Ionospheric disturbances possibly associated with Large Earthquakes
- temporal and spatial analysis -

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Background

★ Many anomalous electromagnetic phenomena possibly associated with large earthquakes have been reported.

(e.g. Hayakawa and Fujinawa, 1994; Hayakawa, 1999; Hayakawa and Molchanov, 2002; Pulinets and Boyarchuk, 2004)

Electromagnetic approach

Most effective method for short-term earthquake prediction!?

Among of them

Detection of TEC (Total Electron Content) changes in the ionosphere is one of the promising methods.

Preseismic TEC change

The 1999 Chi-Chi EQ

GPS-TEC decreased significantly 3, 4 days before EQ. (Liu et al., 2001, 2004)

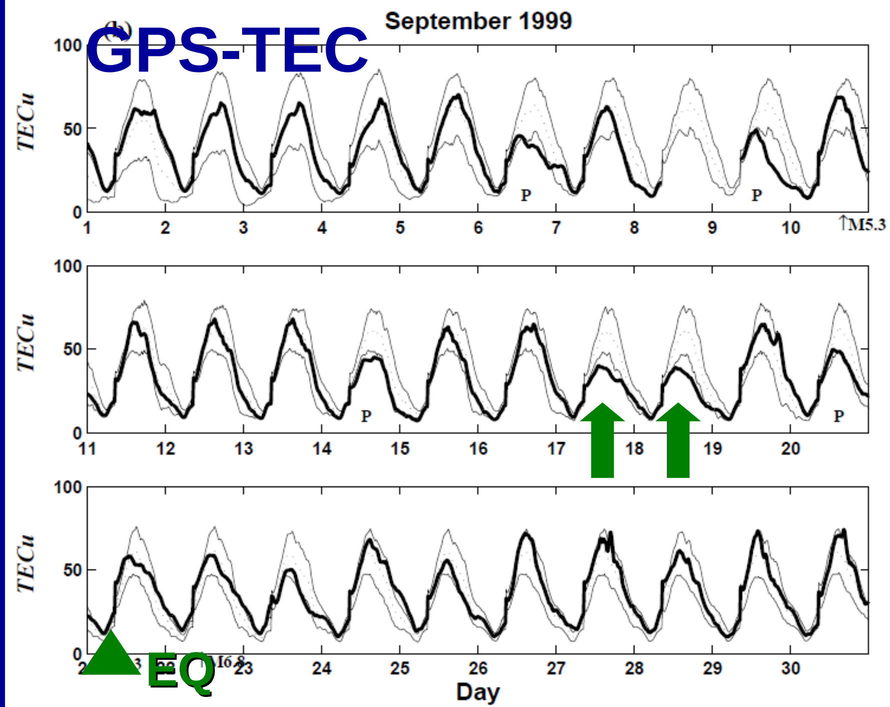
simultaneously

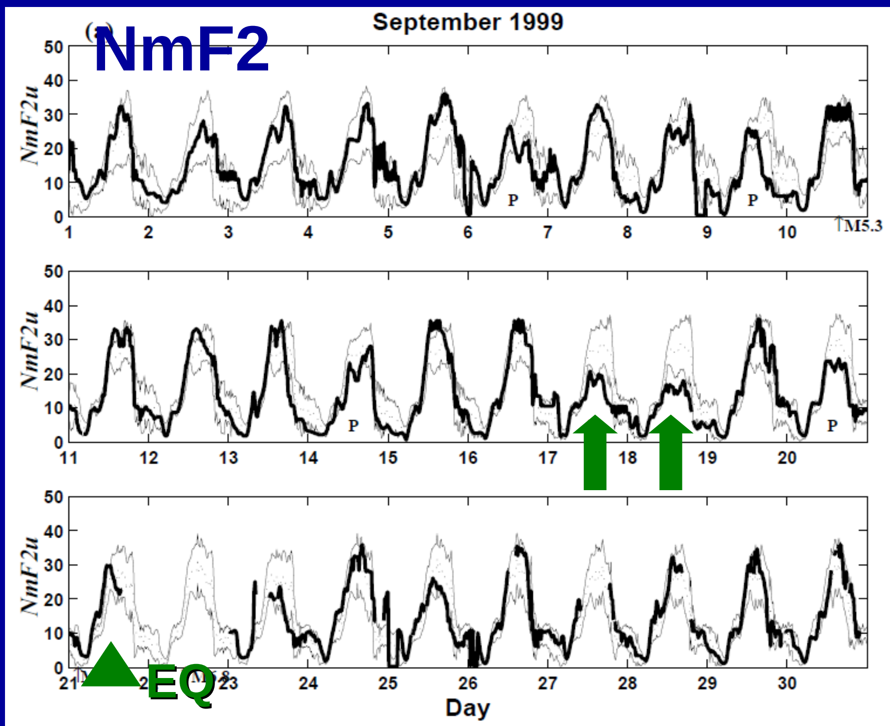
15 days backward running median decreased exceeding IQR.

NmF2 (F2-layer maximum electron density) decreased significantly 3, 4 days before EQ. (Liu et al., 2000, 2004)

From statistical analysis, the ionospheric anomalies appeared 1 - 5 days before M>=5.0 earthquakes in Taiwan.

(Liu et al., 2004, 2006)





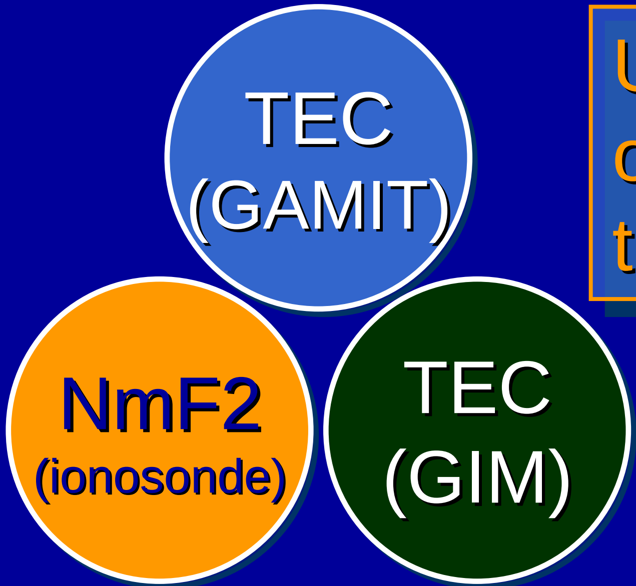
Purpose

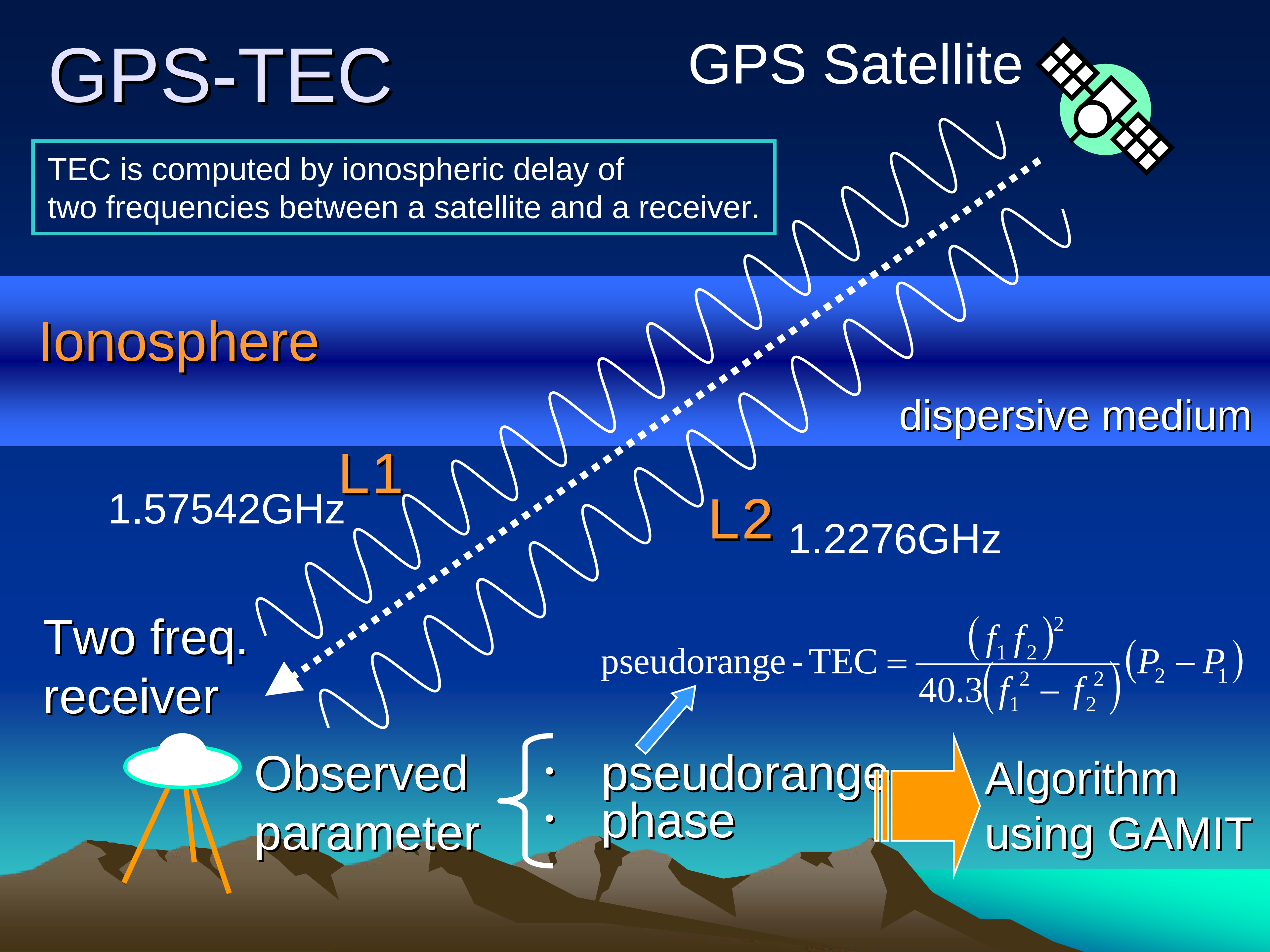
Investigation of the Taiwan Chi-Chi EQ reported by Liu et al.

(e.g. Liu et al., 2001, 2004)

These studies have not been checked whether the anomalies observed in Taiwan were local or global phenomena.

Understand the spatial distribution of ionospheric disturbances prior to the Earthquakes.



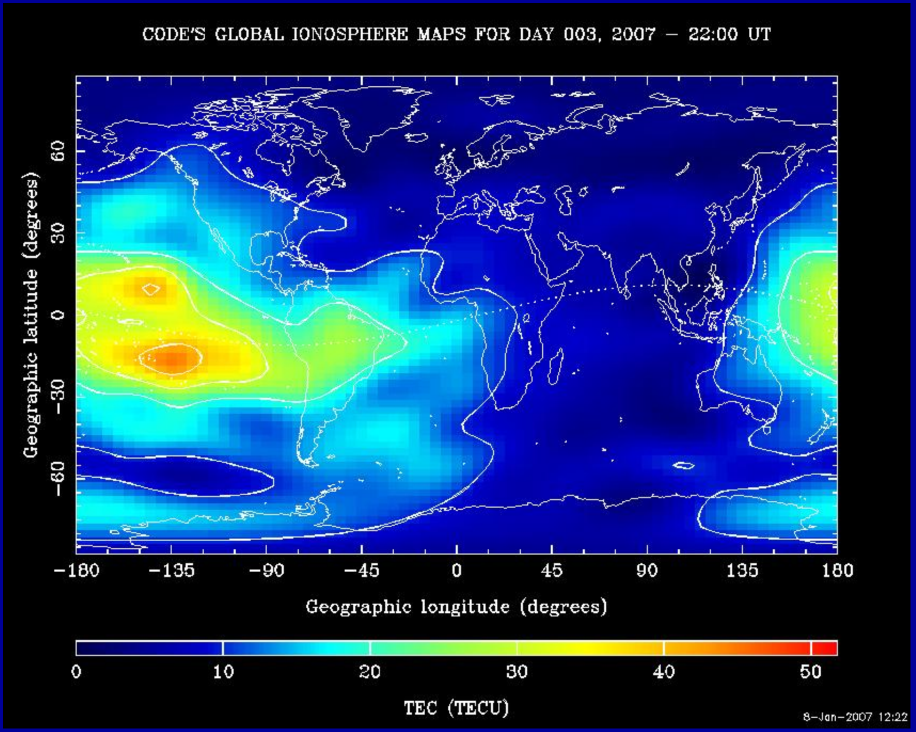

GPS-TEC
GPS Satellite
TEC is computed by ionospheric delay of two frequencies between a satellite and a receiver.
Ionosphere
dispersive medium
L1
1.57542GHz
L2
1.2276GHz
Two freq. receiver
$$\text{pseudorange-TEC} = \frac{(f_1 f_2)^2}{40.3(f_1^2 - f_2^2)}(P_2 - P_1)$$
Observed parameter
• pseudorange
• phase
Algorithm using GAMIT

Global Ionosphere Maps (GIM)

GIM is global TEC data-set produced by the Center for Orbit Determination in Europe (CODE).

Spatial resolution :
2.5 degrees in latitude
5 degrees in longitude
Time resolution : 2 hours

In order to be able to observe GPS-TEC values at a certain location, we extracted data from the GIM and linearly interpolated to yield a 15-min. resolution at a certain location.



Example of GIM data (22UT, Jan. 3, 2007)

Case Study 1:

The 1999 Chi-Chi & Chia-Yi EQs

Case Study 1:

- Chi-Chi EQ -

September 21, 1999 01:47(LT)

September 20, 1999 17:47(UT)

Mw 7.6 (M_L 7.3)

23.85°N, 120.82°E

Depth: 8km

- Chia-Yi EQ -

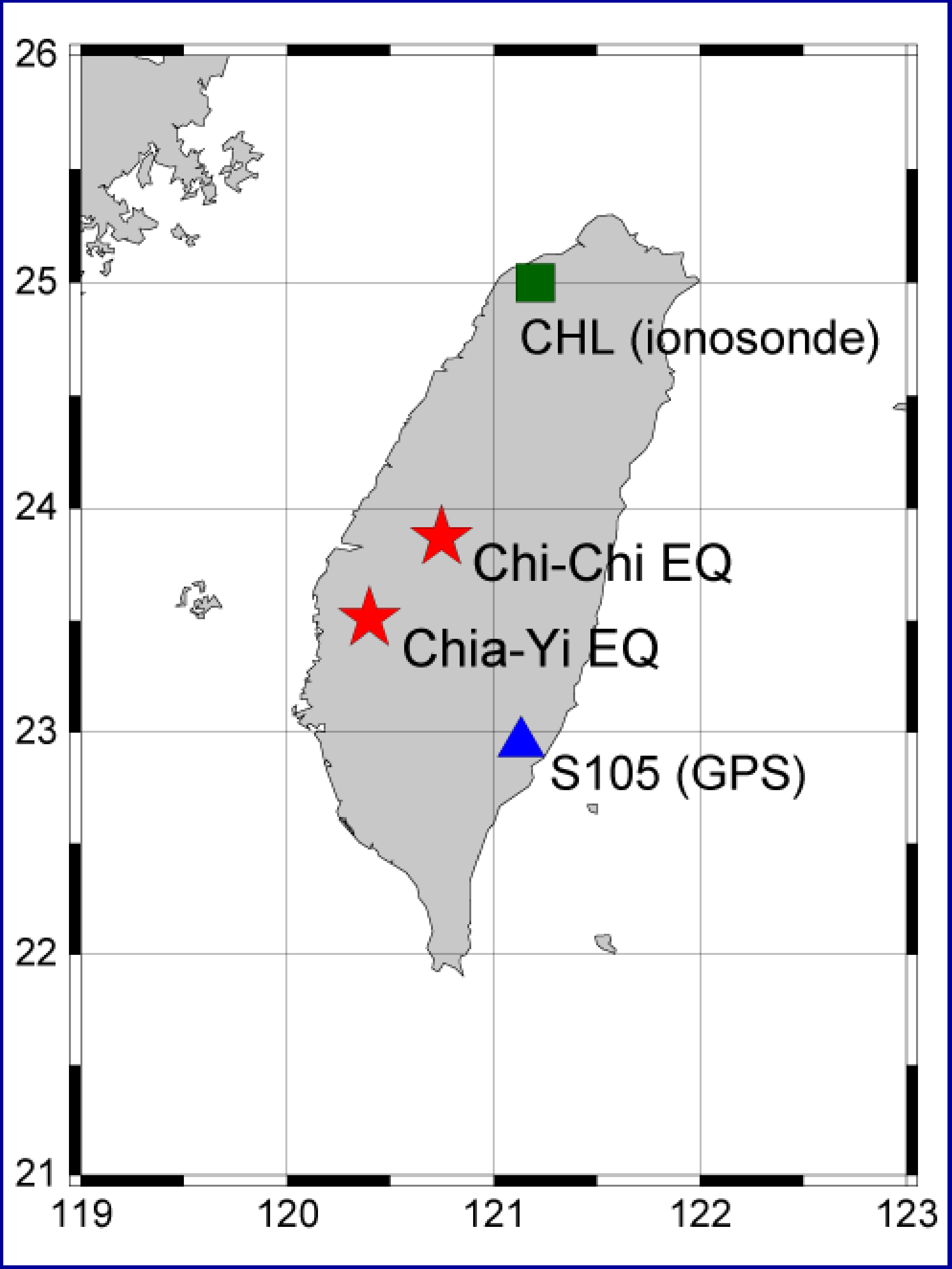
October 22, 1999 10:18 (LT)

October 22, 1999 02:18 (UT)

M_L 6.4

23.52°N, 120.42°E

Depth 16.6km

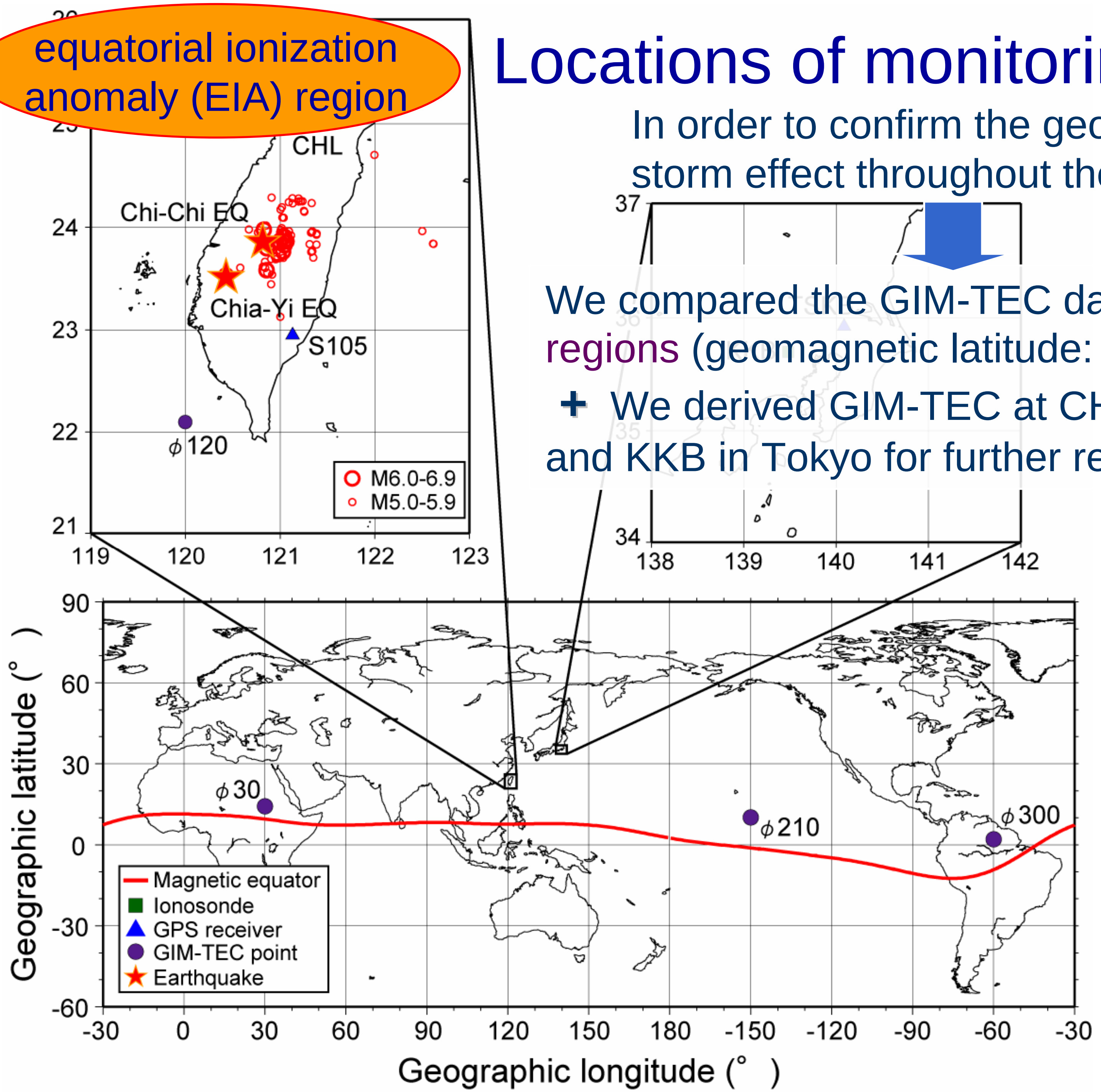


Locations of monitoring station

In order to confirm the geomagnetic storm effect throughout the globe

We compared the GIM-TEC data at 4 EIA regions (geomagnetic latitude: 12°N).

+ We derived GIM-TEC at CHL in Taiwan and KKB in Tokyo for further references.



Variations of NmF2, TEC, GIM-TEC during the Chi-Chi EQ

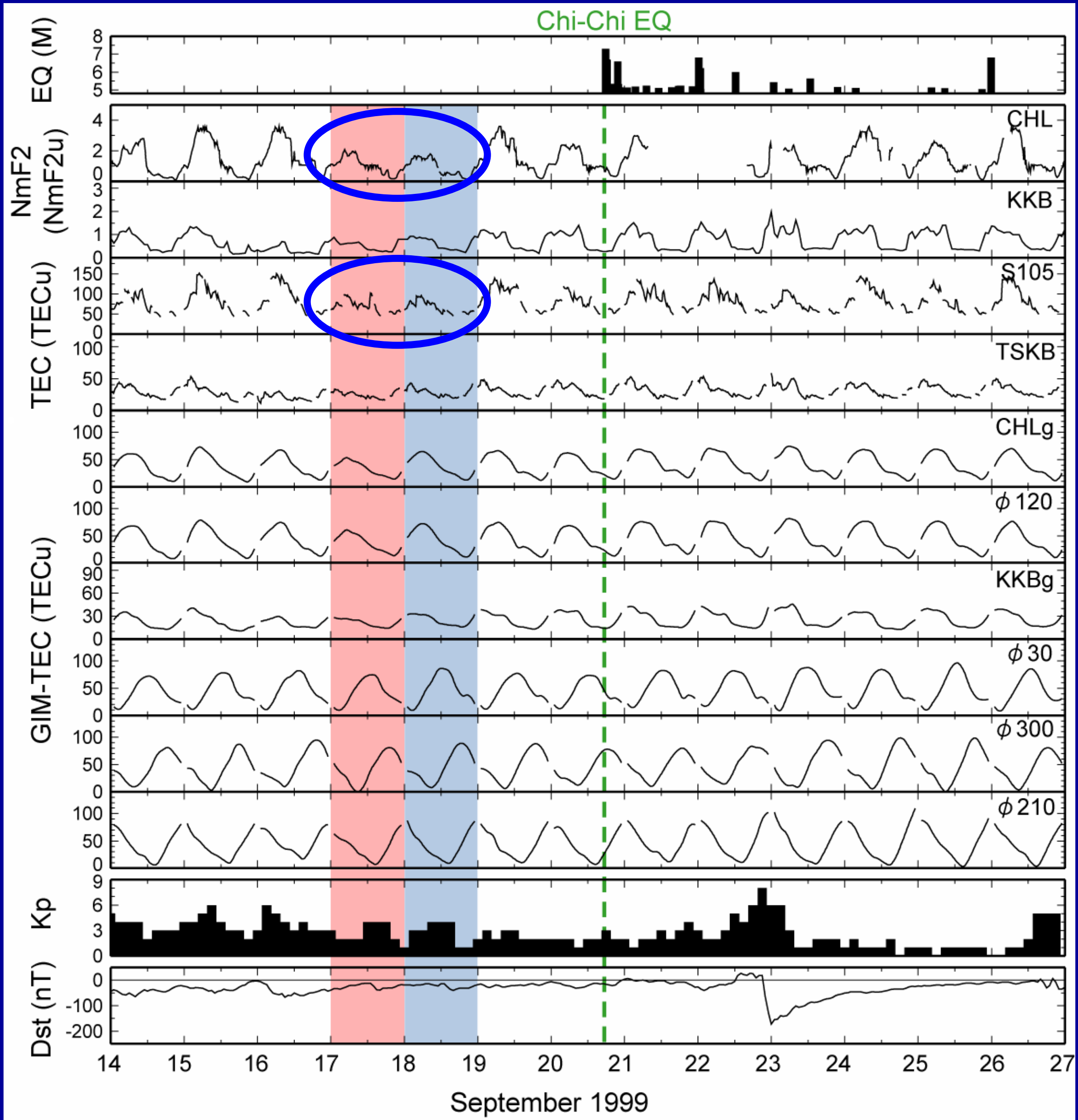
NmF2，GPS-TEC

daily steady variation

3 & 4 days before EQ・・
the peak of TEC
in the daytime in Taiwan
is small compared with
the other days.

However

It is difficult to detect the pre-seismic anomalies using raw data.



Processing of TEC*

To identify abnormal signals associated with EQs

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

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

The recurrence interval of an M≧5.0 EQ between 1991-1999 was about 13-15 days (Liu et al., 2004).

Similar to this Equation

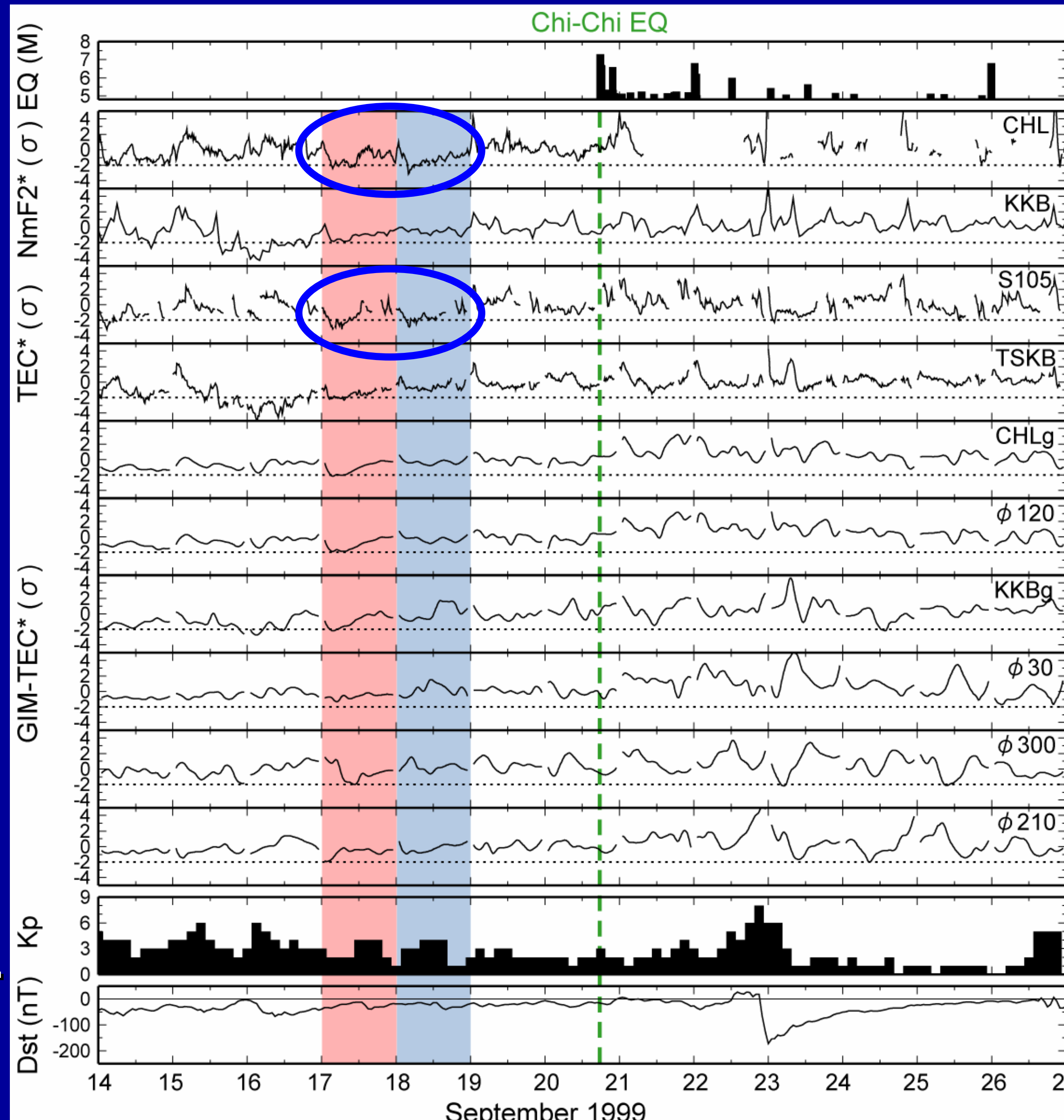
NmF2 → NmF2*
GIM-TEC → GIM-TEC*

Variations of NmF2*, TEC*, GIM-TEC* during the Chi-Chi EQ

NmF2* , TEC* , or GIM-TEC*

fall out of -2σ

We then declare the abnormal signals have been detected.



Anomalies 3 & 4 days before the Chi-Chi EQ

If the normalized data exceed the threshold of -2σ: ○
if the normalized data do not exceed -2σ: ×

		Taiwan	Japan	Others
9/17 (4 days before EQ)	NmF2*	○	×	
	TEC*	○	○	
	GIM-TEC*	○	○	△
9/18 (3 days before EQ)	NmF2*	○	×	
	TEC*	○	×	
	GIM-TEC*	×	×	×

※ While the TEC* value in Taiwan decreases beyond -2σ on September 17, almost at the same time, the GIM-TEC* values at φ210 and φ300 decrease to -1.9σ.

Anomalies 4 days before the Chi-Chi EQ (9/17)

Two geomagnetic SSCs occurred on 9/15. (http://www.cetp.ipsl.fr/~isgi/)

- The ionospheric electron density might significantly decrease from a few hours to 2 days after a SSC. (Davies,1990; Kelly,1989)
- 1 to 2 days after the SSC, the ionospheric disturbance dynamo has an influence on ionospheric electric fields at middle and low latitudes, which significantly decreases the TEC and affects the structure of the EIA. (Liu et al.,1999)

Pulinets and Legen'ka (2003)・・・
the ionospheric disturbances caused by
magnetic storms・・・ planetary character
seismic origin・・・ localized and smaller magnitud

Anomalies 4 days before the Chi-Chi EQ are the disturbances caused by the magnetic storms.

Anomalies 3 & 4 days before the Chi-Chi EQ

If the normalized data exceed the threshold of -2σ: ○
if the data do not exceed -2σ: ×

		Taiwan	Japan	Others
9/17 (4 days before EQ)	NmF2*	○	×	
	TEC*	○	○	
	GIM-TEC*	○	○	△
9/18 (3 days before EQ)	NmF2*	○	×	
	TEC*	○	×	
	GIM-TEC*	×	×	×

No anomaly

Anomalies 3 days before the Chi-Chi EQ (9/18)

Computation of GIM

1999・・・ There were no GPS receivers in Taiwan used for computation GIM.

In Taiwan, the rather approximate GIM value was interpolated by far-distant receivers.

→ GIM value did not reflect the ionospheric local disturbance in Taiwan.

→ The anomalies did not appear in Japan and the other area.

