Space Weather Monitoring and Forecast in Taiwan

Tiger J.Y. Liu (劉 正彥)
National Space Organization, (NSPO) TAIWAN
National Central University (NCU), TAIWAN
jyliu@jupiter.ss.ncu.edu.tw

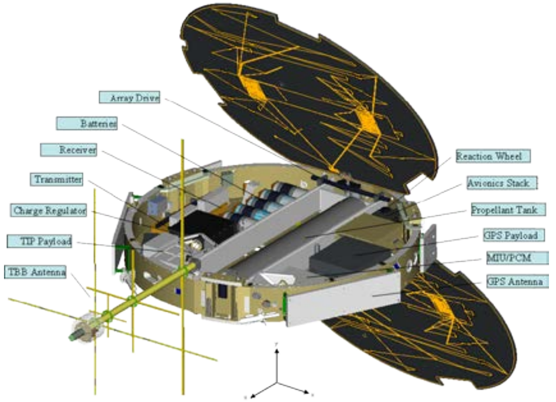
I.T. Lee (李 奕德)
Center Weather Bureau (CWB), TAIWAN

Space Weather Center

- R & D Office (Academia Sinica + Universities: NCU, NCKU)
- Operation Office (Center Weather Bureau; CWB)
- Mission Office (National Space Organization; NSPO)

Content

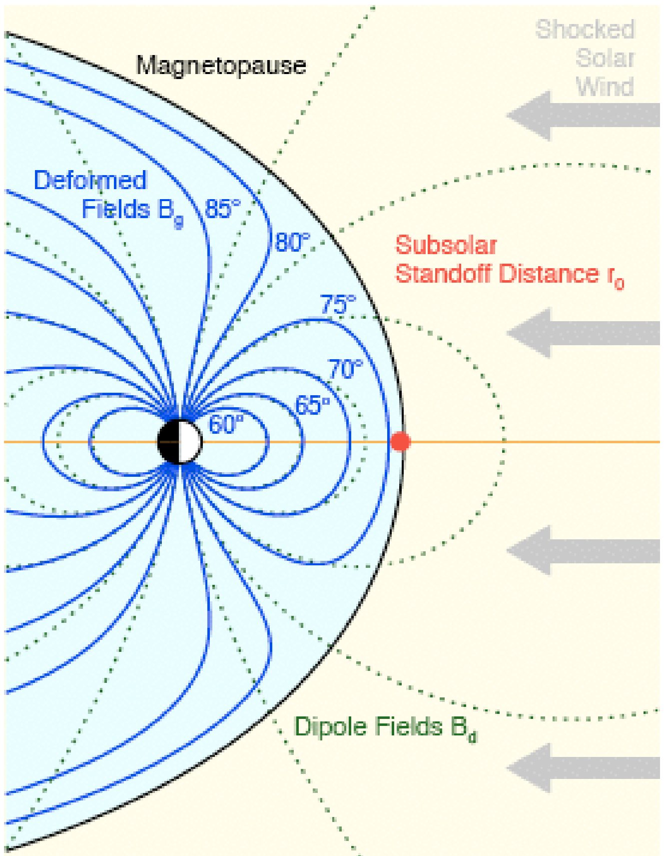
- Introduction
- FORMOSAT-3/COSMIC
- 3D Plasma Structure and Dynamics
- Ionospheric Scintillation
- Thump the Ionosphere
- FORMOSAT-7/COSMIC-2



The Past, Present, and Future

- Space Science education: 1958 -
- Ionosonde observation: 1951 -
- Magnetometer observation: 1965 -
- HF Doppler observation: 1989 -
- GPS TEC observation software: 1994 -
- Magnetopause location prediction: 1997 -
- ROCSAT-1 (FORMOSAT-1): 1999-2004
- FORMOSAT-2/ISUAL: 2004 -
- FORMOSAT-3/COSMIC: 2006 -
- FORMOSAT-5/AIP: 2015
- FORMOSAT-7/TGRO: 2016/2018
- Ionospheric Weather (Data Assimilation Model): 2012 -

The Magnetopause



- The total pressure (including magnetic and thermal pressure) is balanced across the magnetopause.
- The magnetopause location is controlled by IMF Bz and solar wind dynamic pressure Dp.

The Shue et al. [1997] Magnetopause Location Model

- The formula of the Shue et al. [1997] model is listed below:

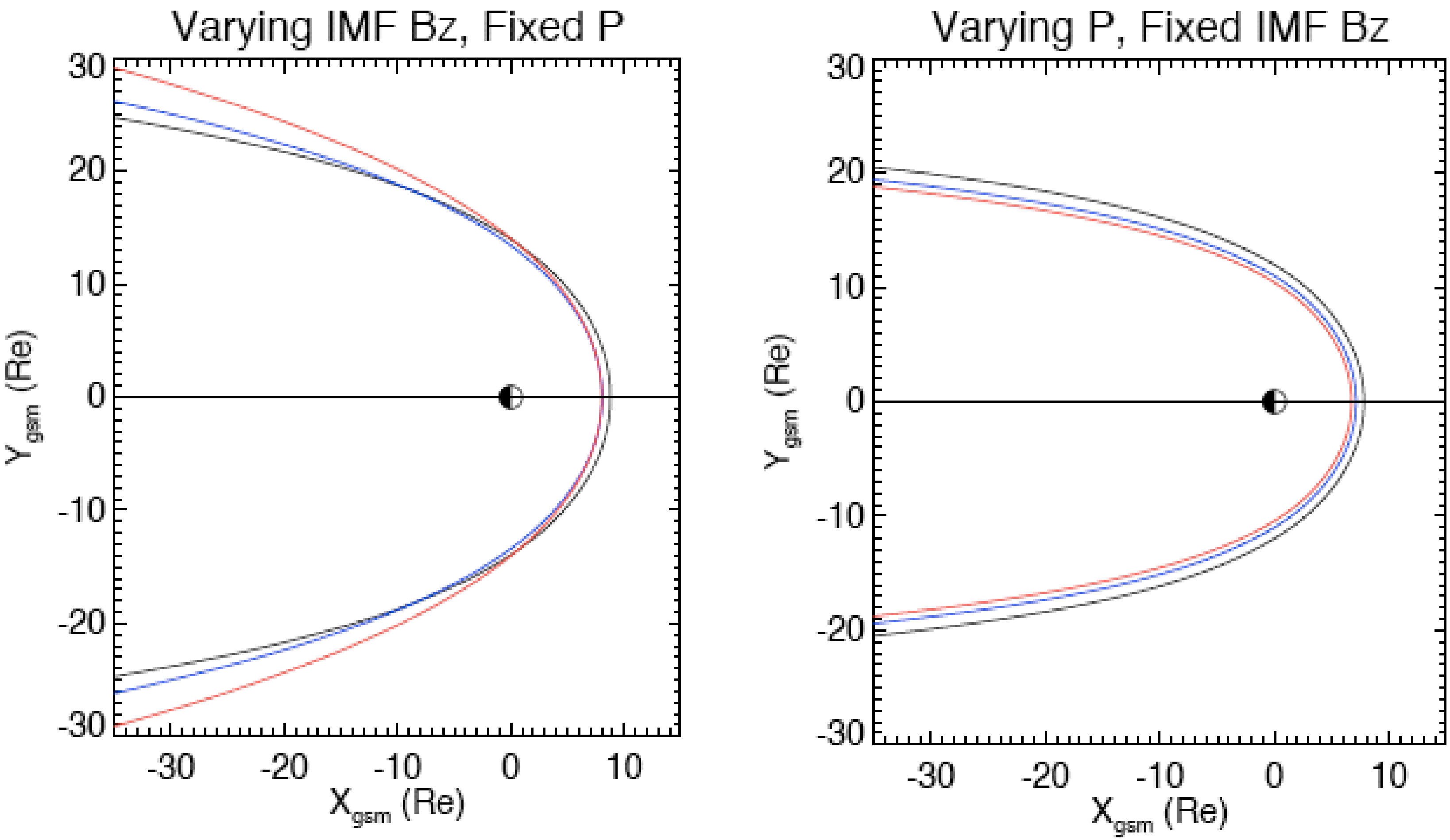
$$r = r_0(\frac{2}{1+\cos\theta})^\alpha$$

$$r_0 = \begin{cases} (11.4 + 0.013B_z)(D_p)^{-\frac{1}{6.6}}, & \text{for } B_z \geq 0 \\ (11.4 + 0.14B_z)(D_p)^{-\frac{1}{6.6}}, & \text{for } B_z < 0 \end{cases}$$

$$\alpha = (0.58 - 0.010B_z)(1 + 0.010D_p)$$

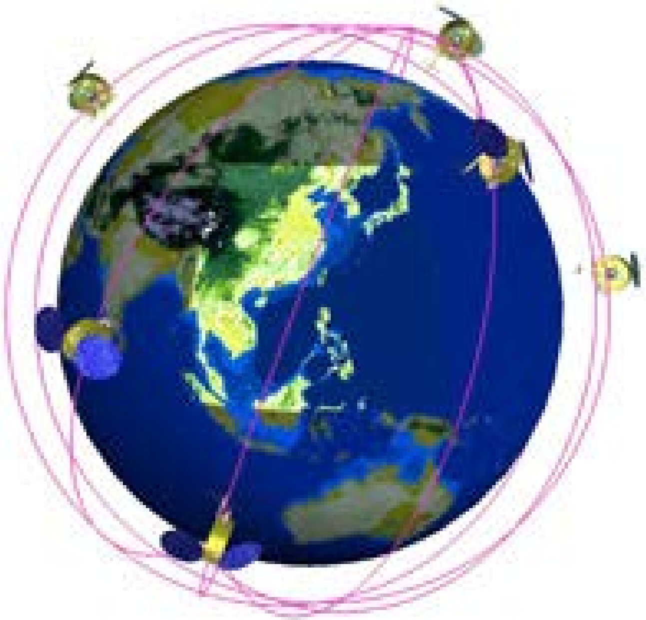
where r_0 is the subsolar standoff distance and α is the flaring degree of the magnetopause.

A Demonstration of the Shue et al. [1997] model



More Information about the Shue et al. [1997] model

- The formula of the model is simple and accurate.
- The model has been widely used in Space community.
- According to the citation report from Web of Science, this paper has been cited in 364 times as of today.



FORMOSAT-3/COSMIC

Global Real-time
Weather (Meteorology)
Space Weather (Ionosphere)
Observation and Prediction

The FORMOSAT-3/COSMIC program is an international collaboration between Taiwan and the United States that will use a constellation of six remote sensing microsatellites to collect atmospheric data for weather prediction and for ionosphere, climate and gravity research. Data from the satellites will be made freely available to the international scientific community in near real-time.

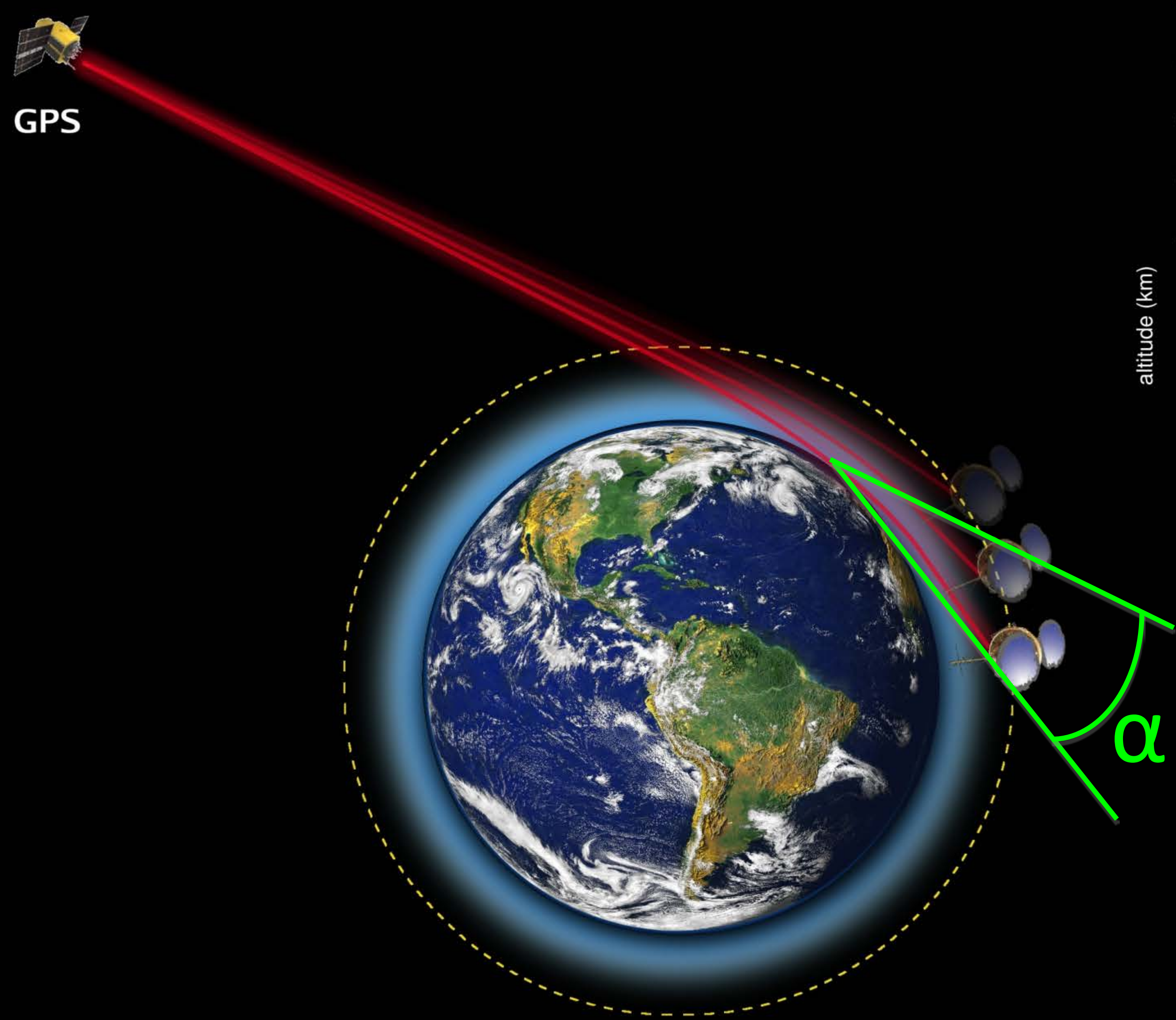
FORMOSAT-3/COSMIC

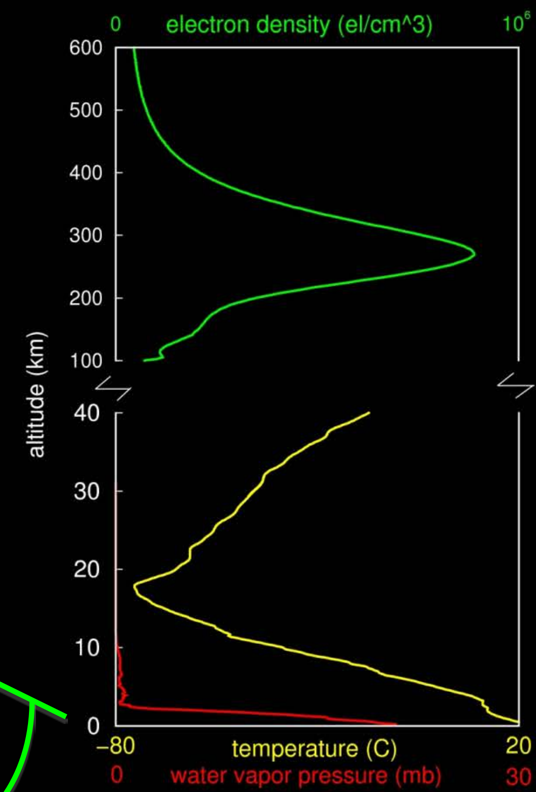
- ***FORMOSAT-3/COSMIC* Constellation was launch at 01:40 UTC, April 14, 2006 (Taiwan Time: April 15 2006) at Vandenberg Air Force Base, CA.** *Minotaur Launch*

- ***Maneuvered into six different orbital planes (inclination ~72°) for optimal global coverage (at ~800 km altitude).***

- ***Five out of Six satellites are in good health and providing science data.***

GPS Radio Occultation

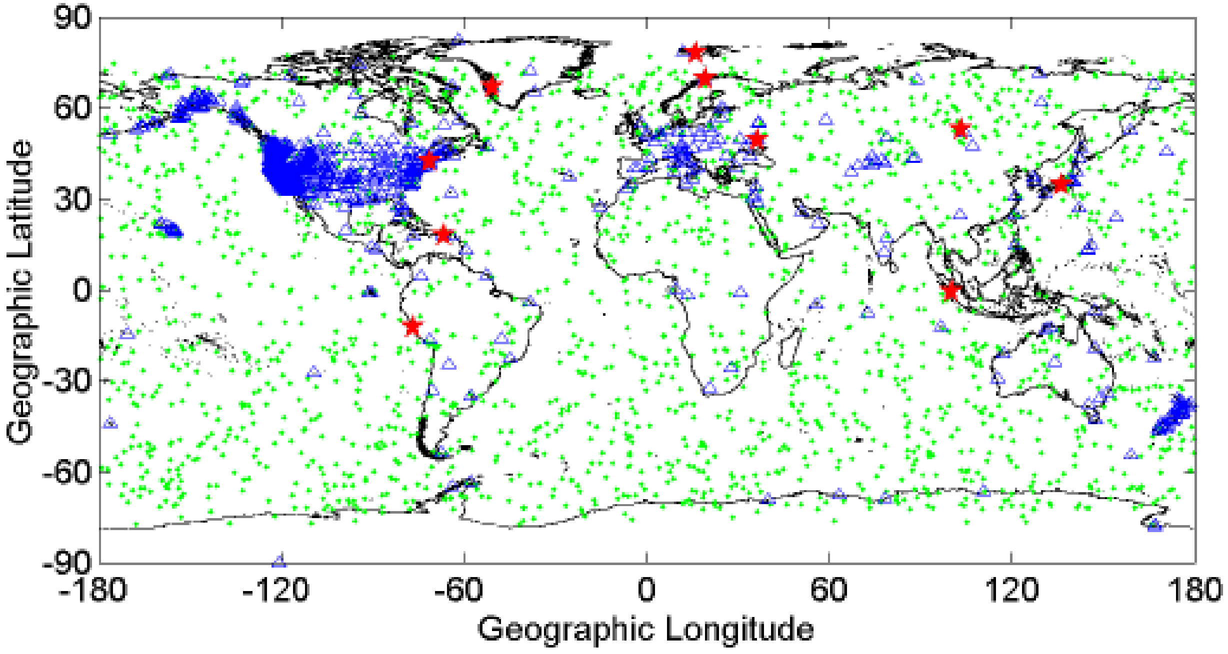




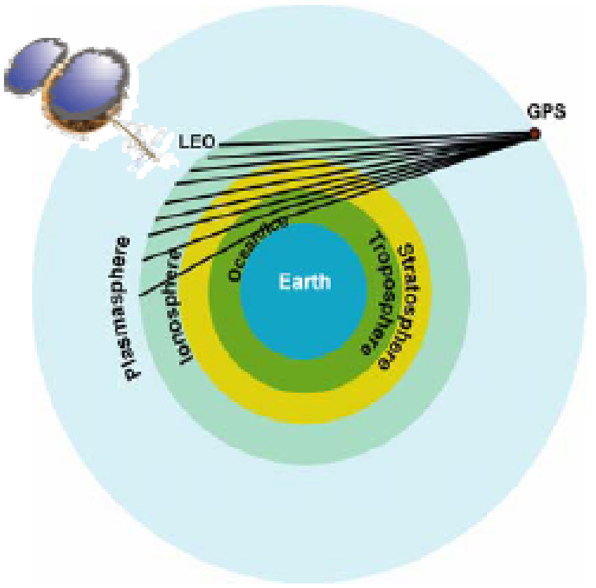
Wavelength and amplitude
of in the vertical direction

