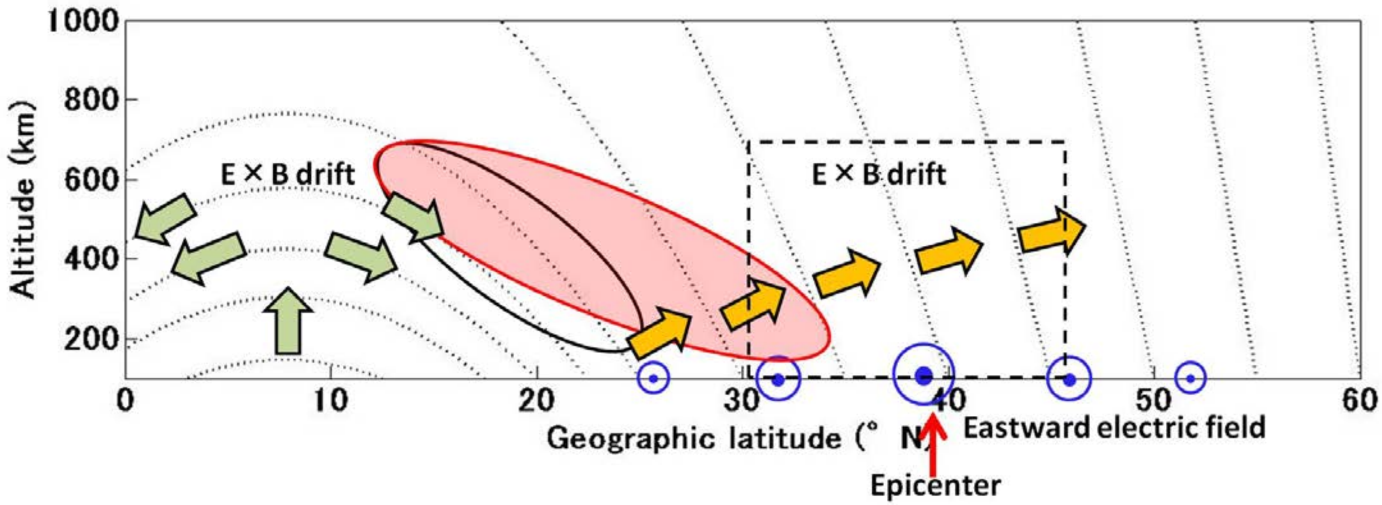
TEC





“electron density increase at altitude of 280～430 km”, and “ TEC increase over Japan”

- **Additive eastward electric field**



Electrons move upward and northward due to E × B drift.

Keep the high electron density due to low collision rate at higher altitude

Increase of electron density and TEC

- **Equator-ward neutral wind**

  - **less evidence of TEC variation from north to south**

Summary

- Investigation on Ionosphere (electron density/TEC) is useful for EQ precursor study .
- For Japan area, positive (increase) TEC anomalies are significant in statistical study and there are epicentral and magnitude dependences.
- Lead time is likely to be less than 5 days and the disturbed area looks wide for EQ-related TEC anomalies .
- Tomographic analysis show that Local decrease of electron density around 250 km height over the epicenter region increase of electron density at the higher altitude and 6/7 of the EQ with a longer GIM-TEC* anomaly (10 hours/day) provides the typical 3D structure before the EQ.
- Tomographic approach is essentially important to clarify the mechanisms.

Thank you for attention