→ Anomalies in Taiwan 3 days before the Chi-Chi EQ are local phenomena.

correlation between TEC* and NmF2*

Taiwan　　Japan

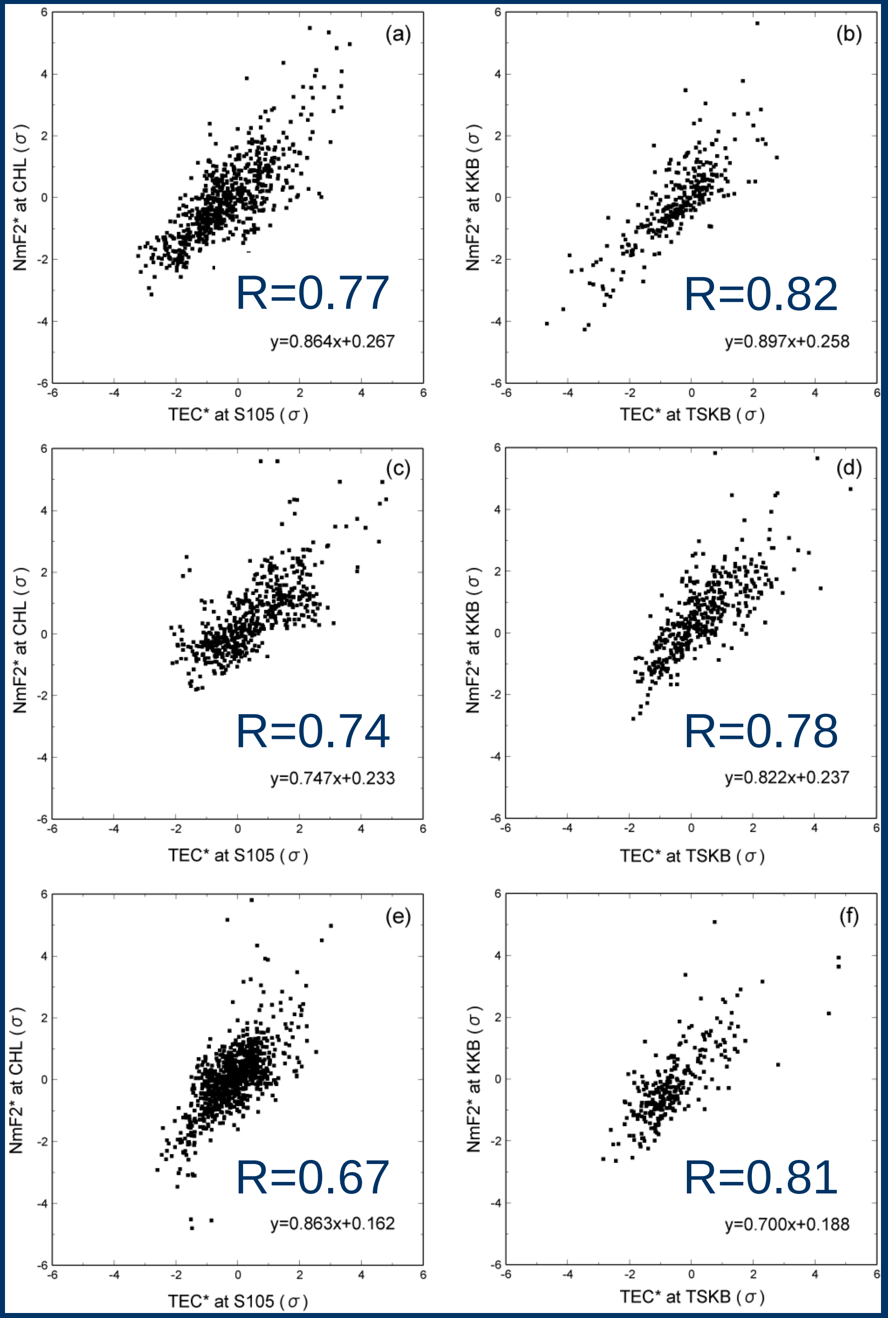
台湾，日本どちらとも良好 相関

Chi-Chi 地震前後 9/14～9/26

9/27～10/15

Chia-Yi 地震前後 10/16～10/28

同じ地域における TEC*とNmF2*の変動は同様



Correlation between TEC* and GIM-TEC*

台湾

2つの地震前後

・・・ 相関は低い

それ以外の期間

・・・ 相関は改善

日本

全期間

・・・ 良好な相関

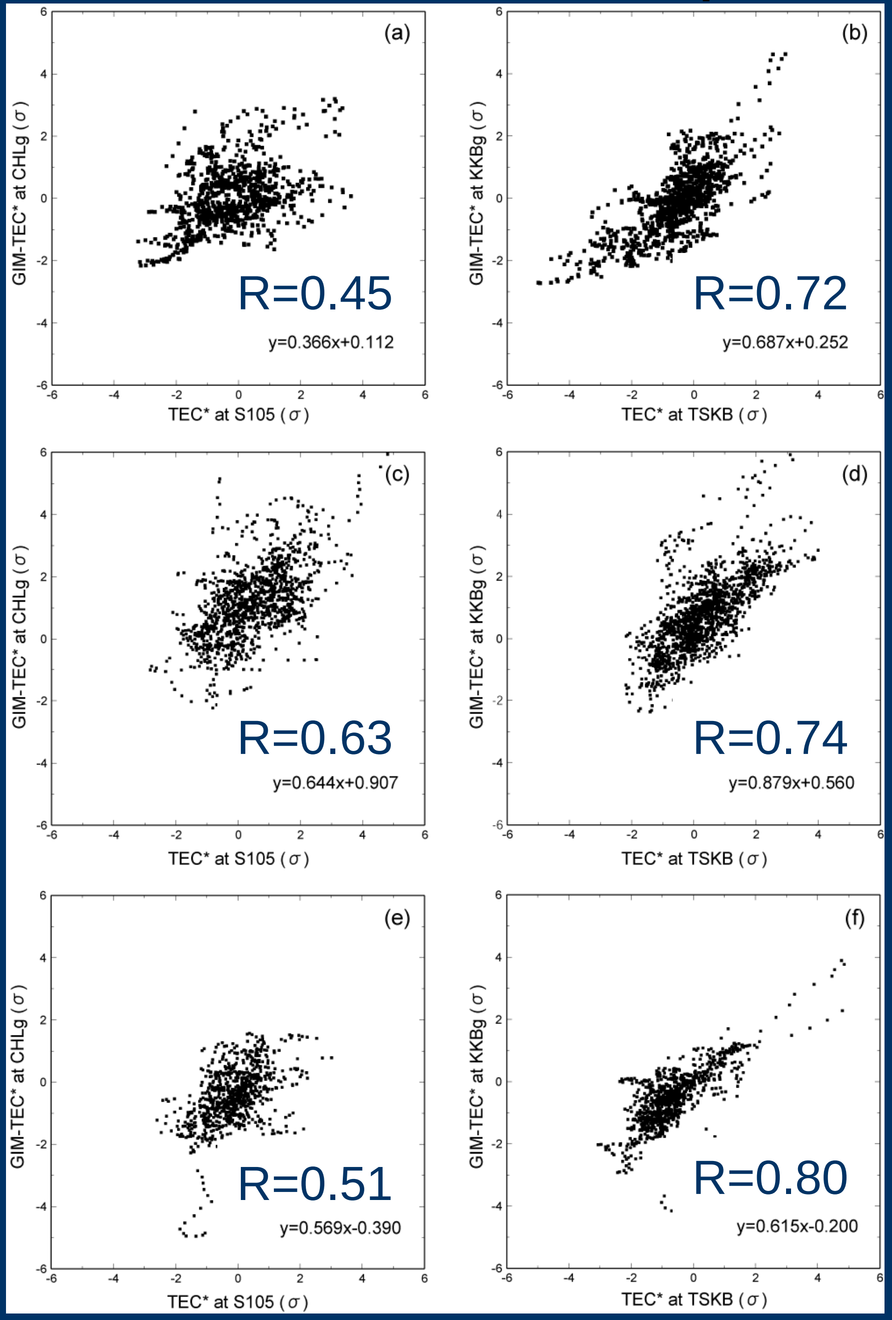
R = 0.7～0.8

Chi-Chi
地震前後
9/14～9/26

9/27～10/15

Chia-Yi
地震前後
10/16～10/28

Taiwan　　Japan



Correlation between TEC* and GIM-TEC*

もし台湾 local な異常であれば，相関は低いと推定される

GIM算出のための GPS観測点・・・
台湾に未設置

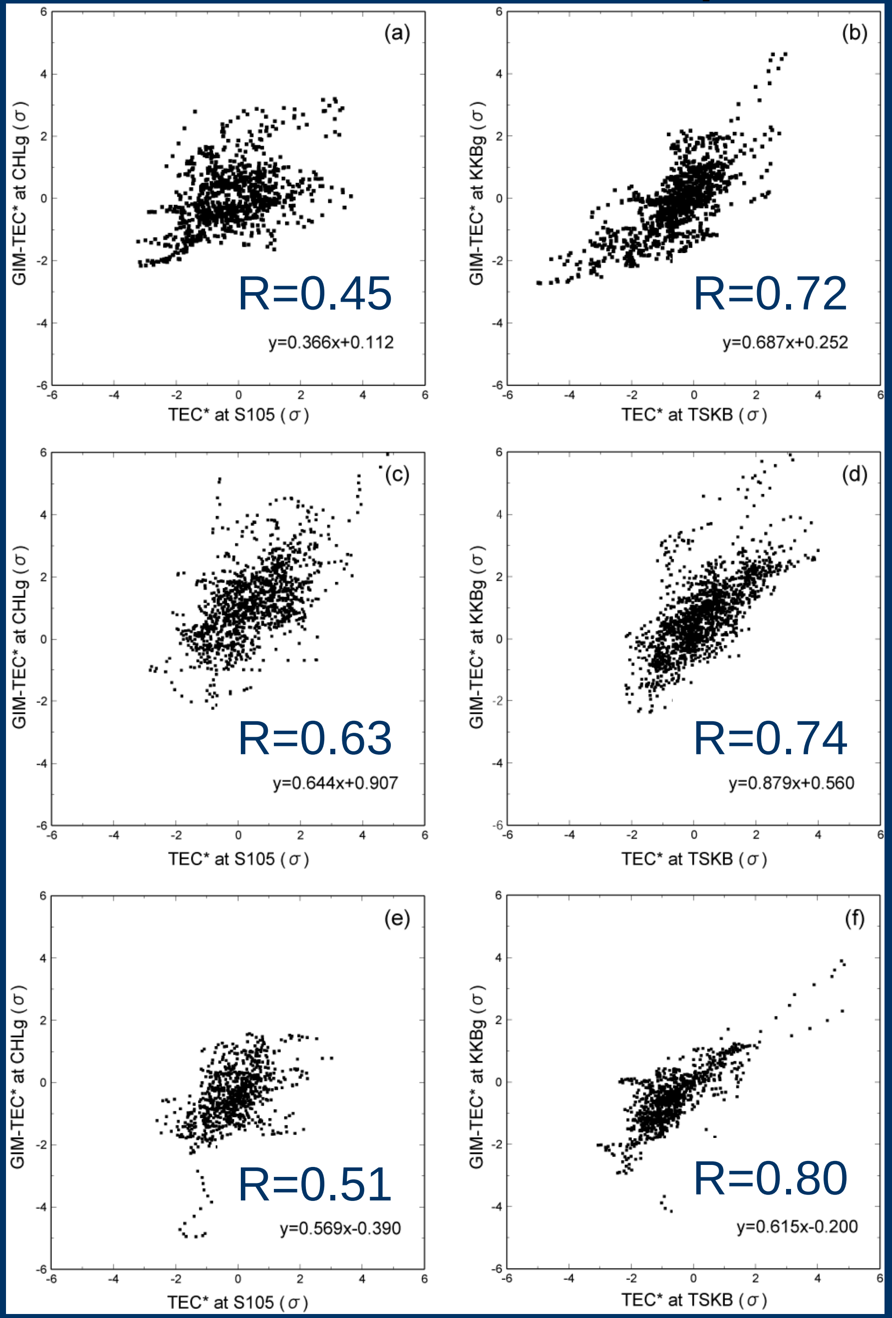
localな電離層擾乱は GIMに反映されていない

Taiwan　Japan

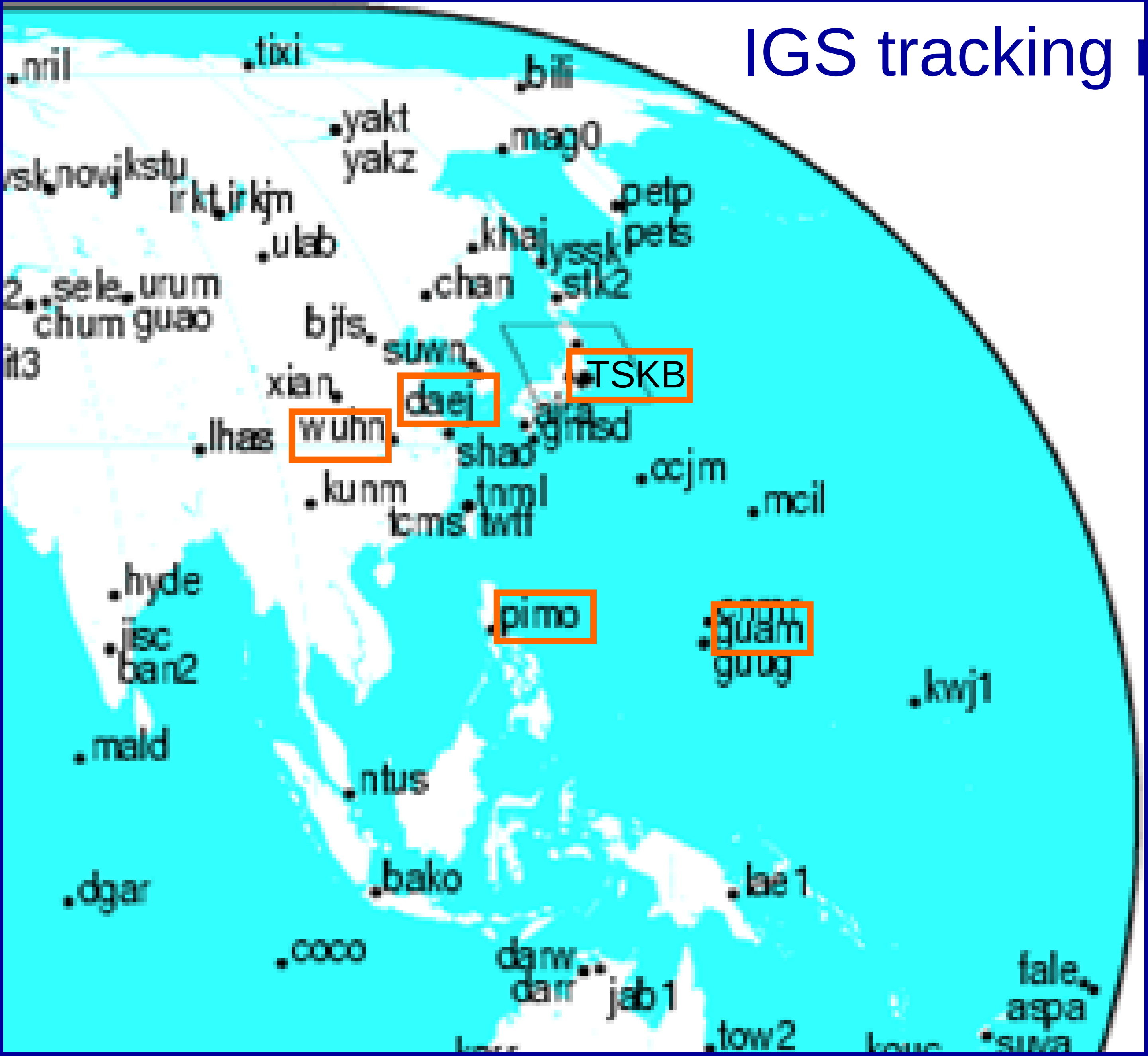
Chi-Chi 地震前後 9/14～9/26

9/27～10/15

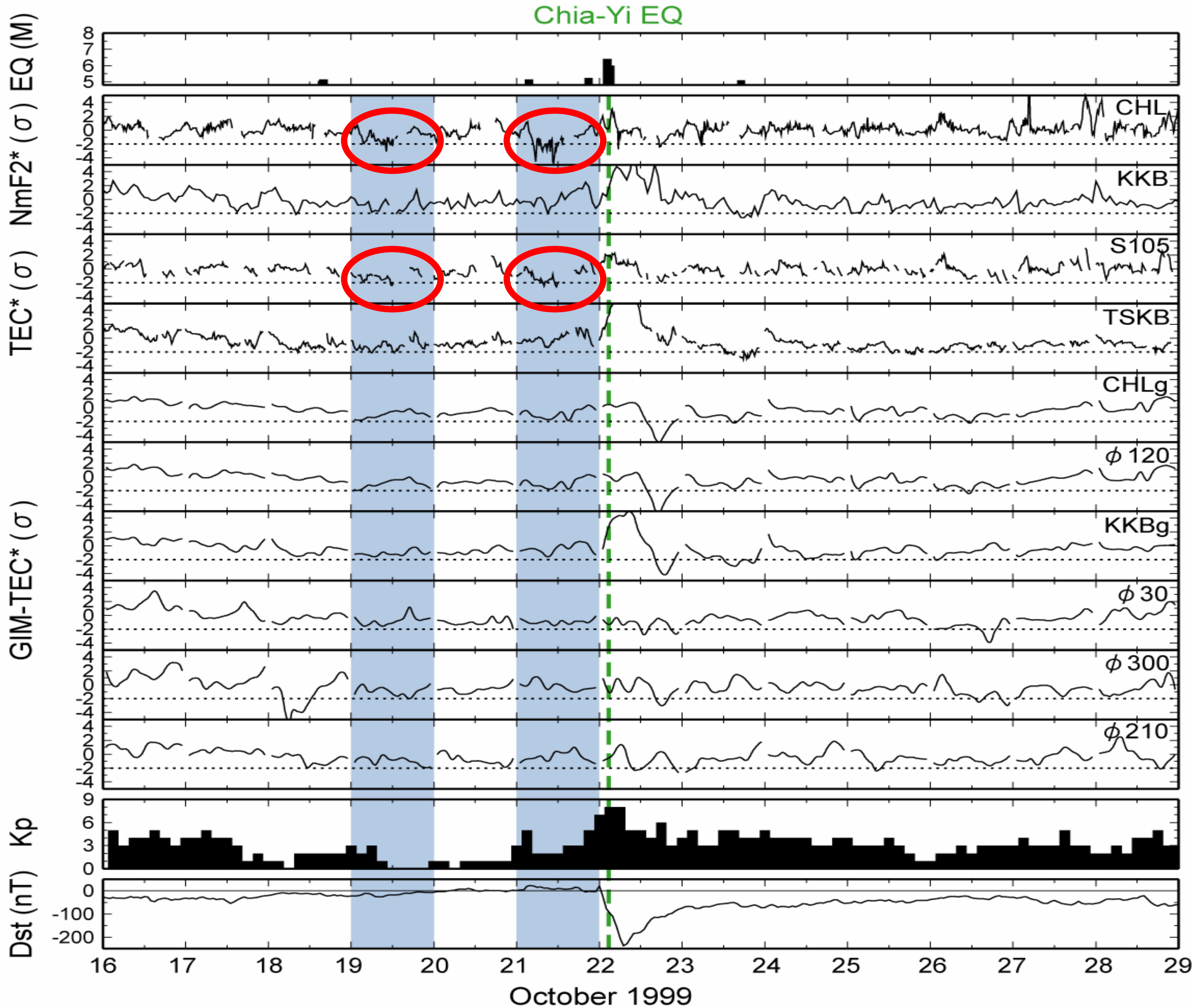
Chia-Yi 地震前後 10/16～10/28



IGS tracking



Variations of NmF2*, TEC*, GIM-TEC* during the Chia-Yi EQ



Anomalies 1 & 3 days before the Chia-Yi EQ

If the normalized data exceed the threshold of -2σ: ○
if the data do not exceed -2σ: ×

		Taiwan	Japan	Others
10/19 & 10/21 (3 & 1 days before EQ)	NmF2*	○	×	
	TEC*	○	×	
	GIM-TEC*	×	×	×

- Occurrence pattern of anomalies is similar to 3 days before the Chi-Chi EQ.
- Geomagnetic condition was relatively quiet.

The anomalies in Taiwan 1 & 3 days before the Chia-Yi EQ are local phenomena.

Summary (Taiwan EQs)

- Ionospheric disturbances 4 days before the Chi-Chi EQ (Mw7.6)

Global change

Not consistent with Liu et al. (2004), Chuo et al. (2002)

- Ionospheric disturbances 3 days before the Chi-Chi EQ (Mw 7.6)
- Ionospheric disturbances 1 & 3 days before the Chia-Yi EQ (M_L 6.4)

Not Global change

Consistent with Liu et al. (2004), Chuo et al. (2002)

Local phenomena around Taiwan prior to the EQs

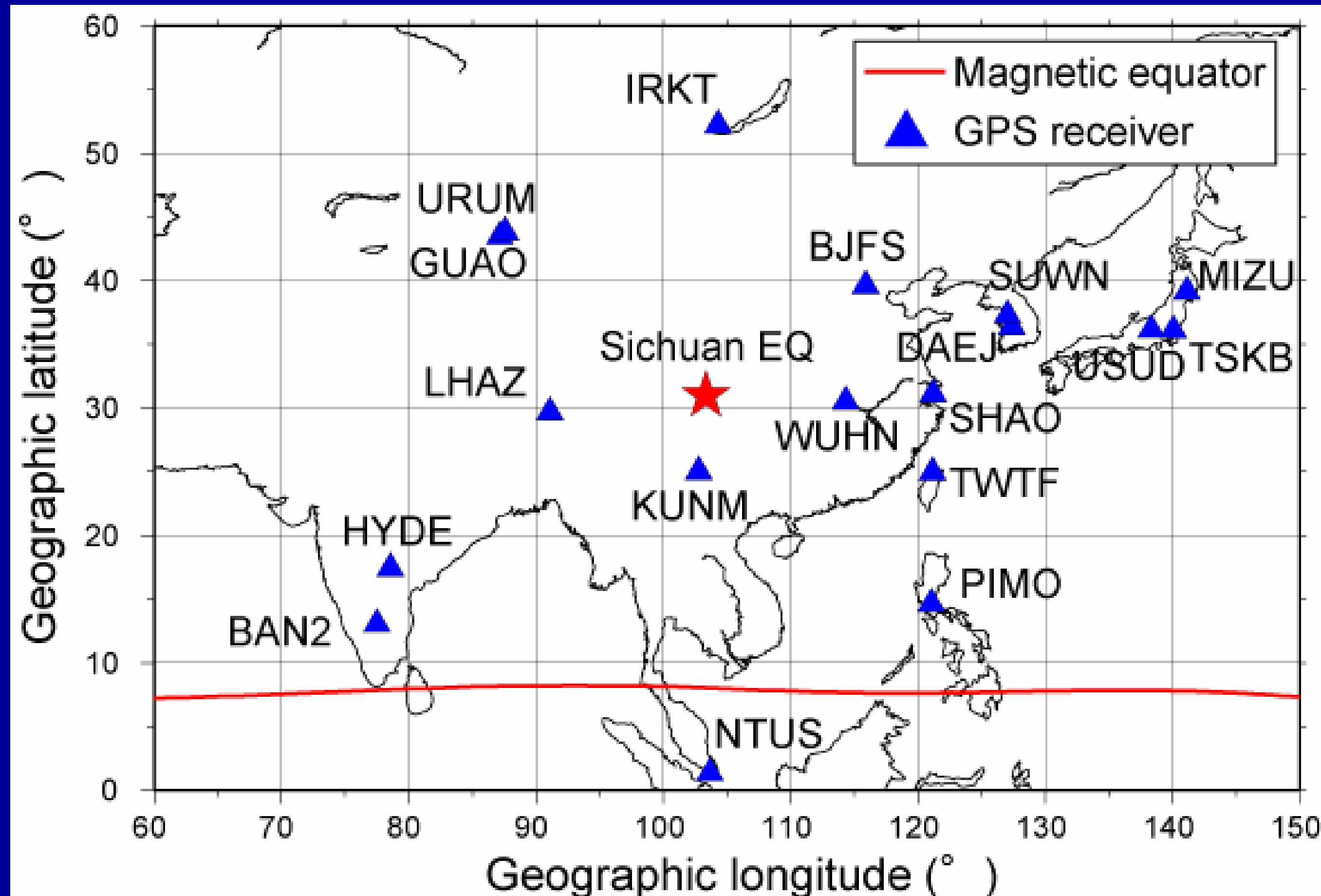
Disturbed areas : within a 2200 km radius and seem to be much smaller

Case Study 2:

The 2008 Wenchuan EQ

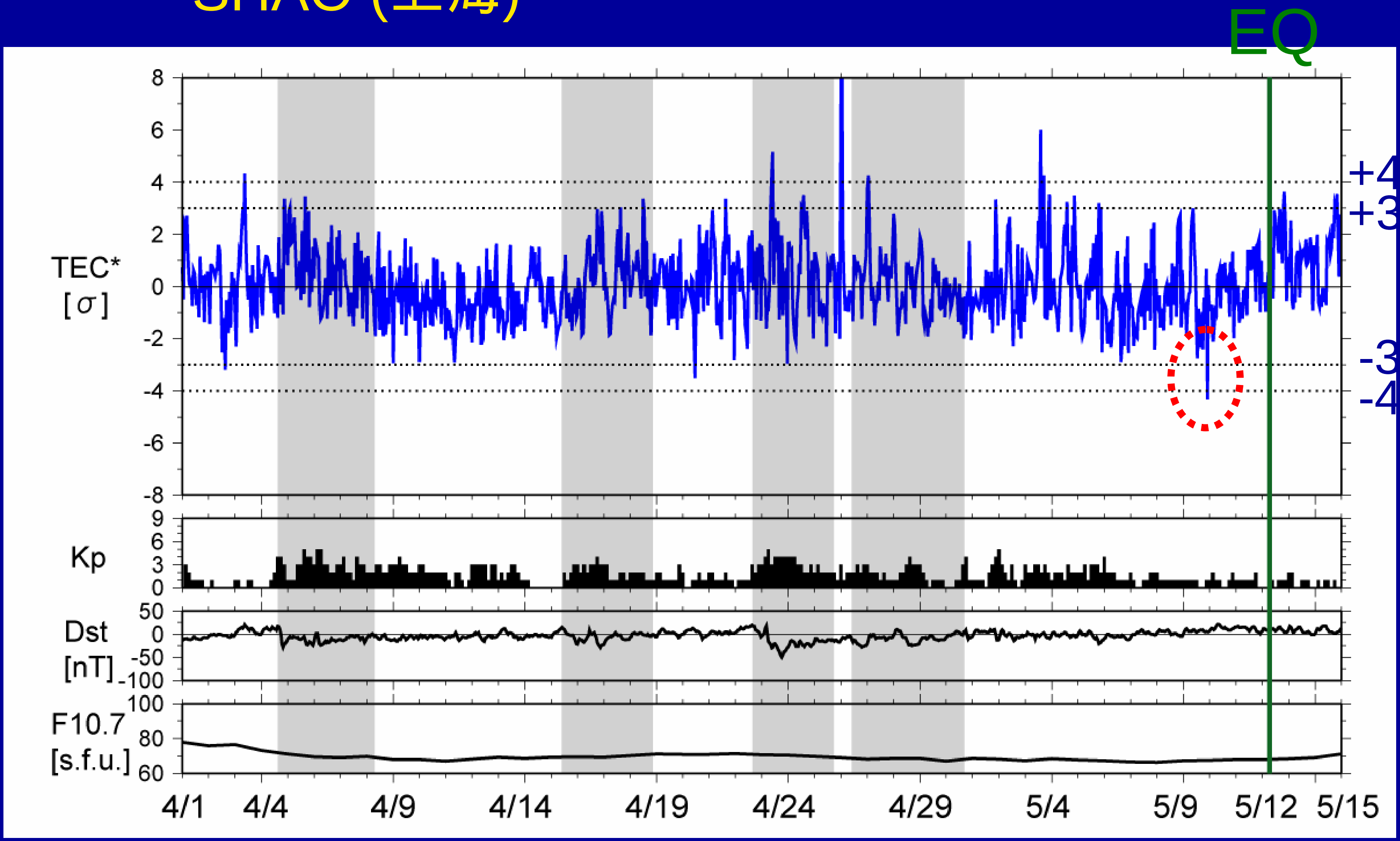
The 2008 Wenchun EQ

20080512
06:28 (UT)
14:28 (LT)
M: 7.9
depth: 19km
epicenter:
30.986N
103.364E



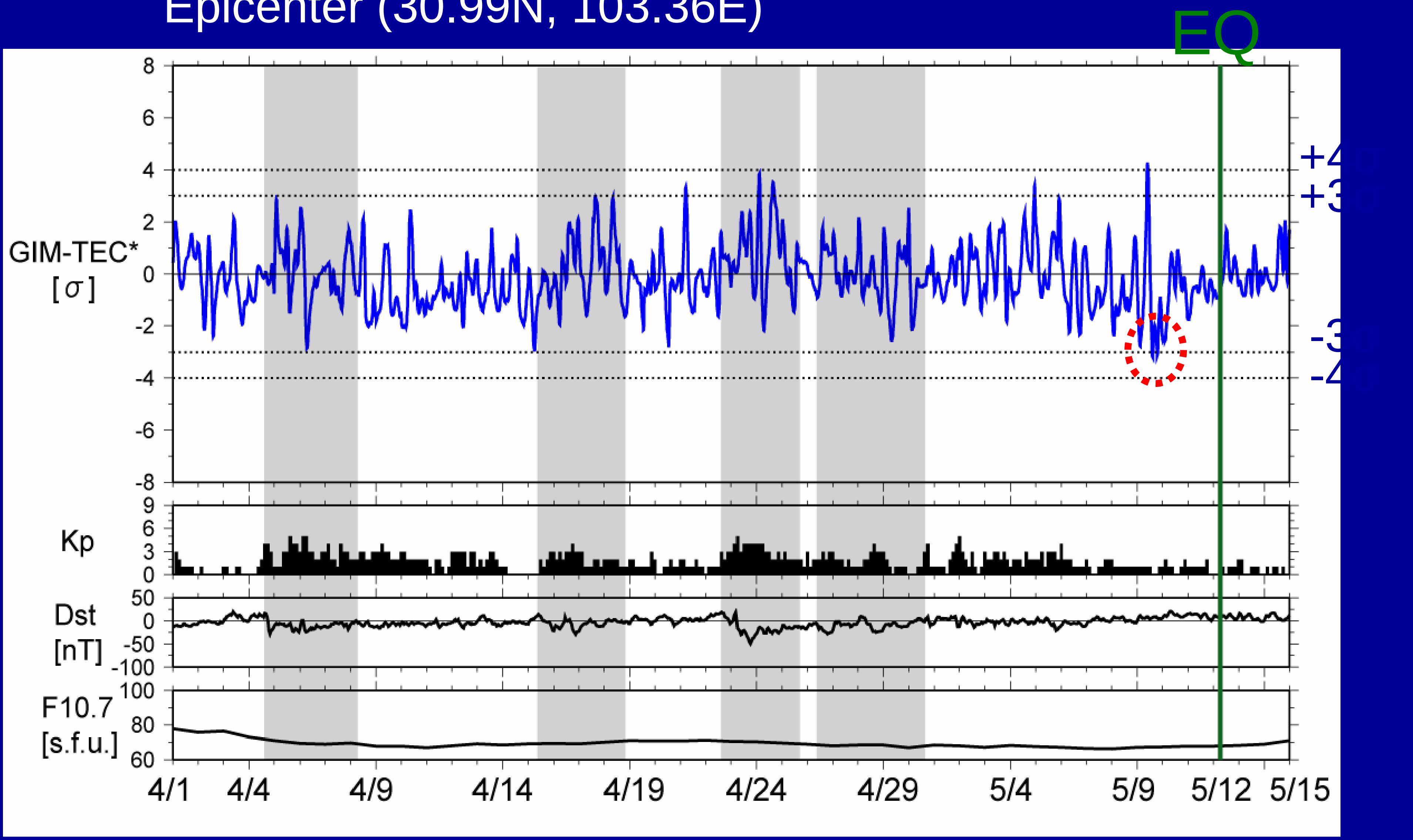
Epicenter and GPS stations (IGS)

SHAO (上海)

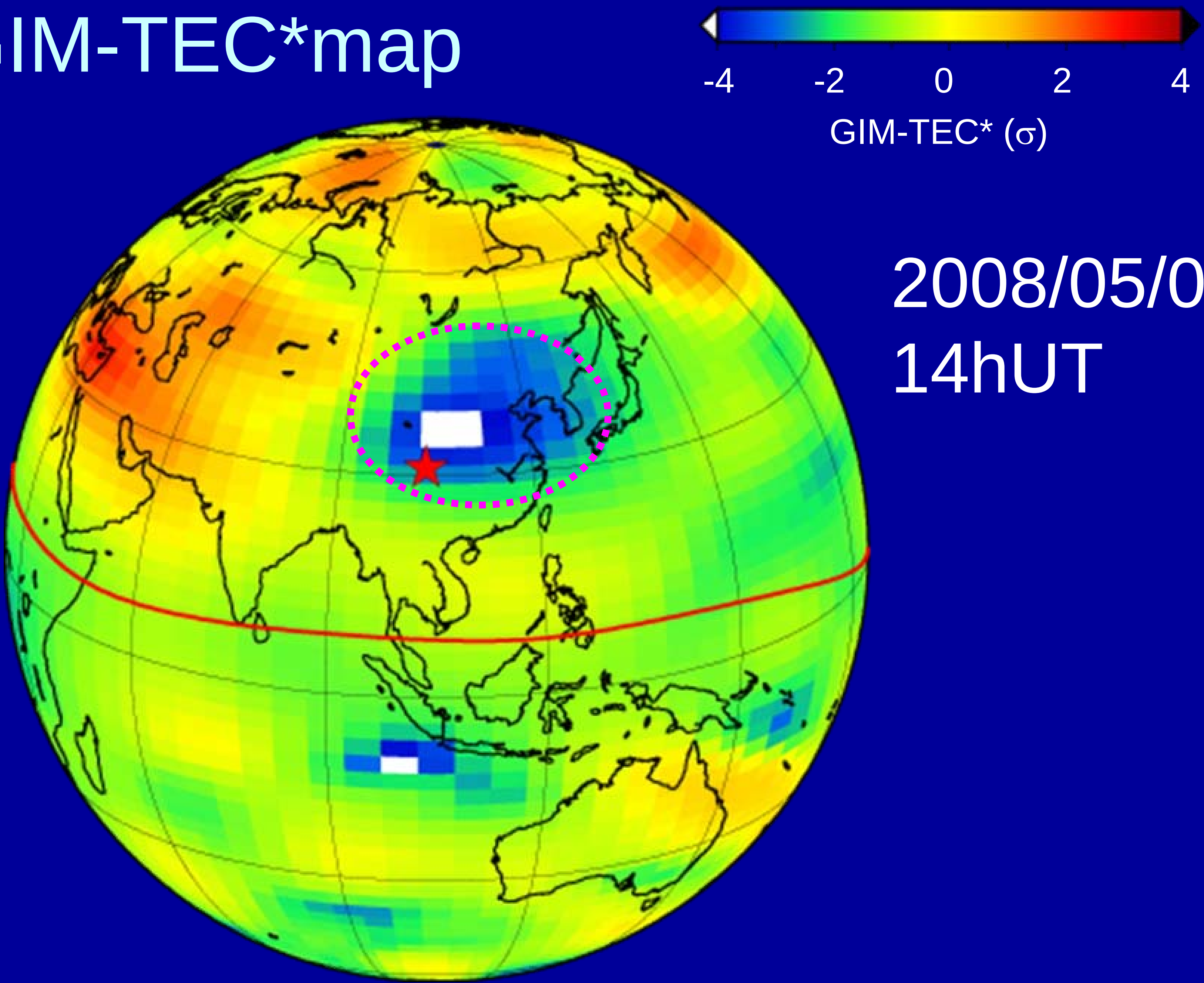


TEC* decreases 3 days before the EQ (-4.3σ)

Epicenter (30.99N, 103.36E)



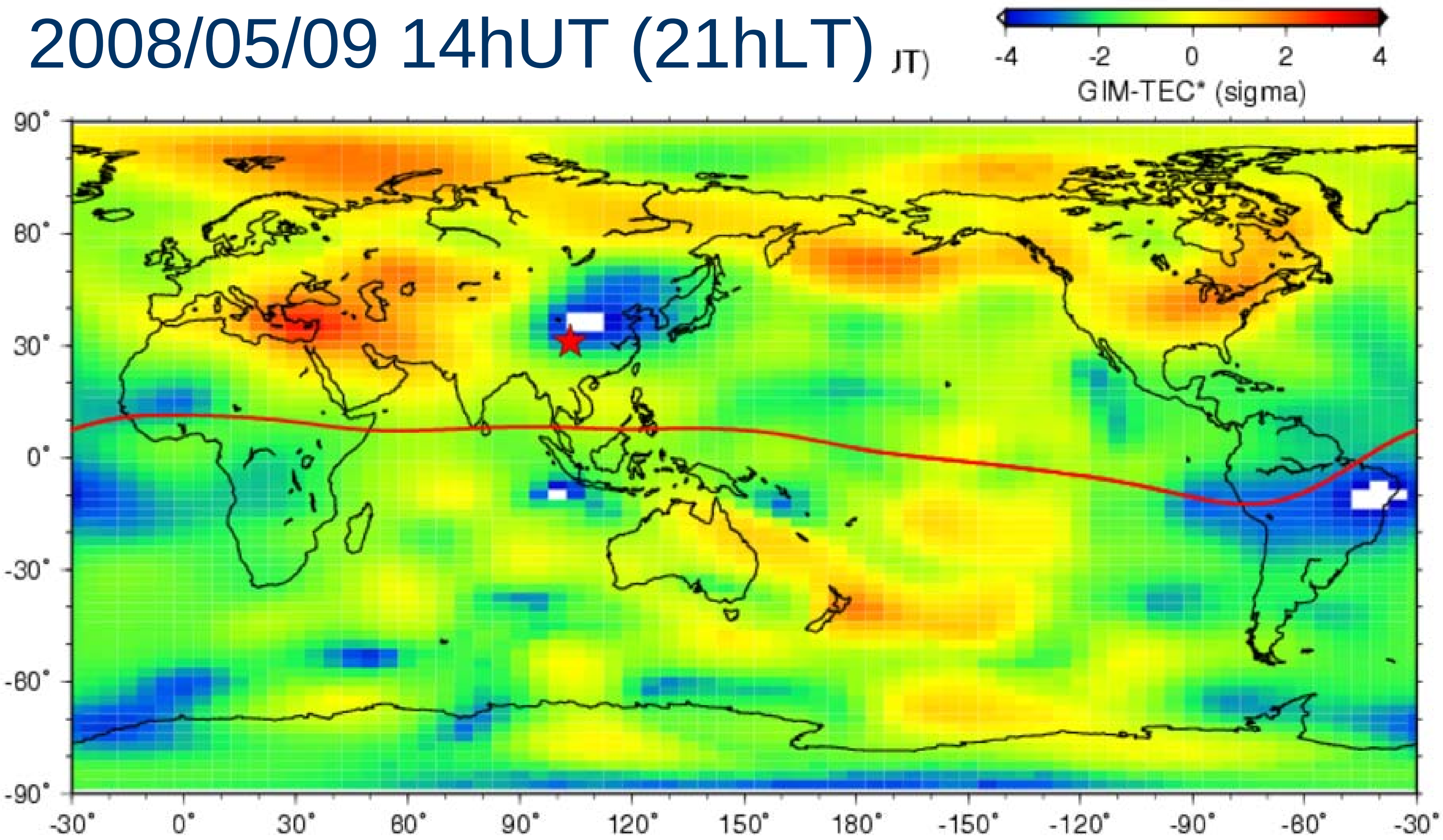
GIM-TEC*map



2008/05/09
14hUT

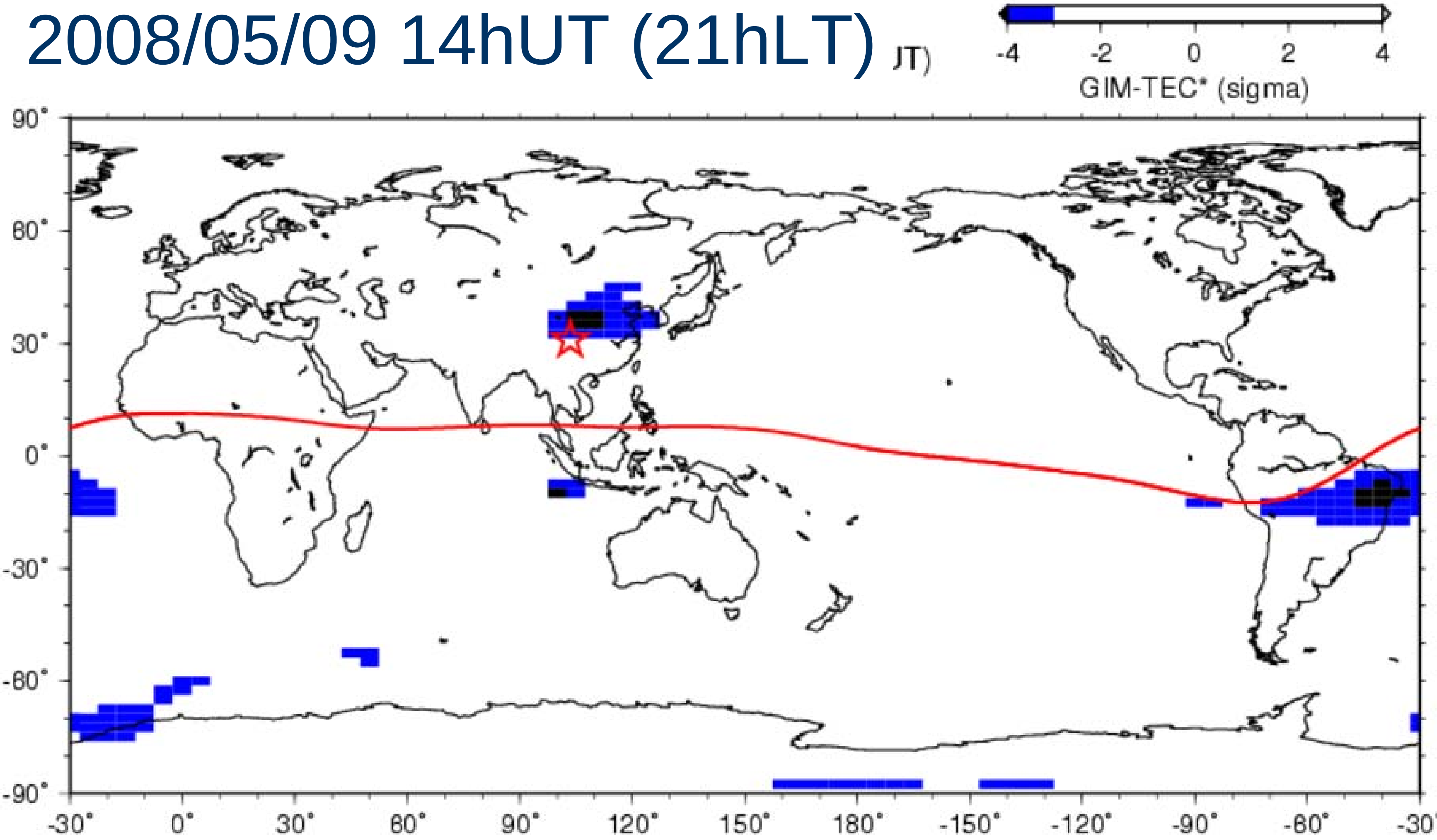
GIM-TEC* map

2008/05/09 14hUT (21hLT)