Global 3D structure

Distribution of occultation events observed by FORMOSAT-3



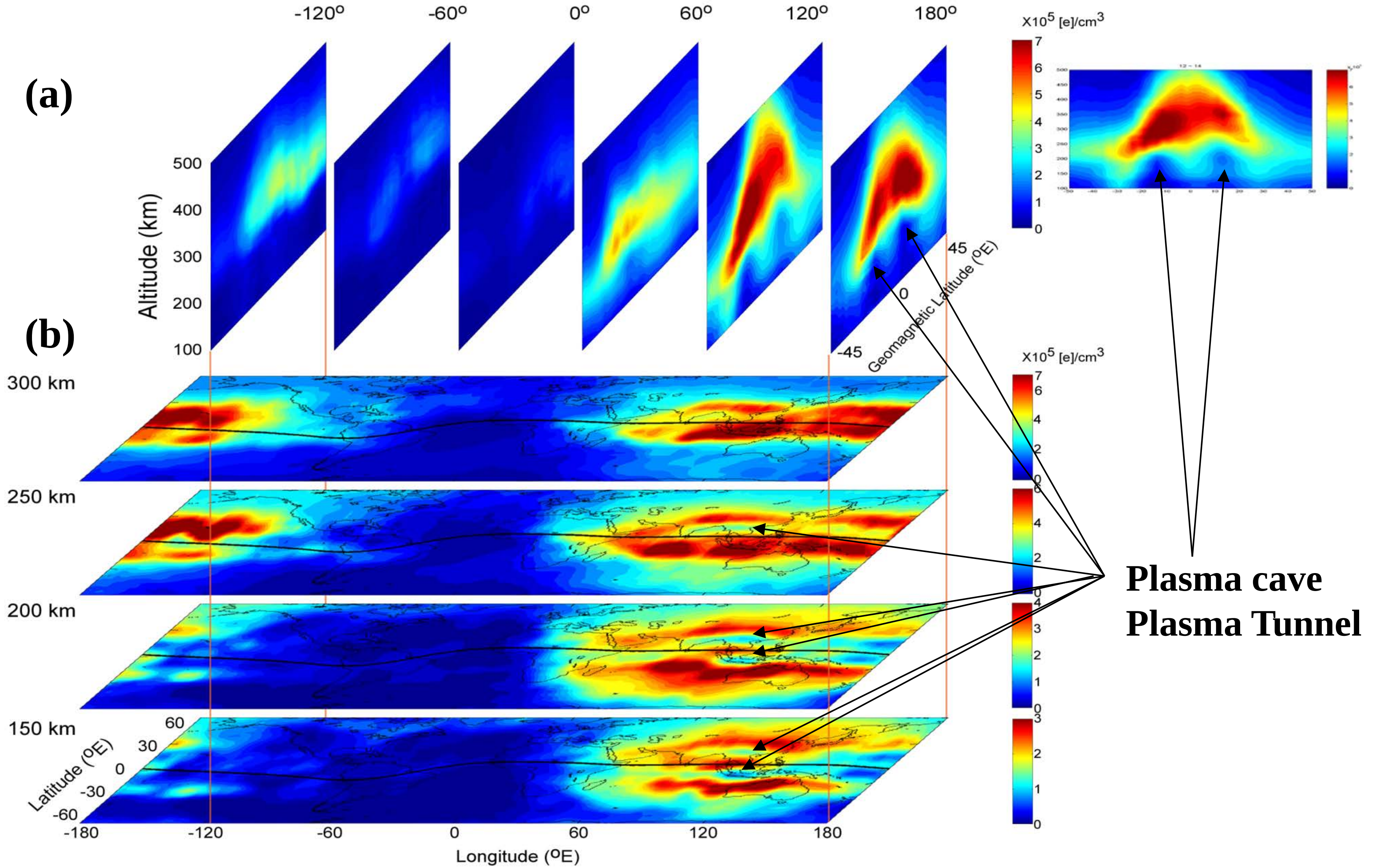
GOX



3D Plasma Structure and Dynamics

- Equatorial Ionization Anomaly
- Mid-latitude Trough
- Weddell Sea Anomaly

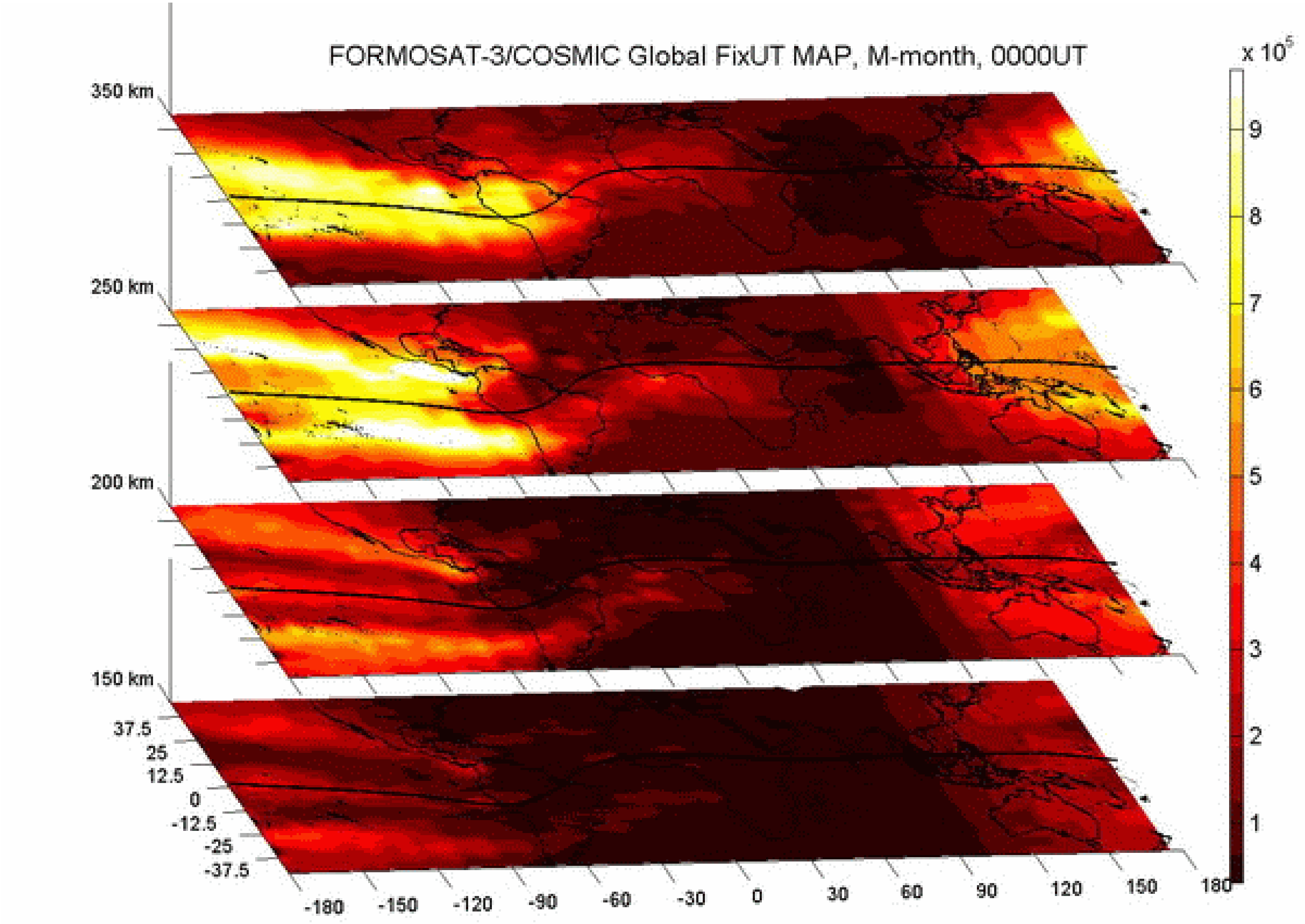
3D Ionospheric plasma Structure



Liu et al. (JGR 2010)

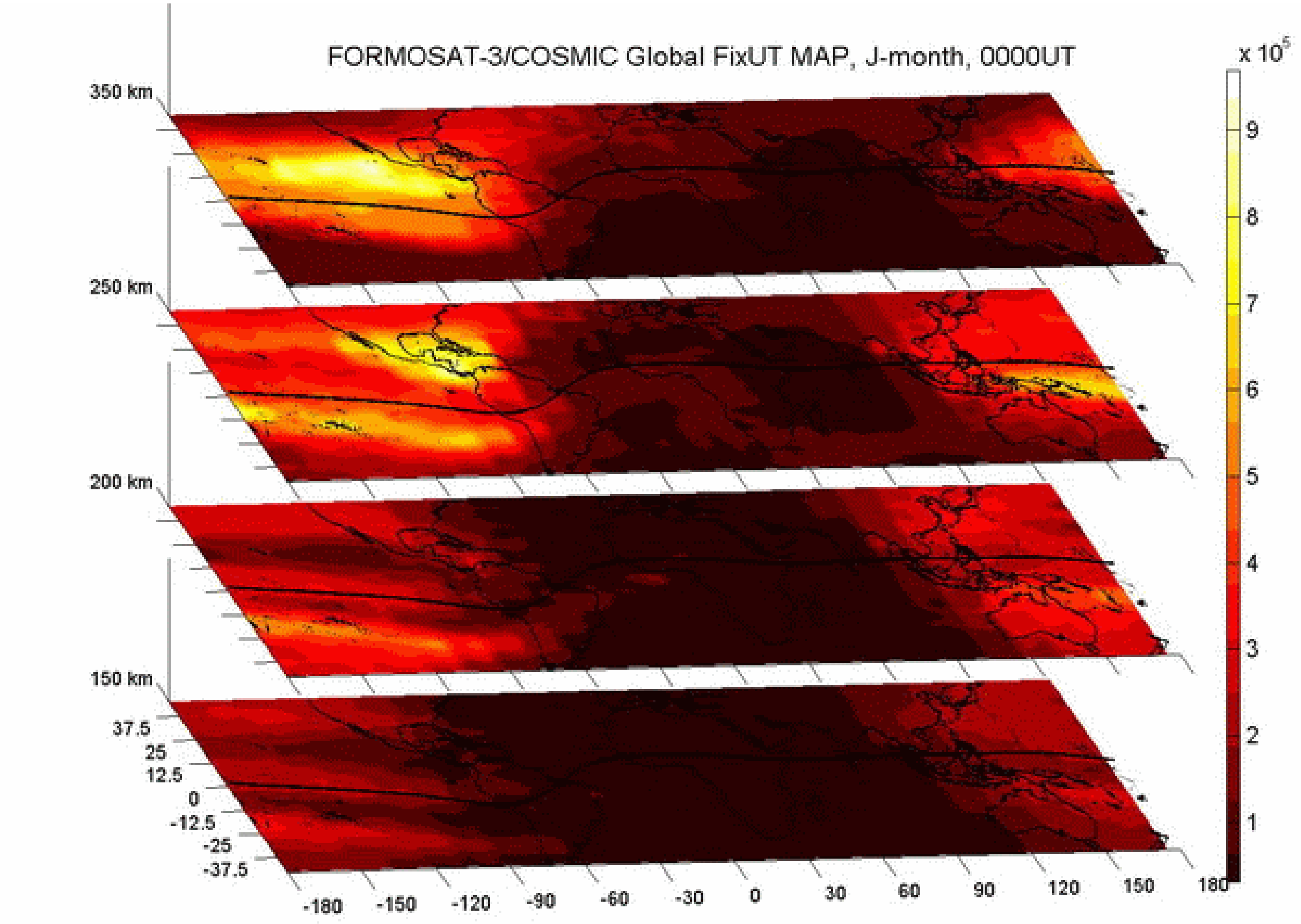
Equatorial Ionization Anomaly

2007 M-month



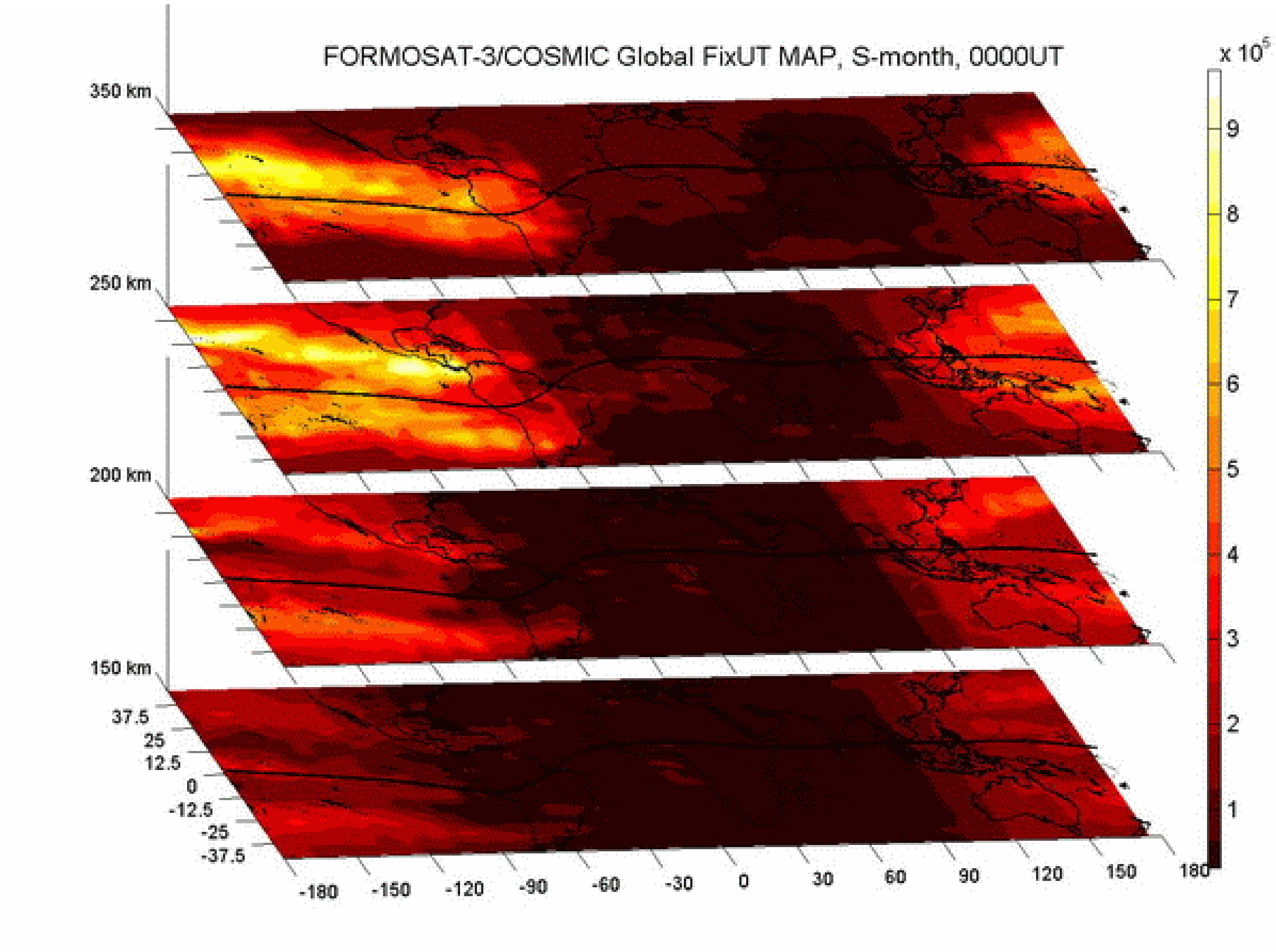
FORMOSAT-3/COSMIC Global FixUT MAP, M-month, 0000UT
x 10^5
9
8
7
6
5
4
3
2
1
350 km
250 km
200 km
150 km
37.5
25
12.5
0
-12.5
-25
-37.5
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180

2007 J-month



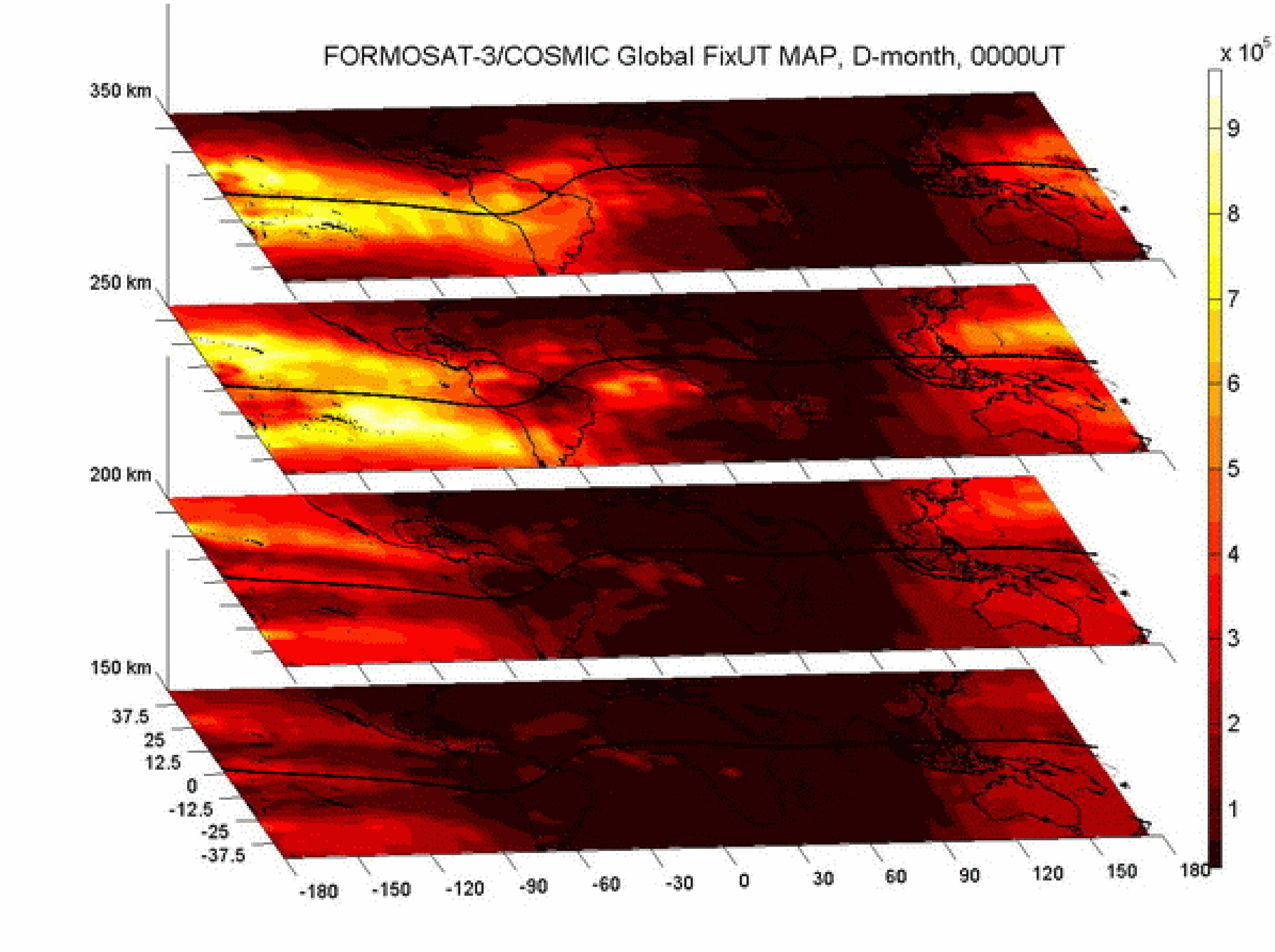
FORMOSAT-3/COSMIC Global FixUT MAP, J-month, 0000UT
350 km
250 km
200 km
150 km
37.5
25
12.5
0
-12.5
-25
-37.5
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
x 10^5
9
8
7
6
5
4
3
2
1

2007 S-month



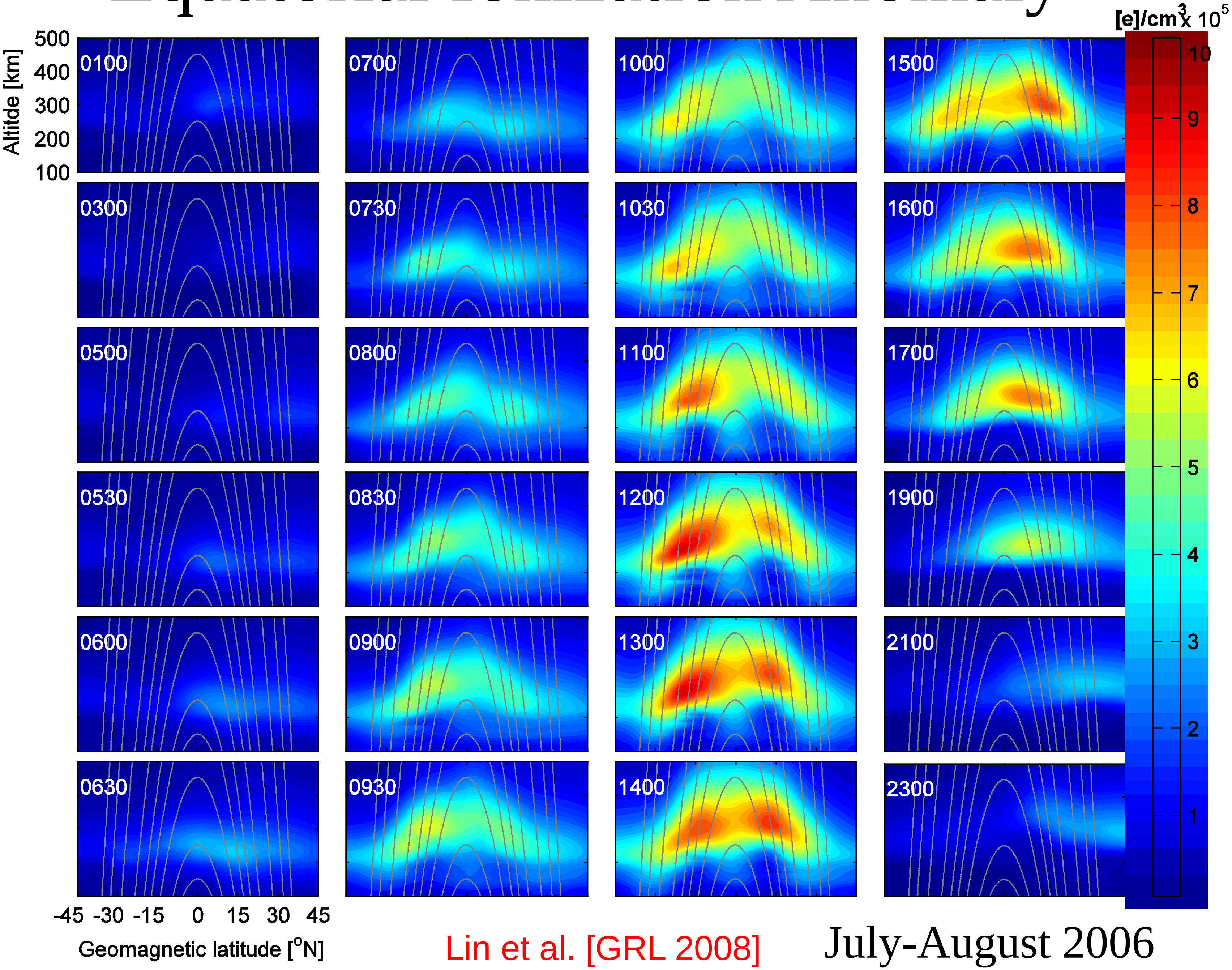
FORMOSAT-3/COSMIC Global FixUT MAP, S-month, 0000UT
350 km
250 km
200 km
150 km
37.5
25
12.5
0
-12.5
-25
-37.5
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
x 10^5
9
8
7
6
5
4
3
2
1