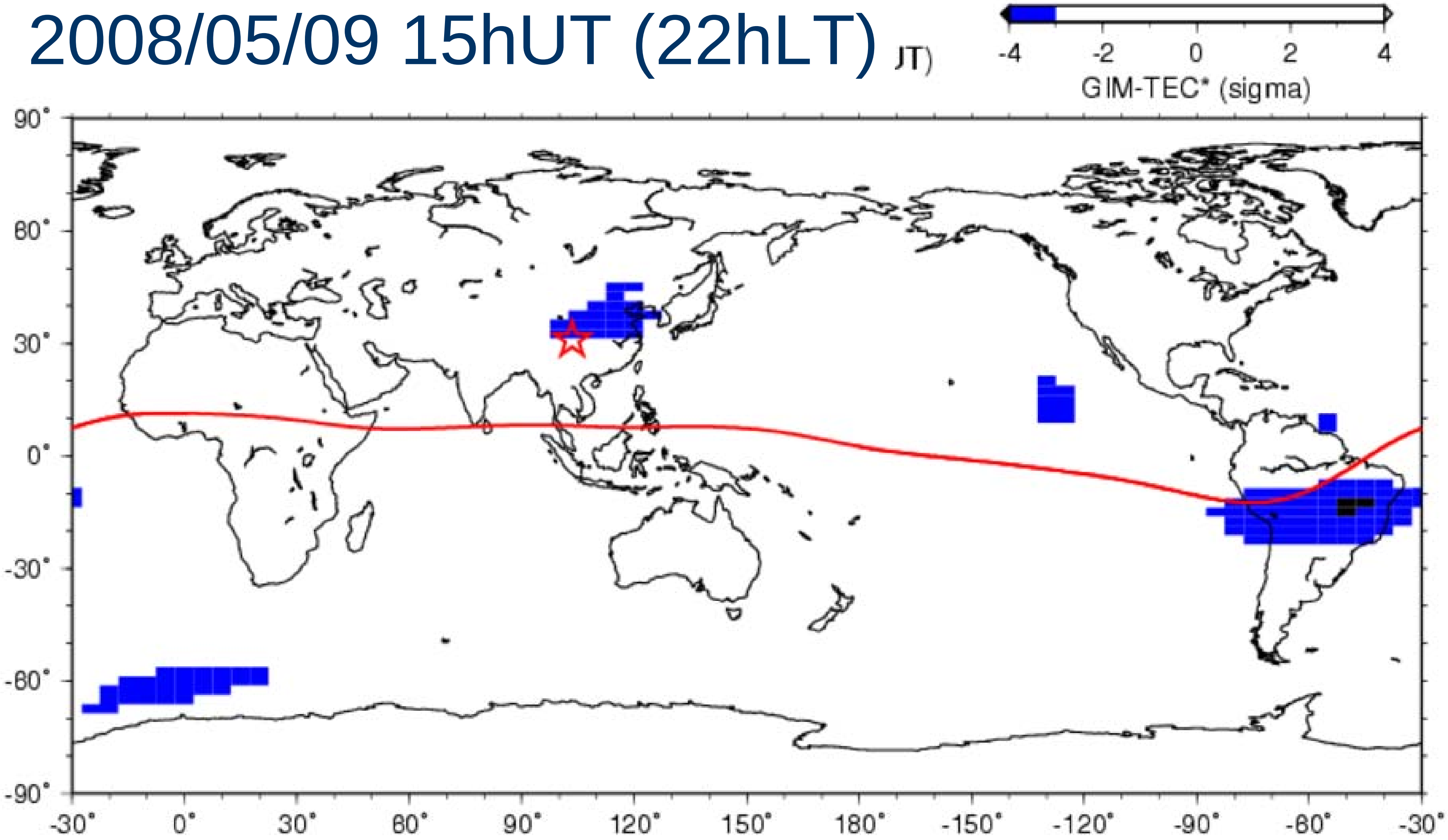


GIM-TEC* map

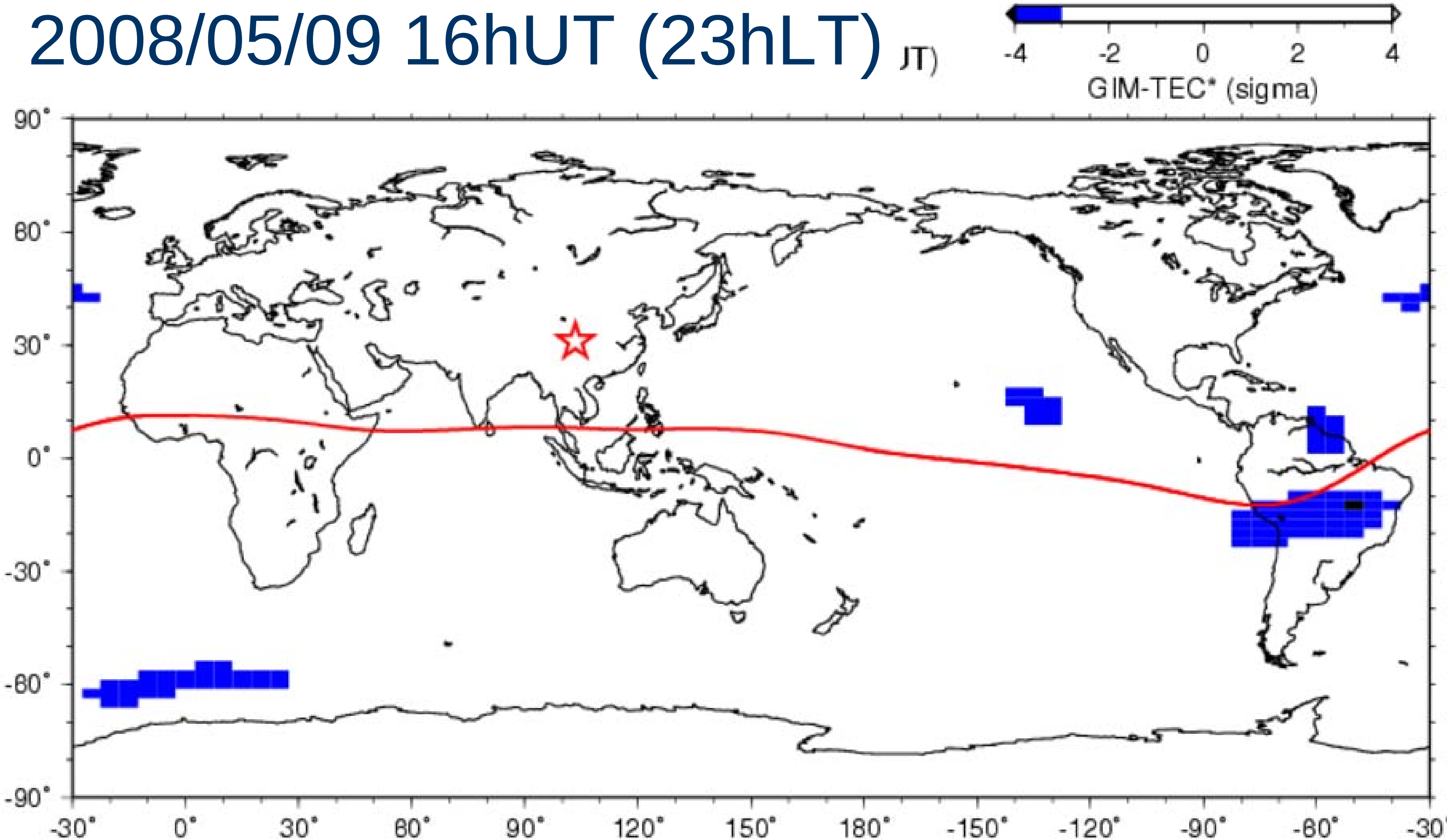
2008/05/09 14hUT (21hLT)



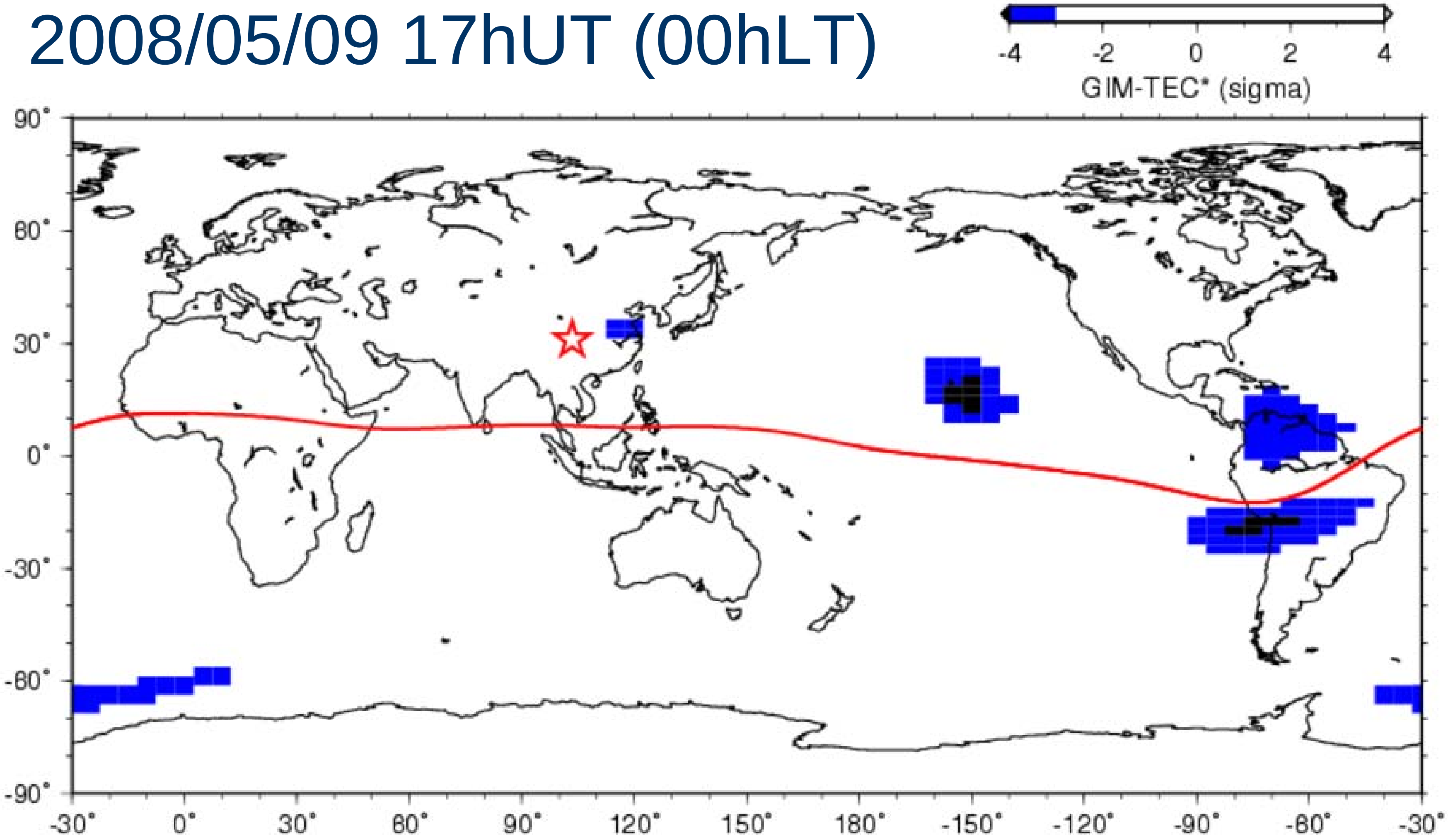
2008/05/09 15hUT (22hLT)



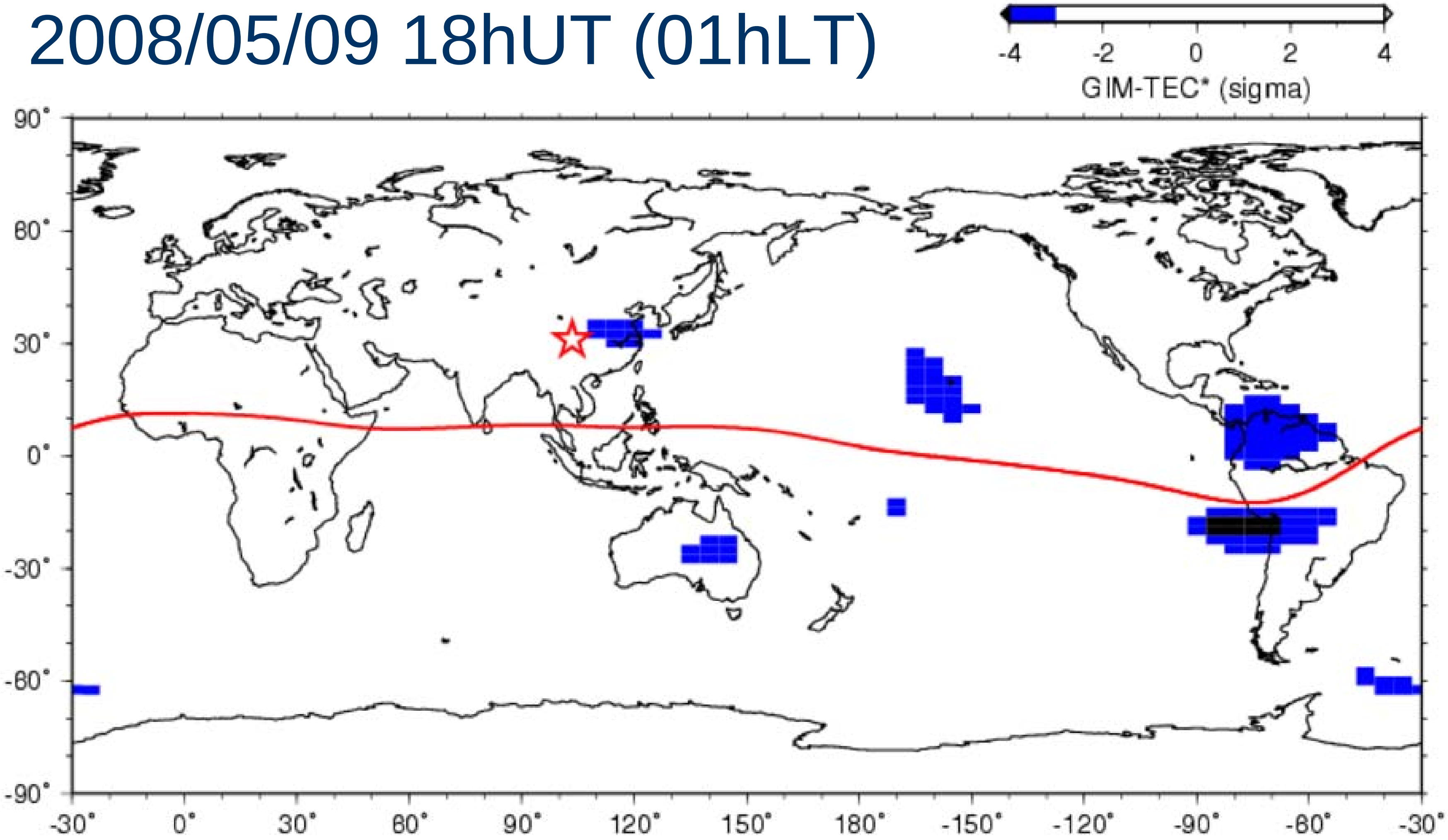
2008/05/09 16hUT (23hLT)



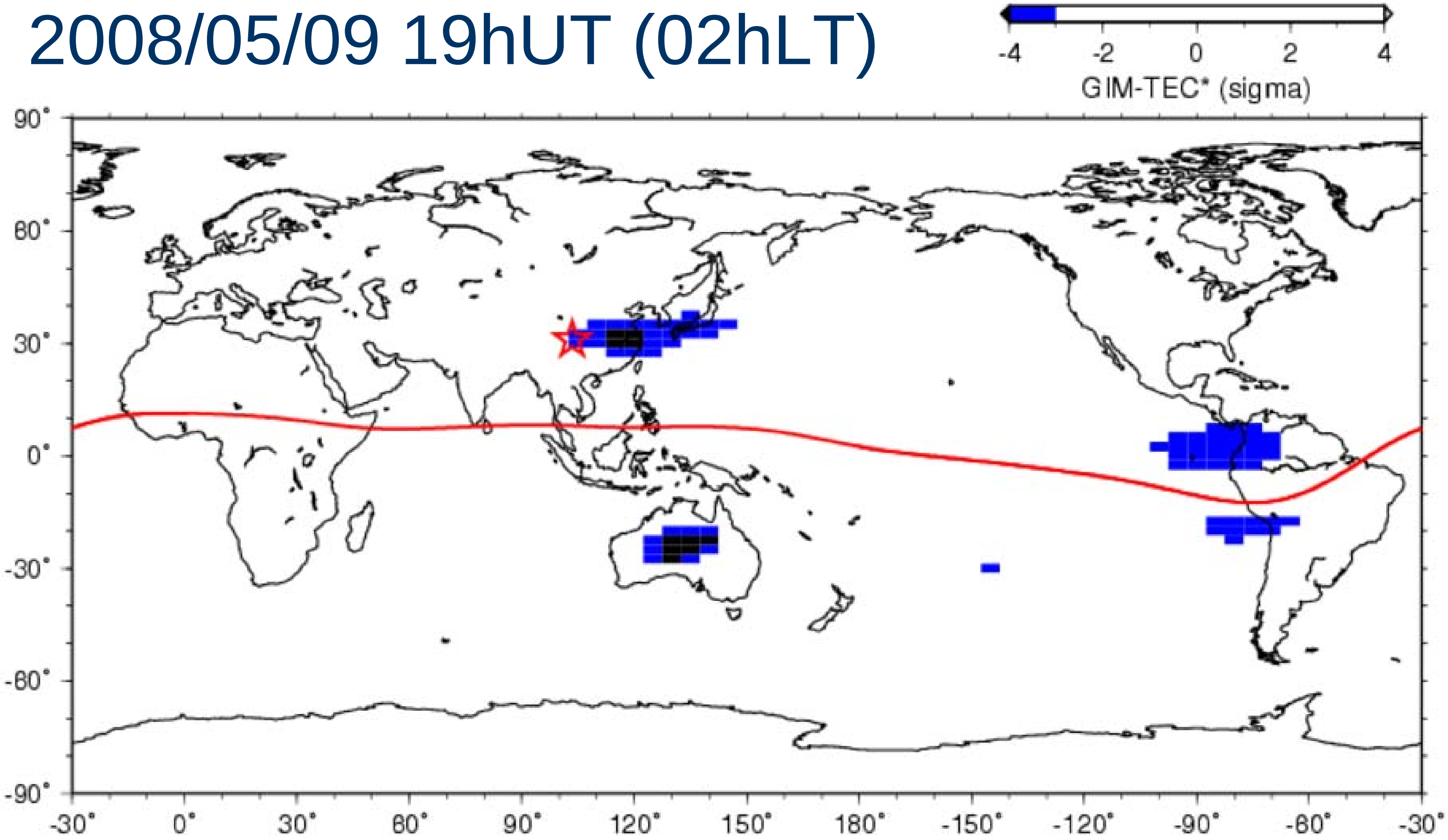
2008/05/09 17hUT (00hLT)



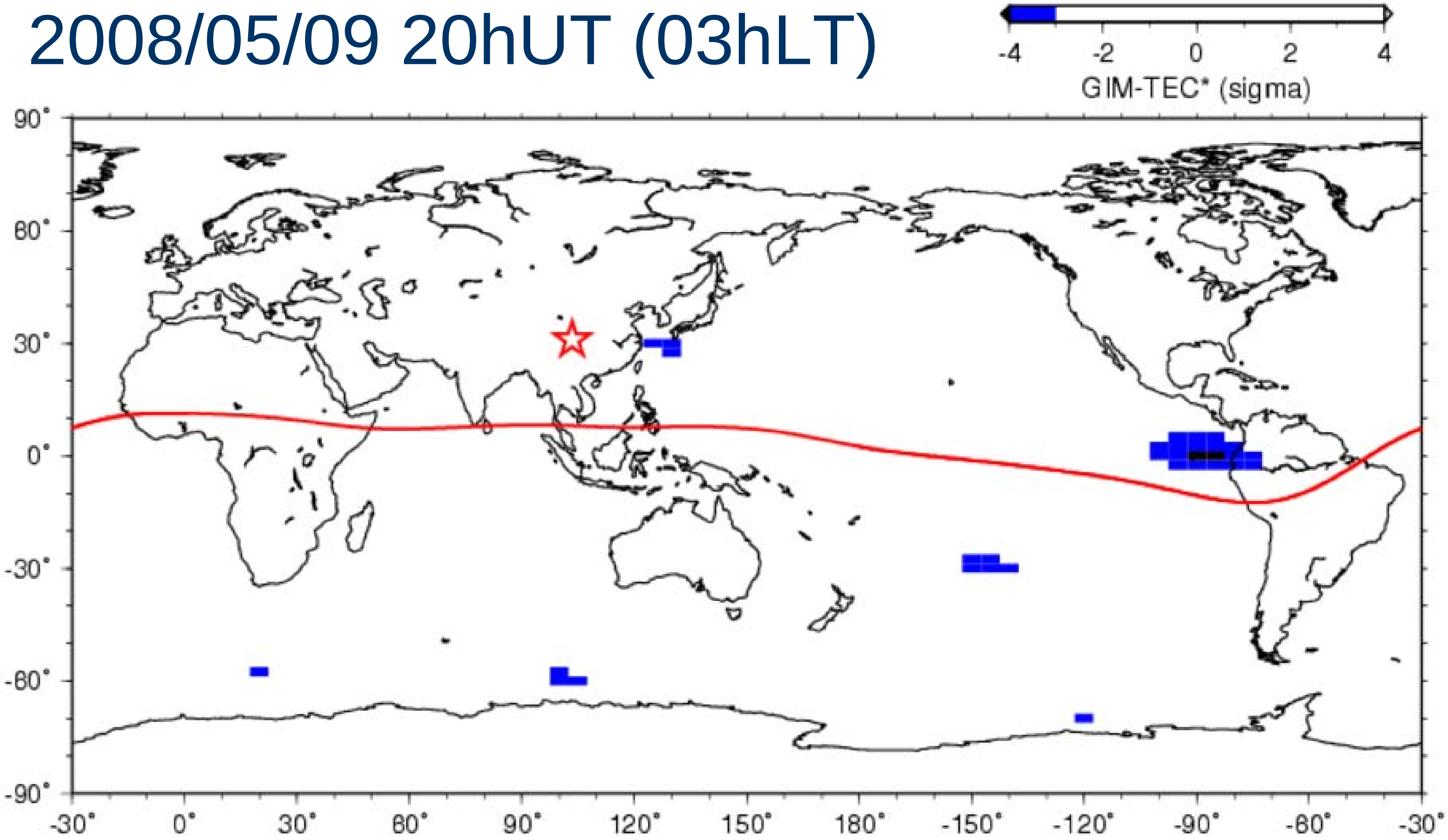
2008/05/09 18hUT (01hLT)



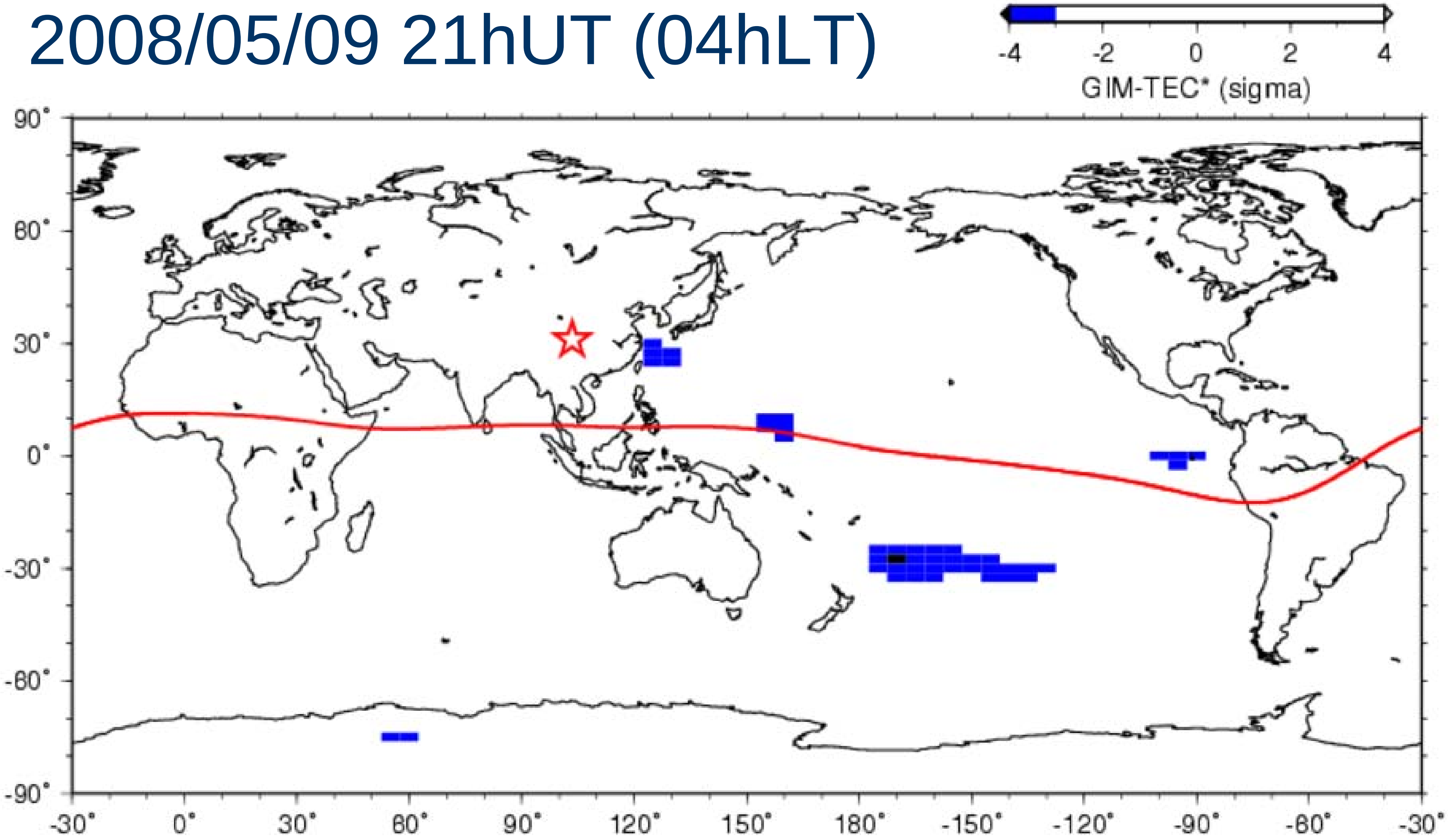
2008/05/09 19hUT (02hLT)



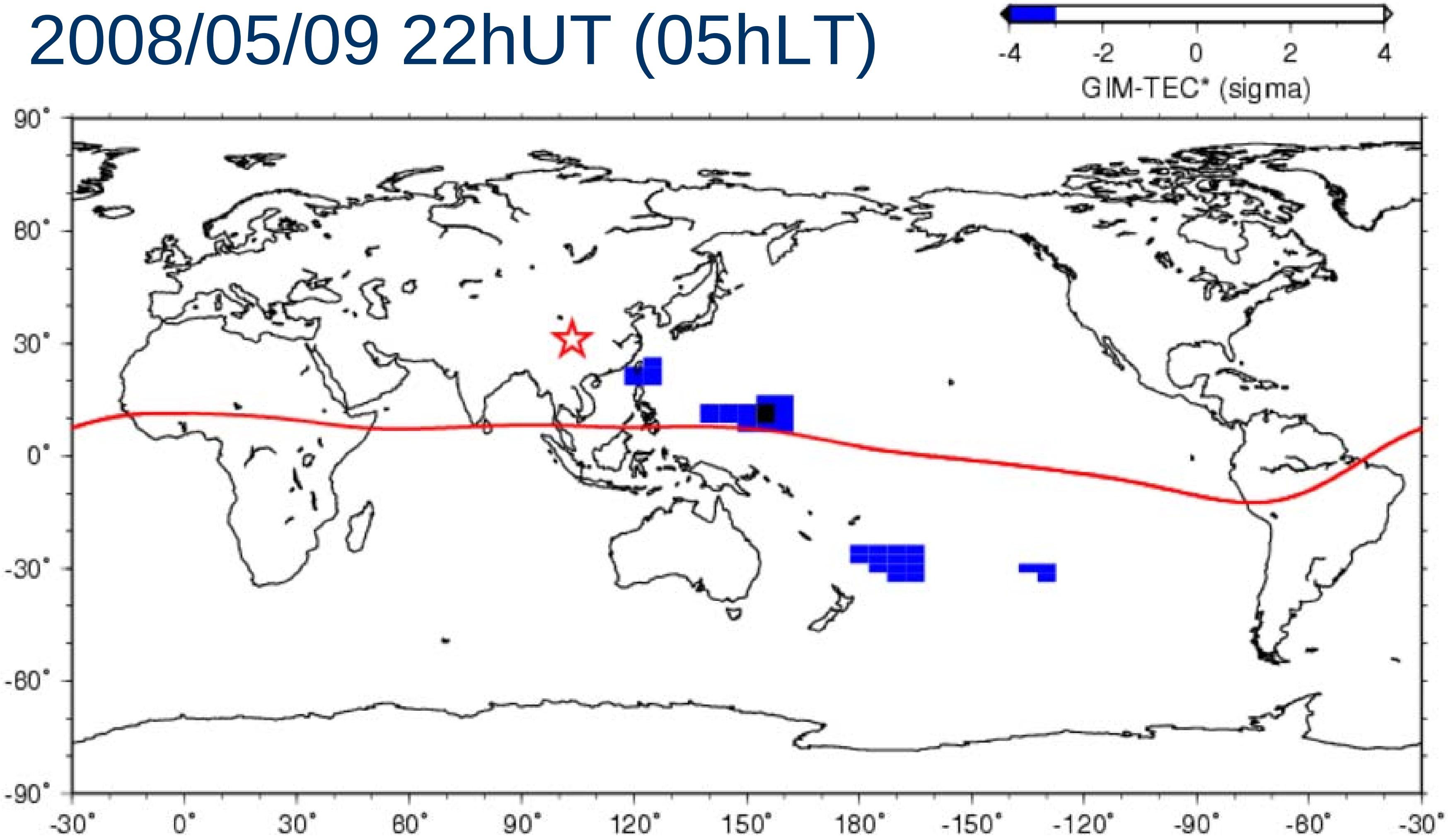
2008/05/09 20hUT (03hLT)



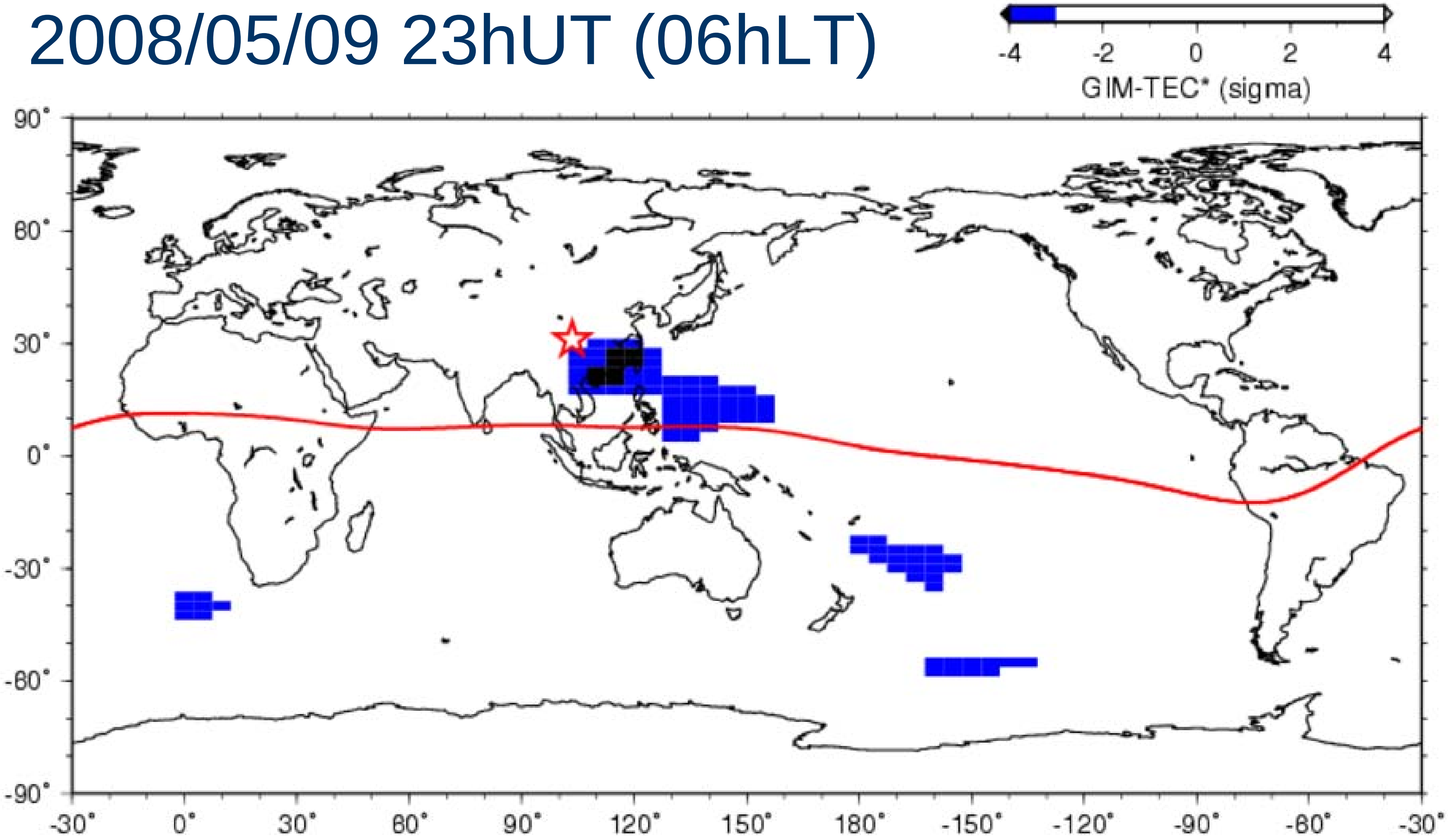
2008/05/09 21hUT (04hLT)



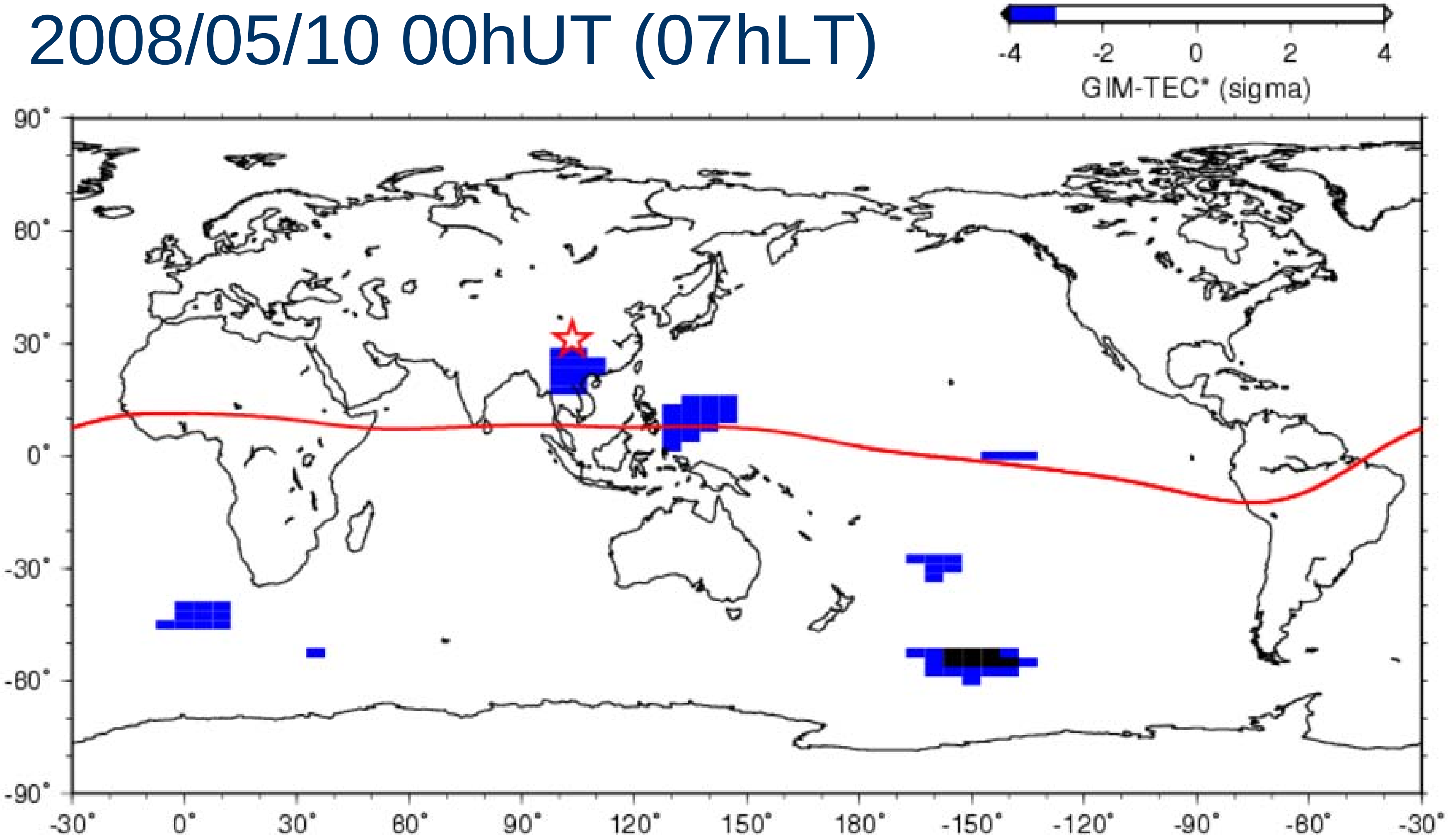
2008/05/09 22hUT (05hLT)



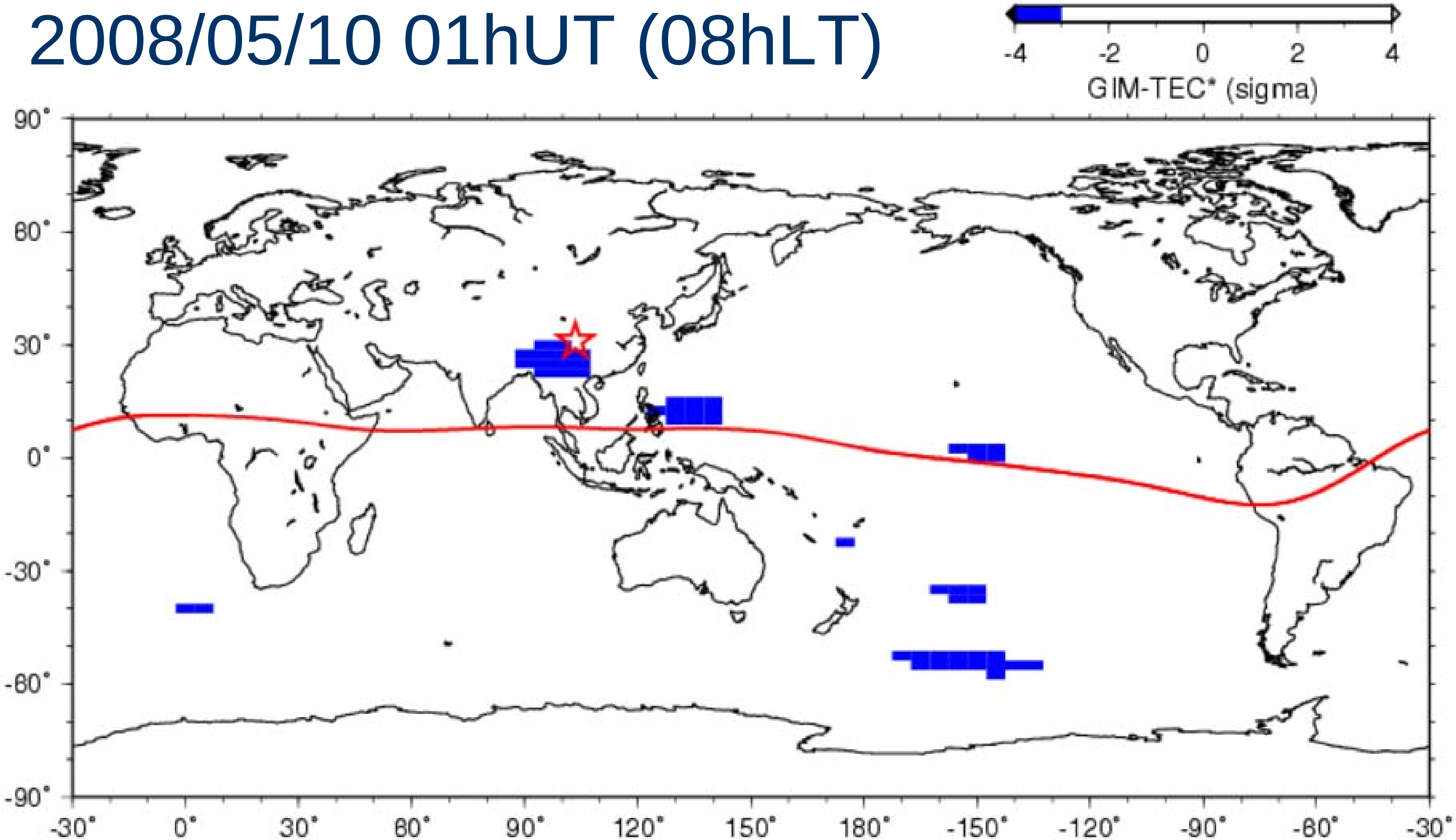
2008/05/09 23hUT (06hLT)



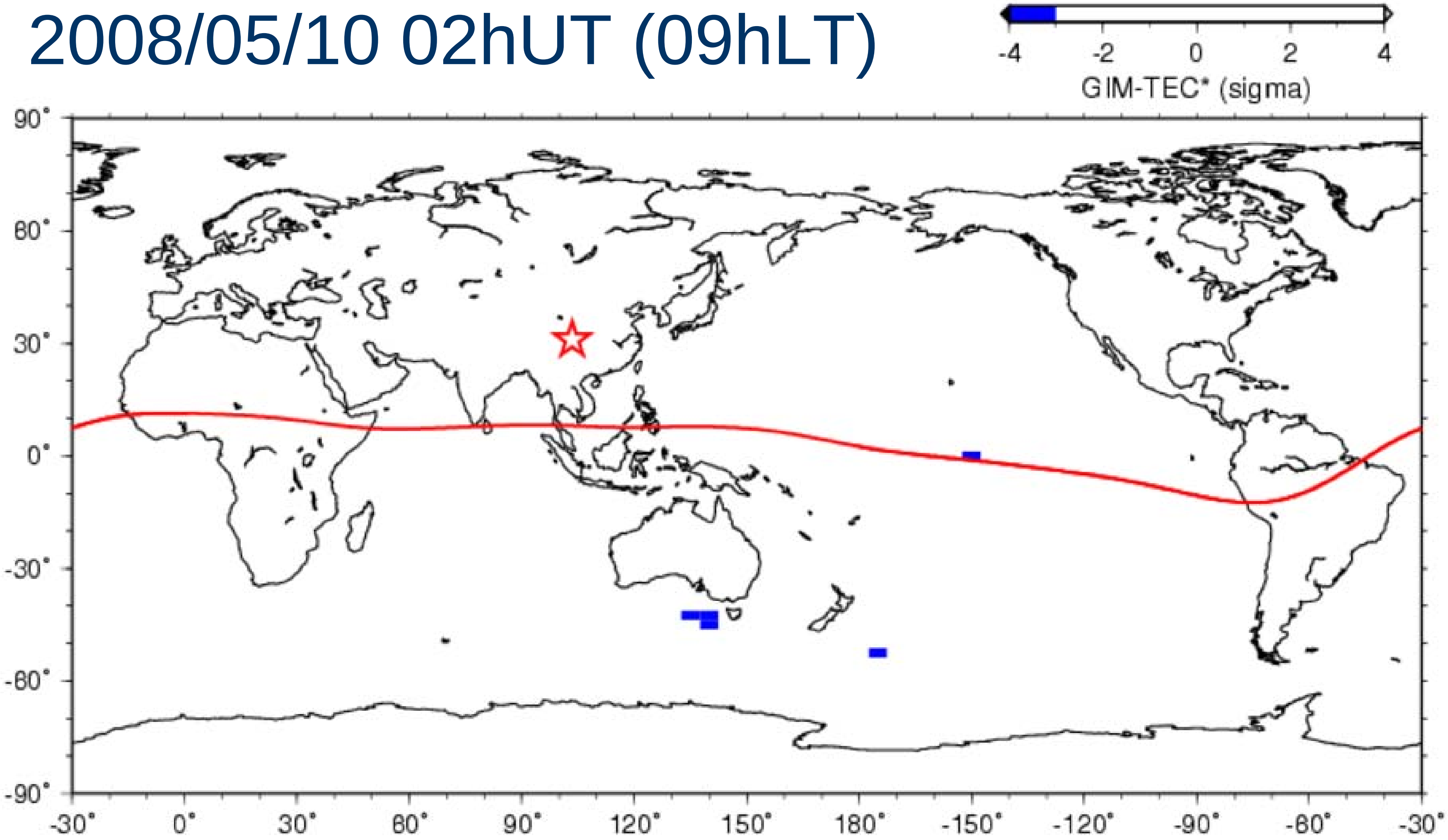
2008/05/10 00hUT (07hLT)



2008/05/10 01hUT (08hLT)



2008/05/10 02hUT (09hLT)

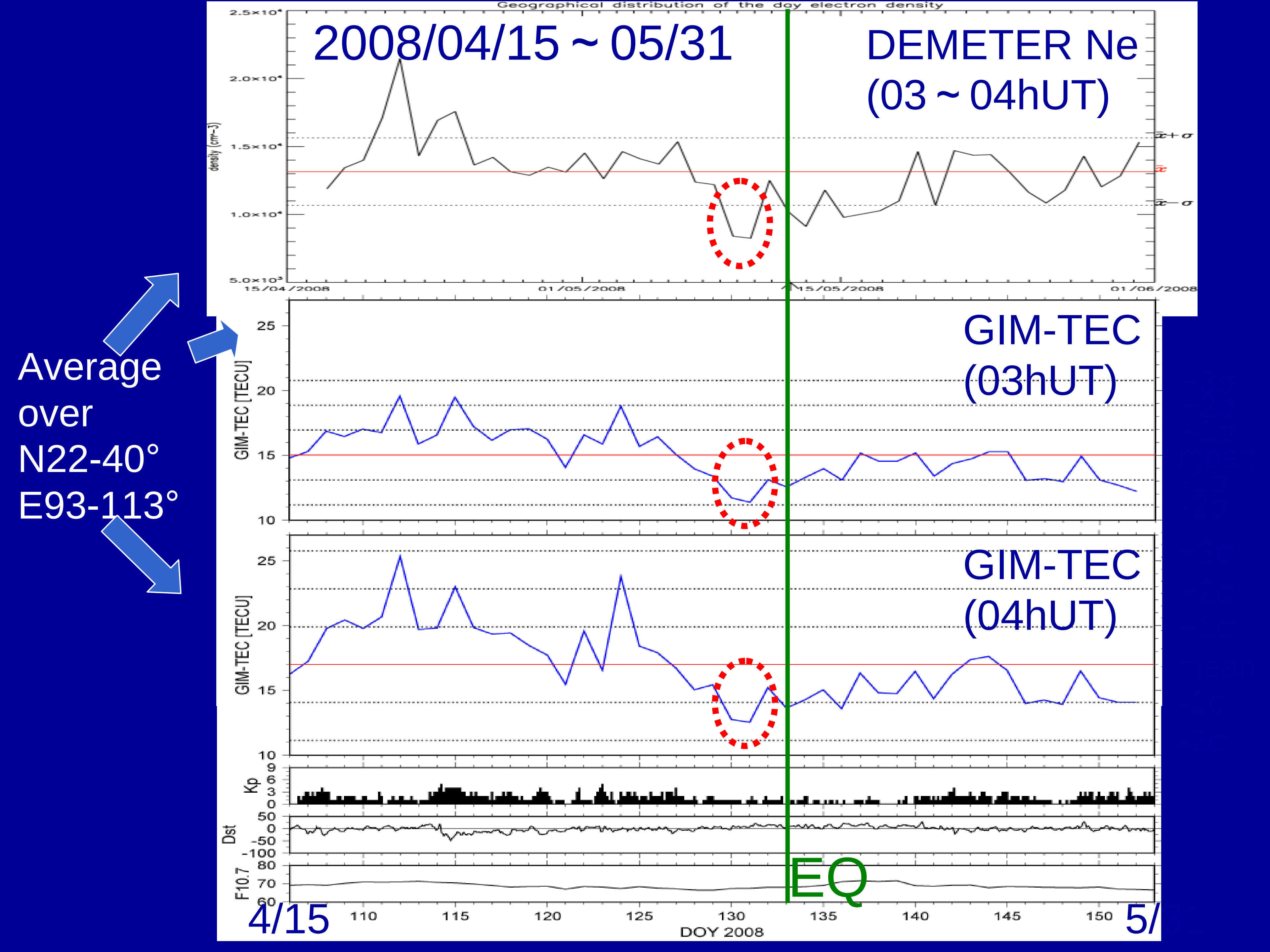


DEMETER

- 打ち上げ日: 2004年6月29日
- 軌道高度: 約700 km
- 太陽同期軌道 (15周 / 日)
  同一地域を10時LT，22時LTの1日2回通過する

搭載センサー

- 三成分磁力計
  ⇒ULF～HF帯 磁場 測定
- 電場プローブ
  ⇒ULF～HF帯 電場 測定
- プラズマ・粒子観測装置
  ⇒大気計測
  （密度，温度，速度，組成など）



2008/04/15 ~ 05/31
DEMETER Ne
(03 ~ 04hUT)
Geographical distribution of the day electron density
GIM-TEC
(03hUT)
GIM-TEC
(04hUT)
Average
over
N22-40°
E93-113°
EQ
4/15
5/
DOY 2008
Kp
Dst
F10.7

Summary of Wenchun EQ

- Decrease TEC three days before the EQ
  (5/9 night - 5/10 morning)

12 hours anomalous behavour around China

→ Not Ionospheric disturbance due to Solar activity

Disturbed Area
N20-45^{o} , E90-140^{o}

Invariant disturbed area for long time

- Variation of GIM-TEC and electron density observed by DEMETER is consistent.

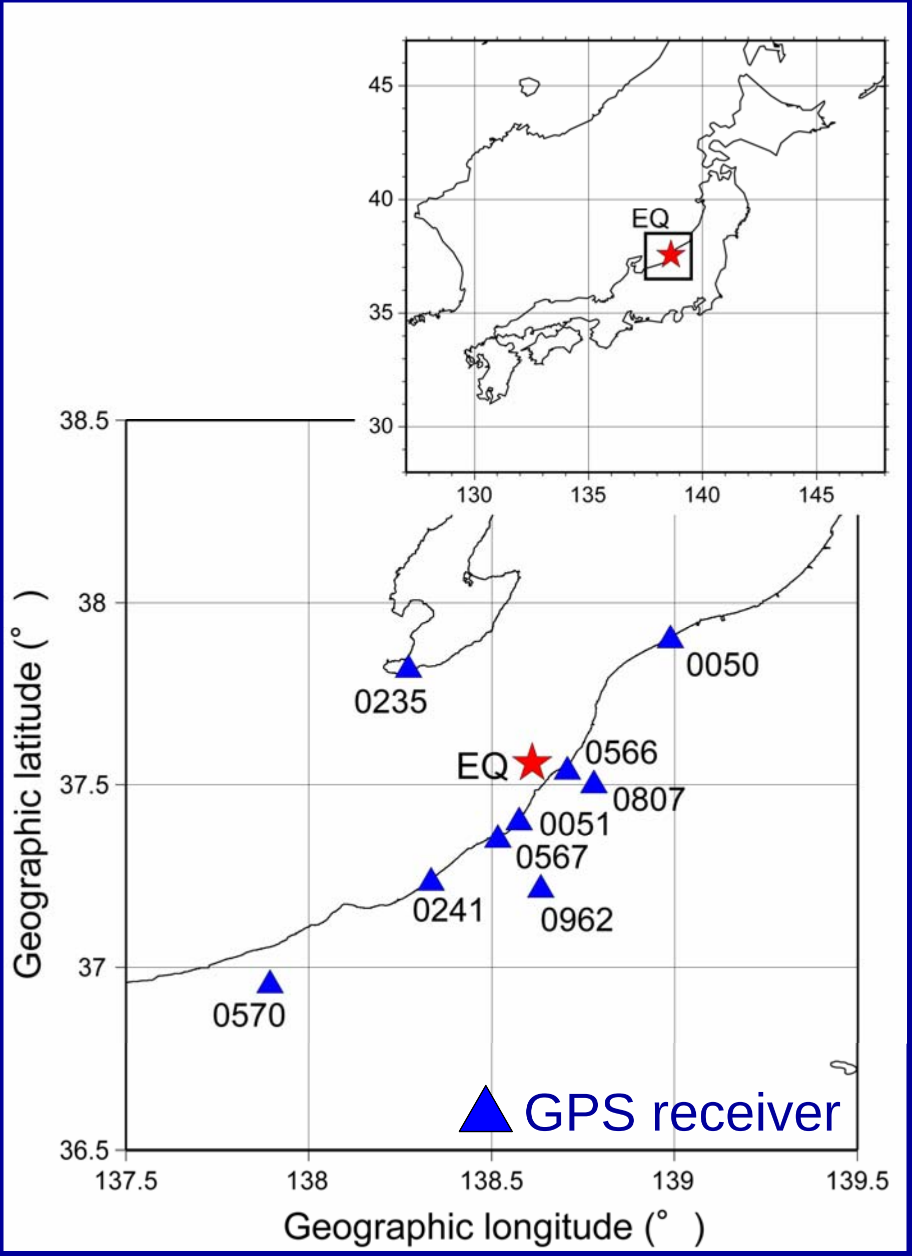
Case study 3:

The 2007 off-shore mid-Niigata EQ

2007 off-shore mid-Niigata EQ

July 16, 2007
10:13 (LT)
01:13 (UT)
M 6.8
37.56°N, 138.61°E
Depth: 17km

GPS station:
GEONET
(operated by the Geographical Survey Institute (GSI) of Japan)



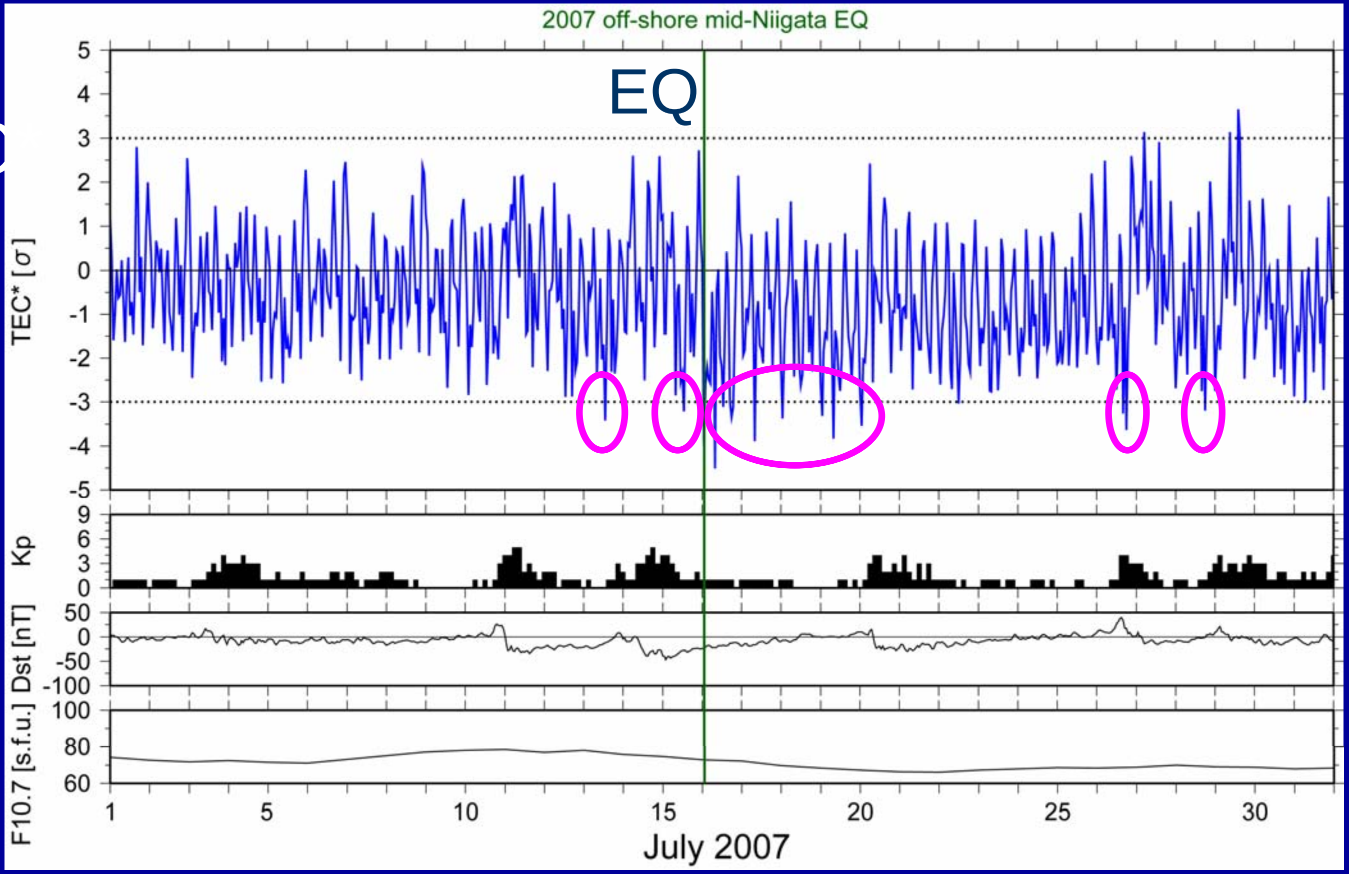
Variation of TEC* during the 2007 off-shore mid-Niigata EQ

0051 (Kashiwazaki-1) station

TEC*, GIM-TEC

exceed -3σ

We then declare the abnormal signals have been detected.

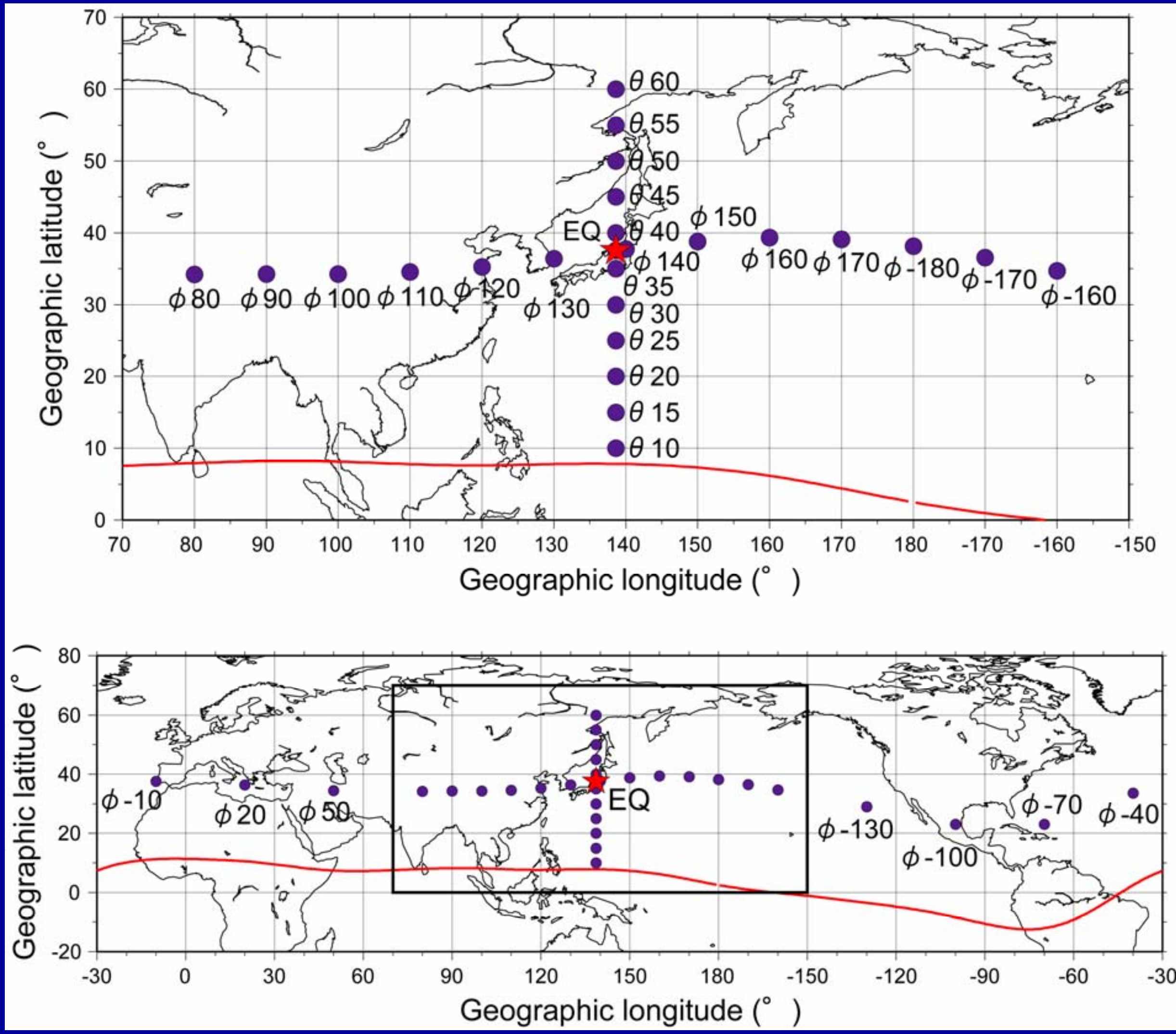


Variations of TEC* of the other stations show similar tendency.

Computation of GIM-TEC*

Computed locations

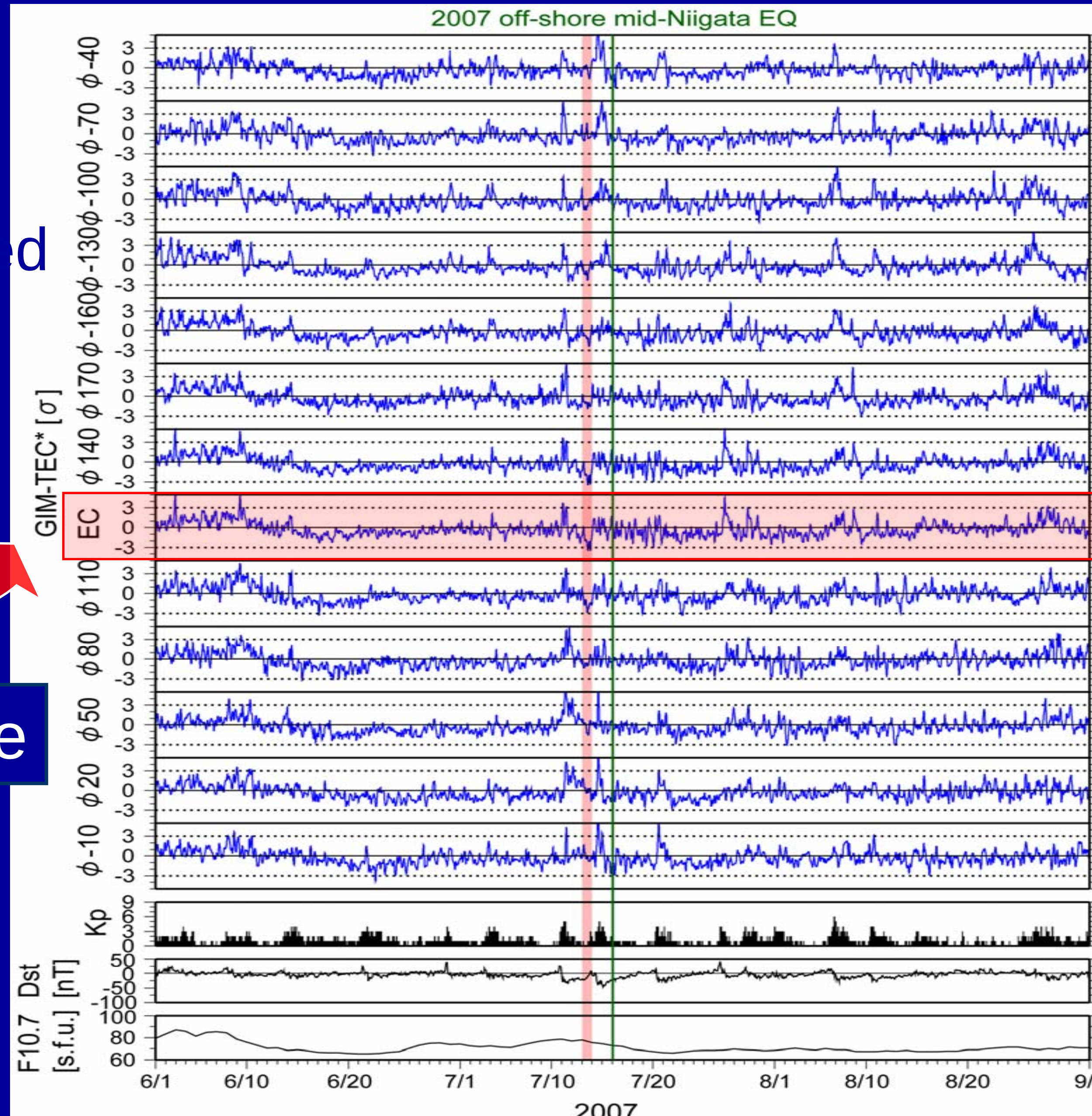
- epicenter
- 20 locations of magnetic latitude same as the EQ (32.25°N)
- 11 locations of geographic long. same as the EQ (138.61°E)



(Magnetic latitude: 32.25°N)

ed

only July 13

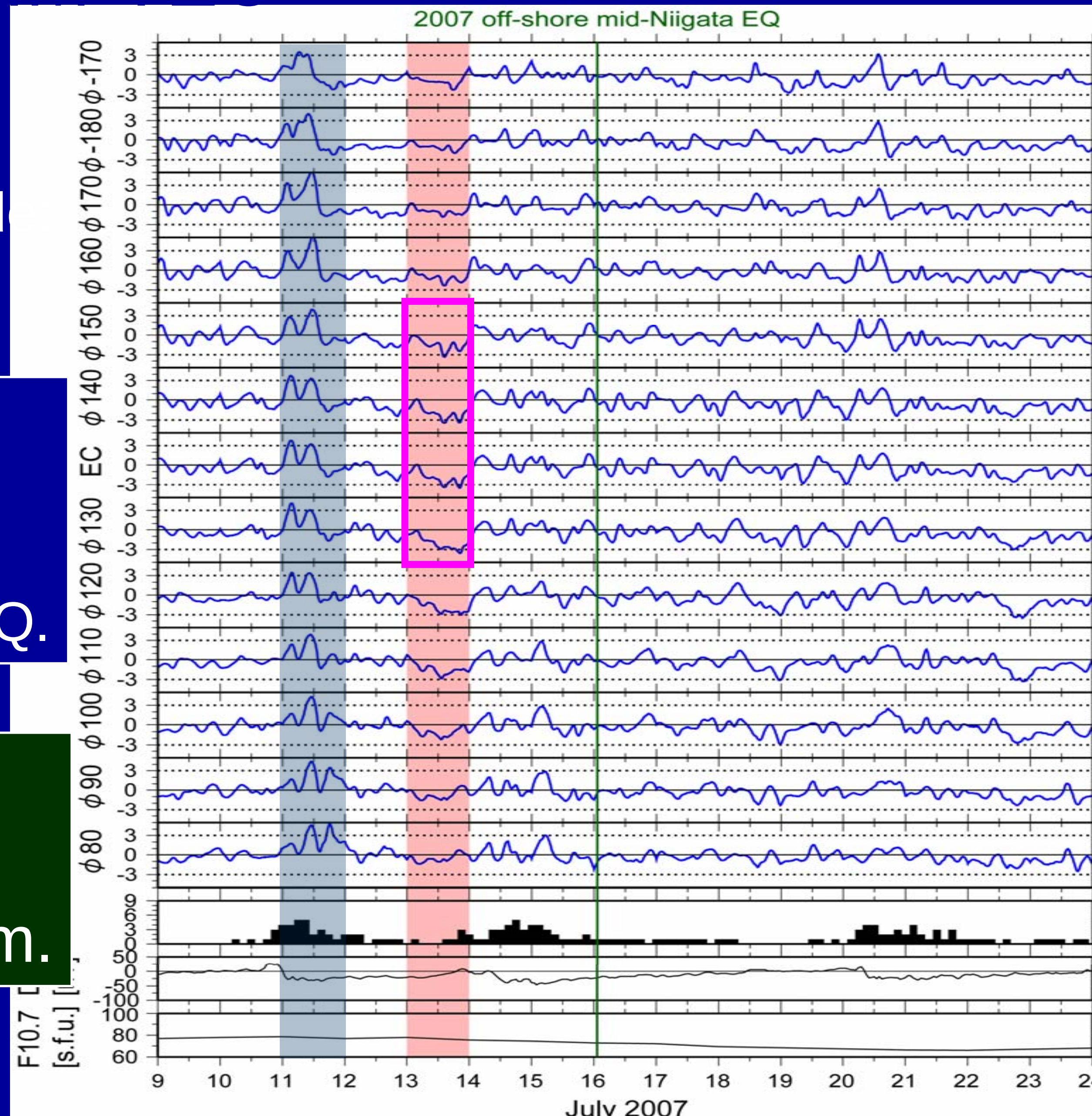


Not global change

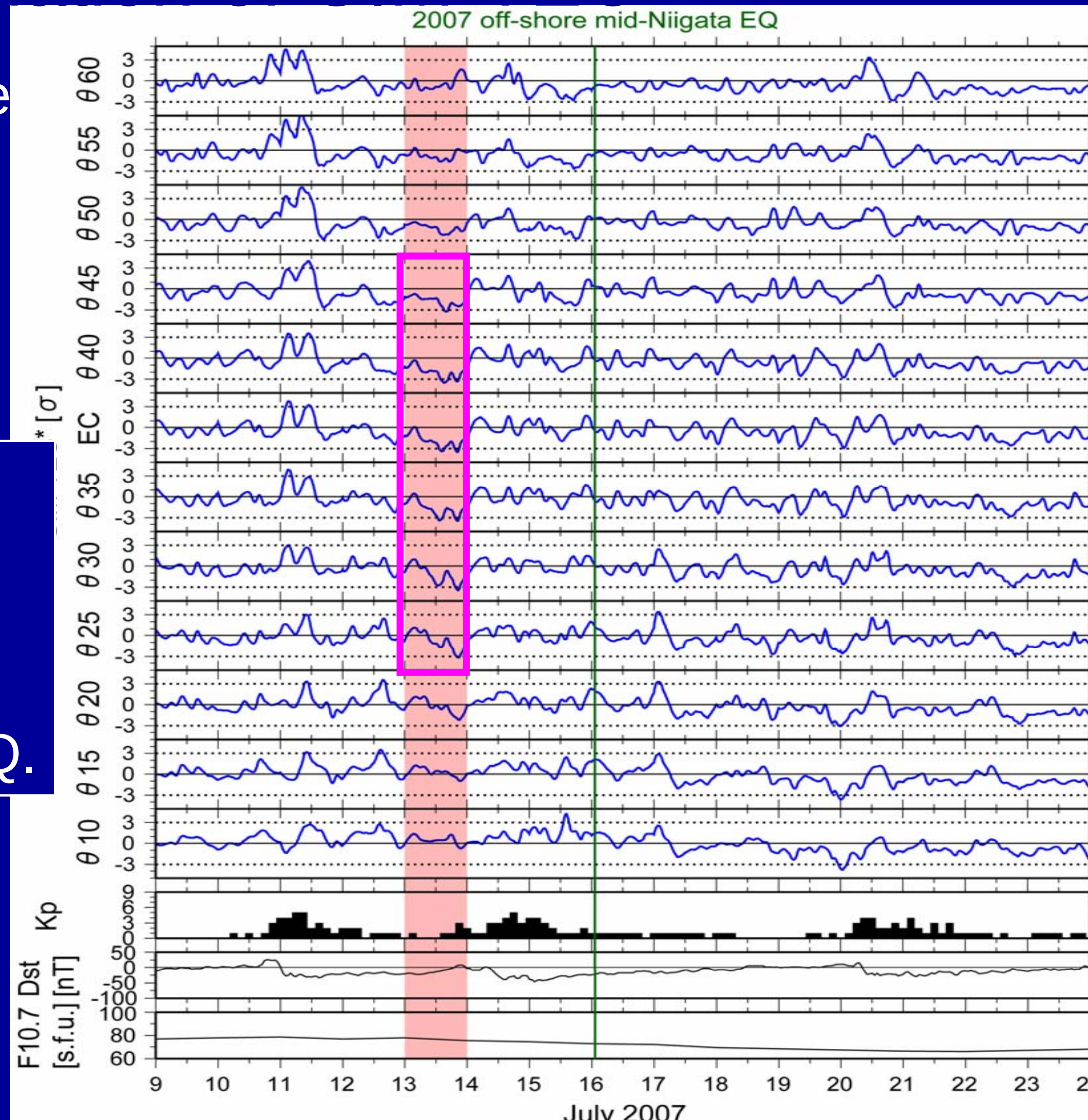
Magnetic latitude:
32.25°N
Geographic longitude:
80°E ~ 170°W

GIM-TEC* at φ130, epicenter, φ140, φ150 exceeded -3σ 3 days before the EQ.