2007 D-month



FORMOSAT-3/COSMIC Global FixUT MAP, D-month, 0000UT
x 10^5
350 km
250 km
200 km
150 km
37.5
25
12.5
0
-12.5
-25
-37.5
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
9
8
7
6
5
4
3
2
1

Equatorial Ionization Anomaly



Lin et al. [GRL 2008]

July-August 2006

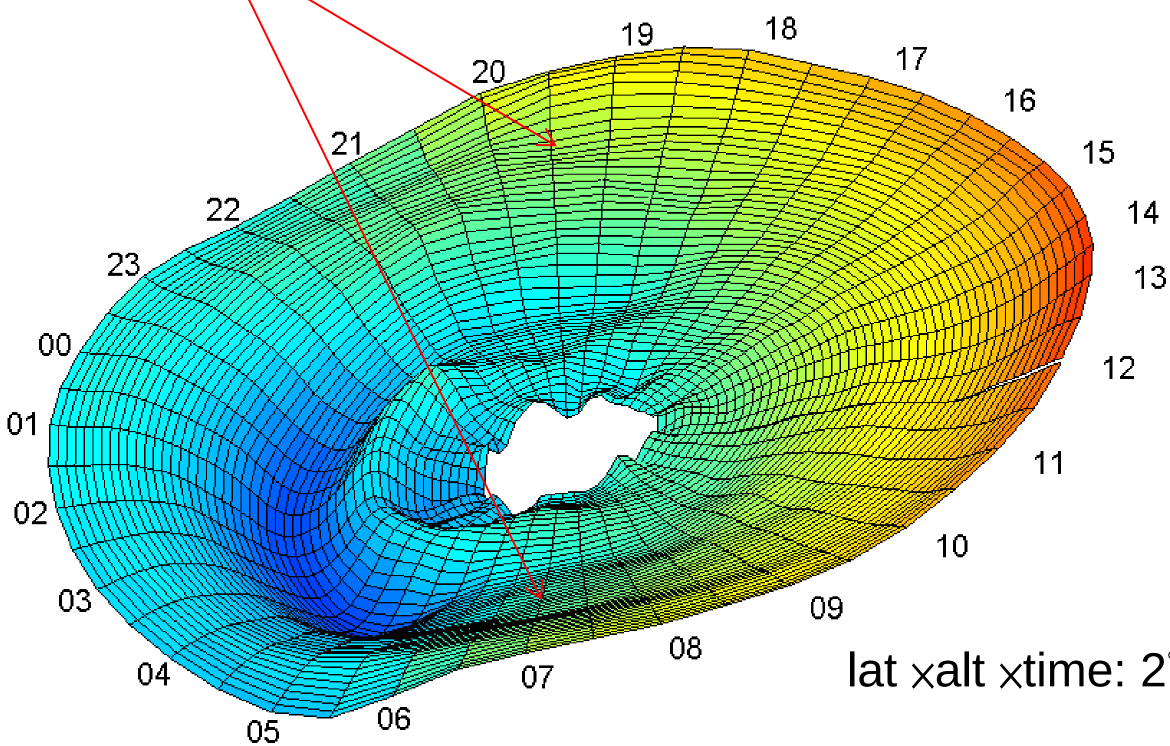
Remark 1

- Results suggest that in addition to the asymmetric neutral composition effect, interactions between the summer-to-winter (transequatorial) neutral winds and strength of the equatorial plasma fountain effect play important roles in producing asymmetric development of the EIA crests as imaged by the F3/C.

Mid-latitude Trough

FORMOSAT-3/COSMIC NmF2 Persudo-3D structure
Northern Hemisphere, M-month

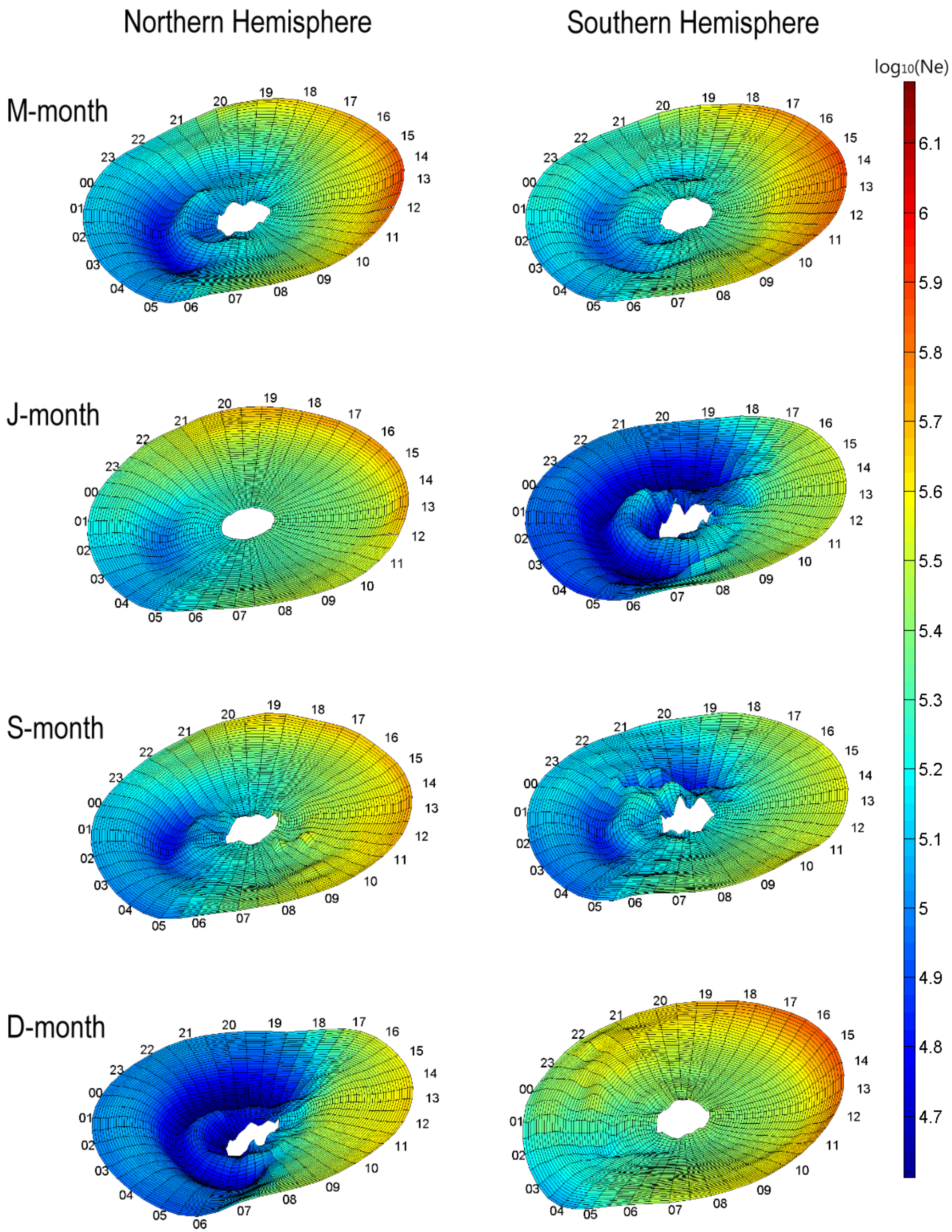
Terminator waves?



lat ×alt ×time: 2°×2km ×0.5hr

Center

Seasonal Variation



Lee et al. (JGR, 2011)

The seasonal averaged pseudo 3 - D images of the F2 peak density map (log10 (Ne), cm^{-3}) from February 2008 to January 2009 in magnetic polar coordinates for the March equinox, June solstice, September equinox, and December solstice. The inner and outer perimeters are 80° and 30° in magnetic latitude. The left and right columns are results in the Northern and Southern hemispheres, respectively. The color and vertical change refer to the electron density, and the numbers around each plot give the geomagnetic local time.

Remark 2

- Results show that the mid-latitude trough extends from dusk to dawn in all four seasons and is most pronounced in the winter hemisphere.
- The troughs in the two hemispheres are asymmetric, where the trough in the Northern Hemisphere is more evident and stronger than that in the Southern Hemisphere during the equinoctial seasons.

Ionospheric Weddell Sea Anomaly

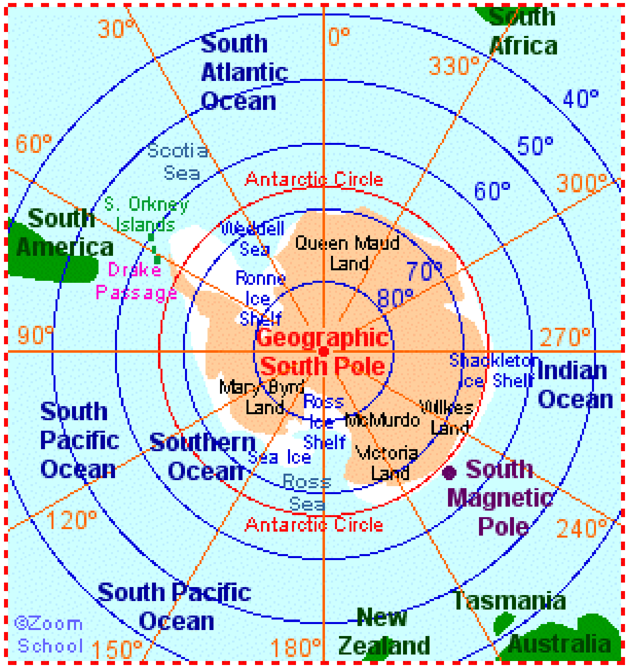
Stronger electron density Ne in nighttime than that in daytime over the Weddell Sea area during the Summer

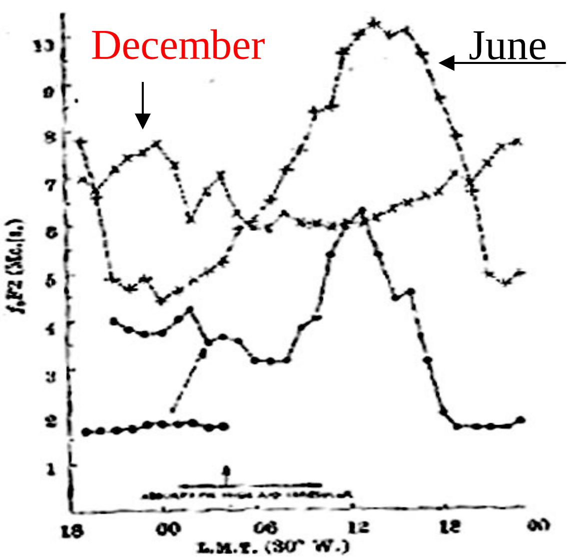
The Ionospheric Weddell Sea Anomaly

1. Stronger nighttime Ne than that during daytime

2. Discovered 50 years ahead of renewed observation by FORMOSAT-3/COSMIC

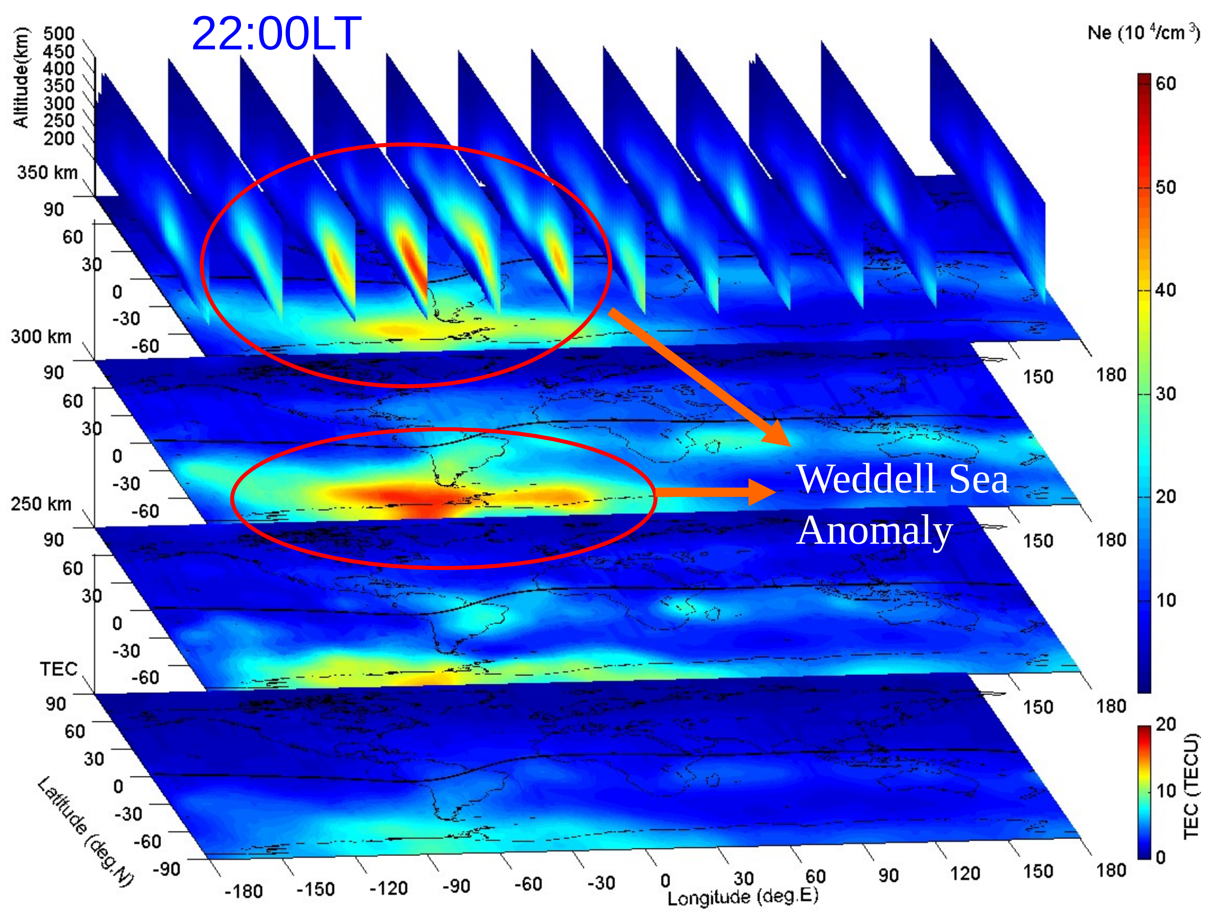
3. First glance of its vertical structure by F3/C!





Ionosonde Observation

(Bellchambers and Piggott, 1958)



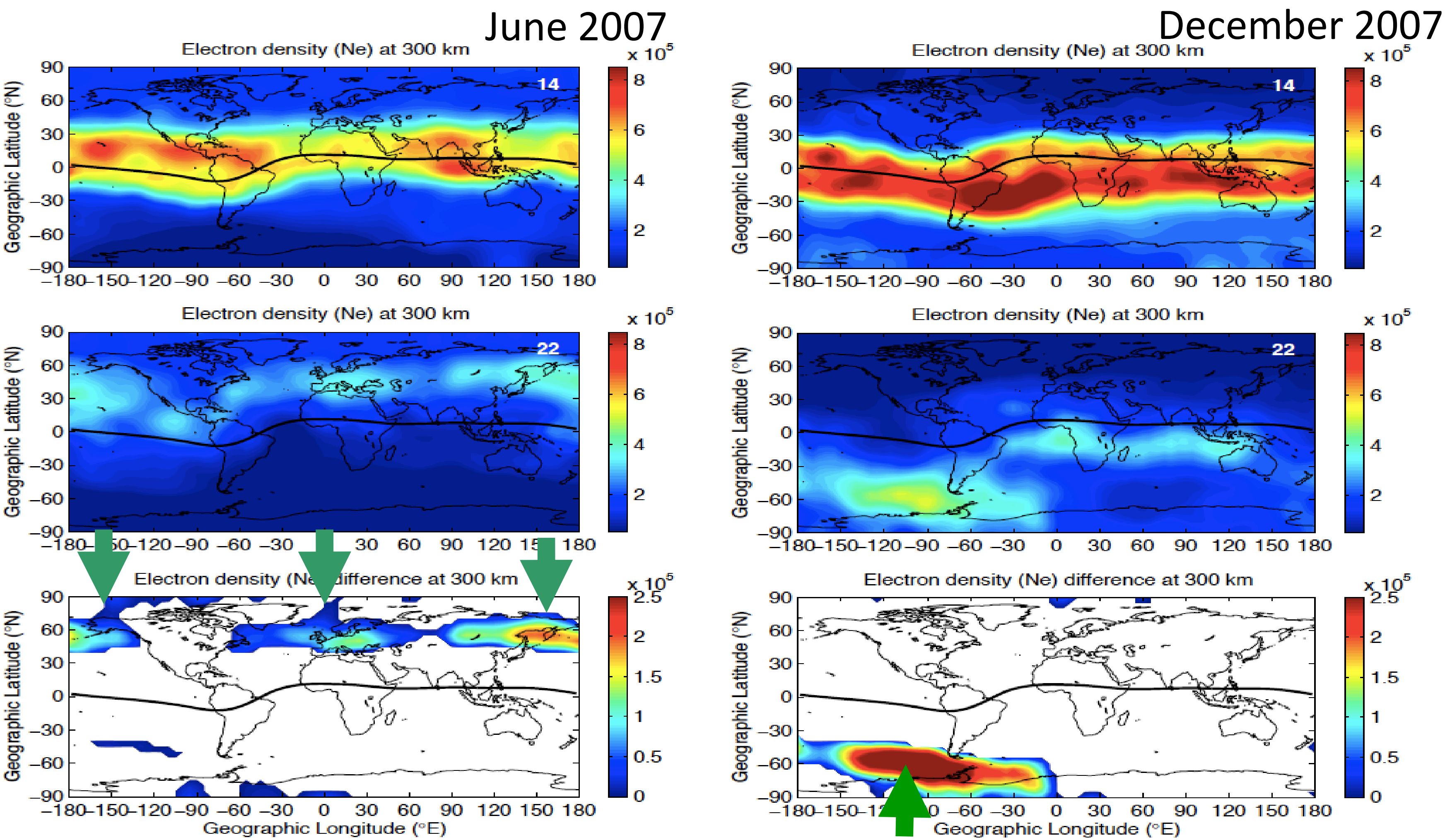
Lin et al. [2009]