Global positive anomaly induced by magnetic storm.



Geographic longitude
138.61°E
Geographic latitude:
10°N ~ 60°N



Negative anomaly was detected at θ25, θ30, θ35, epicenter, θ40, θ45 3 days before the EQ.

UT	LT	φ110	φ120	φ130	EC	φ140	φ150	φ160	φ170
0	9								
1	10								
2	11								
3	12								
4	13								
5	14								
6	15								
7	16								
8	17								
9	18								
10	19								
11	20								
12	21								
13	22								
14	23								
15	0								
16	1								
17	2								
18	3								
19	4								
20	5								
21	6								
22	7								
23	8								

UT	LT	θ20	θ25	θ30	θ35	EC	θ40	θ45	θ50
0	9								
1	10								
2	11								
3	12								
4	13								
5	14								
6	15								
7	16								
8	17								
9	18								
10	19								
11	20								
12	21								
13	22								
14	23								
15	0								
16	1								
17	2								
18	3								
19	4								
20	5								
21	6								
22	7								
23	8								

Anomalies were detected at φ130 ~ φ150 and θ25 ~ θ45 from night time until morning time.

Spatial distribution of GIM-TEC* anomalies (July 13)

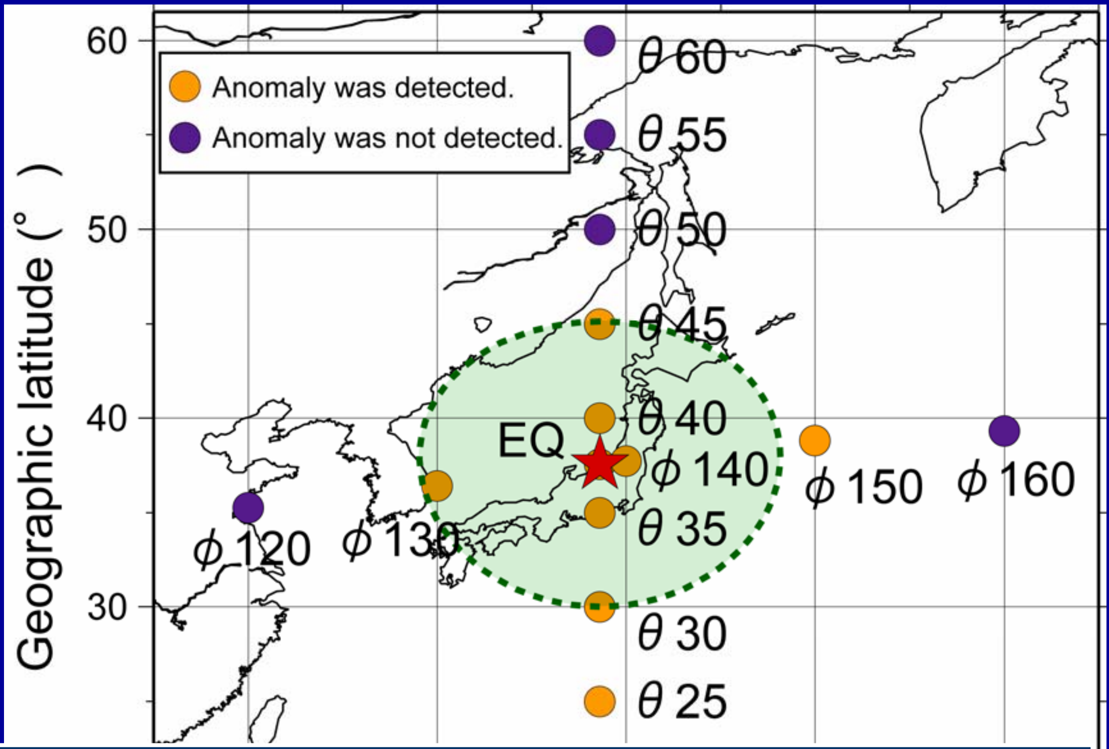
Dobrovolsky et al. (1979)

・・・ the precursory phenomena can be observed within the earthquake preparation area.

$$R = 10^{0.43M}$$

R: radius of the EQ preparation area

M: 6.8 ⇒ R = 839 km



Spatial distribution of the reduction anomalies coincides approximately with the EQ preparation area.

TEC* anomaly 1 day before the EQ (7/15)

July 15 : the next day of the geomagnetic disturbed day.
(Kp index: 5+)

The ionospheric electron density might significantly decrease from a few hours to 2 days after a geomagnetic storm sudden commencement (SSC). (Davies,1990; Kelly,1989)

⇨ Global ionospheric disturbance exceeded -3σ was not detected.

TEC* anomaly 1 day before the EQ (7/15)

Computation of GIM data

GPS data observed at MIZU, MTKA, TSKB, and USUD were used in Japan area.

GIM was interpolated by means of the spherical harmonics.

➡ It is difficult to express the significant local disturbance in GIM data.

➡ The anomaly did not appear throughout the globe.

➡ **TEC* anomaly observed in epicentral region 1 day before the EQ was significant local phenomenon.**

TEC* anomalies after the EQ (7/16 ~ 7/20)

- Geomagnetic condition : quiet
  (maximum value of Kp index: 1+)
- GIM-TEC* at epicenter did not decrease exceeding -3σ.

↓ similar to the TEC* anomaly appeared on July 15

TEC* anomalies observed in epicentral region after the EQ were significant local phenomena possibly associated with the aftershocks.

Summary

- Ionospheric disturbances 1 day before the EQ (7/15) & after the EQ (7/16 ~ 20)

  The disturbed areas were localized significantly.

- Ionospheric disturbance 3 days before the EQ (7/13)

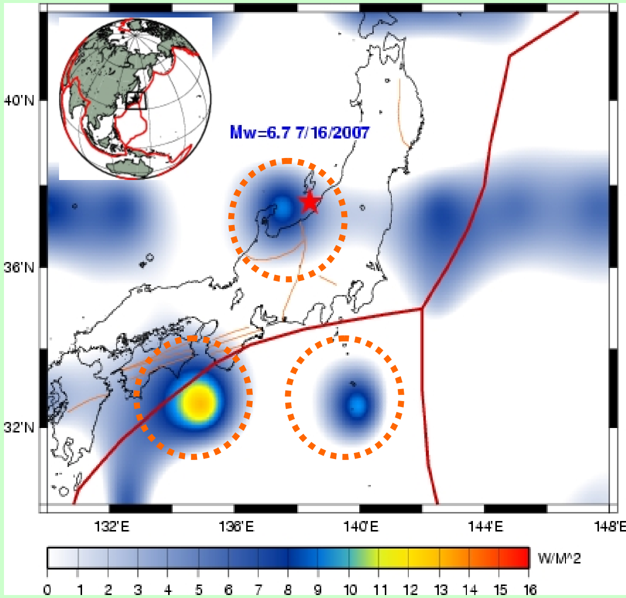
  The spatial distribution was about 20°in lat. and long.
  & coincides approximately with the EQ preparation area.

Not global change

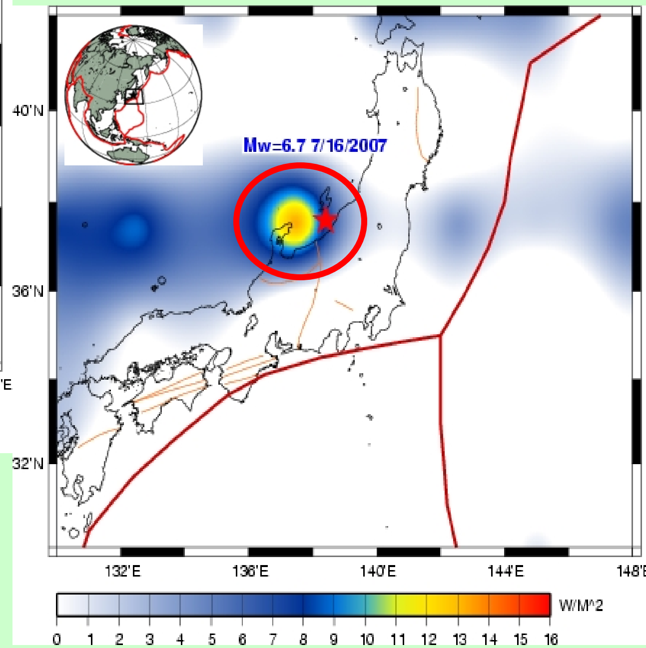
After removing global changes,
・ we can distinguish the local disturbances associated with earthquakes.
・ we can also estimate the spatial distribution

Validation over Japan (forecast mode)

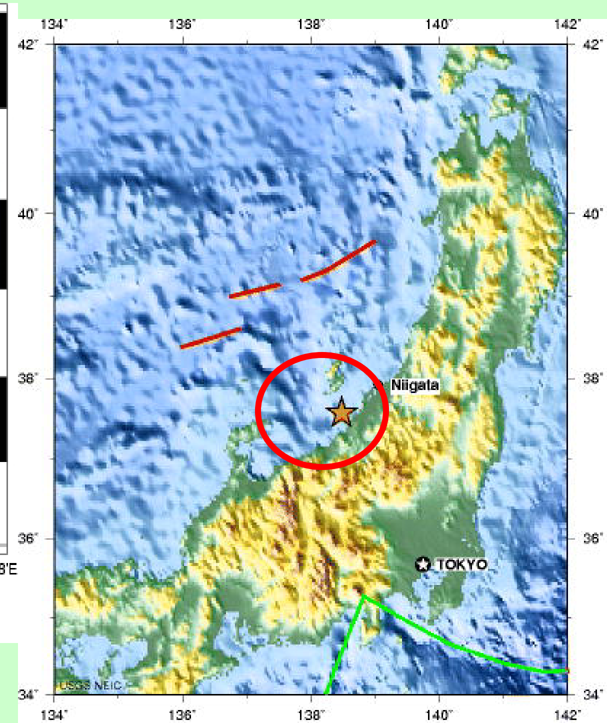
Evolution of daily Earth radiation anomalies. Earthquake has occurred
2007-07-16 01:13 (Mw 6.7) NEAR WEST COAST OF HONSHU, JAPAN 37.6 138.4



July 4, 2007



July 14, 2007



NEAR WEST COAST OF HONSHU, JAPAN
2007 07 16 01:13:22 UTC 37.57N 138.48E Depth: 10.0 km, Magr
Earthquake Location

July 16, 2007, USGS

Time evolution:
July 4 – EQ Alert
July 14- EQ Warning
July 16- EQ Event

(Ouzounov, EMSEV & DEMETER 20080909

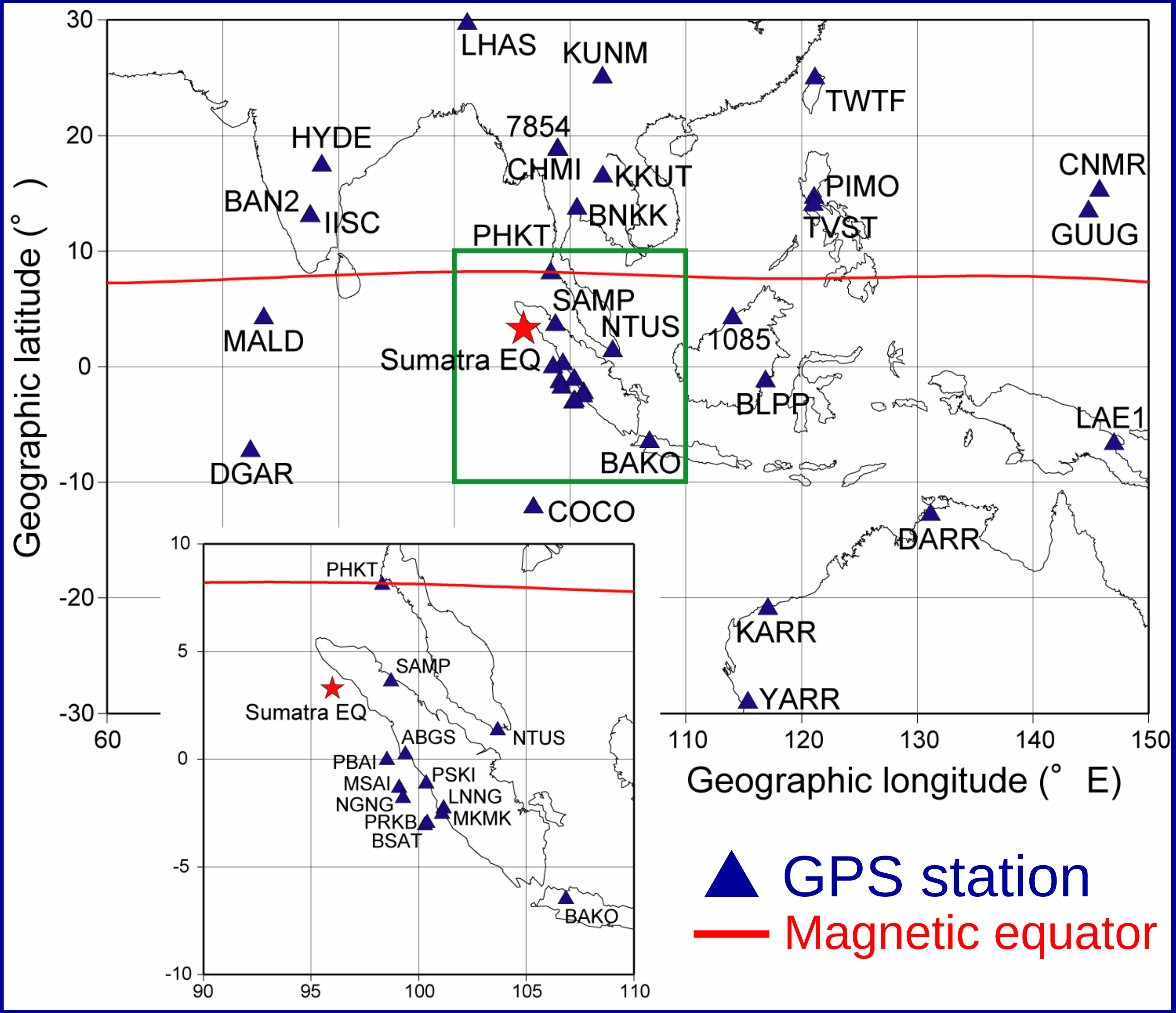
Case Study 4:

The 2004 Sumatra-Andaman EQ

Sumatra-Andaman EQ

20041226
00:58 (UT)
07:58 (LT)
Mw: 9.2
depth: 30km
Epicenter:
3.316N
95.854E

GPS stations:
IGS, SuGAr, JAMSTEC ,
Shizuoka Univ.



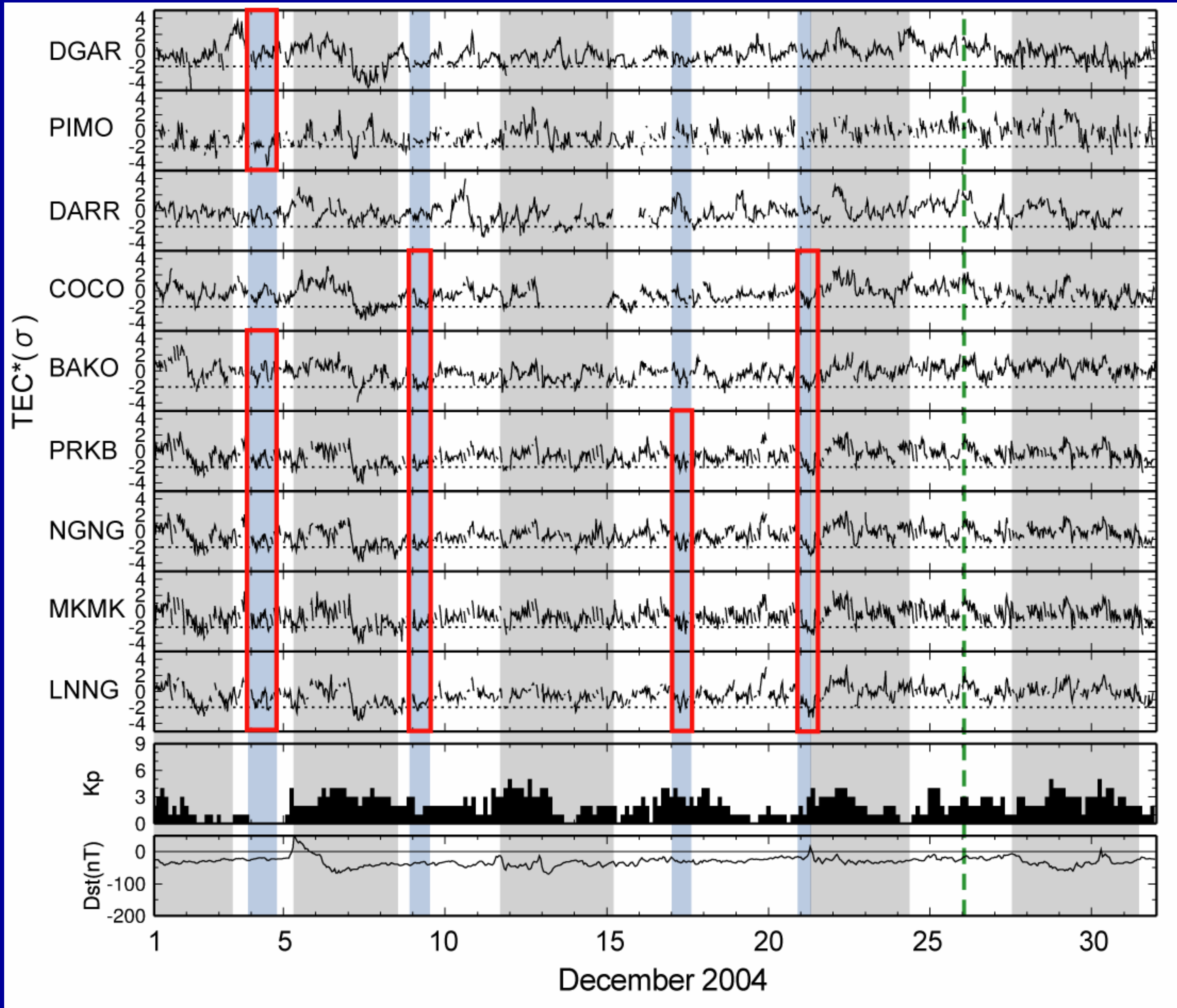
5, 9, 17, 22 days before the EQ,
TEC* around Sumatra decreases excess -2σ

Sumatra EQ

TEC* ,
GIM-TEC*

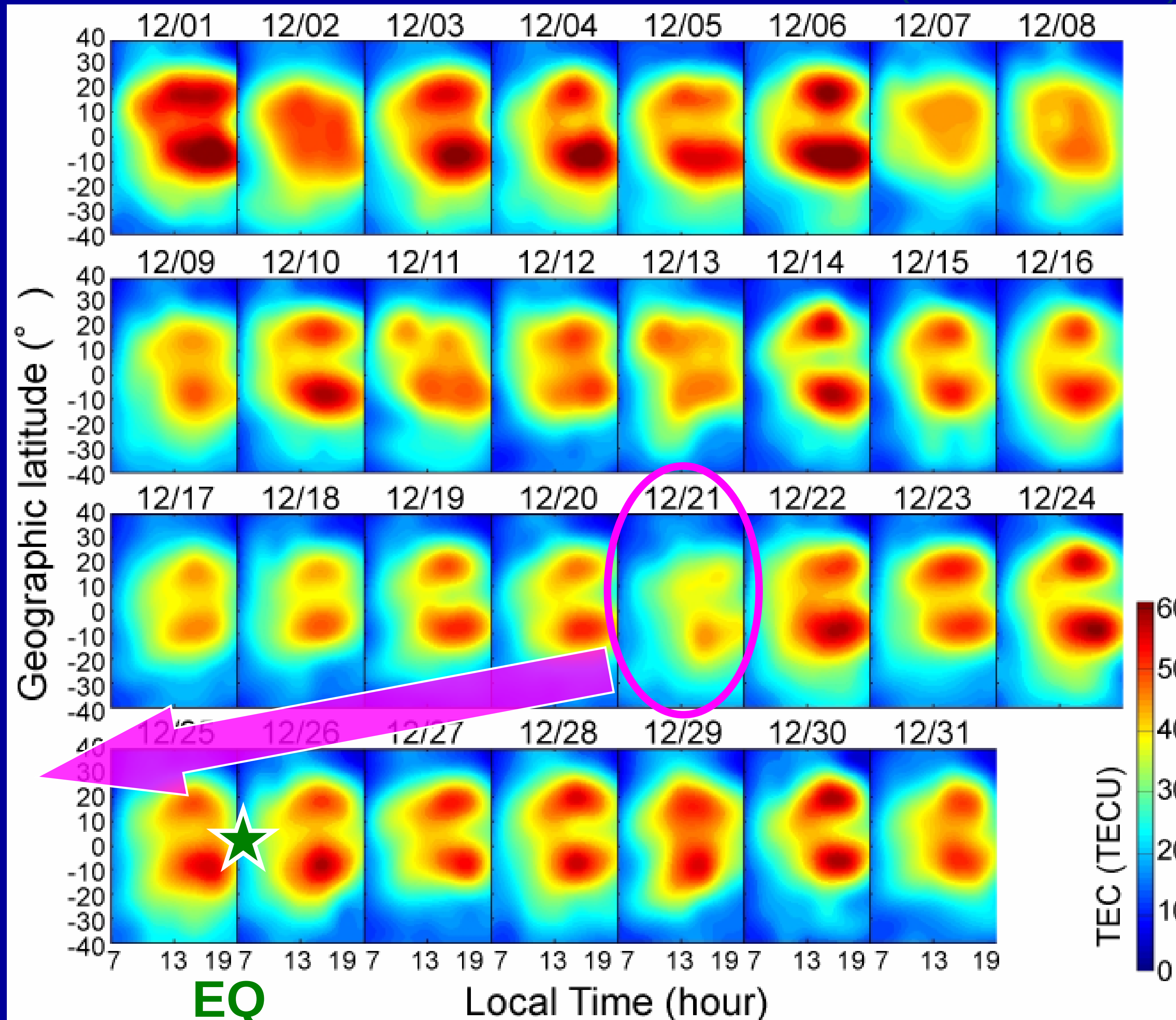
Δ <-2σ

Anomaly



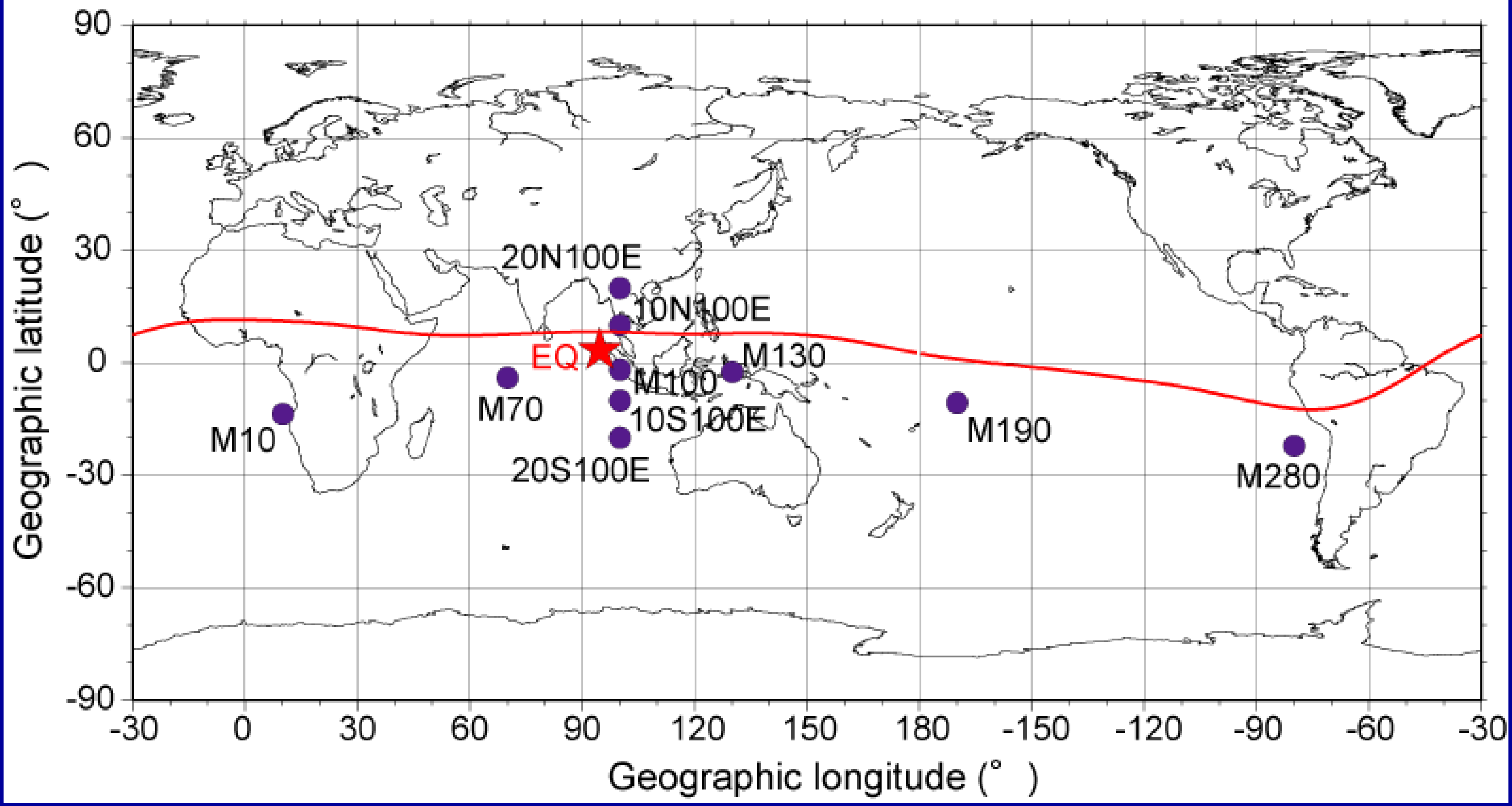
2004年12月1日～31日
07時～19時LT (0時～12時UT)

LT-Lat dependence of GIM-TEC along 100E



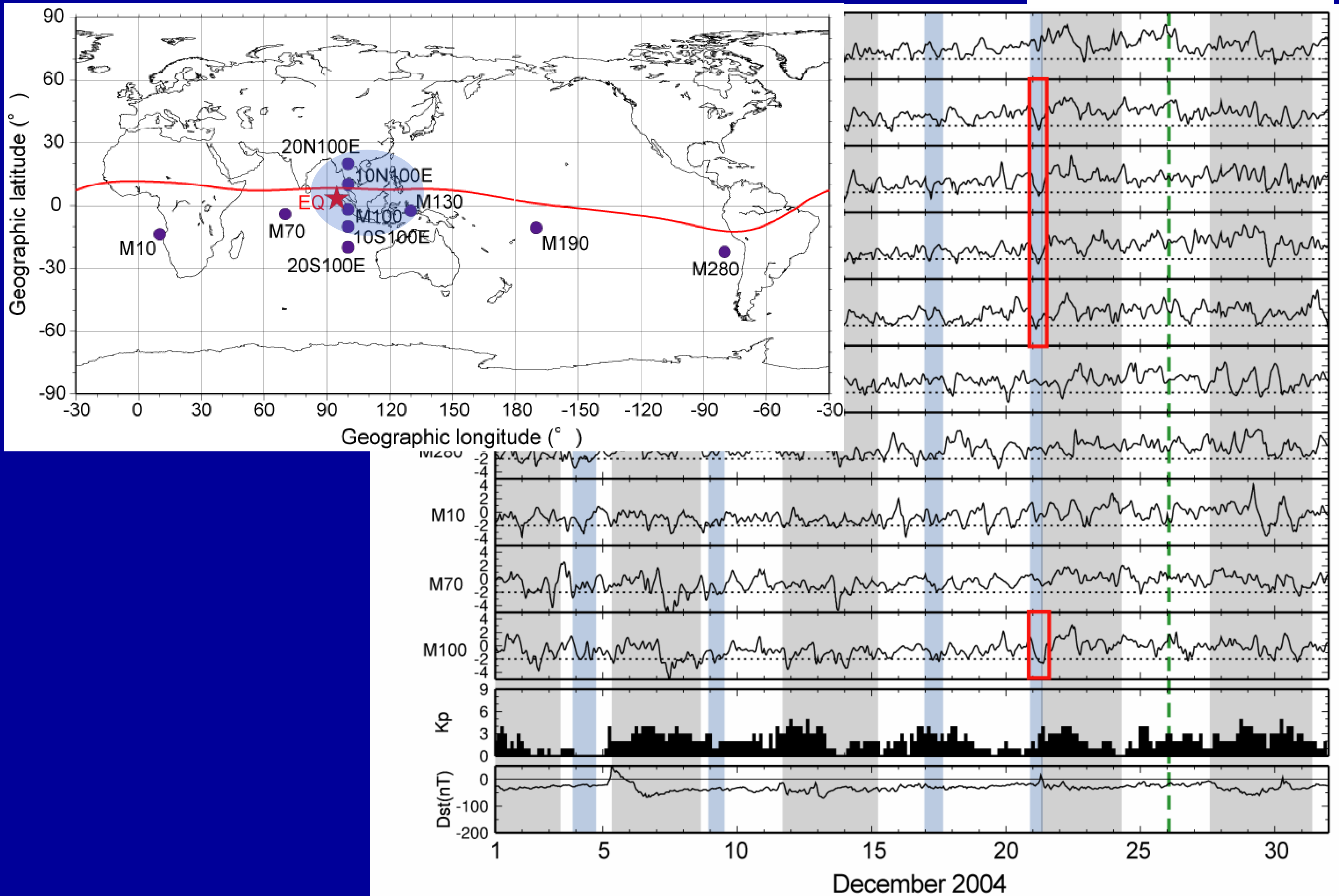
Equatorial Anomaly is smaller than the other days

Computing points of GIM-TEC*



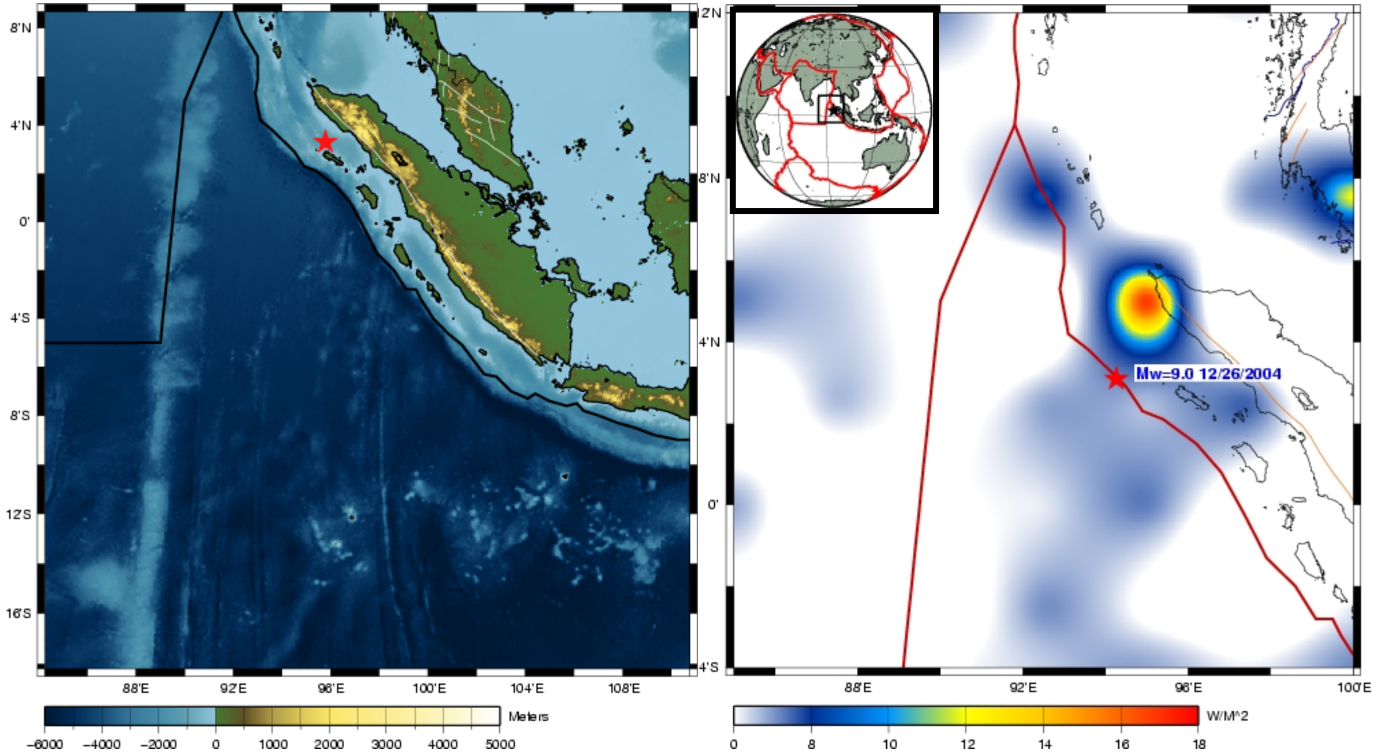
6 points along the geomagnetic lat. of -12º
5 points along E100