Not only occurred in the Southern hemisphere but also in the North

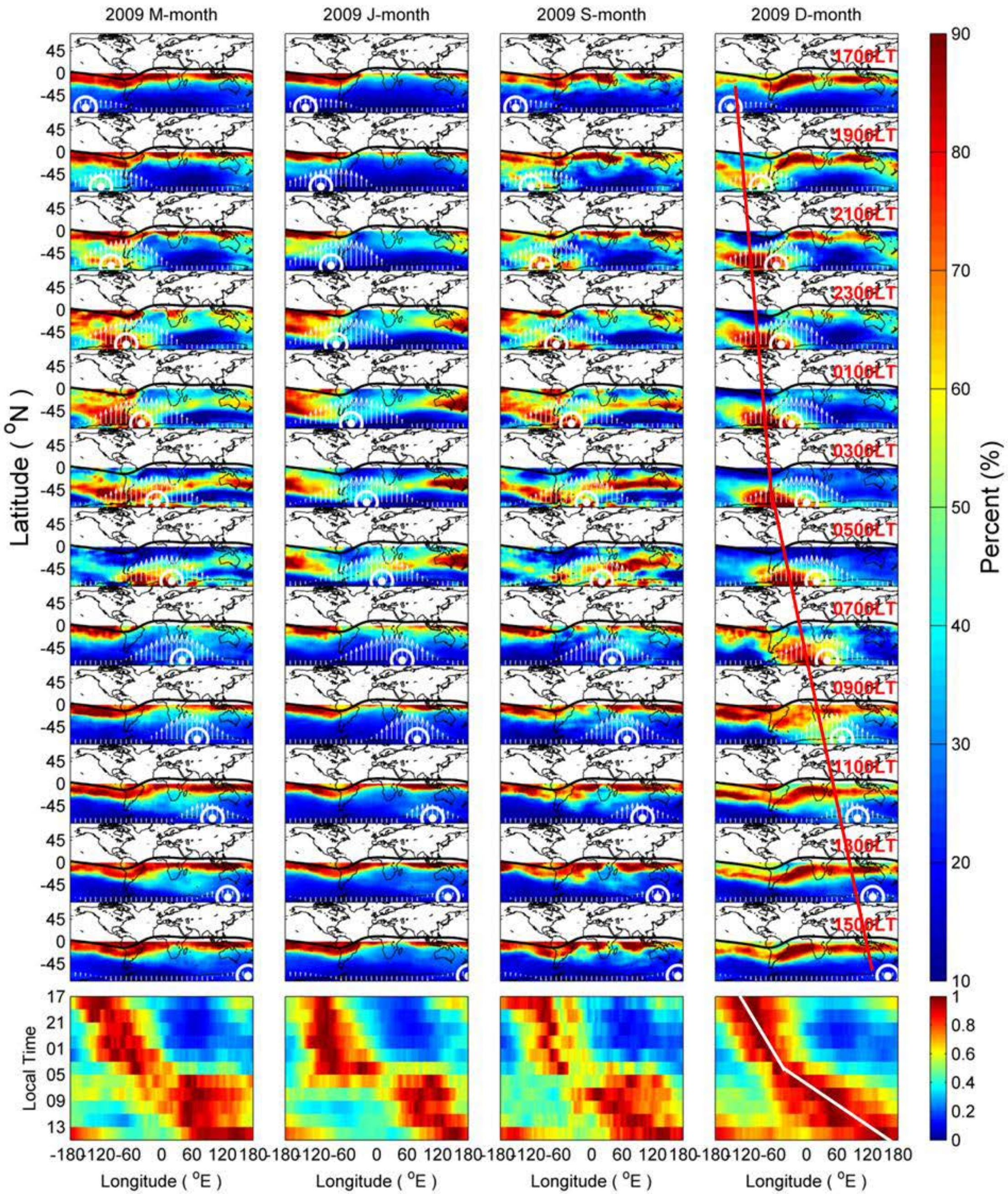
- Categorized as the Mid-latitude Summer Nighttime Anomaly (MSNA)

  Ne(2200LT) > Ne(1400LT)

  - driven by equatorward meridional neutral wind

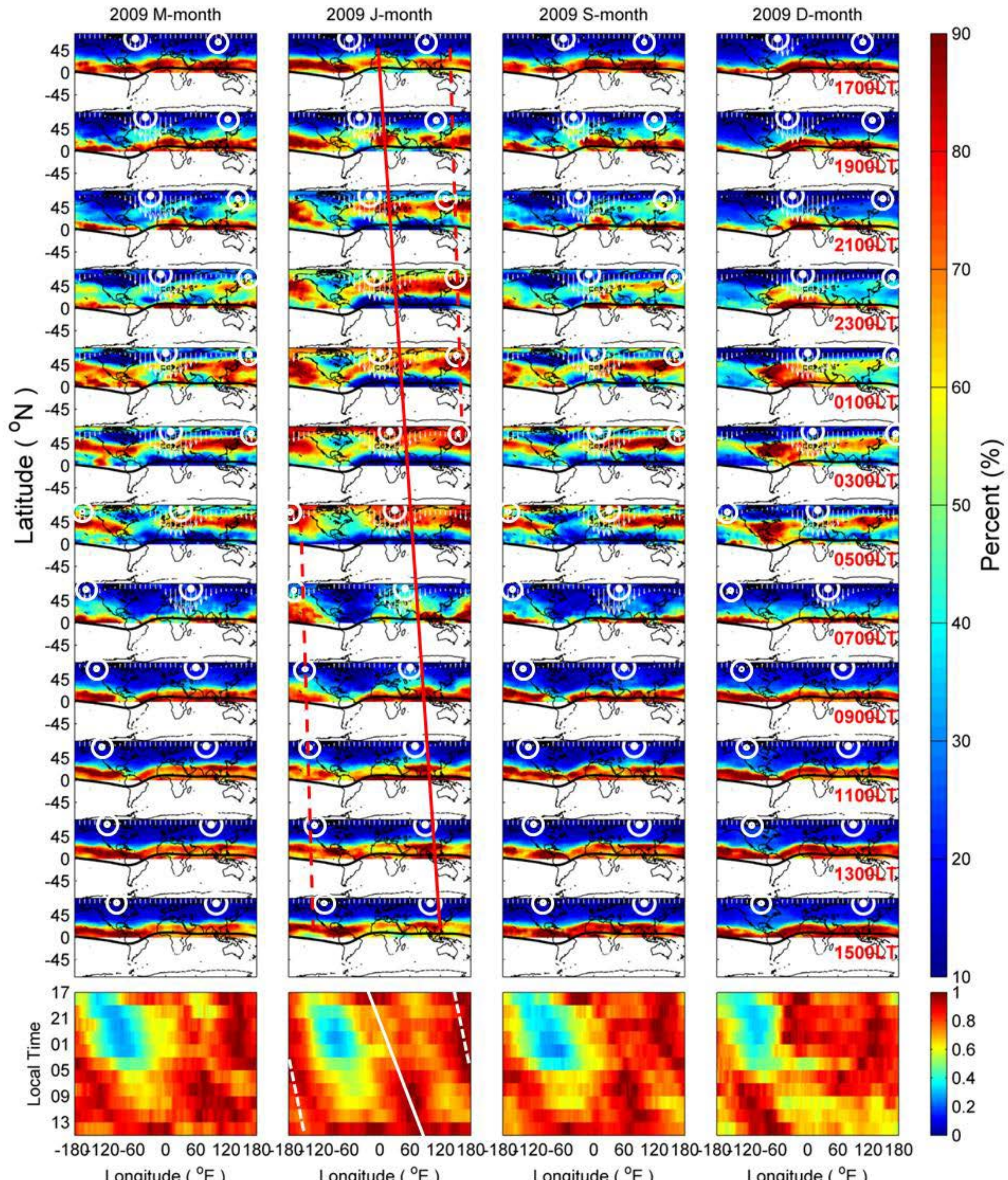


Lin et al. [2010]



Diurnal variations of F3/C electron density maps at 300km altitude at various global fixed local times in the four months in the southern hemisphere

Chang et al. [2014]



Diurnal variations of F3/C electron density maps at 300km altitude at various global fixed local times of the four months in the northern hemisphere.

Chang et al. [2014]

Remark 3

- It is found that the multiple-speeds in the eastward phase shift are about of 167 and 296m/s for the WSA feature in the southern hemisphere, while the peaked double MSNA feature with speeds yield 91 and 121m/s in the northern hemisphere.
- The simultaneous eastward phase shifts in the electron density and the plasma flows suggest that the neutral winds are essential.
- The WSA/MSNA features in fact yield eastward phase shift and appear all year round.

Ionospheric Scintillation

S. Basu et al. / Journal of Atmospheric and Solar-Terrestrial Physics 64 (2002) 1745–1754 1747

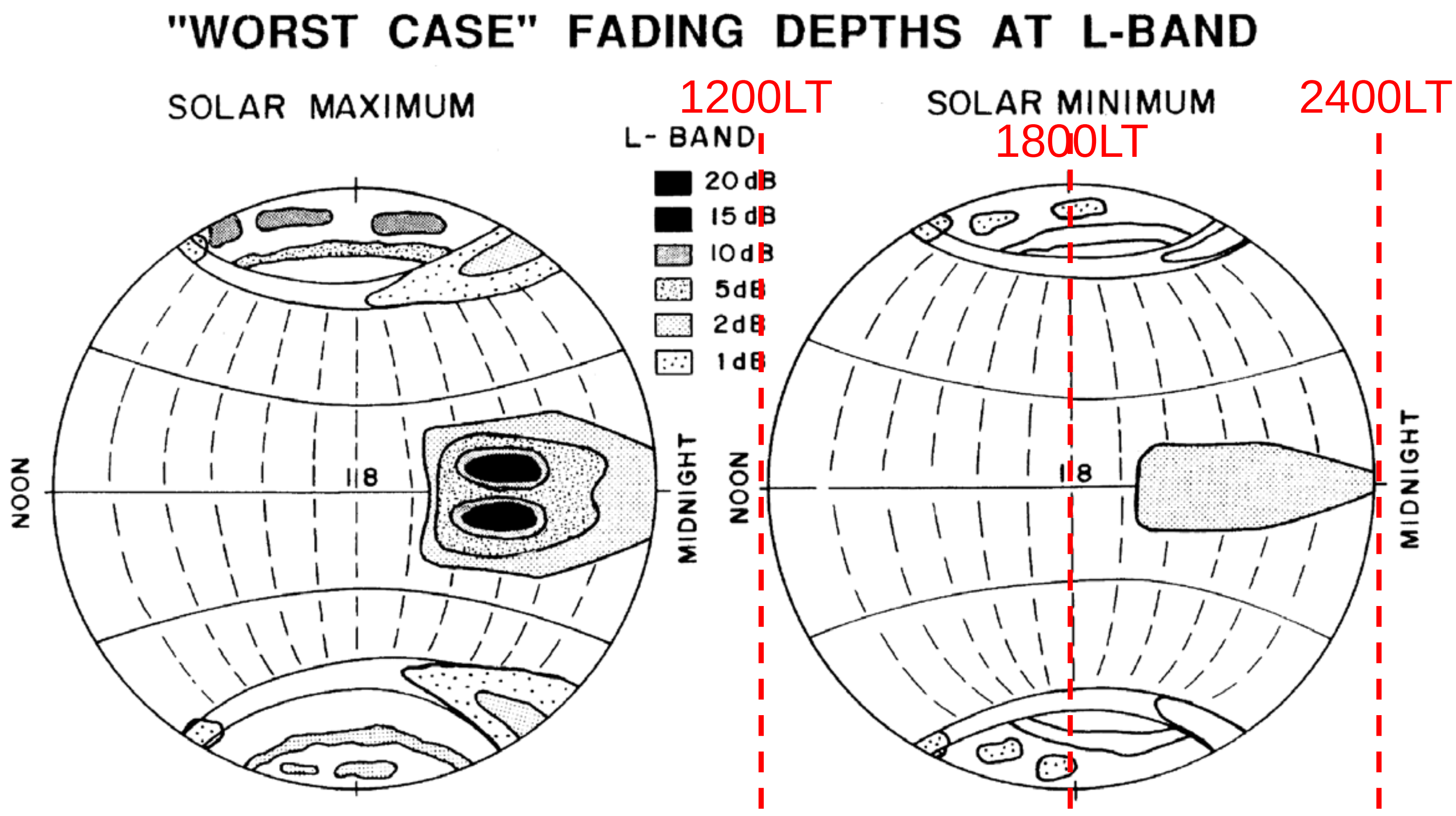
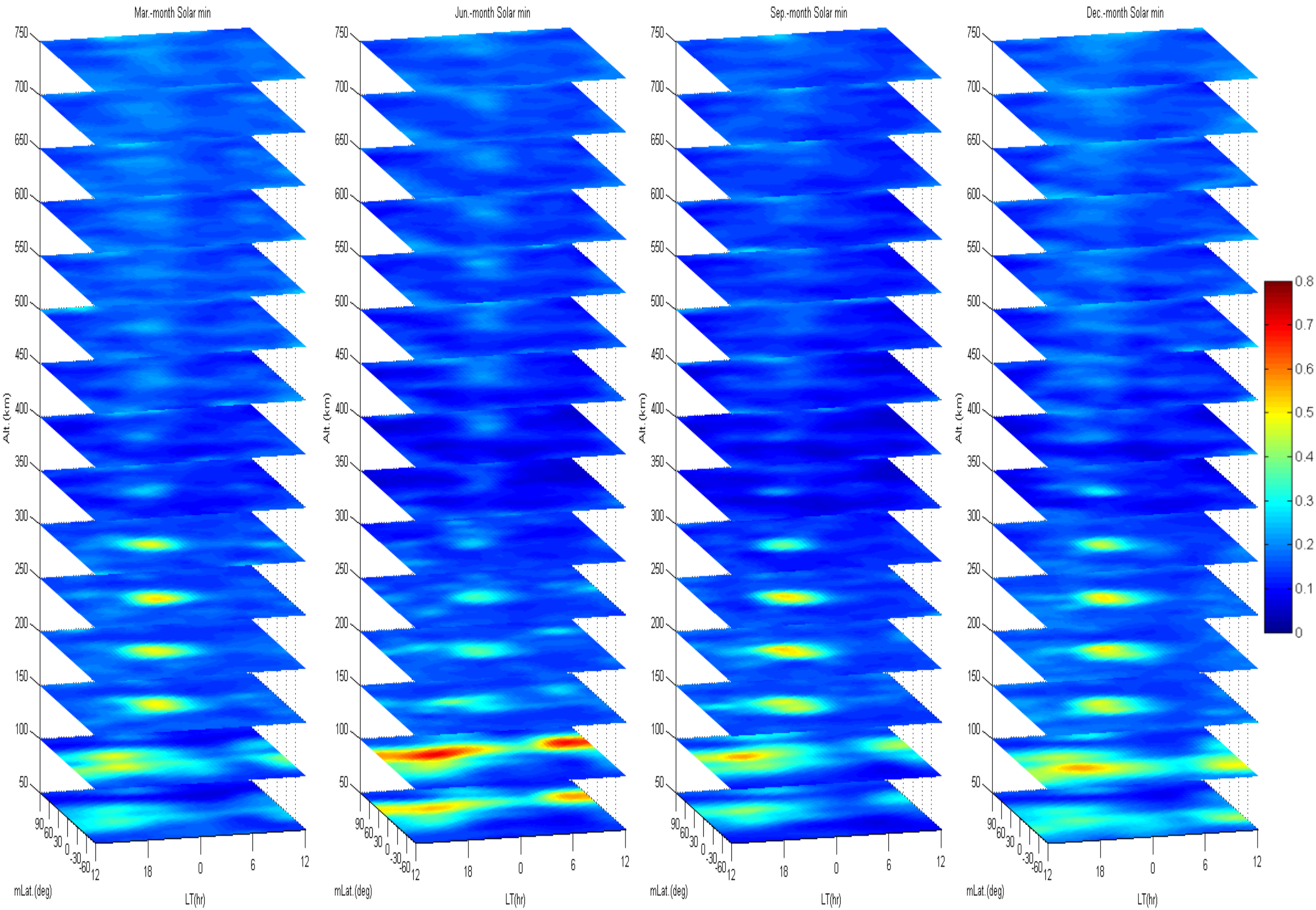


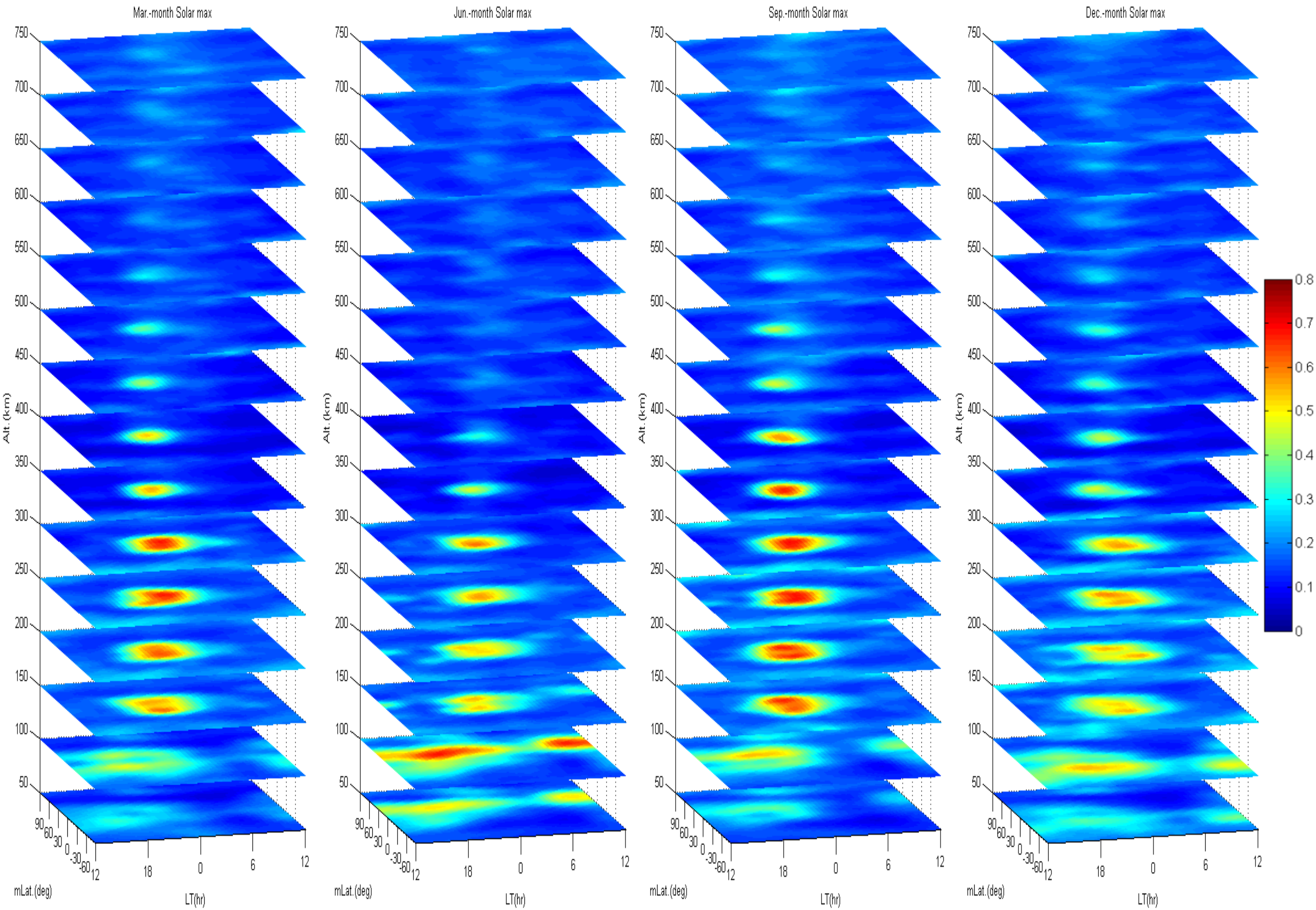
Fig. 1. Schematic of the global morphology of scintillations at L-band frequencies during the solar maximum (left panel) and solar minimum (right panel) conditions. Reproduced from S. Basu and K.M. Groves, Specification and forecasting of outages on satellite communication and navigation systems, Space Weather, Geophysical Monograph 125, 424–430, 2001. Published 2001 by the American Geophysical Union. Reproduced/modified by permission of American Geophysical Union.

Basu et al. [JASTP 2002]

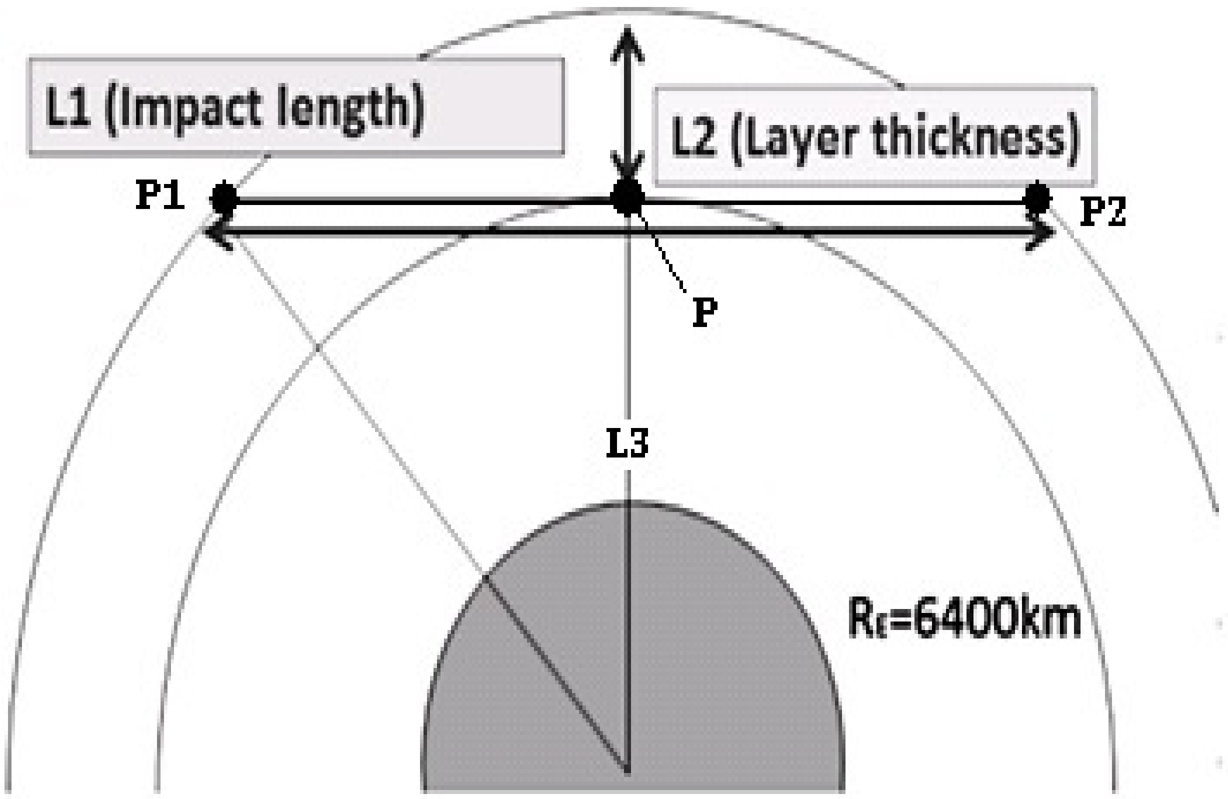
S4 Max altitude slice at various MLT in Solar min 2008-2009



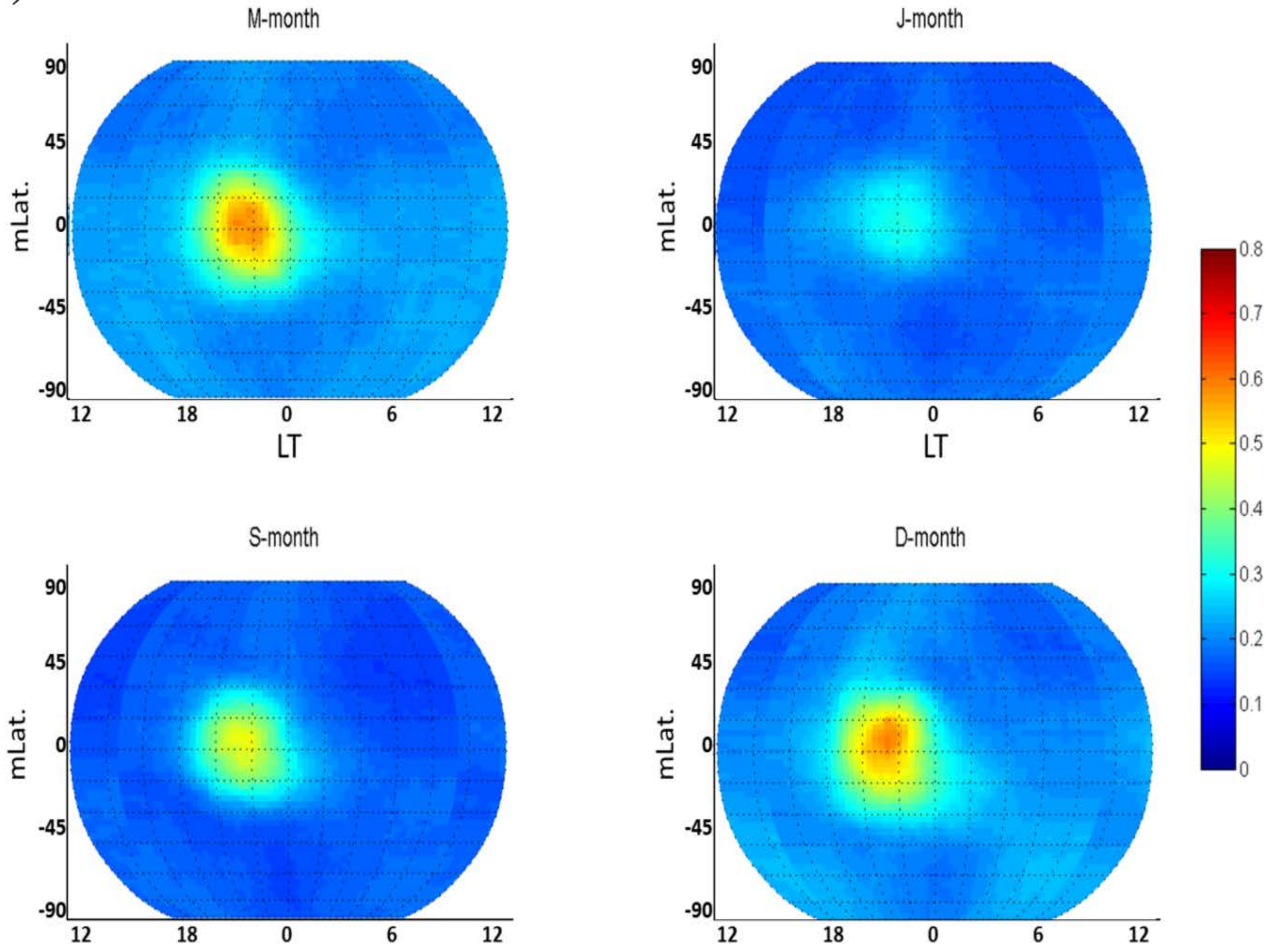
S4 Max altitude slice at various MLT in Solar Max 2012-2013

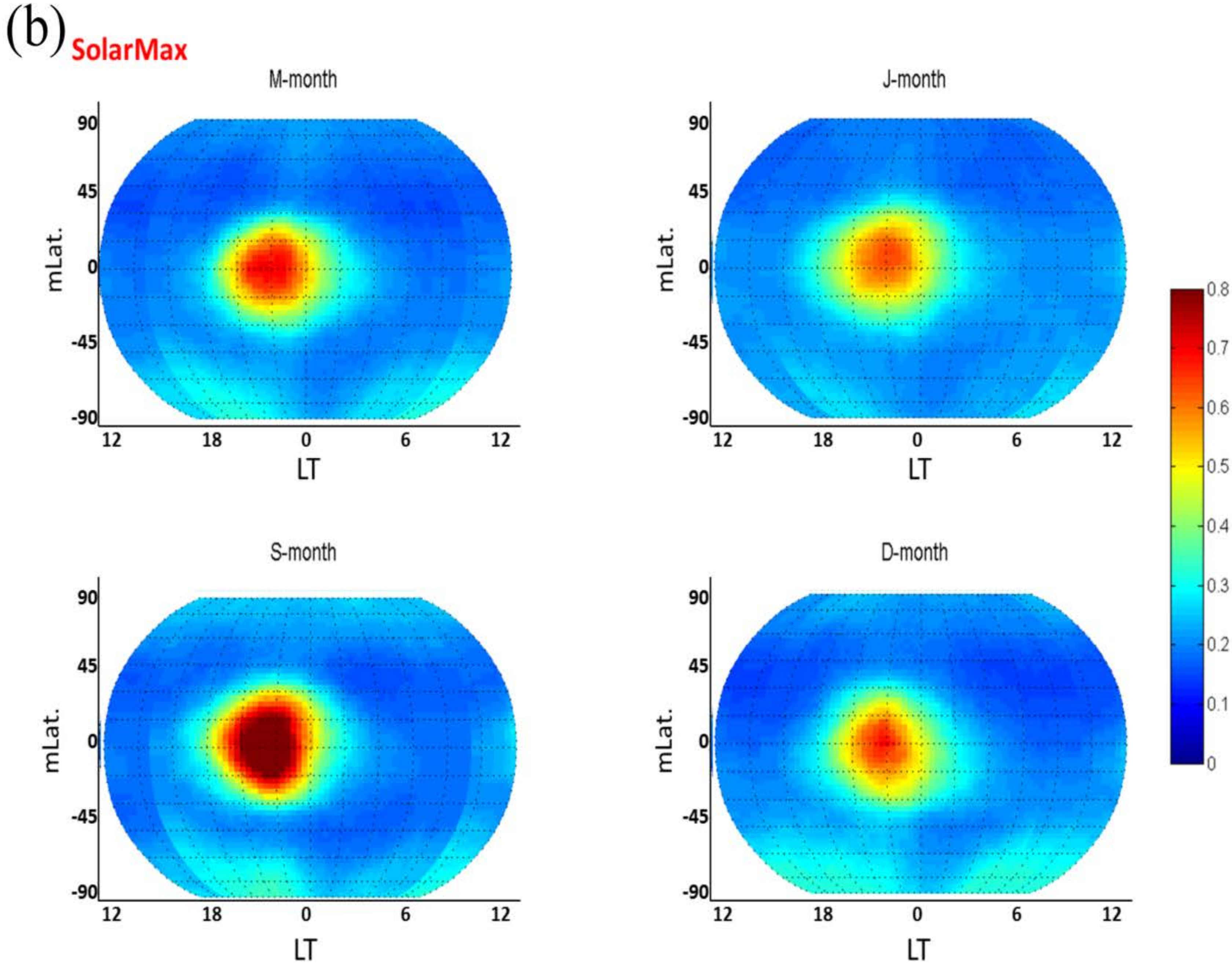


Conversion of Scintillation S4 Experienced on the Ground



(a) SolarMin

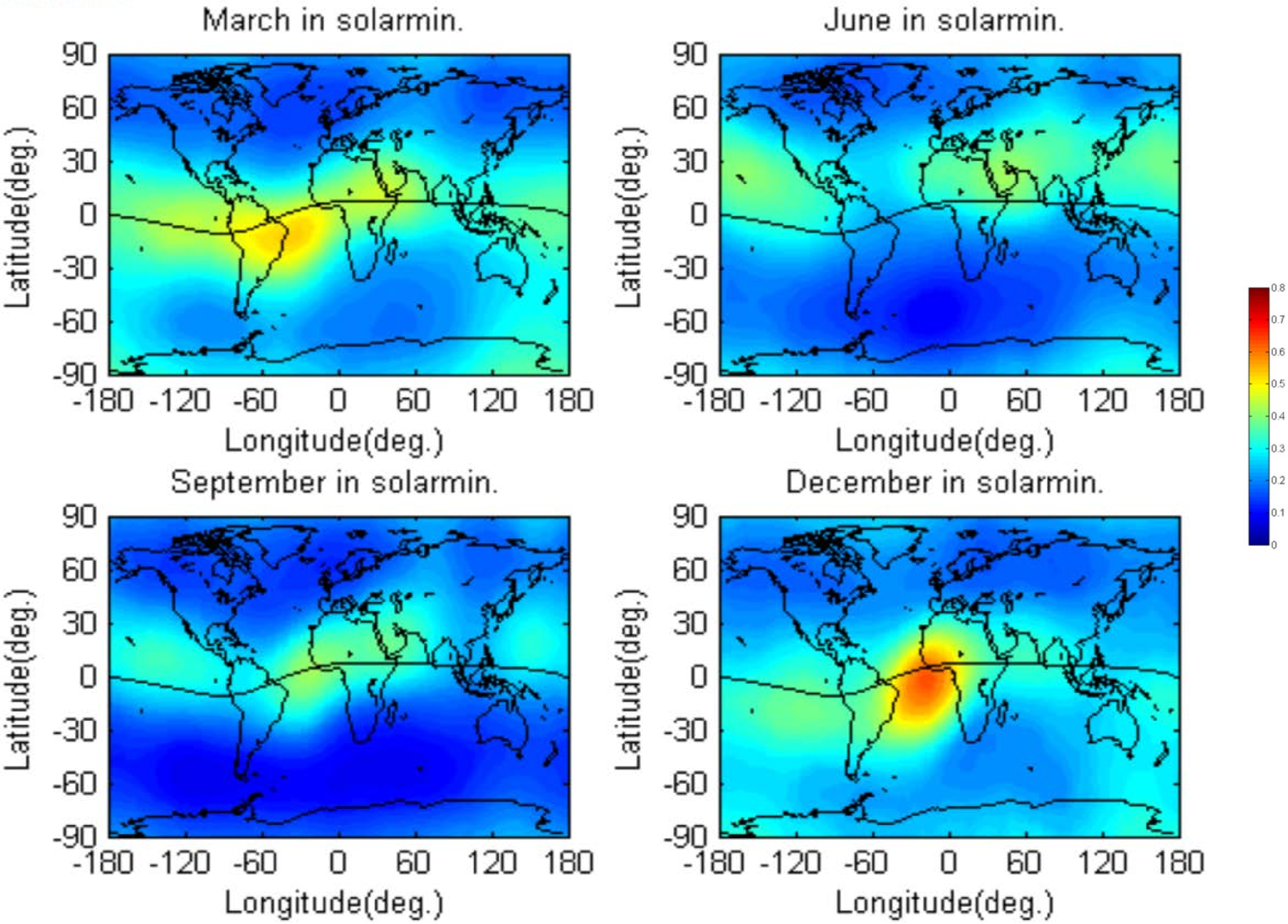

M-month
J-month
S-month
D-month
mLat.
LT
90
45
0
-45
-90
12
18
0
6
12
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0



(b)
SolarMax
M-month
J-month
S-month
D-month
mLat.
LT
90
45
0
-45
-90
12
18
0
6
12
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

(a)

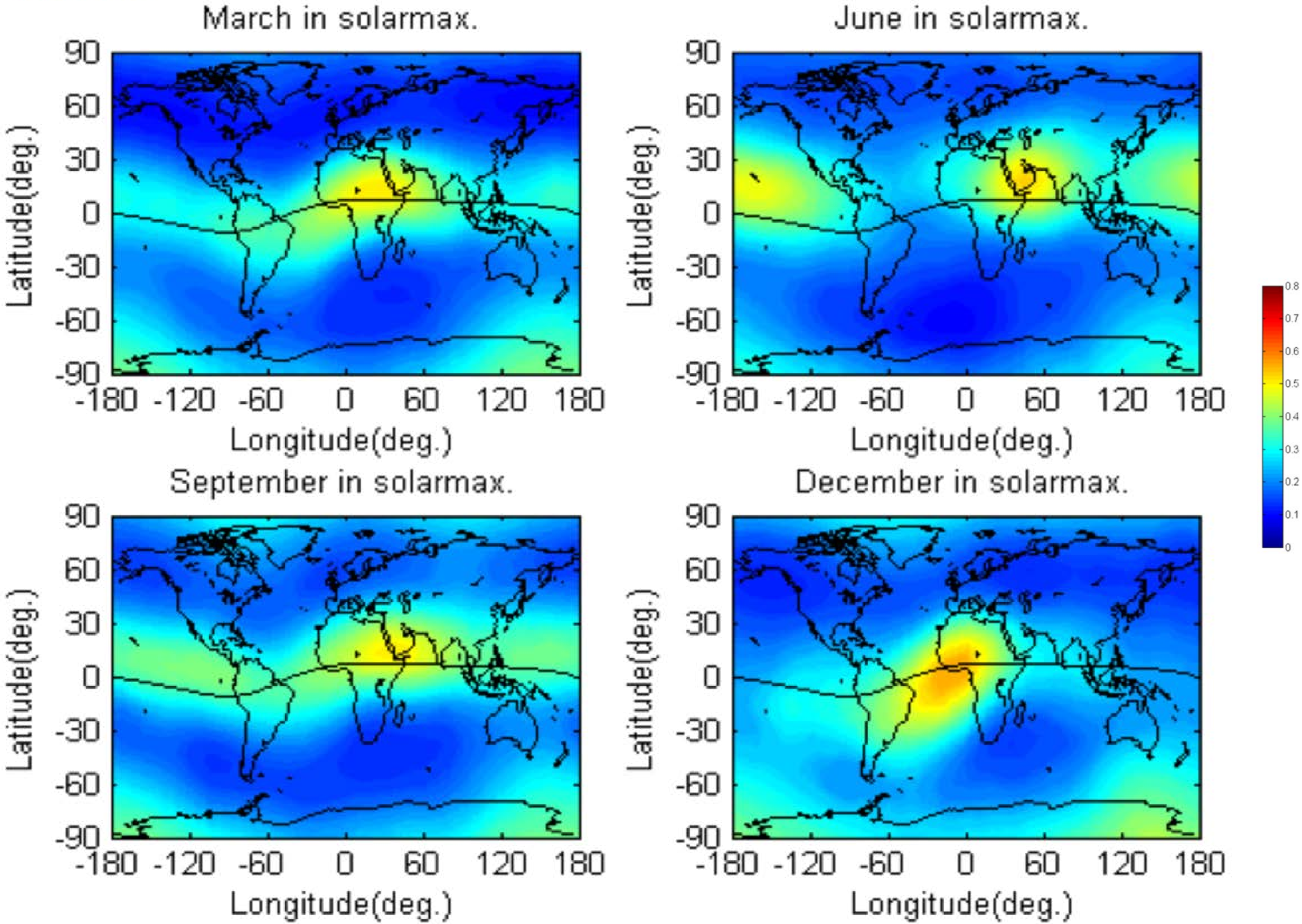
SolarMin



March in solarmin.
June in solarmin.
September in solarmin.
December in solarmin.
Latitude(deg.)
Longitude(deg.)
90
60
30
0
-30
-60
-90
-180
-120
-60
0
60
120
180
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

(b)

SolarMax


March in solarmax.
June in solarmax.
September in solarmax.
December in solarmax.
Latitude(deg.)
Longitude(deg.)
90
60
30
0
-30
-60
-90
-180
-120
-60
0
60
120
180
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

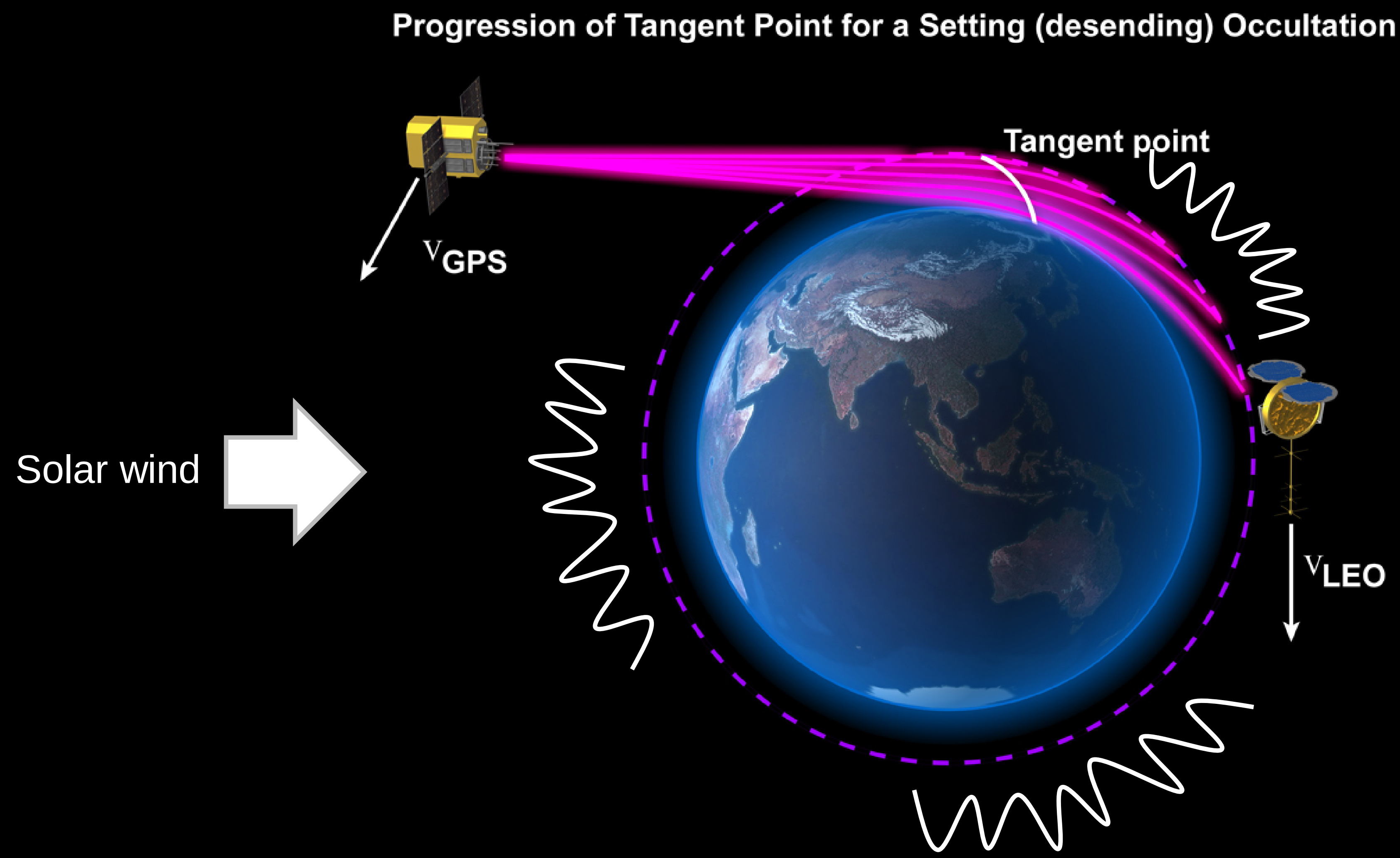
Remark 4

- The most prominent signatures of the F3/C S4 max in the E- (F-)region are in middle (equatorial-low) latitudes of the Summer J-month (equinox) months.
- The F3/C S4 max in the E-region is mainly contributed by the Es (sporadic-E) layer. Neutral wind is essential!
- The F3/C S4 max in the F-region lies between 20N and 20S and expends to higher latitudes in the equinox and D months. E×B plasma fountain is essential!