Sumatra EQ

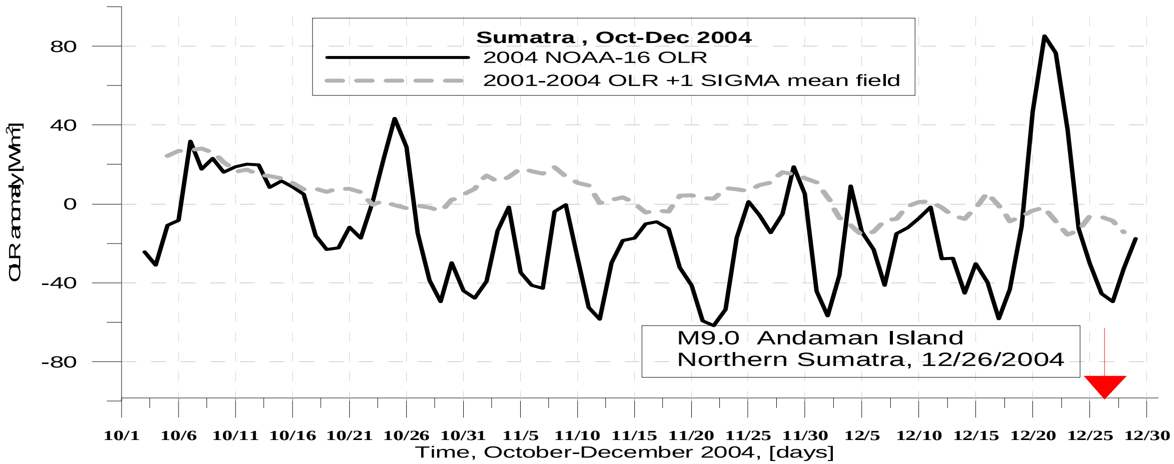


Geographic latitude (°)
Geographic longitude (°)
20N100E
10N100E
EQ
M130
M100
10S100E
20S100E
M10
M70
M190
M280
M10
M70
M100
Kp
Dst(nT)
December 2004

Northern Sumatra Dec 26,2004, M9.0



A/ Map of OLR monthly variations for November 2004, month prior to M9.0 Sumatra Andaman Island, Northern Sumatra of December 26, 2004. Epicenter (3.09N/94.26E)



B/Time-series of daily OLR anomaly for October 1, 2004 – December 31, 2004 over the epicenter of (3.09N/ 94.26E) [Ouzounov et al, 2008]

Summary (Sumatra-Andaman)

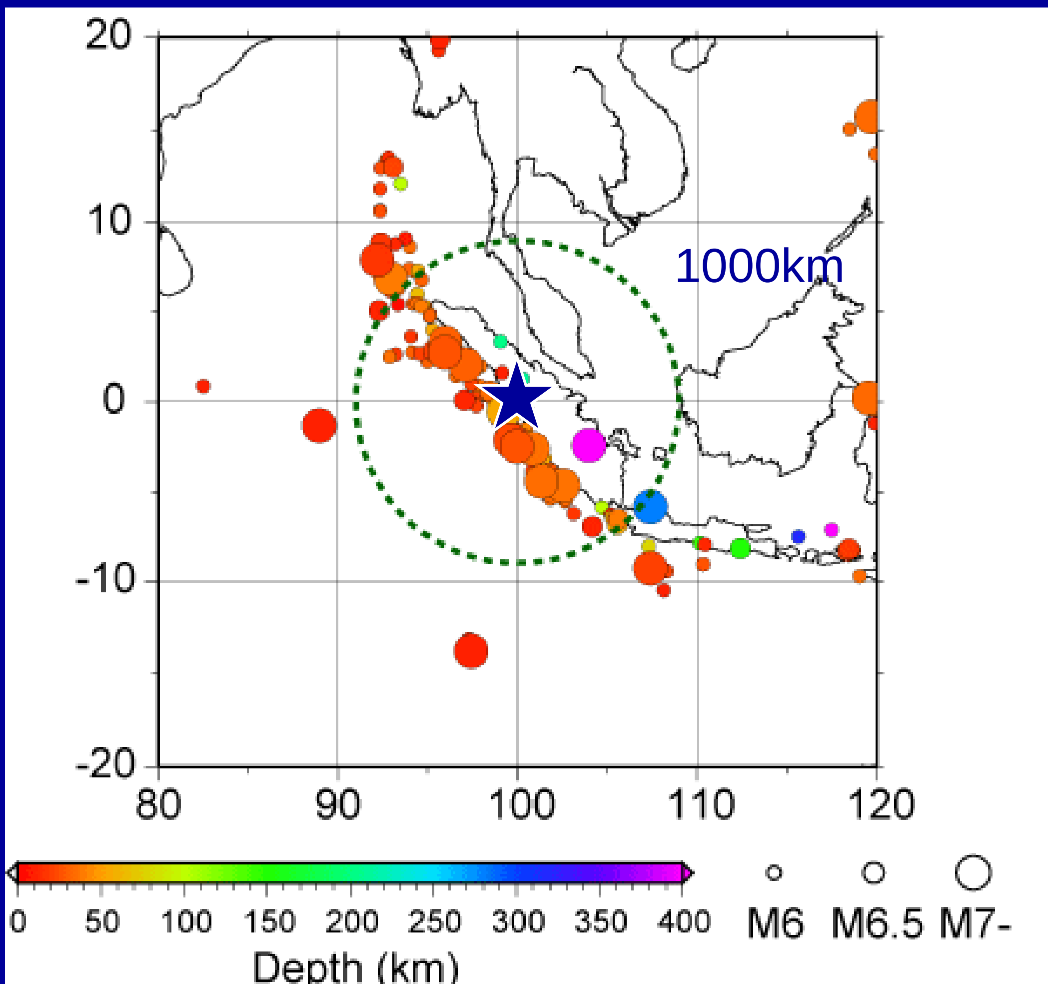
- Ionospheric disturbances 5 days before(12/21) 9 days before(12/17) , 17 days before (12/9)

TEC decrease in EA region around Sumatra Island

⇨ **Not global phenomena**

Suggestion of relationship between EA (mechanism) and EQ

Statistical Analysis of GIM-TEC* anomaly around Sumatra Island

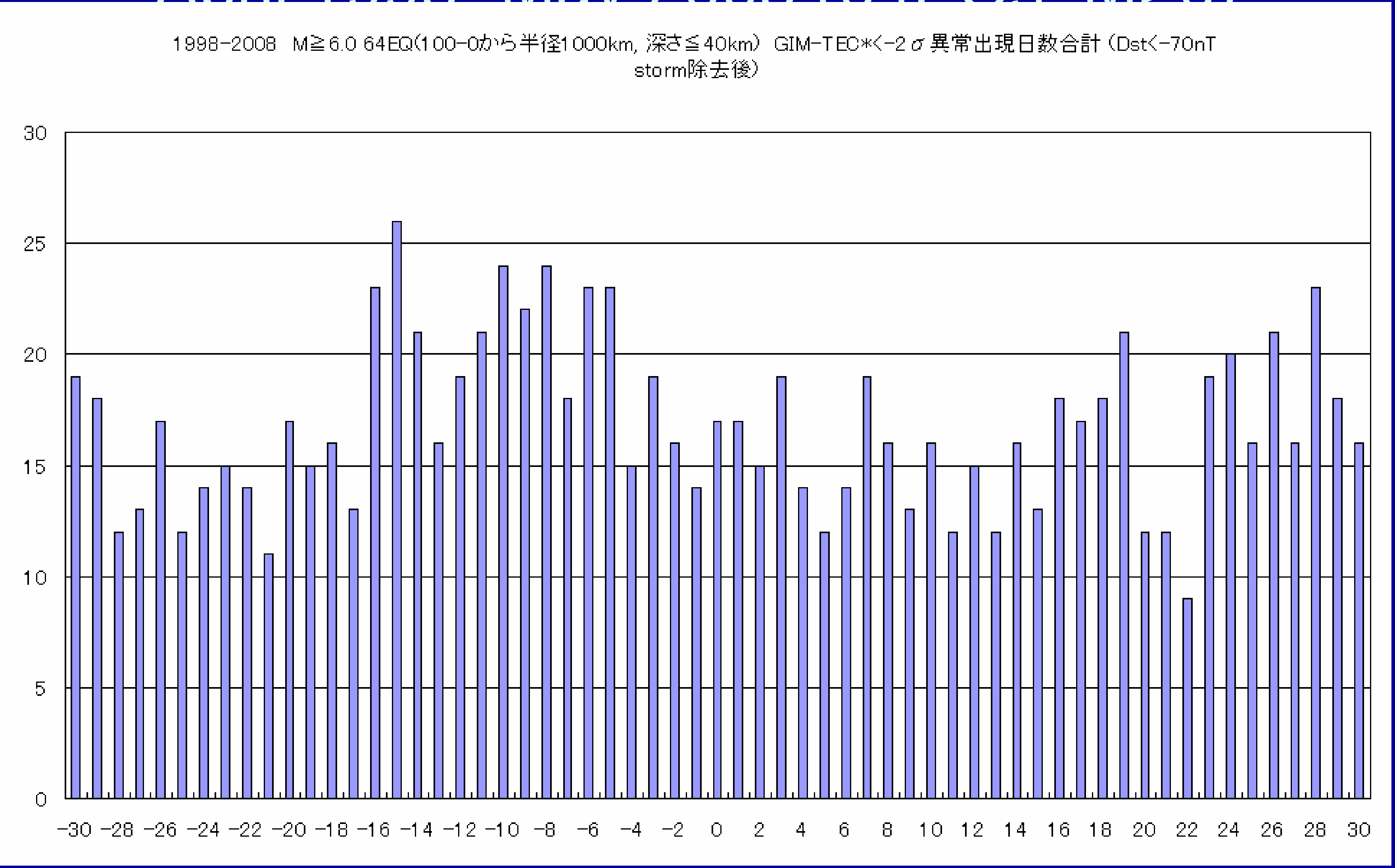


EQ catalog: USGS
April 1998- May 2008

Investigated area:

- Center (100E，0N)
- radius < 1000km
- M>6.0，depth<40km
- 64 EQs

Superimposed Analysis
April 1998- May 2008 (64EQs, M>6)



Conclusion

Development of temporal Spatial distribution on Ionsopheric disturbances GPS-TEC using GAMIT

+

LOCAL map

GIM-TEC using Global Ionosphere Maps (GIM)

Statistical evalustion with a certain window length

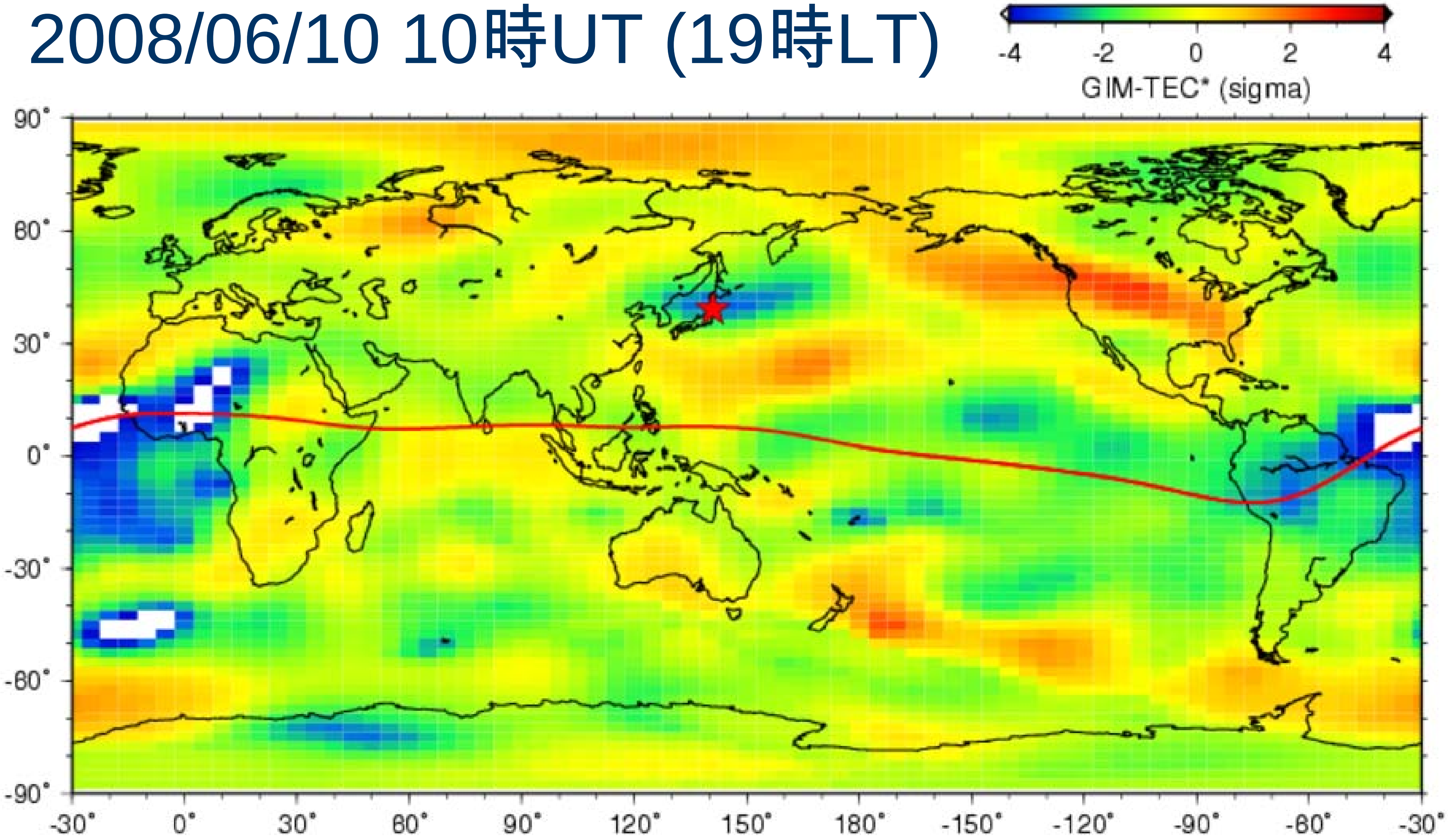
GLOBAL map

Detection of possible EQ-related LOCAL ionospheric disturbancein time and space

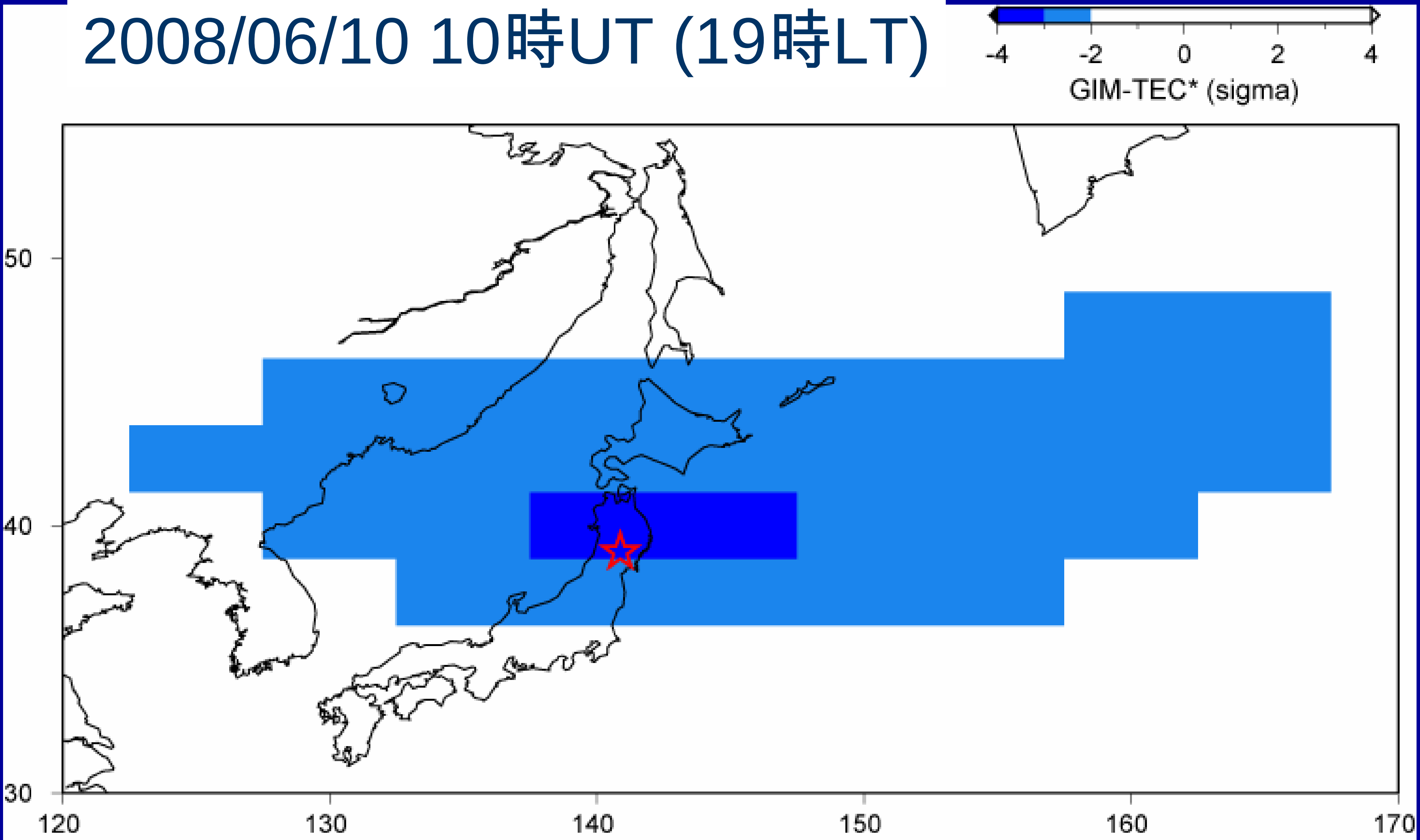
GIM-TEC*マップ

岩手・宮城内陸地震
2008/06/13 23:43 UT, M7.2, 8km

2008/06/10 10時UT (19時LT)

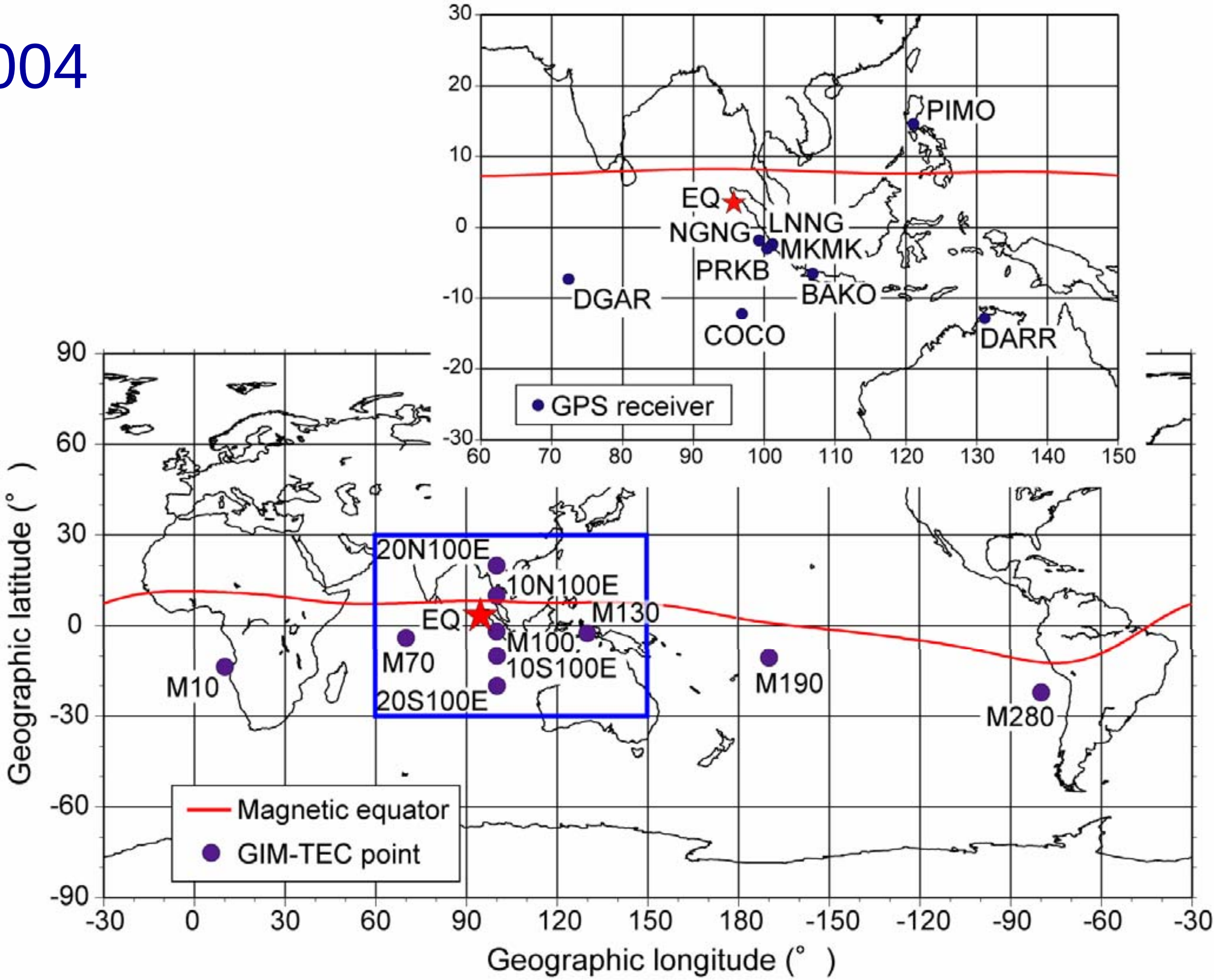


2008/06/10 10時UT (19時LT)



Sumatra-Andaman EQ

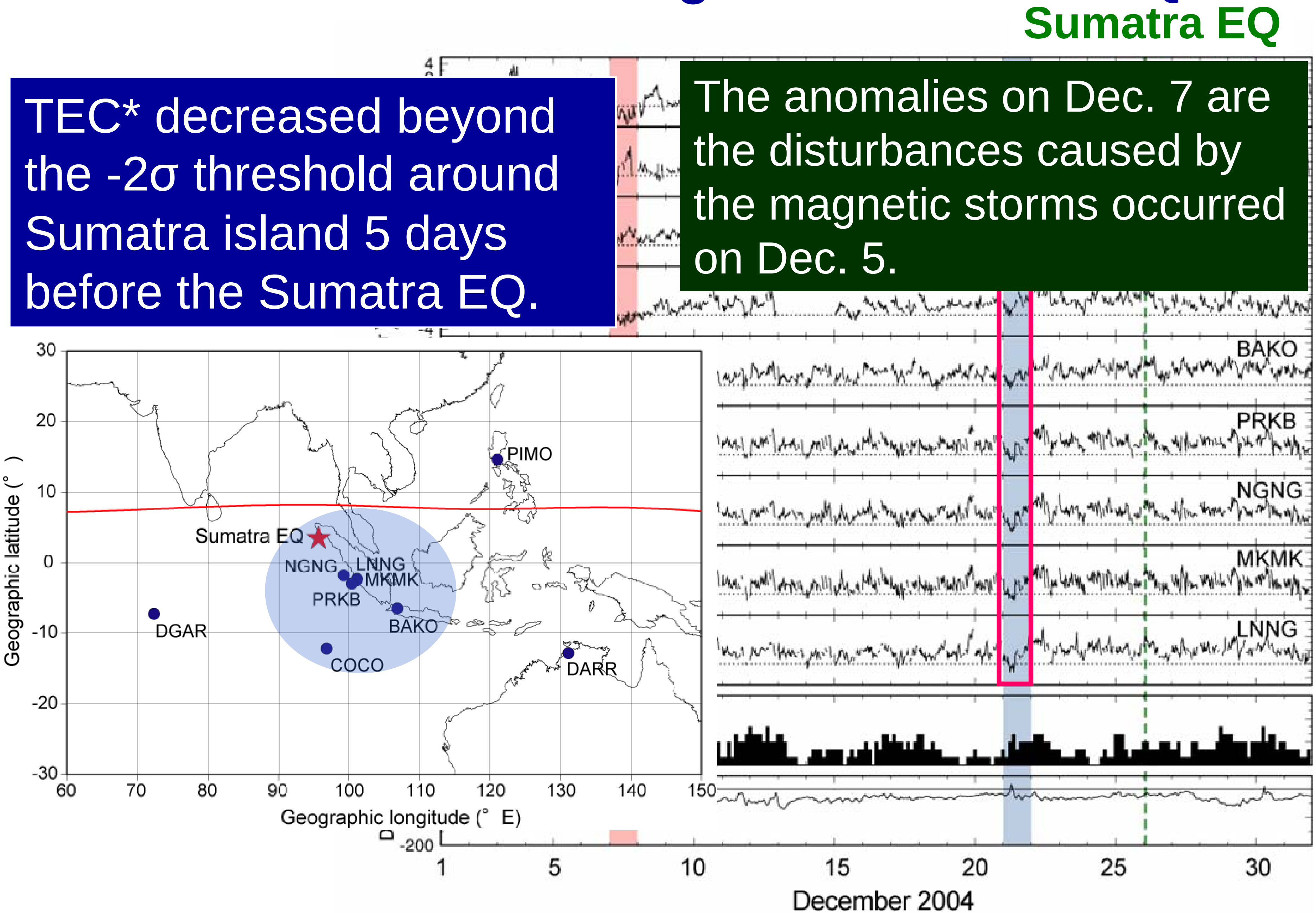
December 26, 2004
00:58 (UT)
07:58 (LT)
Mw 9.2
3.3°N, 95.98°E
Depth: 30km



Variation of TEC* during the Sumatra EQ

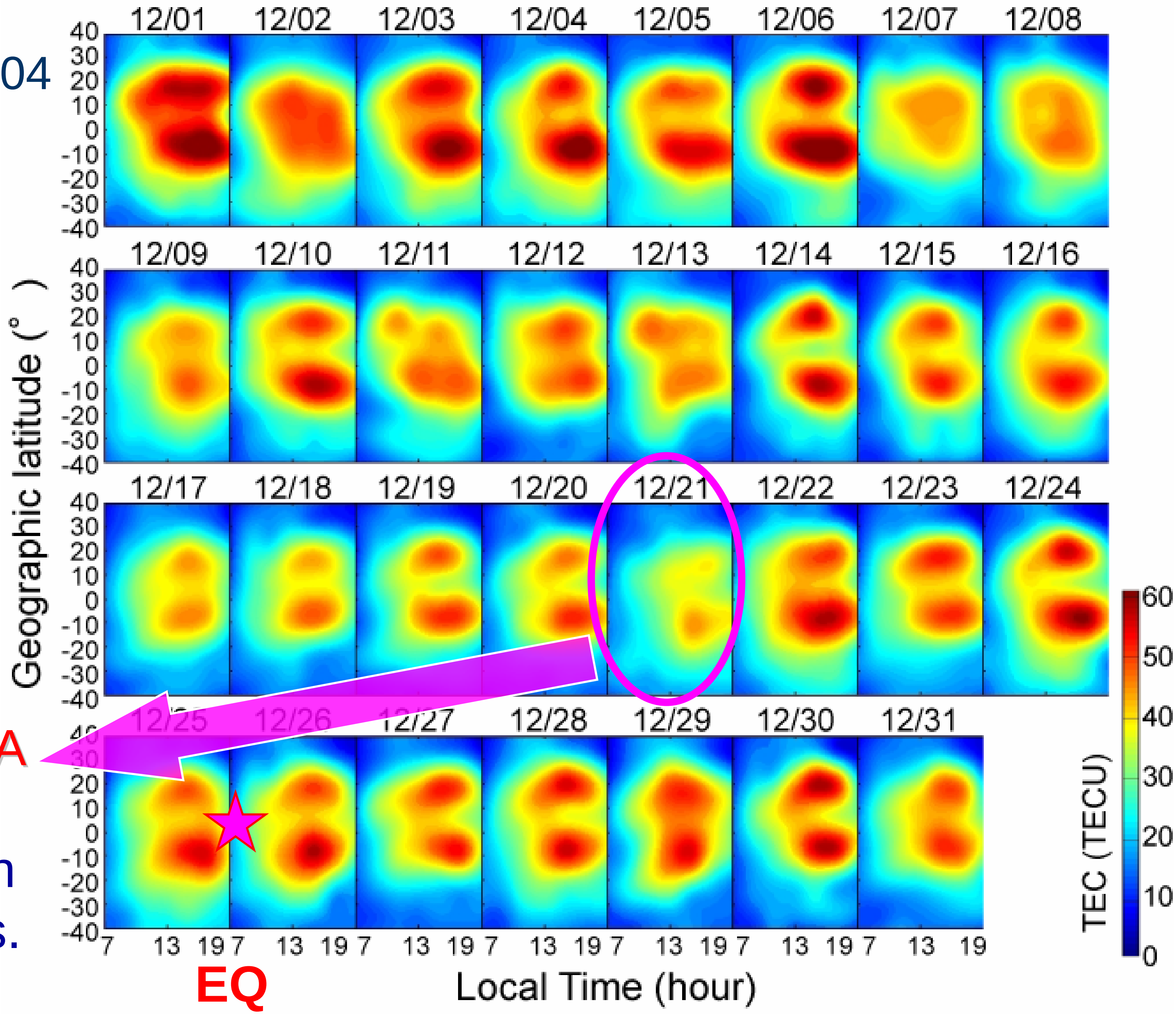
TEC* decreased beyond the -2σ threshold around Sumatra island 5 days before the Sumatra EQ.

The anomalies on Dec. 7 are the disturbances caused by the magnetic storms occurred on Dec. 5.



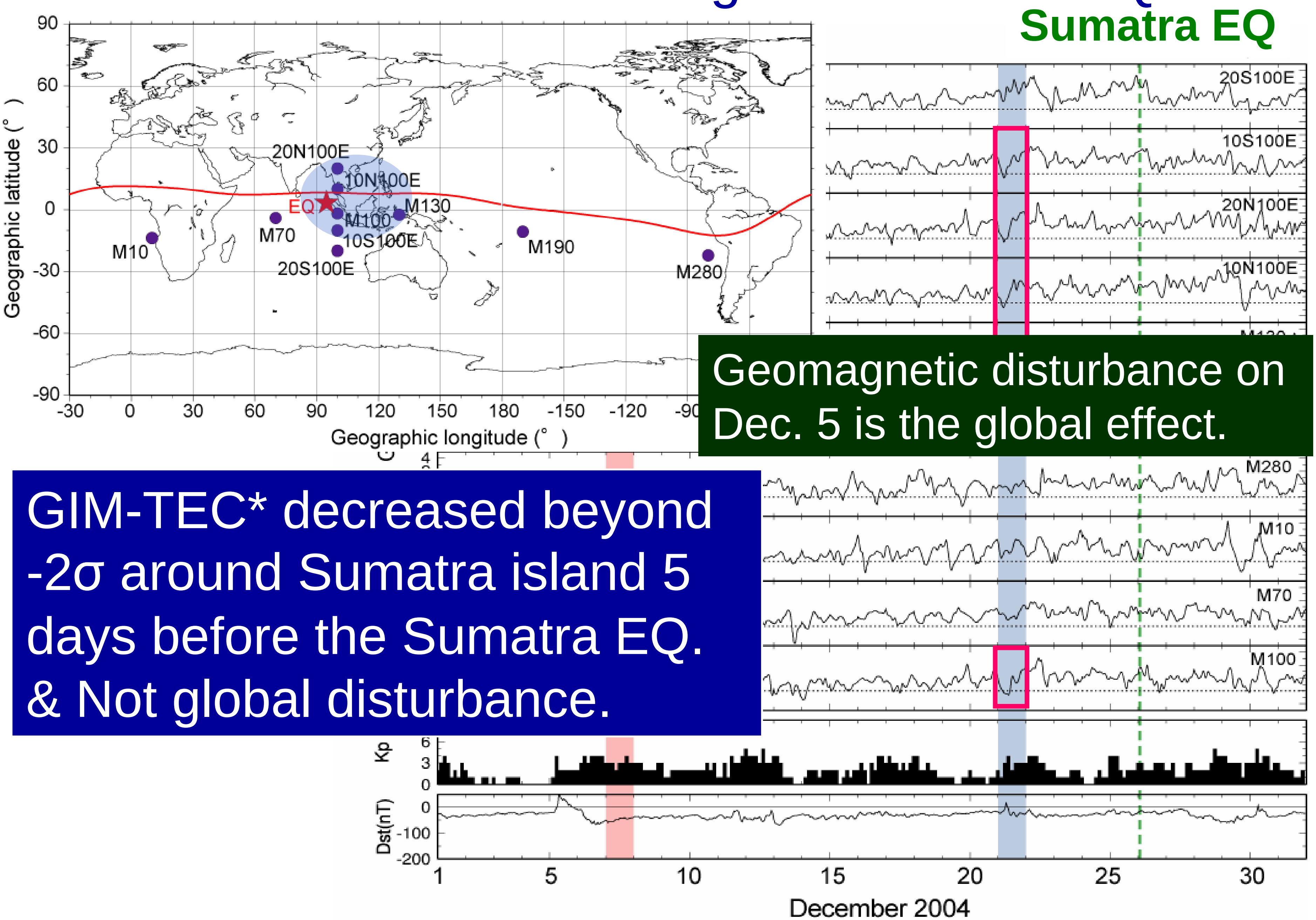
Latitude-time-GIM-TEC plots (along the meridian of 100°E)

Dec. 1 ~ 31, 2004
07 ~ 19h LT
(0 ~ 12h UT)



Intensity of EIA is small compared with the other days.

Variation of GIM-TEC* during the Sumatra EQ



Geomagnetic disturbance on Dec. 5 is the global effect.

GIM-TEC* decreased beyond -2σ around Sumatra island 5 days before the Sumatra EQ. & Not global disturbance.

Conclusion (Sumatra EQ)

- Ionospheric disturbance 19 days before the Sumatra EQ (12/7)

→ Global change caused by magnetic storm

- Ionospheric disturbance 5 days before the Sumatra EQ (12/21)

The disturbance appeared around epicenter in the EIA region. The spatial distribution is about 30°in latitude and 40°in longitude.

→ Not global change

After removing global changes,

・ we can distinguish the local disturbances associated with earthquakes.

・ we can also estimate the spatial distribution

Acknowledgment

Authors thank to CALTECH, SOPAC, and IGS for providing GPS data and to NiCT for ionosonde data in Japan.

Future problem

- 地磁気嵐等の地震以外の現象によるTECの変動パターンの把握
- 地震に関連する電離圏擾乱の時空間構造の解明
- 長期間のデータ解析，統計処理

Purpose

Investigation of the Taiwan Chi-Chi EQ reported by Liu et al.

(e.g. Liu et al., 2001, 2004)

↓

These studies have not been checked whether the anomalies observed in Taiwan were local or global phenomena.