Thump the Ionosphere

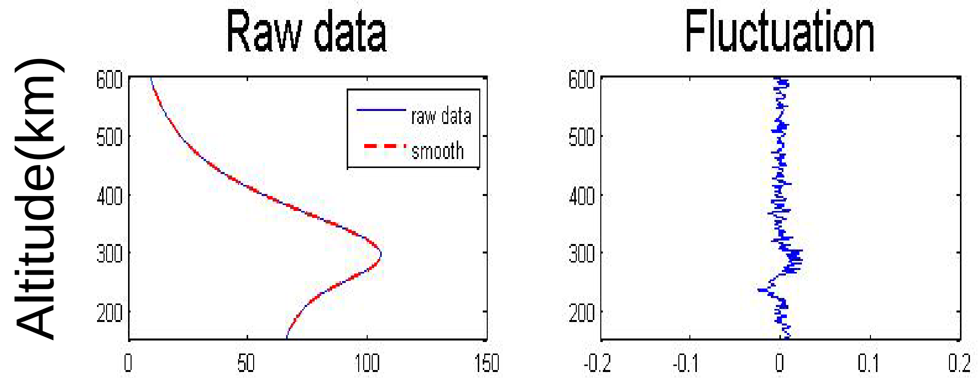
- magnetic storm
- earthquake
- solar eclipse

Storm the Ionosphere

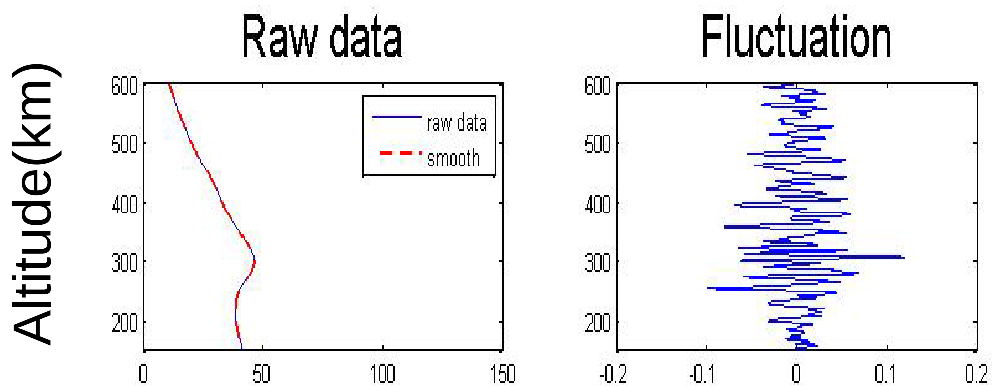


Vertical fluctuation profile

Quiet time

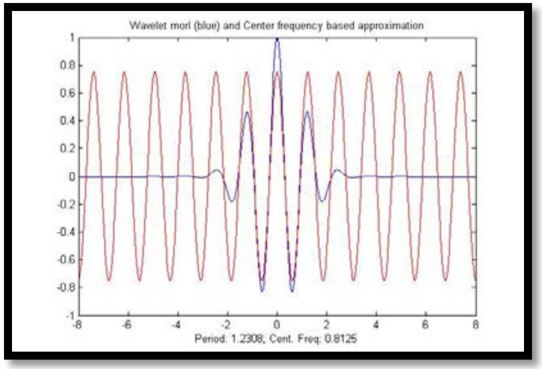


Storm tme

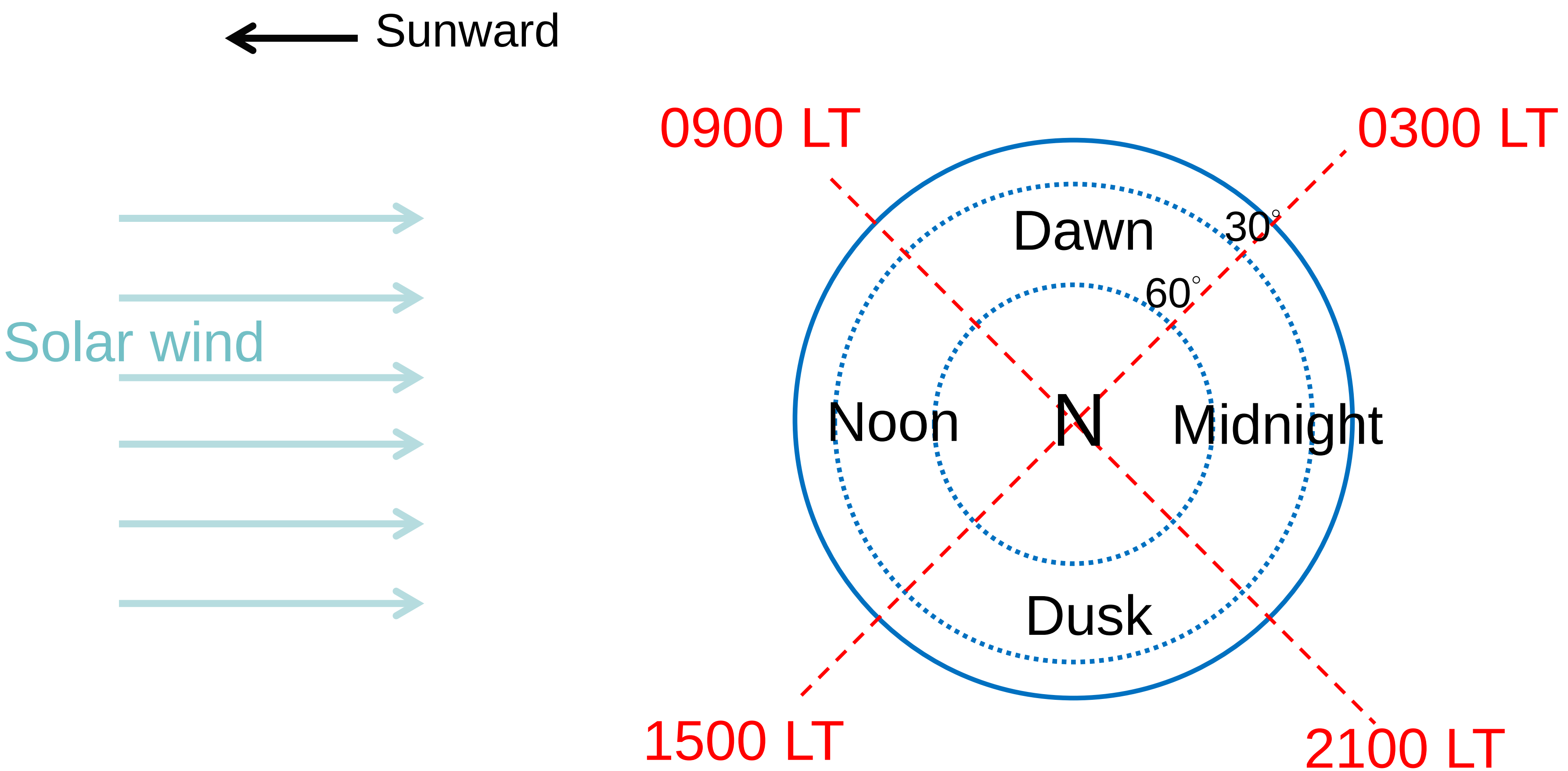


TEC (TECu)

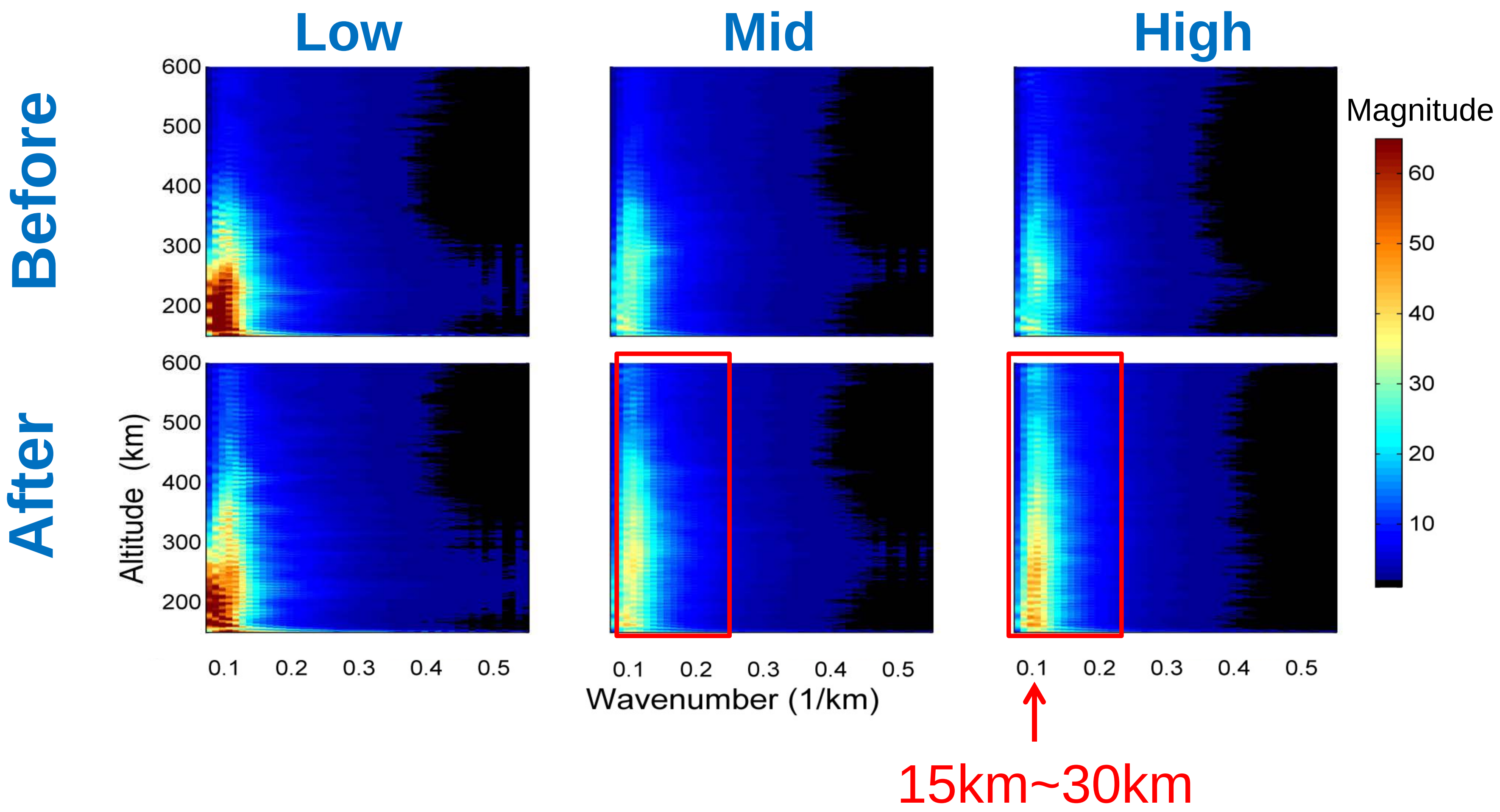
Mother wavelet- Morlet



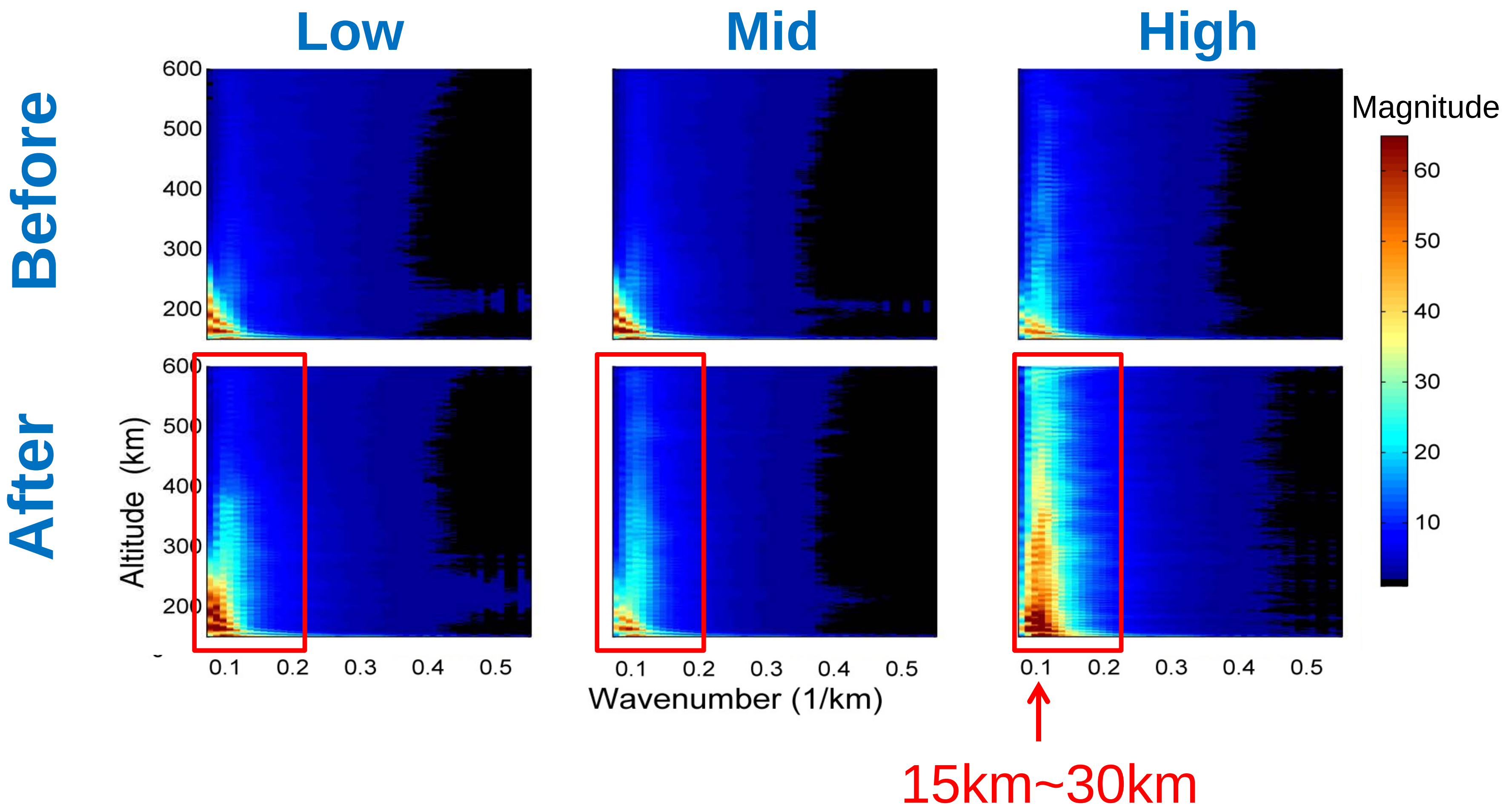
Wave number


Sunward
Solar wind
0900 LT
0300 LT
Dawn
30°
60°
Noon
N
Midnight
Dusk
1500 LT
2100 LT

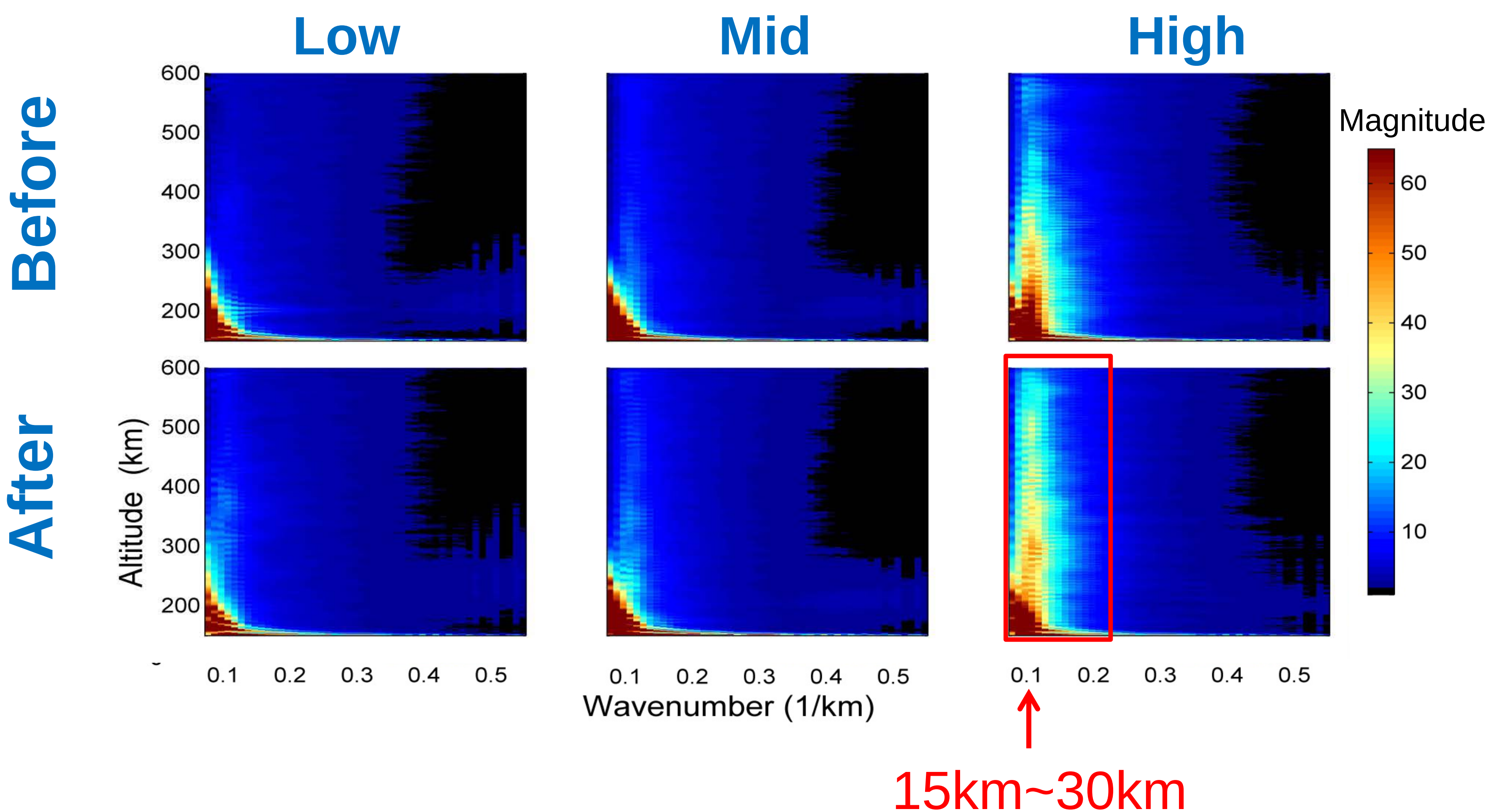
2010/05/02 TEC vertical fluctuation
Midnight side



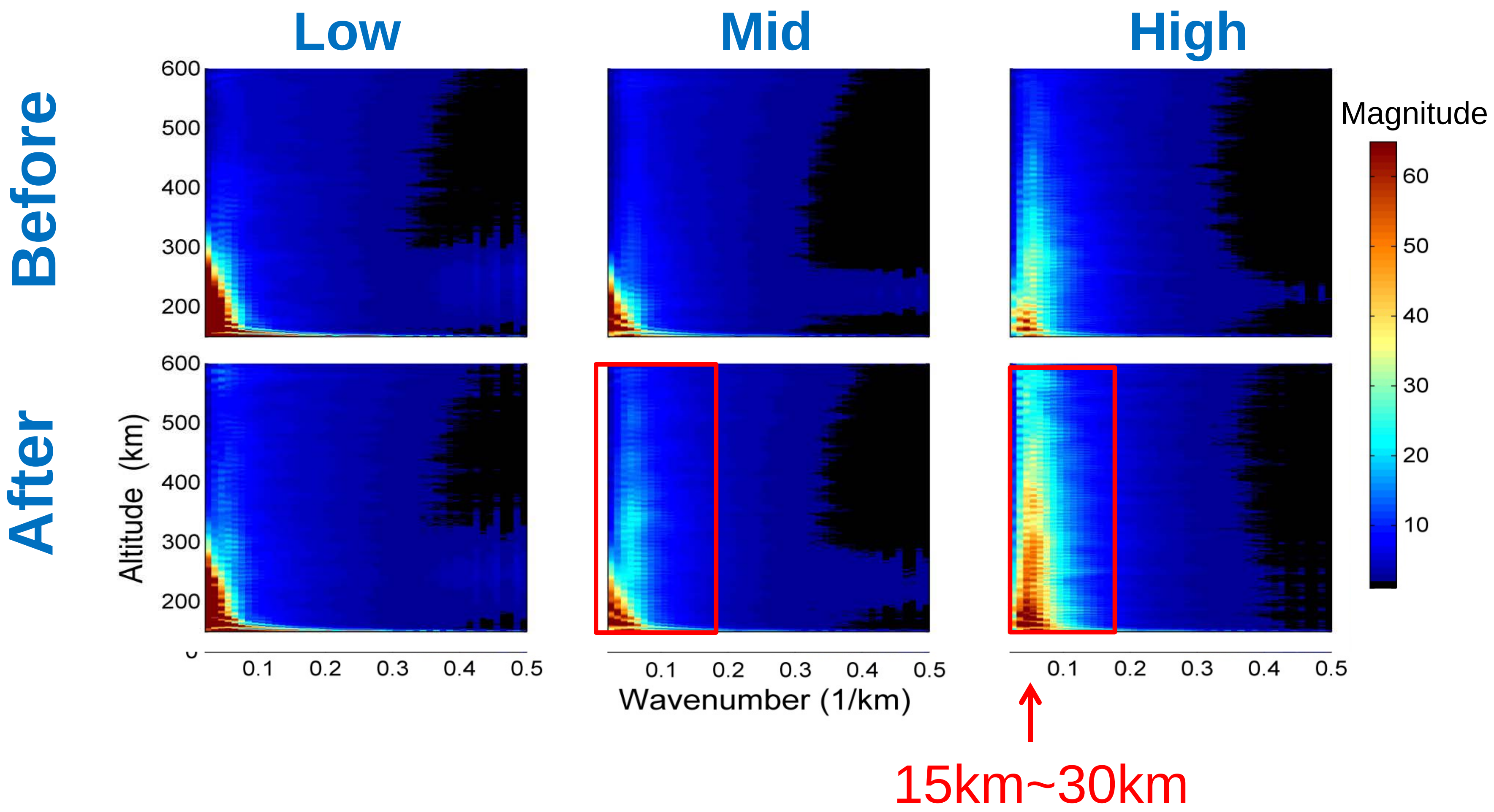
2010/05/02 TEC vertical fluctuation
Dawn side



2010/05/02 TEC vertical fluctuation
Noon side



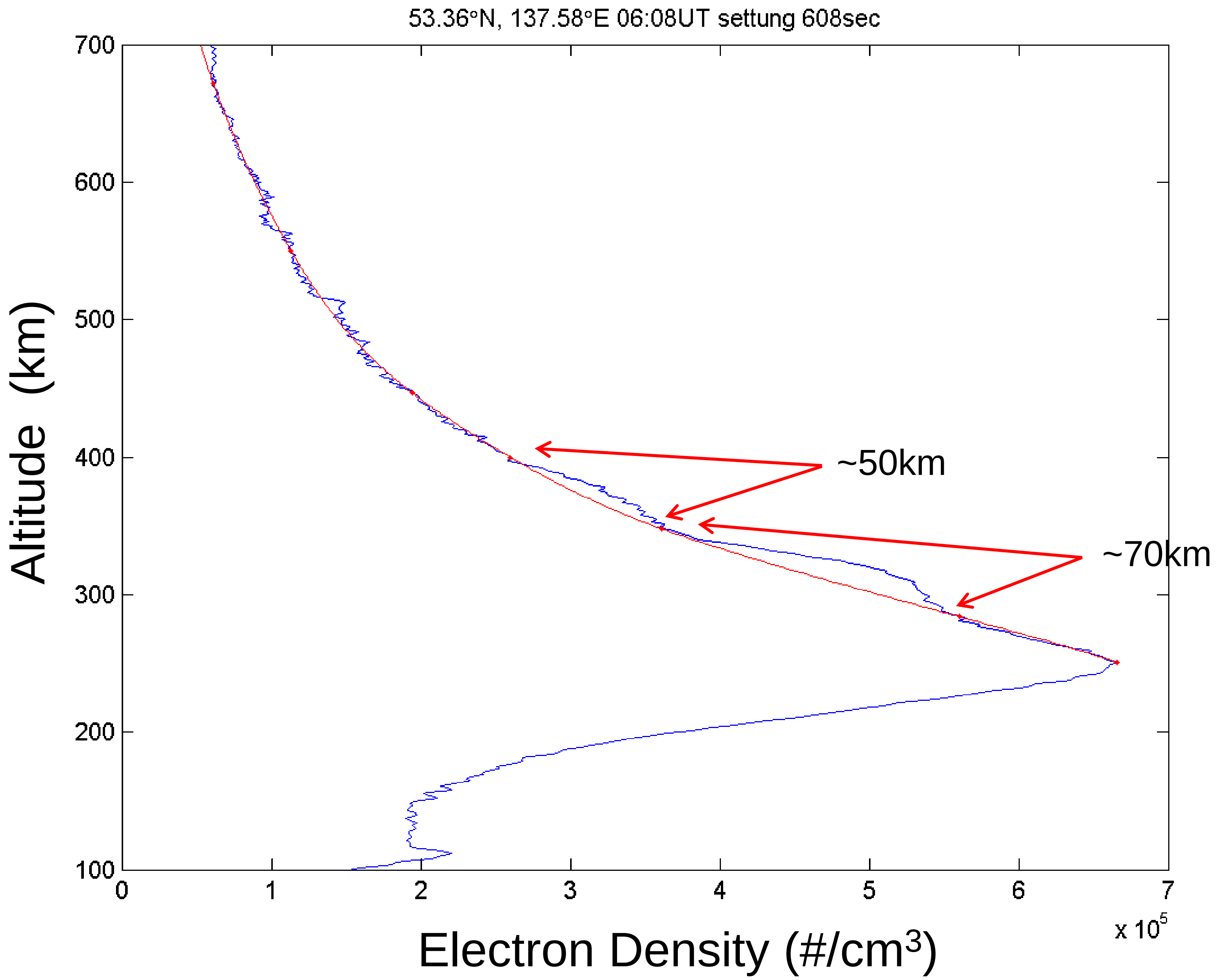
2010/05/02 TEC vertical fluctuation
Dusk side



Earthquake Details

This is a computer-generated message -- this event has not yet been reviewed by a seismologist.

Magnitude	8.9 9.0
Date-Time	**Friday, March 11, 2011 at 05:46:23 UTC** Friday, March 11, 2011 at 02:46:23 PM at epicenter Time of Earthquake in other Time Zones
Location	38.322°N, 142.369°E
Depth	24.4 km (15.2 miles) set by location program
Region	NEAR THE EAST COAST OF HONSHU, JAPAN
Distances	130 km (80 miles) E of **Sendai, Honshu, Japan** 178 km (110 miles) E of **Yamagata, Honshu, Japan** 178 km (110 miles) ENE of **Fukushima, Honshu, Japan** 373 km (231 miles) NE of **TOKYO, Japan**
Location Uncertainty	horizontal +/- 13.5 km (8.4 miles); depth fixed by location program
Parameters	NST=350, Nph=351, Dmin=416.3 km, Rmss=1.46 sec, Gp= 29°, M-type="moment" magnitude from initial P wave (tsuboi method) (Mi/Mwp), Version=A
Source	USGS NEIC (WDCS-D)
Event ID	usc0001xgp



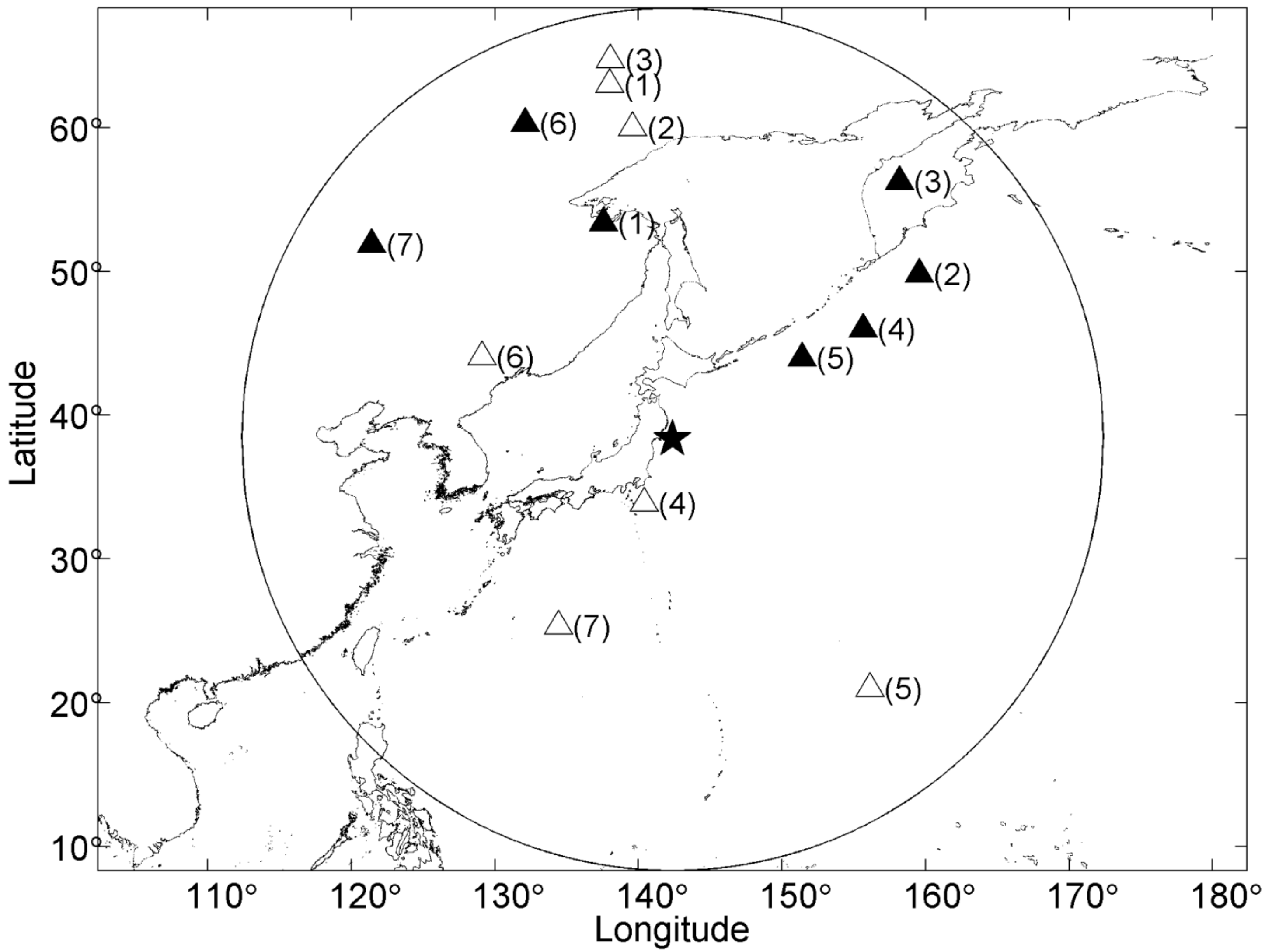
The electron density profile observed 22 minutes after earthquake.

Disturbances in F3/C electron density profiles during the 11 March 2013 Tohoku earthquake

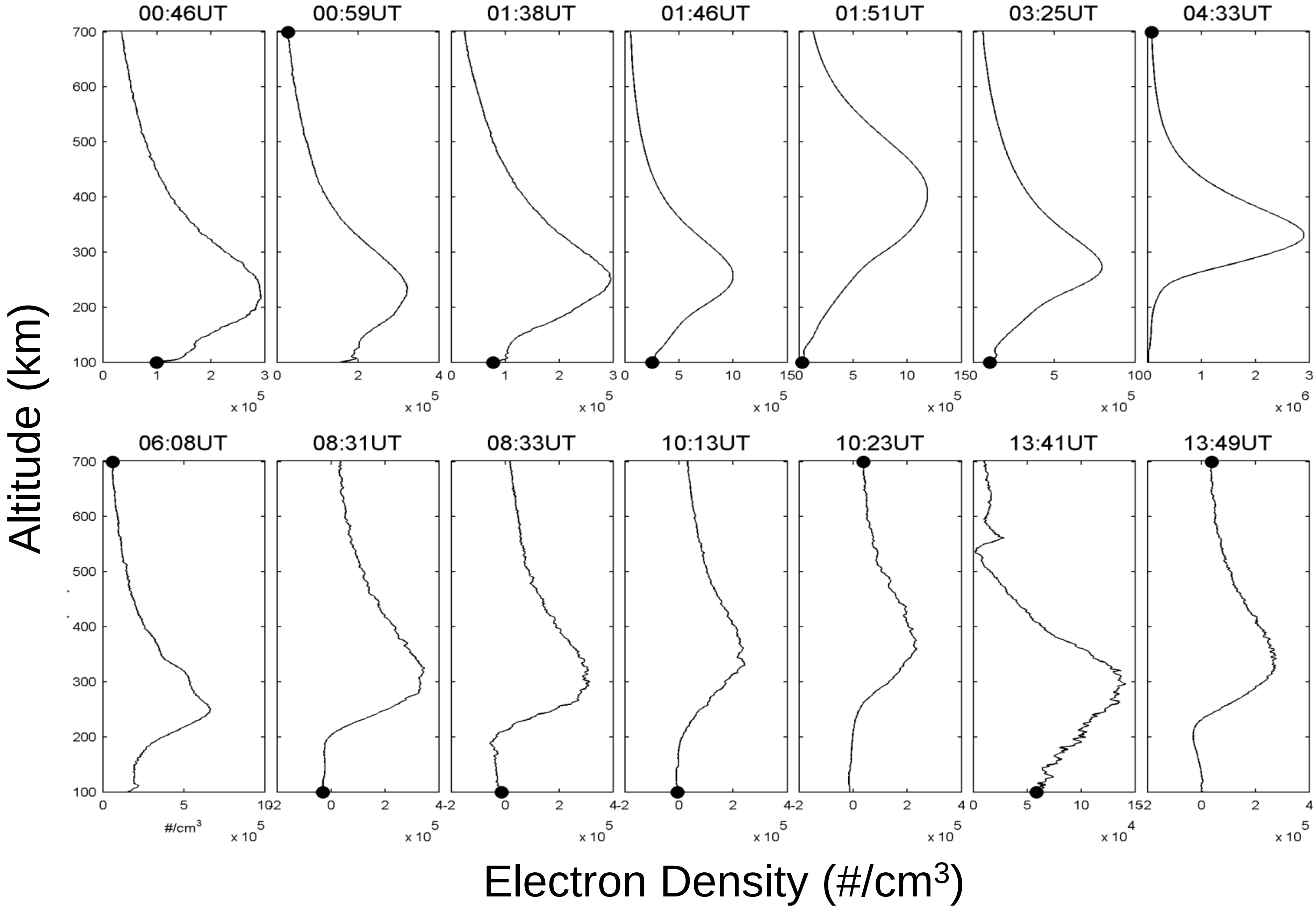
Table 1: Observation Points Near the Epicenter 0-8 hr after the Tohoku Earthquake

No.	Location	Arrival (UT)	Travel (second)	Distance (km)	Speed (m/sec)
	38.32°N, 142.37°E	05:46		Epicenter	
1	53.28°N, 137.36°E	06:08	1320	1581	2196
2	49.83°N, 159.58°E	08:31	9900	2072	223
3	56.26°N, 158.19°E	08:33	10020	2394	239
4	45.98°N, 155.66°E	10:13	16020	1535	100
5	43.99°N, 151.39°E	10:23	16620	1067	67
6	60.28°N, 132.12°E	13:41	27420	2425	87
7	51.86°N, 121.44°E	13:49	28980	2494	88

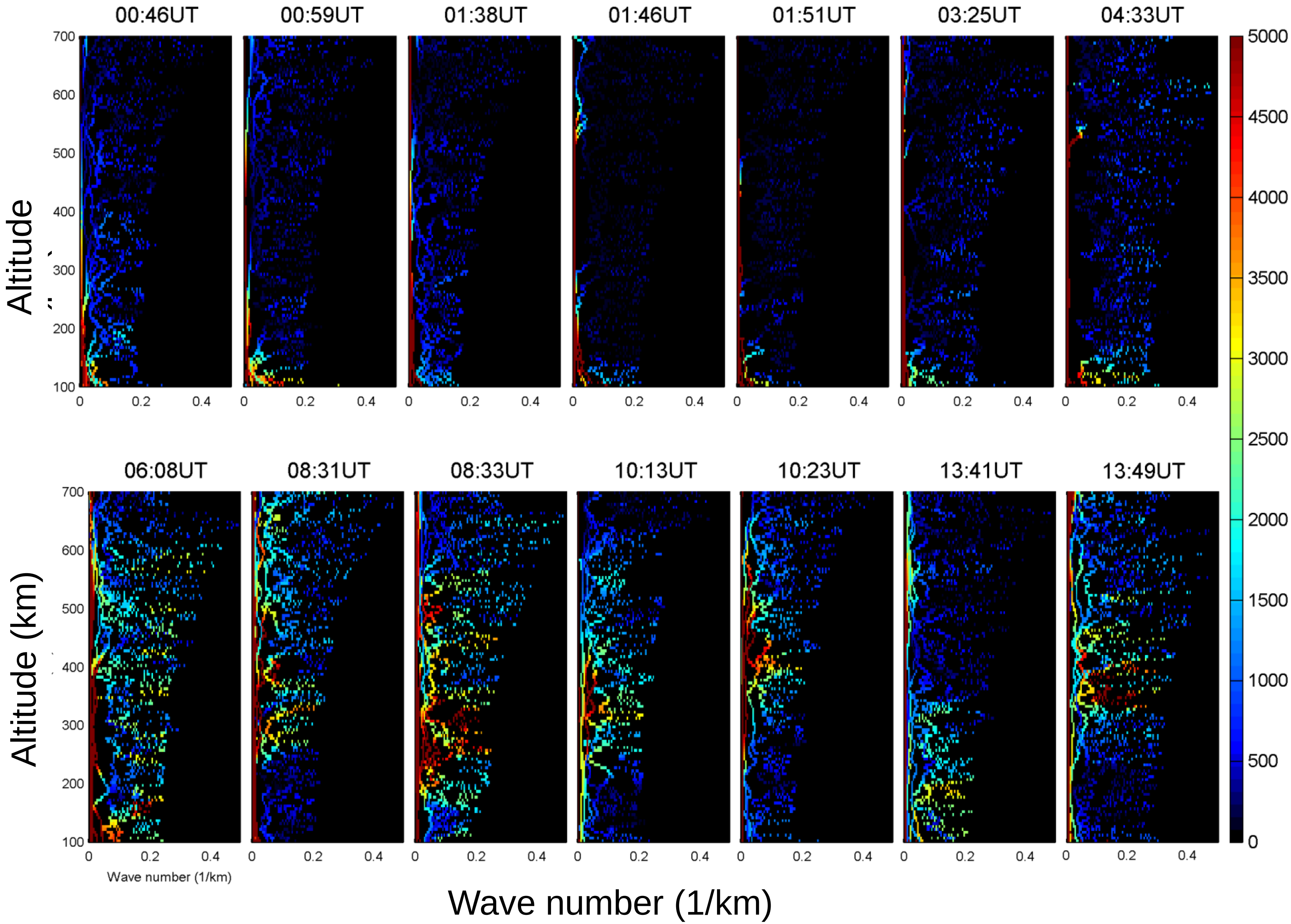
*speed=Distance/(Travel-600)