↓

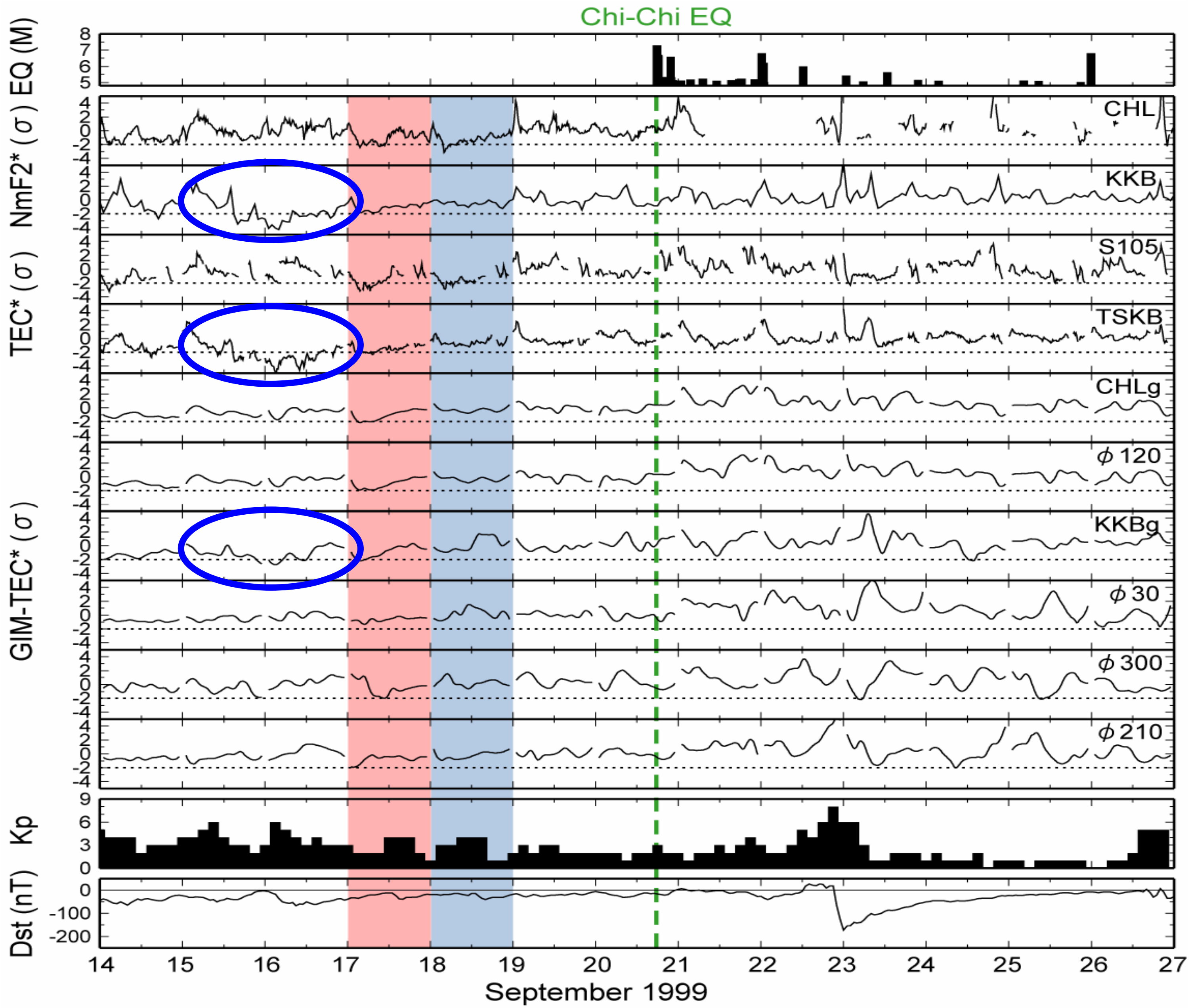
Understand the spatial distribution of ionospheric disturbances prior to the Earthquakes.

TEC (GAMIT)

NmF2 (ionosonde)

TEC (GIM)

Variations of NmF2*, TEC*, GIM-TEC* during the Chi-Chi EQ



Anomalies 5 & 6 days before the Chi-Chi EQ

If the normalized data exceed the threshold of -2σ: ○

if the data do not exceed -2σ: ×

		Taiwan	Japan	Others
9/15 & 9/16 (6 & 5 days before EQ)	NmF2*	×	○	
	TEC*	×	○	
	GIM-TEC*	×	○	×

- Three sequential magnetic storms occurred from Sep. 12 to 15.

(refer to the Dst index) (Shiokawa et al., 2002)

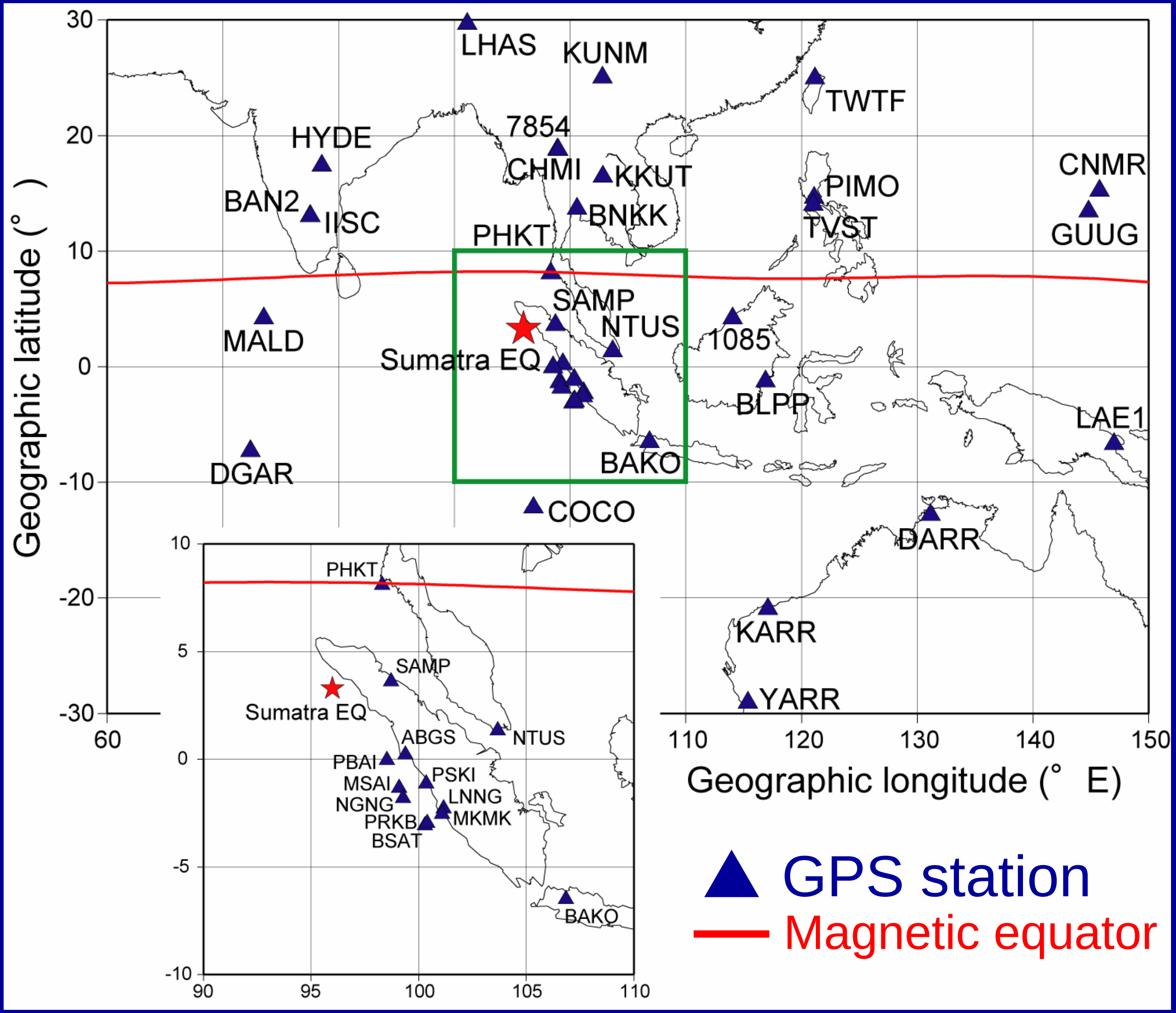
- Large-scale traveling ionospheric disturbance (LSTID) observed around Japan at 14 -15h UT on Sep. 15.

(Shiokawa et al., 2002)

Anomalies in Japan 5 & 6 days before the Chi-Chi EQ are the influences of the magnetic storms.

Sumatra-Andaman EQ

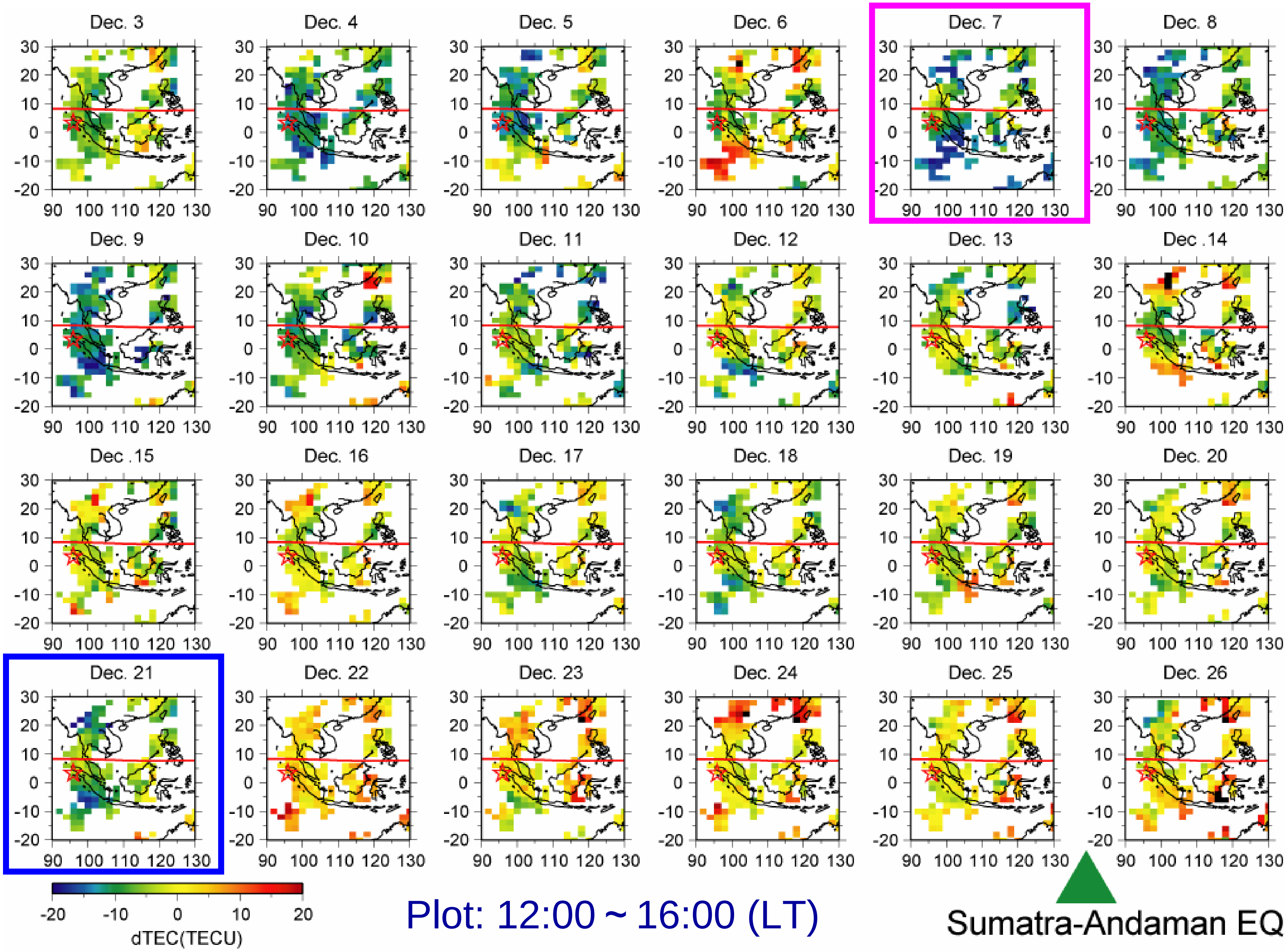
Dec. 26, 2004
00:58 (UT)
07:58 (LT)
Mw 9.2
3.3°N, 95.98°E
Depth: 30km



Spatial distribution of ΔTEC

15 days backward running median

$\Delta TEC(t) = TEC(t) - TEC_{\_model}(t)$



Plot: 12:00 ~ 16:00 (LT)

Sumatra-Andaman EQ

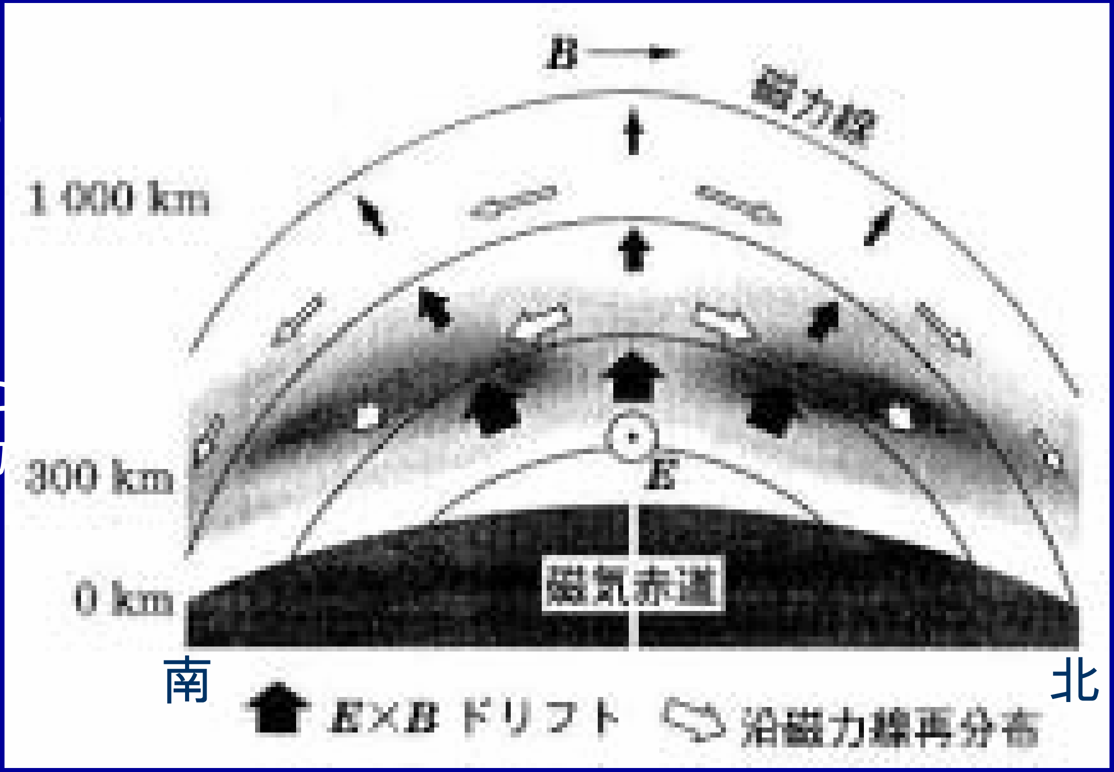
赤道異常 (equatorial anomaly)

磁気赤道をはさんで電子密度の高い領域が南北に
二つに分かれる構造

赤道周辺のF層での昼間の
東向き電場と，水平で北向き
の磁場により，鉛直上向きの
E*×*Bドリフトが発生．

上昇に伴って磁力線に沿った
プラズマの平衡が破れ，磁力
線に沿って下降．

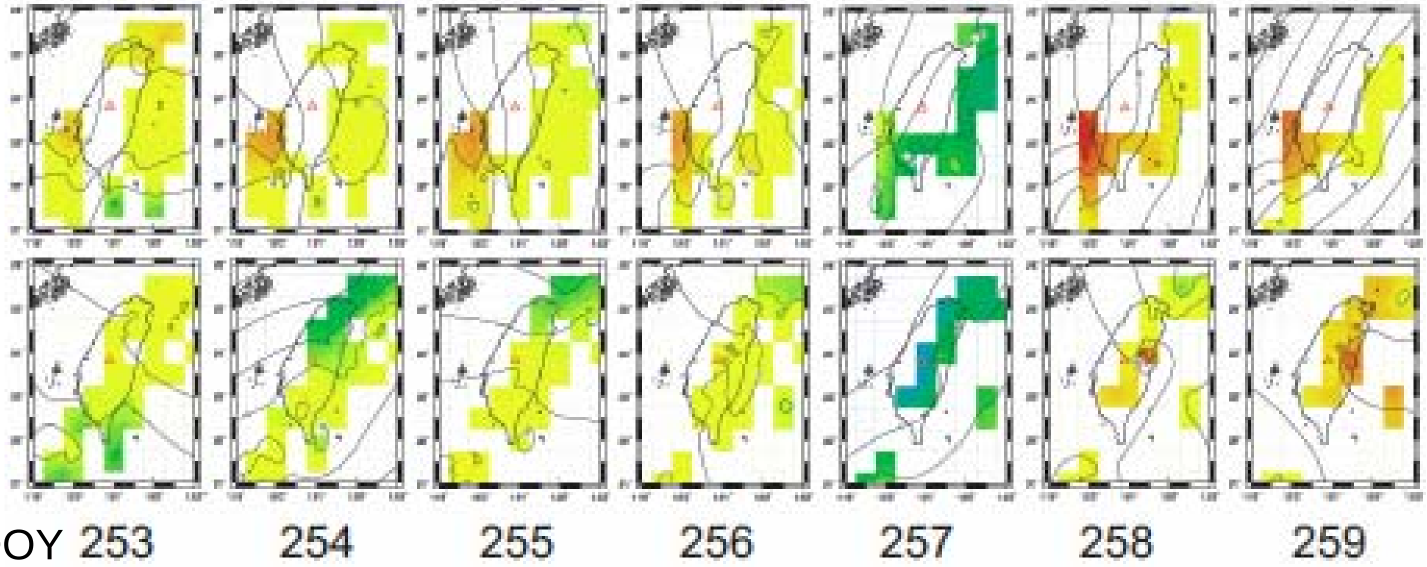
プラズマの再分布により，
磁気緯度10～15°付近に
電子密度の高い領域が形成．



(恩藤，丸橋，2000)

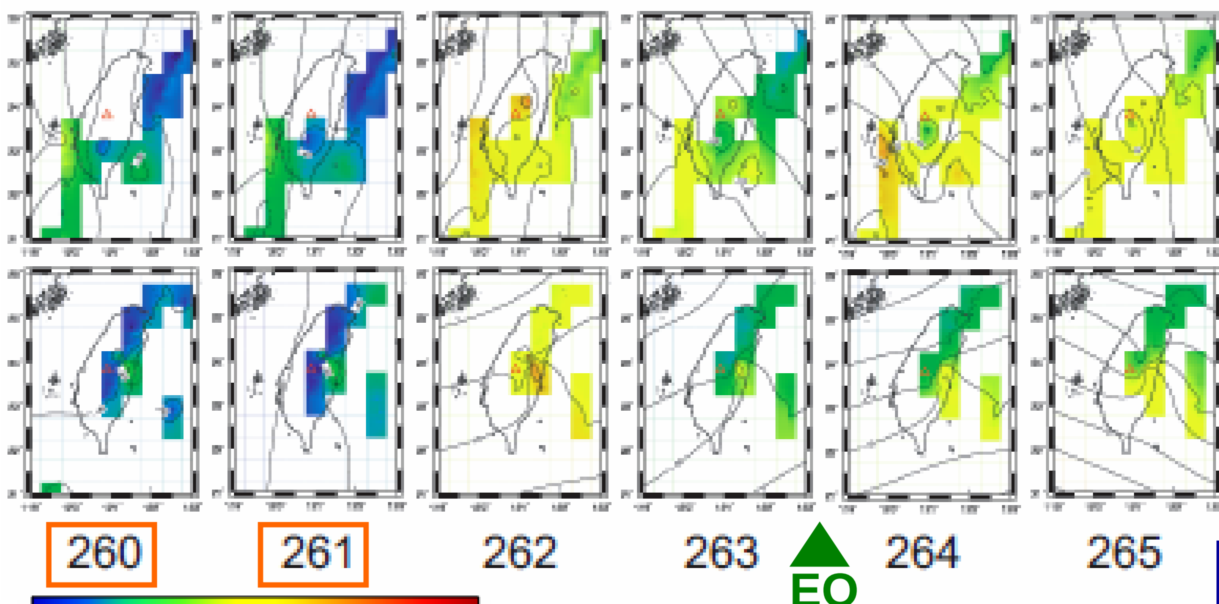
dTECの空間分布

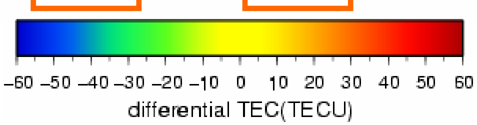
(1999/09/10 – 1999/09/22)



12～14 h (LT)
4～6 h (UT)

14～16 h (LT)
6～8 h (UT)





Grid interval:0.5°×0.5°

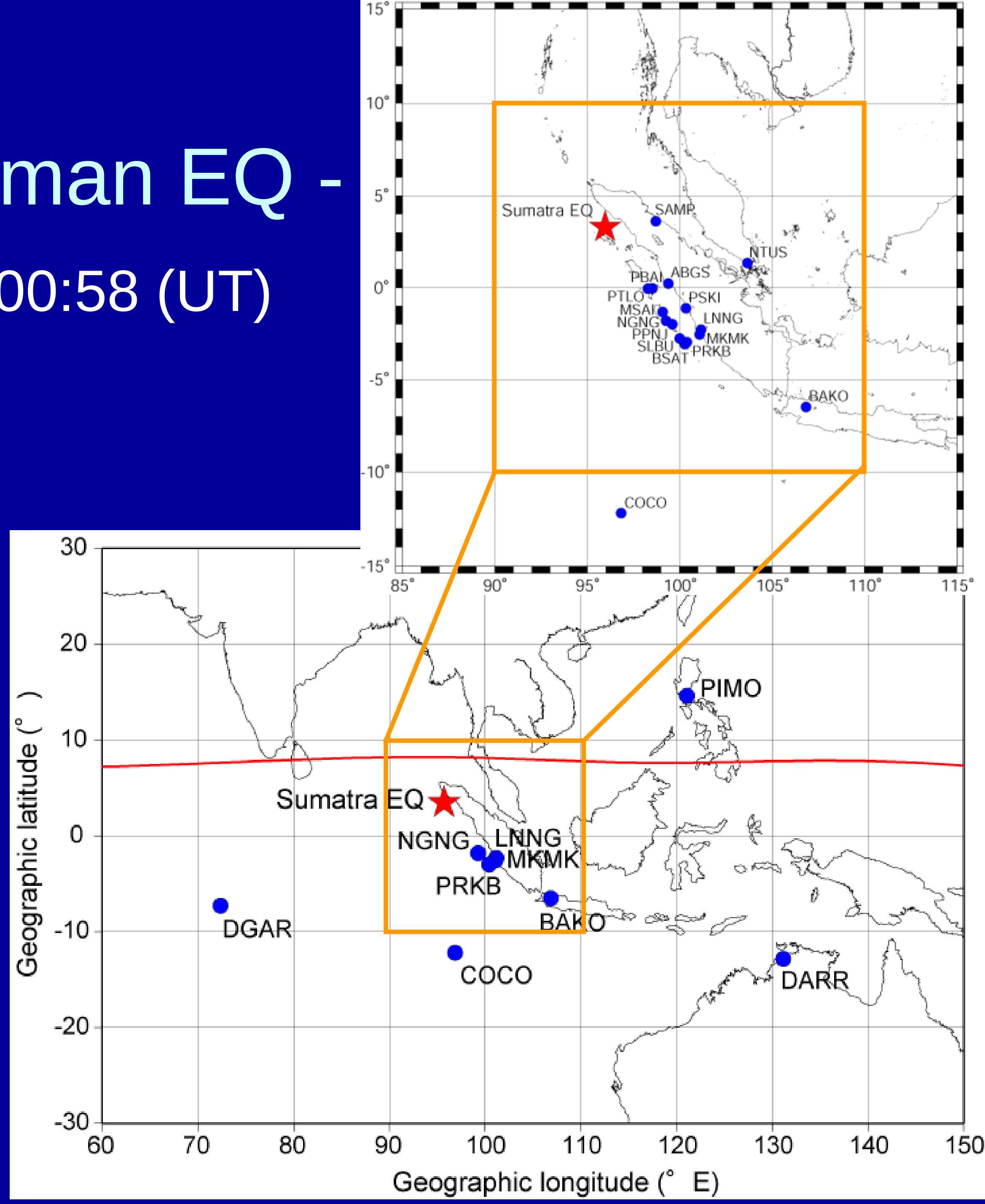
Chi-Chi地震の3，4日前の昼間～夕方にdTECの顕著な減少を確認

Liu et al.(2000)と調和的

Result 2
- Sumatra-Andaman EQ -

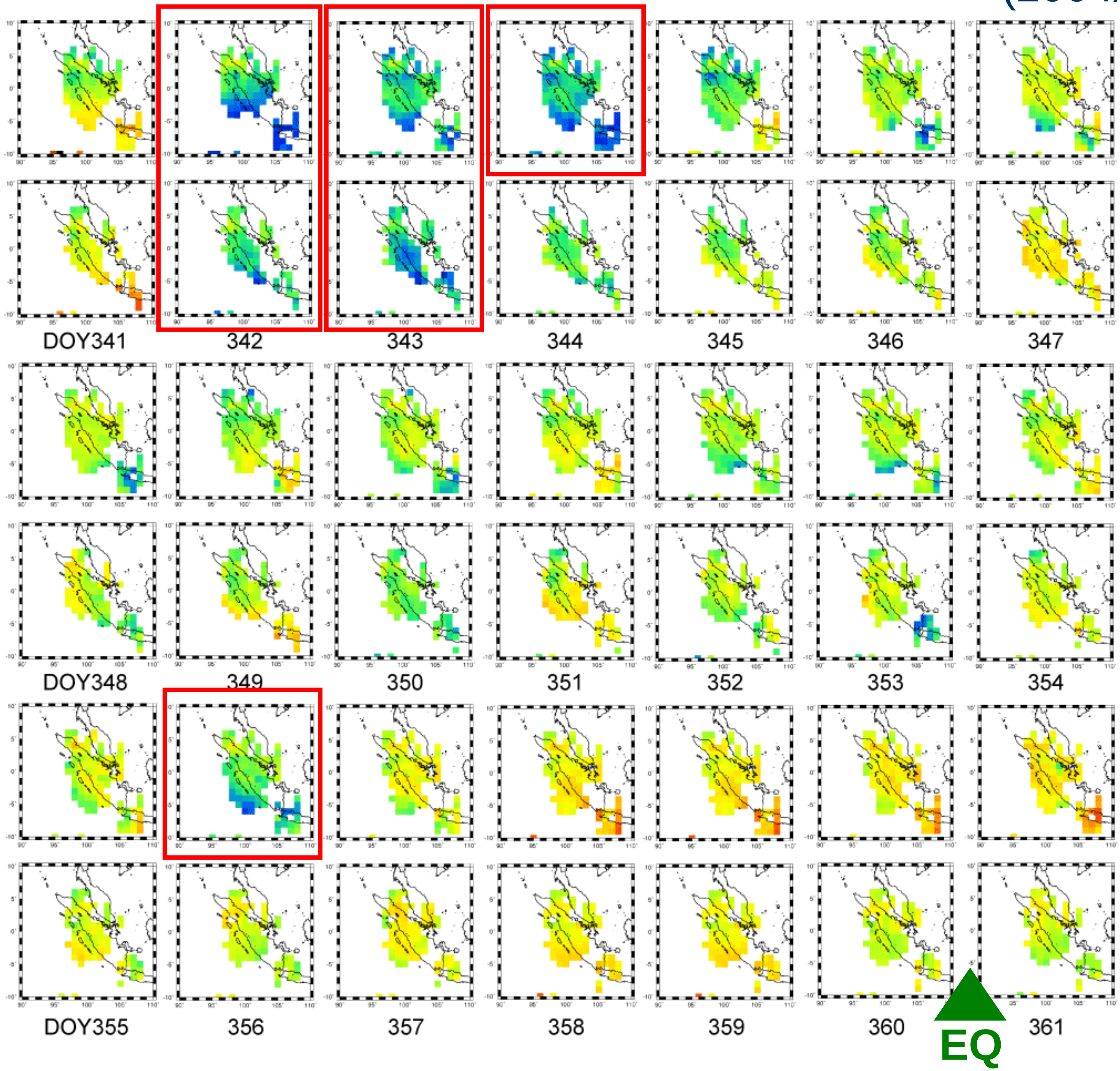
December 26, 2004 00:58 (UT)
Day of year: 361
M=9.0
D=30km
3.3°N 95.98°E

SuGAr array
ABGS, BSAT, LNNG ,
MKMK, MSAI, NGNG,
PBAI, PPNJ, PRKB,
PSKI, PTLO, SLBU
IGS array etc.
BAKO, COCO, NTUS,
SAMP, DGAR, etc.



dTECの空間分布

(2004/12/06 – 2004/12/26)



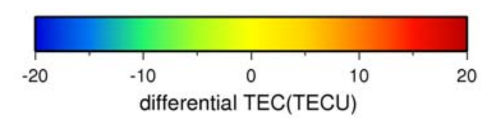
12～18 h (LT)
5～11 h (UT)

18～24 h (LT)
11～17 h (UT)

スマトラ地震の5, 17, 18, 19日前の午後，スマトラ島全域でdTEC減少

震央から離れた地域においても，dTECは減少していた

Grid interval:1°×1°



今後の課題

- F10.7
- Kp index
- Dst index

電離層に関連する各種観測データや
季節，衛星仰角などによるTECデータの分類，集約

↓

TECモデルの構築

↓

3Dトモグラフィーを利用した，地震に関連する電離層ダイナミクスの可視化

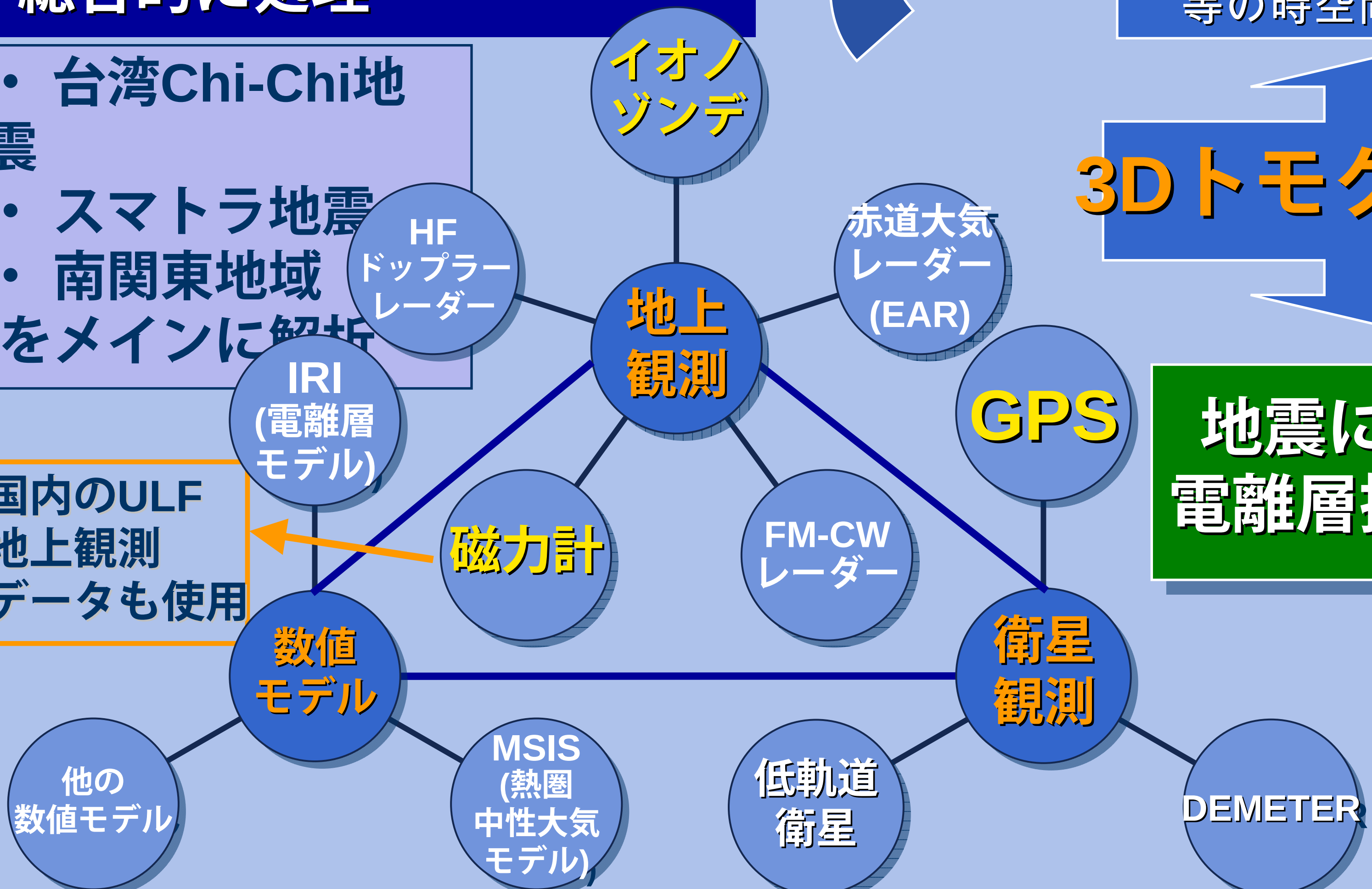
今後の課題

衛星観測，地上観測データを総合的に処理

- 台湾Chi-Chi地震
- スマトラ地震
- 南関東地域

をメインに解析

国内のULF地上観測データも使用



電離層ダイナミクス

- 伝搬性電離層擾乱(TID)
- プラズマバブル
- 赤道異常

等の時空間分布の把握

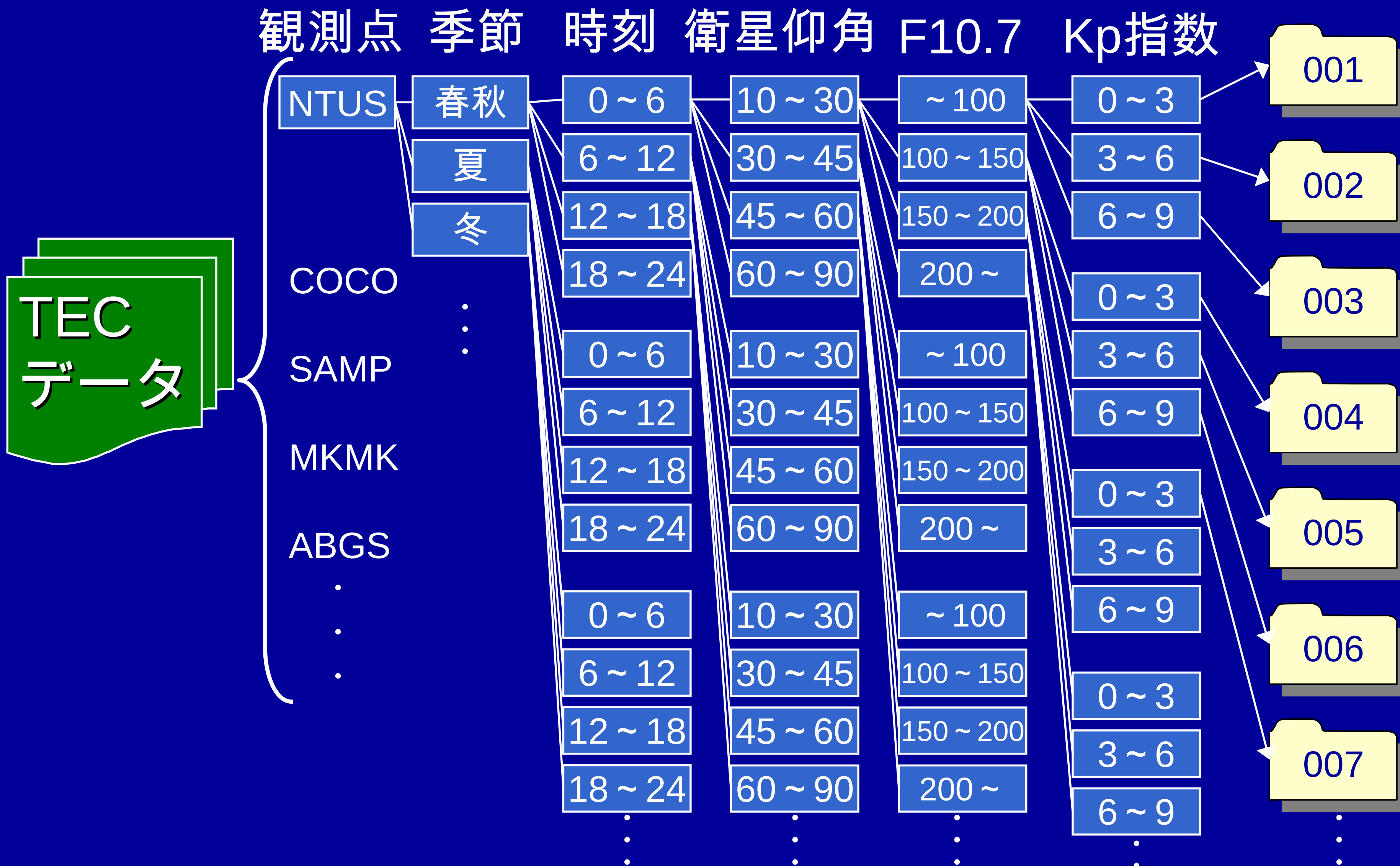
3Dトモグラフィー

地震に関連する電離層擾乱の弁別

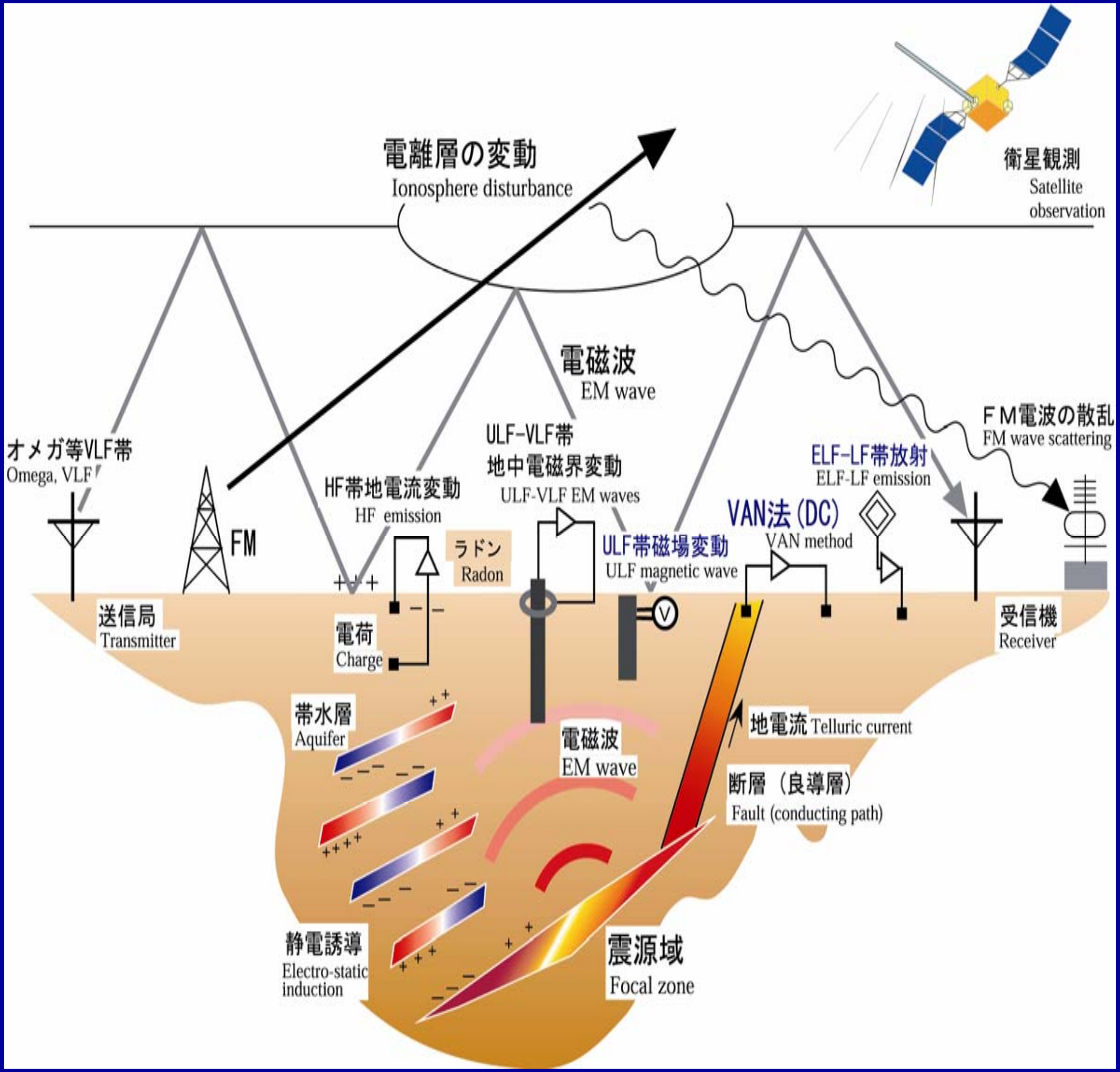
今後の課題

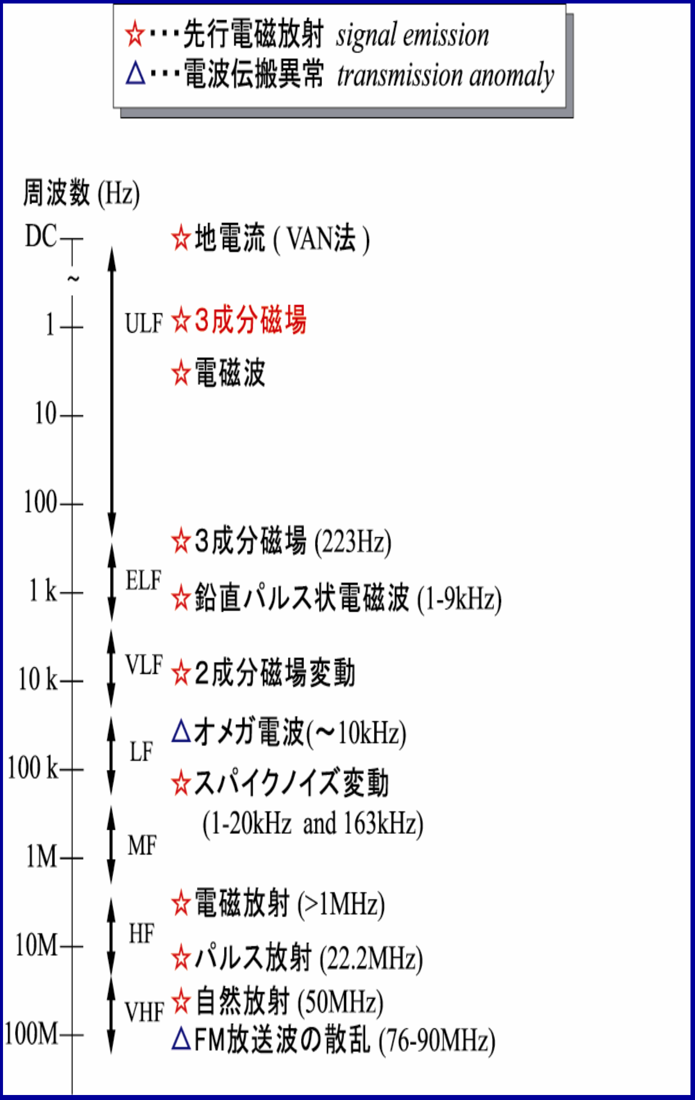
TECデータを各パラメータで分類，集約，モデル化

TECデータの分類

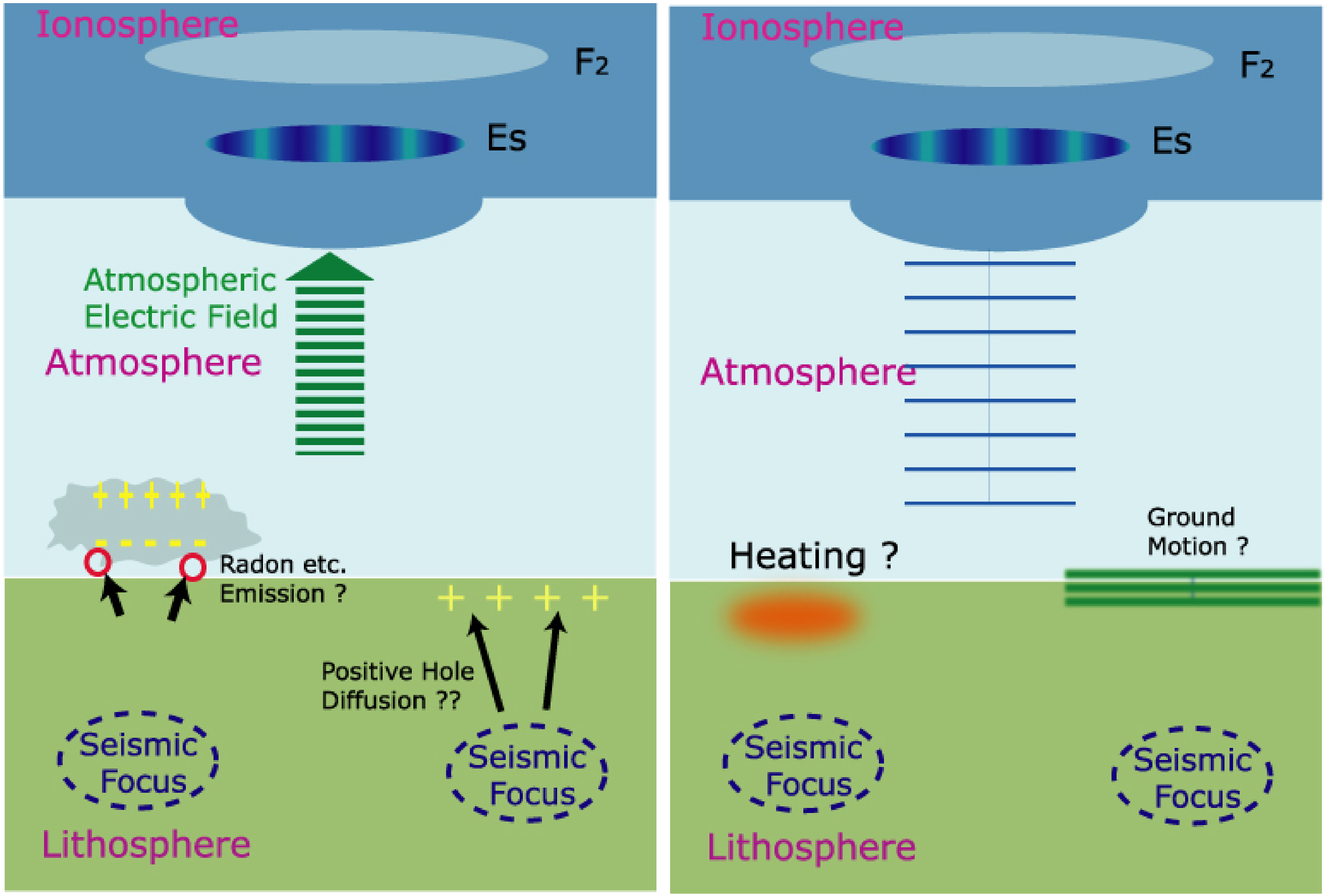


電磁気学的手法による地震発生直前予測





地圏-大気圏-電離圏結合(LAIカップリング)



解析に必要なファイル

- RINEXファイル (観測ファイル)
- IGS sp3ファイル (衛星軌道情報ファイル，精密暦)

- sestbl. (解析条件設定ファイル)
- sittbl. (各観測点データの処理手法設定ファイル)
- station.info (観測点情報ファイル)
- Lファイル (観測点座標値ファイル)

RINEXファイル

```
 2.10           OBSERVATION DATA    G (GPS)             RINEX VERSION / TYPE
teqc  2002Mar14     GSI, JAPAN          20050721 05:10:11UTCPGM / RUN BY / DATE
Linux 2.0.36|Pentium II|gcc -static|Linux|486/DX+           COMMENT
teqc  2002Mar14     GSI, JAPAN          20050719 11:31:15UTCCOMMENT
3020                                                        MARKER NAME
GSI, JAPAN          GEOGRAPHICAL SURVEY INSTITUTE, JAPAN    OBSERVER / AGENCY
00000               TRIMBLE 5700        Nav 1.24 Sig 0.00   REC # / TYPE / VERS
                    TRM29659.00     GSI                     ANT # / TYPE
 -3989770.5147  3310590.1829  3702829.0625                  APPROX POSITION XYZ
        0.0000        0.0000        0.0000                  ANTENNA: DELTA H/E/N
     1     1                                                WAVELENGTH FACT L1/2
     4    L1    C1    L2    P2                              # / TYPES OF OBSERV
    30.0000                                                 INTERVAL
teqc windowed: start @ 2005 Jul 19 00:00:00.000             COMMENT
teqc windowed:  end  @ 2005 Jul 19 23:59:59.000             COMMENT
  2005     7    19     0     0    0.0000000     GPS         TIME OF FIRST OBS
                                                            END OF HEADER
 05  7 19  0  0  0.0000000  0  8G 2G 4G 6G 8G10G26G27G29
 -39359726.984    20594600.461   -30659960.6184   20594592.3284
 -28334950.133    23861046.492   -22068593.8374   23861042.8364
 -13339343.504    23600488.891   -10384249.3654   23600483.5084
 -27129223.781    21812913.359   -21129596.9974   21812908.0274
 -36189683.816    20531069.461   -28188259.4704   20531062.7974
 -23717706.555    21457623.891   -18467005.7924   21457617.8594
 -18565058.848    23666016.281   -14457936.6694   23666010.5124
 -28958614.816    20768171.414   -22552629.4724   20768164.8054
 05  7 19  0  0 30.0000000  0  8G 2G 4G 6G 8G10G26G27G29
```

GAMITによる自動解析

一連の解析はsh_gamitを実行することによって自動処理される

GAMITでの処理の流れ

makexp：session.infoファイル(解析シナリオファイル)の作成

↓

sh_sp3fit：IGS精密暦ファイル→Gファイルへの変換

↓

makej： Jファイル（衛星時計ドリフトデータ）の作成

↓

makex：RINEXファイル→Xファイル・ Kファイル（受信機時計ドリフトデータ）への変換

↓

fixdrv：バッチファイル作成

arc：衛星軌道推定（Ｇファイル→Ｔファイル）

yawtab：食にある衛星の姿勢計算

octtab：海洋潮汐補正テーブルの作成

grdtab:大気荷重変形テーブルの作成

model：受信機のサンプリング時刻の推定

autcln：自動験測，残差出力

cfmrg：推定パラメータの整理

solve：験測済みデータによる最終解

DPHファイル

autclnコマンドによって出力される残差データファイル

* Clock information for site SIO5 receiver ASH . PRN 01

Epoch	L1 cyc	L2 cyc	P1 cyc	P2 cyc	LC cyc	LG cyc	PC cyc	WL cyc	N cyc	LSV	Azimuth	Elev	PF
995	-53.89	-69.15	51.97	69.37	-0.021	-53.87	-5.32	-0.20	17.22	1	208.0761	11.2040	0
996	-53.79	-69.03	56.20	70.03	-0.009	-53.78	4.16	0.43	-11.40	1	208.1307	11.4115	0
997	-53.72	-68.94	58.43	67.77	-0.004	-53.72	14.31	0.44	-47.38	1	208.1859	11.6192	0
998	-53.66	-68.86	55.37	73.74	-0.016	-53.65	-5.31	0.82	25.49	1	208.2417	11.8271	0
999	-53.60	-68.76	57.16	73.42	-0.053	-53.55	-0.14	1.04	8.71	1	208.2983	12.0351	0
1000	-53.59	-68.77	57.72	70.62	-0.008	-53.58	6.85	0.75	-18.41	1	208.3554	12.2433	0
1001	-53.56	-68.73	48.37	72.21	-0.018	-53.55	-20.11	-0.21	69.83	1	208.4133	12.4516	0
1002	-53.50	-68.63	56.61	72.32	-0.043	-53.45	0.66	0.86	4.45	1	208.4718	12.6601	0
1003	-53.50	-68.64	57.33	68.78	-0.034	-53.46	9.51	0.51	-29.86	1	208.5309	12.8688	0

$$TEC_{slp} = \frac{(f_1 f_2)^2}{40.3(f_1^2 - f_2^2)}(P_2 - P_1)$$

疑似距離による
STECが算出される

DCB (Differential Code Biases)

算出したTECの値が**負**になる場合があった

(特にGEONETデータ)

疑似距離観測には，周波数間(P1-P2, P1-C1)バイアス(DCB;Differential Code Biases)と呼ばれる計器バイアスが存在

衛星と受信機の双方に存在

衛星DCB・・・ GAMIT10.2から補正可能に

(現在:GAMIT10.21)

受信機DCB・・・ 現在のGAMITでは補正不可能

受信機DCB

観測点による受信機DCBの差異

ヨーロッパ軌道決定センター(CODE)が公開している
DCBファイルを参照

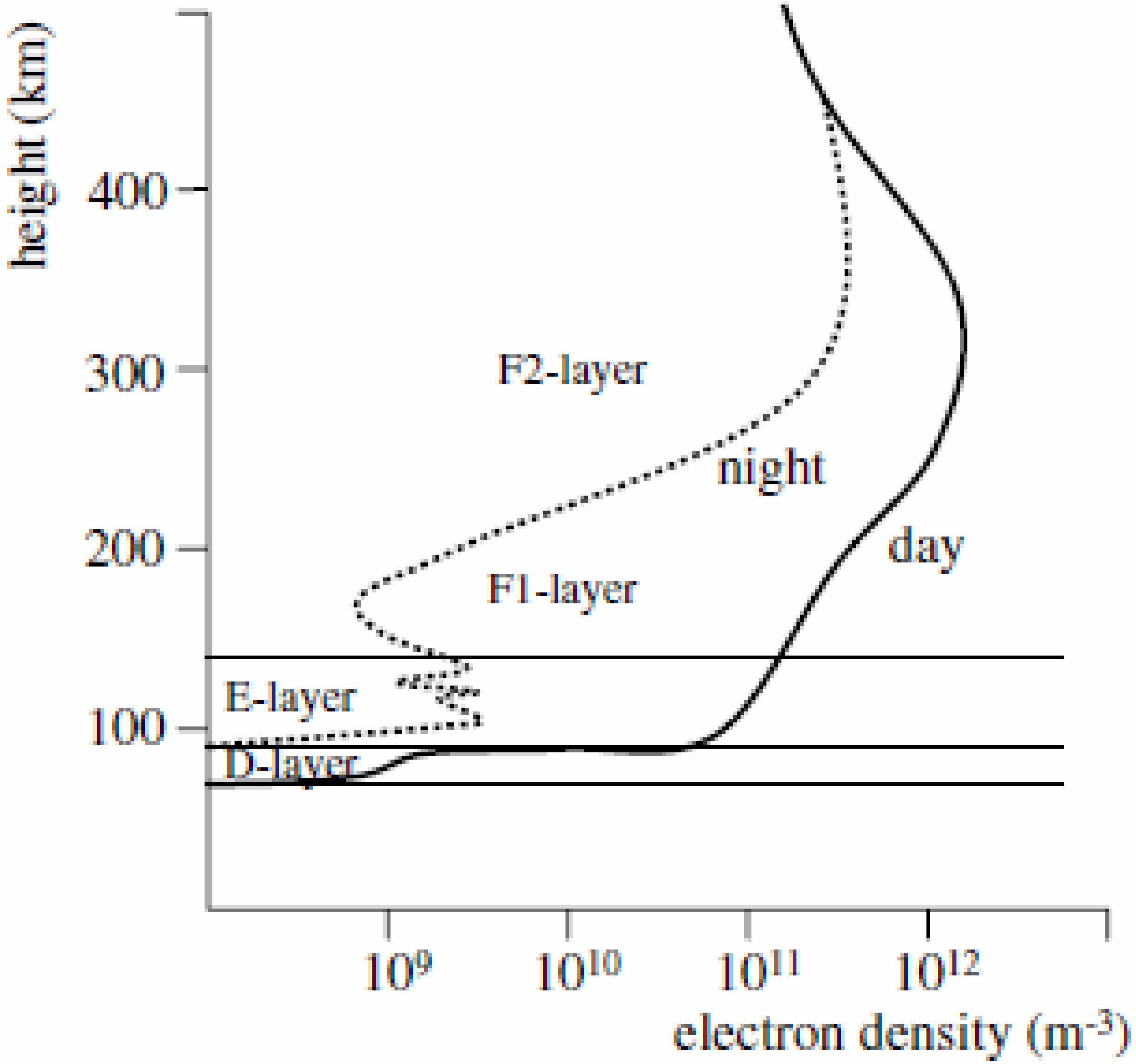
- DCBが大きい観測点が多数存在 (36～-21ns)
- Trimble5700観測点は14～18ns

GEONET観測点はほぼ
Trimble5700で統一

TEC絶対値ではなく変動量を利用

or

受信機DCBの算出へ


height (km)
400
300
200
100
F2-layer
night
day
F1-layer
E-layer
D-layer
10^9
10^{10}
10^{11}
10^{12}
electron density (m^{-3})

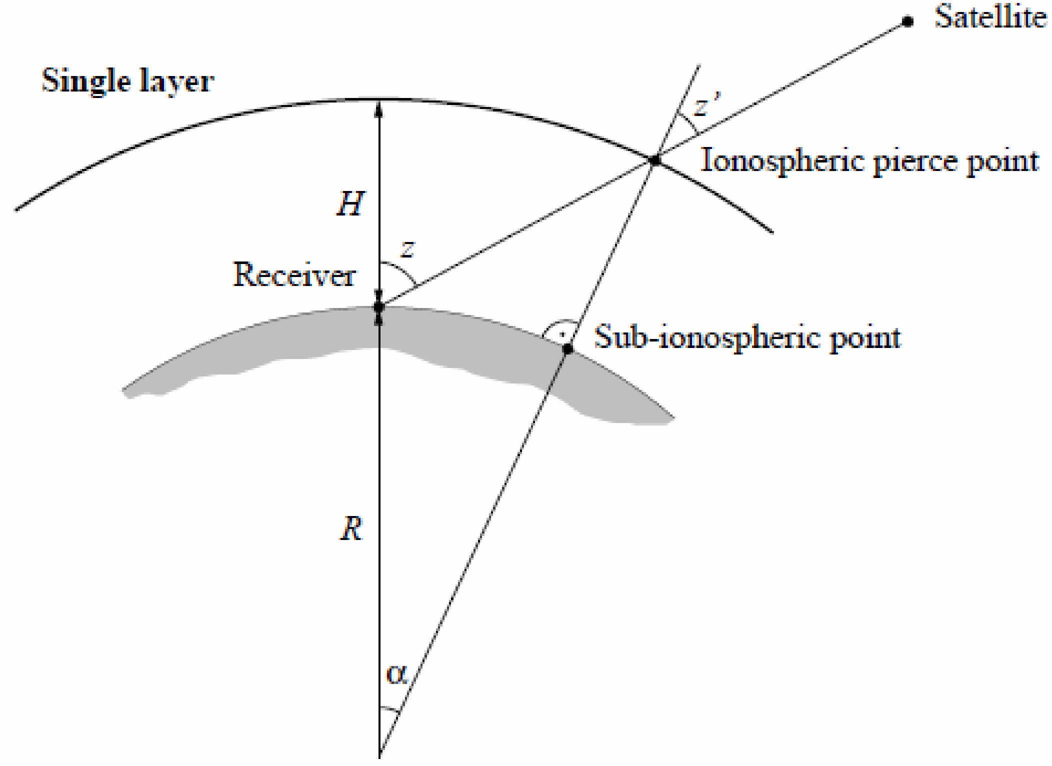


Figure 13.3: Single-layer model

搬送波波長　f1: 0.19m，f2: 0.24m
測位用信号　Pコード: 29.3m，C/Aコード: 293m

Session Table for regional + global analysis

sestbl. (解析条件設定ファイル)

Processing Agency = CUG

Station Number = *
Satellite Number = *
Satellite Constraint = Y ; Y/N Units are ppm for ICs, percent for radiation pressure parameters

all	a	e	i	node	arg per	M	rad1	rad2	rad3	rad4	rad5	rad6	rad7	rad8	rad9
	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Type of Analysis = 0-ITER ; 0-ITER/1-ITER/2-ITER/1-CLEAN/2-CLEAN/3-CLEAN
Data Status = RAW ; CLN/RAW
Choice of Observable = LC_AUTCLN ; L1_SINGLE/L1&L2/L1_ONLY/L2_ONLY/LC_ONLY/
; L1,L2_INDEPEND./LC_HELP/LC_AUTCLN
Choice of Experiment = RELAX. ; BASELINE/RELAX./ORBIT

Ionospheric Constraints = 0.0 mm + 8.00 ppm ; Set for mid-solar max
Zenith Delay Estimation = YES ; YES/NO
Interval Zen = 1 ; zenith-delay parameters at 2-hr-intervals
Zenith Constraints = 0.50 ; zenith-delay a priori constraint in meters (default 0.5)
Zenith Model = PWL ; PWL (piecewise linear)/CON (step)
Zenith Variation = 0.02 100. ; zenith-delay variation, tau in meters/sqrt(hr), hrs
Elevation cutoff = 15. ; Elevation angle cutoff for postfit solution; default 0 to use autcln cutoff
Atmospheric gradients = YES ; YES/NO (default no)
Number Grad = 1 ; number of gradient (E/W or N/S) parameters) (default 1)
Gradient Constraints = 0.01 ; gradient at 10 deg elevation in meters
Gradient Variation = 0.01 100. ; gradient variation, tau in meters/sqrt(hr), hrs (defaults .01 100)
Output met = NO ; output the a priori met data to a z-file (Y/N; default N)
Station Constraint = Y ; Y/N
Ambiguity resolution WL = 0.15 0.15 1000. 99. 1000. ; Increased chi-square ratio to stop searched
Ambiguity resolution NL = 0.15 0.15 1000. 99. 1000. ; values from being used; set dist = 500. for LC_HELP

Reference System for ARC = IGS92 ; WGS84/WGS72/MERIT/IGS92(default)/EGM96
Initial ARC = YES ; YES/NO default = NO for BASELINE/KIINEMATIC, YES for RELAX/ORBIT
Update T/L files = L_ONLY ; T_AND_L (default), T_ONLY, L_ONLY, NONE
Final ARC = NO
Yaw Model = YES ; YES/NO default = YES
Delete eclipse data = NO ; ALL/NO/POST (Default = NO); 30 mins post shadow removal is
; hardwired for ALL/POST
AUTCLN Command File = autcln.cmd ; Filename; default none (use default options)
AUTCLN Postfit = R ; Run autcln for postfit run; R causes repeat run.
Use N-file = Y ; Y/N (default no): automatic procedure to reweight by station
Delete AUTCLN input C-files = I ; YES/NO default = NO ; I -- Intermediate keep (stops) second model
Earth Rotation = 7 ; Diurnal/Semidirunal terms: Binary coded: 1=pole 2=UT1 4=Ray model default=7
Estimate EOP = 15 ; Binary coded: 1 wob 2 ut1 4 wob rate 8 ut1 rate
Wobble Con = 0.01 0.01 ; default = 3. 0.3 arcsec arcsec/day
UT1 Con = 0.00001 0.01 ; default = .2 0.02 sec sec/day
Etide model = IERS03 ; IERS92/IERS03 (default IERS03)
Tides applied = 31 ; Binary coded: 1 earth 2 freq-dep 4 pole 8 ocean 16 remove mean for pole tide 32 atmosphere default = 31
Use stations.oct = Y ; Y/N for using stations.oct; default (N) is to get all ocean tides from grid.oct
Apply Atm loading = N ; Y/N for atmospheric loading; need atmdisp.YYYY grid file
Antenna Model = ELEV ; NONE/ELEV/AZEL default = NONE
SV antenna model = ELEV : NONE/ELEV/AZEL deafult = NONE; set NONE if rcvr model is relative, ELEV if rcvr model is absolute
Radiation Model for ARC = BERNE ; SPHRC/BERNE/SRDYB/SVBDY default = BERNE
Lunar eclipses = Y ; Set = N to turn off lunar eclipses in ARC to match model of GAMIT < 10.2 (default Y)
Decimation Factor = 4 ; Decimation factor in solve
Quick-pre observable = LC_ONLY ; For 1st iter or autcln pre, default same as Choice of observable
Quick-pre decimation factor = 10 ; 1st iter or autcln pre, default same as Decimation Factor
Station Error = ELEVATION 10. 0.0001 ; 1-way L1 , a**2 + b**2/sin(elev)**2 in mm, default = 4.3 7.0
Inertial frame = J2000 ; B1950/J2000 (default = J20000)

sittbl. (各観測点データの処理手法設定ファイル)

```
SITE             FIX  WFILE  --COORD.CONSTR.-- --EPOCH--  CUTOFF  APHS CLK  KLOCK  CLKFT  DZEN  WZEN  DMAP  WMAP
---MET. VALUE----  NZEN  ZCNSTR  ZENVAR ZENTAU
<< IGS PRIMARY FIDUCIALS >>
USUD usud        NNN   NONE  0.005 0.005 0.010  001-  *    15.0   ELEV NNN     3         SAAS  SAAS  NMFH  NMFW  1013.25
20.0 50.0   25    1.000  0.0200  100.0
TSKB Tsukuba      NNN   NONE  0.005 0.005 0.010  001-  *    15.0   ELEV NNN     3         SAAS  SAAS  NMFH  NMFW  1013.25
20.0 50.0   25    1.000  0.0200  100.0
KUNM kunm         NNN   NONE  0.005 0.005 0.010  001-  *    15.0   ELEV NNN     3         SAAS  SAAS  NMFH  NMFW  1013.25
20.0 50.0   25    1.000  0.0200  100.0
DAEJ daej        NNN   NONE  0.005 0.005 0.010  001-  *    15.0   ELEV NNN     3         SAAS  SAAS  NMFH  NMFW  1013.25 20.0
50.0   25    1.000  0.0200  100.0
PIMO pimo        NNN   NONE  0.005 0.005 0.010  001-  *    15.0   ELEV NNN     3         SAAS  SAAS  NMFH  NMFW  1013.25 20.0
50.0   25    1.000  0.0200  100.0
WUHN wuhn        NNN   NONE  0.005 0.005 0.010  001-  *    15.0   ELEV NNN     3         SAAS  SAAS  NMFH  NMFW  1013.25
20.0 50.0   25    1.000  0.0200  100.0
SHAO shao        NNN   NONE  0.005 0.005 0.010  001-  *    15.0   ELEV NNN     3         SAAS  SAAS  NMFH  NMFW  1013.25
20.0 50.0   25    1.000  0.0200  100.0
<< TAIWAN stations >>
s01r s01r        NNN   NONE  1.000 1.000 1.000  001-  *    15.0   ELEV NNN     3         SAAS  SAAS  NMFH  NMFW  1013.25 20.0
50.0   25    1.000  0.0200  100.0
s058 s058        NNN   NONE  1.000 1.000 1.000  001-  *    15.0   ELEV NNN     3         SAAS  SAAS  NMFH  NMFW  1013.25 20.0
50.0   25    1.000  0.0200  100.0
s101 s101        NNN   NONE  1.000 1.000 1.000  001-  *    15.0   ELEV NNN     3         SAAS  SAAS  NMFH  NMFW  1013.25 20.0
50.0   25    1.000  0.0200  100.0
s102 s102        NNN   NONE  1.000 1.000 1.000  001-  *    15.0   ELEV NNN     3         SAAS  SAAS  NMFH  NMFW  1013.25 20.0
50.0   25    1.000  0.0200  100.0
s103 s103        NNN   NONE  1.000 1.000 1.000  001-  *    15.0   ELEV NNN     3         SAAS  SAAS  NMFH  NMFW  1013.25 20.0
50.0   25    1.000  0.0200  100.0
s104 s104        NNN   NONE  1.000 1.000 1.000  001-  *    15.0   ELEV NNN     3         SAAS  SAAS  NMFH  NMFW  1013.25 20.0
50.0   25    1.000  0.0200  100.0
s105 s105        NNN   NONE  1.000 1.000 1.000  001-  *    15.0   ELEV NNN     3         SAAS  SAAS  NMFH  NMFW  1013.25 20.0
50.0   25    1.000  0.0200  100.0
s23r s23r        NNN   NONE  1.000 1.000 1.000  001-  *    15.0   ELEV NNN     3         SAAS  SAAS  NMFH  NMFW  1013.25 20.0
50.0   25    1.000  0.0200  100.0
```

station.info (観測点情報ファイル)

```
# Station.info written by MSTINF user gps          on 2005-11-27  01:49
* Merged station.info from    1 Input files:
* Reference file : station.info
*
*
*SITE  Station Name      Session Start      Session Stop       Ant Ht   HtCod  Ant N    Ant E    RcvCod  SwVer  AntCod
 CHEN  CHEN          1999 200  0  0  0  9999 999  0  0  0   1.2345  DHARP   0.0000   0.0000  TR8000   0.00  TRBROG
 CHIA  CHIA          1999 200  0  0  0  9999 999  0  0  0   1.7317  DHARP   0.0000   0.0000  TRMSST   0.00  TRMSST
 CHNL  CHNL          1999 200  0  0  0  9999 999  0  0  0   0.0300  DHARP   0.0000   0.0000  TRMSSI   0.00  TRMSST
 CHYN  CHYN          1999 200  0  0  0  9999 999  0  0  0   0.0000  DHARP   0.0000   0.0000  LC_CRS   0.00  LC_504
 CK01  CK01          1999 200  0  0  0  9999 999  0  0  0   0.0000  DHARP   0.0000   0.0000  TR8000   0.00  ROGAOA
.
 DAEJ  DAEJ          1999 200  0  0  0  9999 999  0  0  0   0.0000  DHARP   0.0000   0.0000  TRMSSI   0.00  TRMDMG
.
 HOKN  HOKN          1999 200  0  0  0  9999 999  0  0  0   0.0000  DHARP   0.0000   0.0000  TRMSSI   0.00  TRBROG
 HUAL  HUAL          1999 200  0  0  0  9999 999  0  0  0   1.2345  DHARP   0.0000   0.0000  TR8000   0.00  TRBROG
.
 KAYT  KAYT          1999 200  0  0  0  9999 999  0  0  0   0.0794  DHARP   0.0000   0.0000  TRMSSE   7.26  TRMSST
 KULN  KULN          1999 200  0  0  0  9999 999  0  0  0   0.0000  DHARP   0.0000   0.0000  TRMSST   0.00  TRMSST
 KUNM  KUNM          1999 200  0  0  0  9999 999  0  0  0   0.0793  DHARP   0.0000   0.0000  TR8000   3.20  TRBROG
.
 NCTU  NCTU          1999 200  0  0  0  9999 999  0  0  0   0.0300  DHARP   0.0000   0.0000  TRMSSE   0.00  TRMSSE
.
 PIMO  PIMO          1999 200  0  0  0  9999 999  0  0  0   0.0790  DHARP   0.0000   0.0000  TR8000   0.00  TRBROG
.
 S011  S011          1999 200  0  0  0  9999 999  0  0  0   0.0000  DHARP   0.0000   0.0000  TRMSST   0.00  TRMSST
 S012  S012          1999 200  0  0  0  9999 999  0  0  0   0.0000  DHARP   0.0000   0.0000  TRMSST   0.00  TRMSST
 S01R  S01R          1999 200  0  0  0  9999 999  0  0  0   0.0300  DHARP   0.0000   0.0000  TRMSSI   0.00  TRBROG
 S058  S058          1999 200  0  0  0  9999 999  0  0  0   1.5365  DHARP   0.0000   0.0000  TRMSSI   0.00  TRMSST
 S101  S101          1999 200  0  0  0  9999 999  0  0  0   0.0300  DHARP   0.0000   0.0000  TRMSSE   0.00  TRMSST
```

Lファイル (観測点座標値ファイル)

```
 CHEN_GPS -3055984.52002  5011701.08698  2486668.50650   0.00000   0.00000   0.00000 1999.7110
CHIA_GPS -2964473.00807  5046119.81303  2527206.73630   0.00000   0.00000   0.00000 1999.7110
CHNL_GPS -2978743.52486  5044117.00153  2515253.63409   0.00000   0.00000   0.00000 1999.7110
CHYN_GPS -2954201.34775  5057373.78087  2516768.21265   0.00000   0.00000   0.00000 1999.7110
CK01_GPS -2956266.16499  5077239.87393  2474278.41796   0.00000   0.00000   0.00000 1999.7110
HOKN_GPS -2944927.63782  5073145.72594  2495922.66698   0.00000   0.00000   0.00000 1999.7110
HUAL_GPS -3056584.16357  4965781.13888  2575810.93900   0.00000   0.00000   0.00000 1999.7110
S011_GPS -2962664.46226  5061988.23348  2497671.99438   0.00000   0.00000   0.00000 1999.7110
S058_GPS   -2157717.35     4432001.53     2040387.26   0.0000 0.0000 0.0000 1999.71
 S104_GPS -3046038.46284  5031710.23307  2458452.44710   0.00000   0.00000   0.00000 1999.7110
S105_GPS -3036718.11336  5031463.72045  2472063.16621   0.00000   0.00000   0.00000 1999.7110
S23R_GPS -2998517.92265  5068969.19309  2440519.09752   0.00000   0.00000   0.00000 1999.7110
SANI_GPS   -2972975.95     4993405.70     2620276.14   0.0000 0.0000 0.0000 1999.71
 S101_GPS -3030967.58187  4924099.40011  2683160.17727   0.00000   0.00000   0.00000 1999.5822
S102_GPS -3095834.41254  5040451.84326  2378363.62496   0.00000   0.00000   0.00000 1999.5822
S103_GPS -2966672.46332  5041400.79854  2534183.12608   0.00000   0.00000   0.00000 1999.6205
NCTU_GPS -2983882.10173  4966539.60682  2657905.59314   0.00000   0.00000   0.00000 1999.6973
KULN_GPS -2974829.32984  5048841.94204  2510583.89262   0.00000   0.00000   0.00000 1999.6863
S012_GPS -2979082.18511  5059846.60587  2482857.08866   0.00000   0.00000   0.00000 1999.7164
```