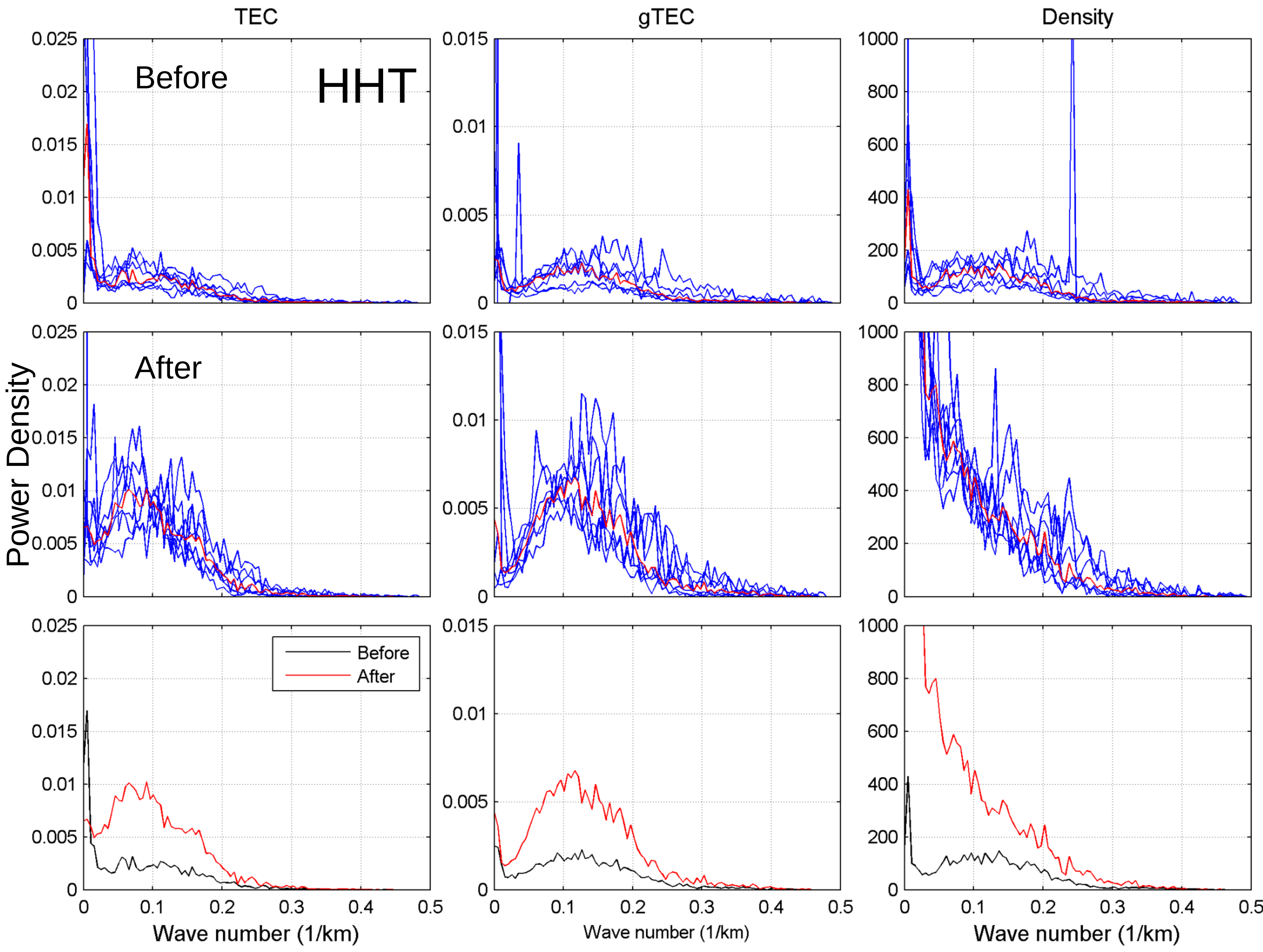
Electron density profiles observed by F3/C RO within 3000 km from the epicenter. The black circle Indicates 3000km from the epicenter. The star and triangle symbols denote locations of the epicenter and the profiles 1-8hours after the earthquake . The open triangle symbols denote locations of the profiles 1-5 hours before the earthquake.



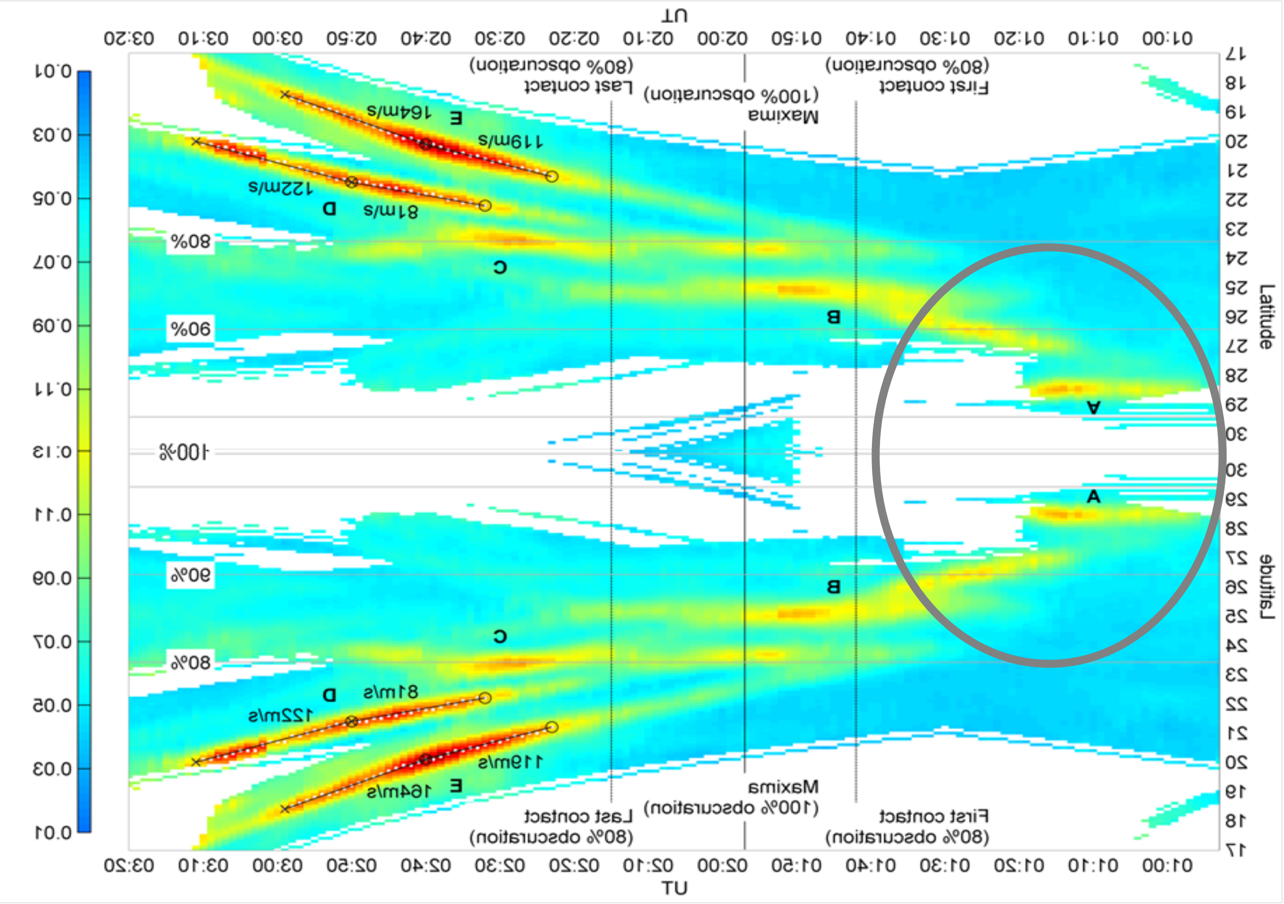
The electron density profiles 1-5hours before the earthquake (top panels), and those 1-8 hours after (bottom panels).



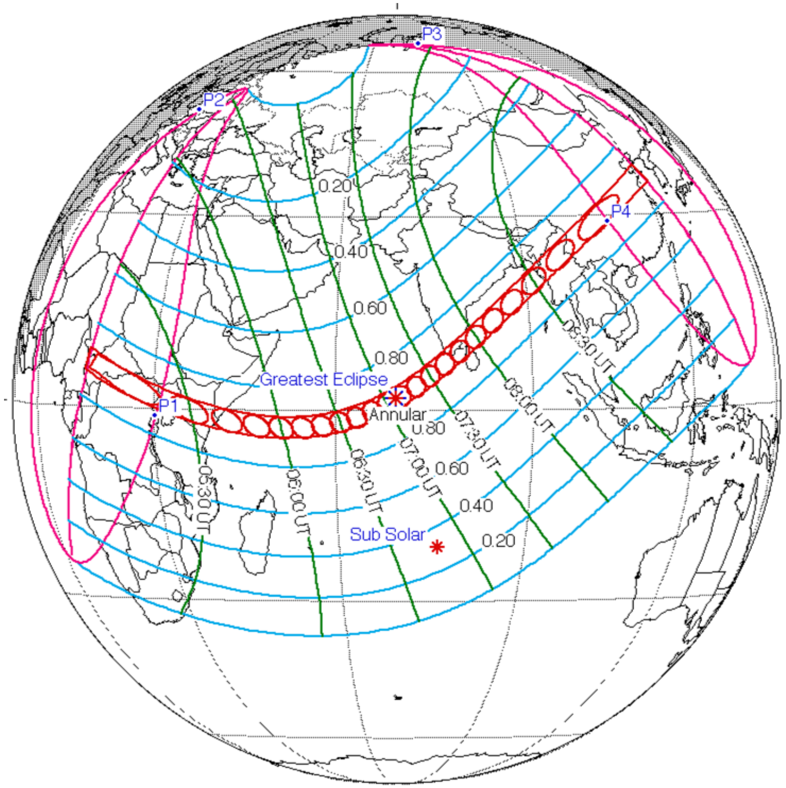
Spectra derived by using HHT.


TEC
gTEC
Density
Before
HHT
After
Power Density
Before
After
Wave number (1/km)
Wave number (1/km)
Wave number (1/km)

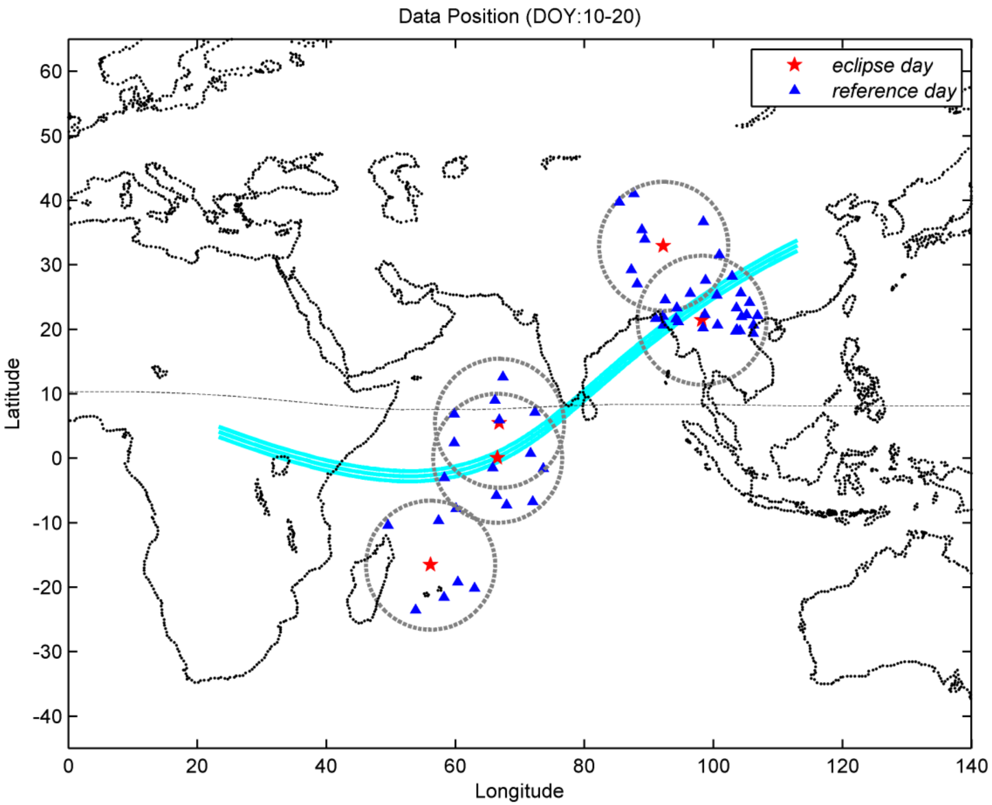
2010/01/15 Annual Solar Eclipse
(Ring of Fire)


UT
Latitude
First contact
(80% obscuration)
Maxima
(100% obscuration)
Last contact
(80% obscuration)
A
B
C
D
E
81m/s
122m/s
119m/s
164m/s
80%
90%
100%

2010/01/15 Annual Solar Eclipse (Ring of Fire)



(http://eclipse.gsfc.nasa.gov/eclipse.html, NASA)

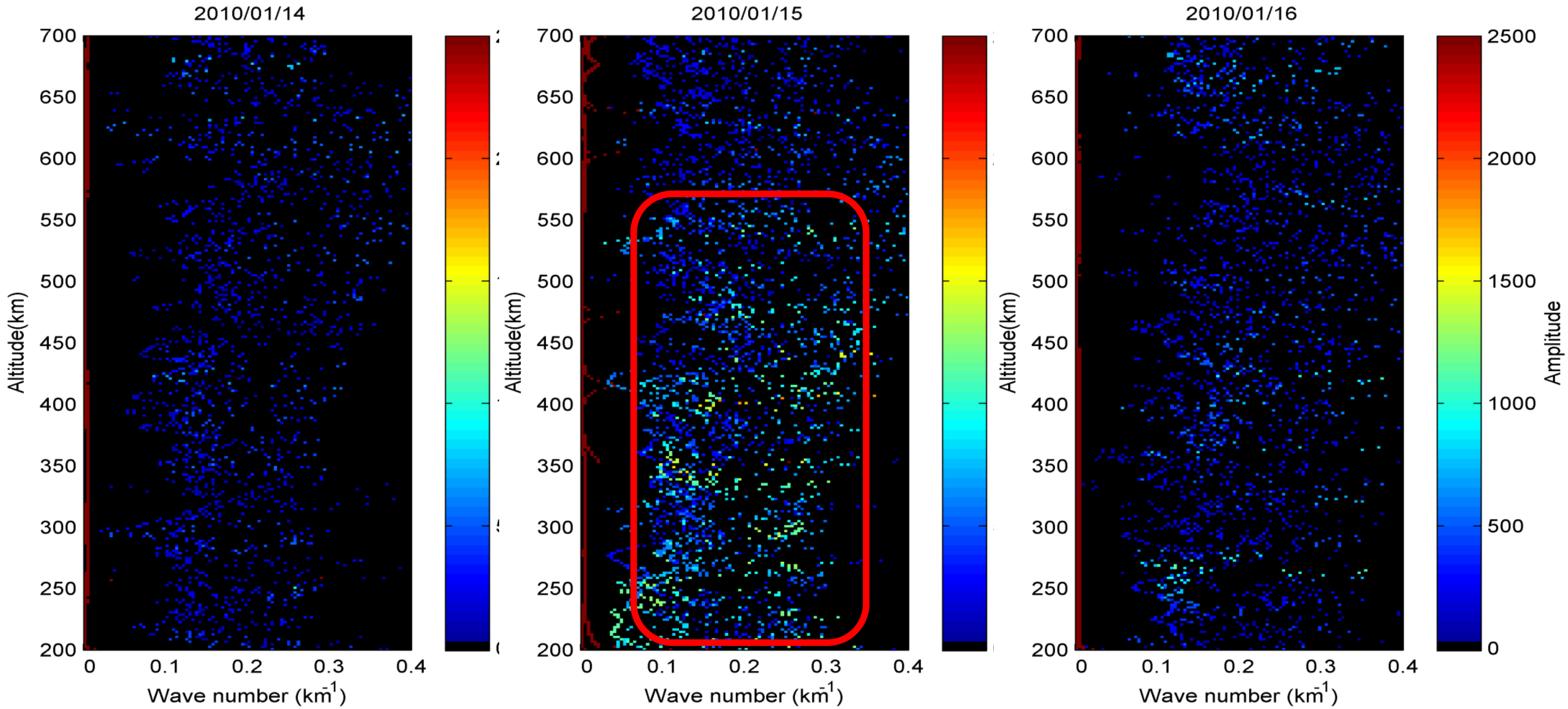


Eclipse period 05:18-08:55 UT

Observation zone: 5

Reference data point in each zone: 7/11/8/12/23

Day 1 Before Eclipse Day 2010/01/15 Day 1 After

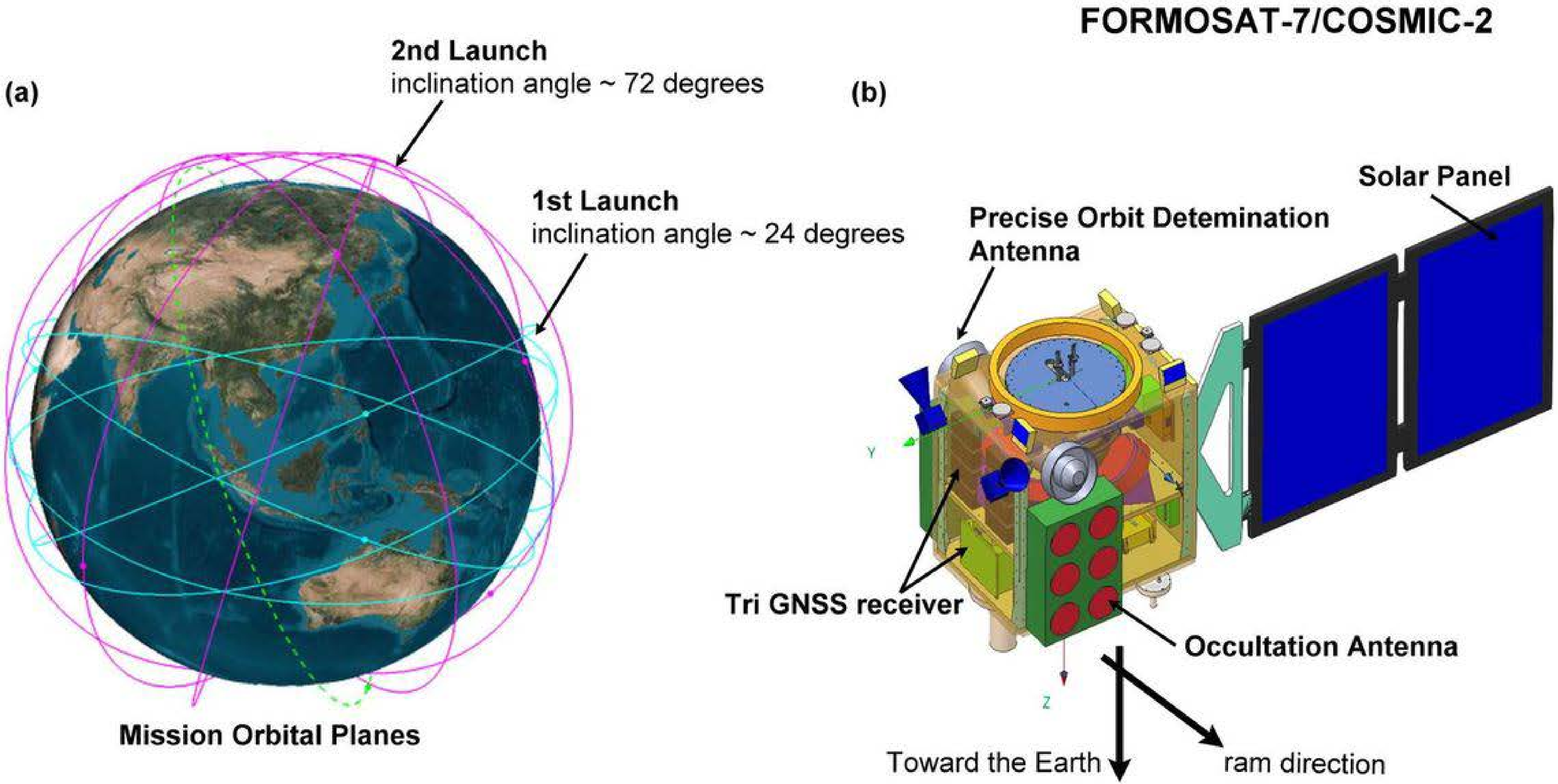


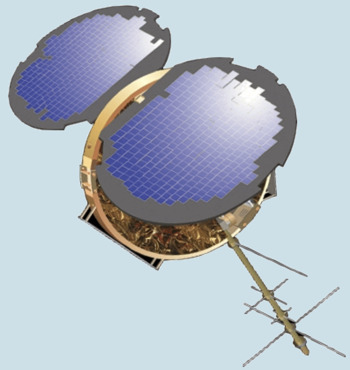
Power spectra on day 1 before, eclipse day 2010/01/15, and day 1 after.

Remark 5

- F7/C2 TriG RO sounding shall be a powerful tool observing disturbances of the lithosphere-ionosphere-solar wind coupling triggered by earthquakes, tsunami, volcano eruptions, typhoons, magnetic storms, solar eclipses, etc.

FORMOSAT-7/COSMIC-2

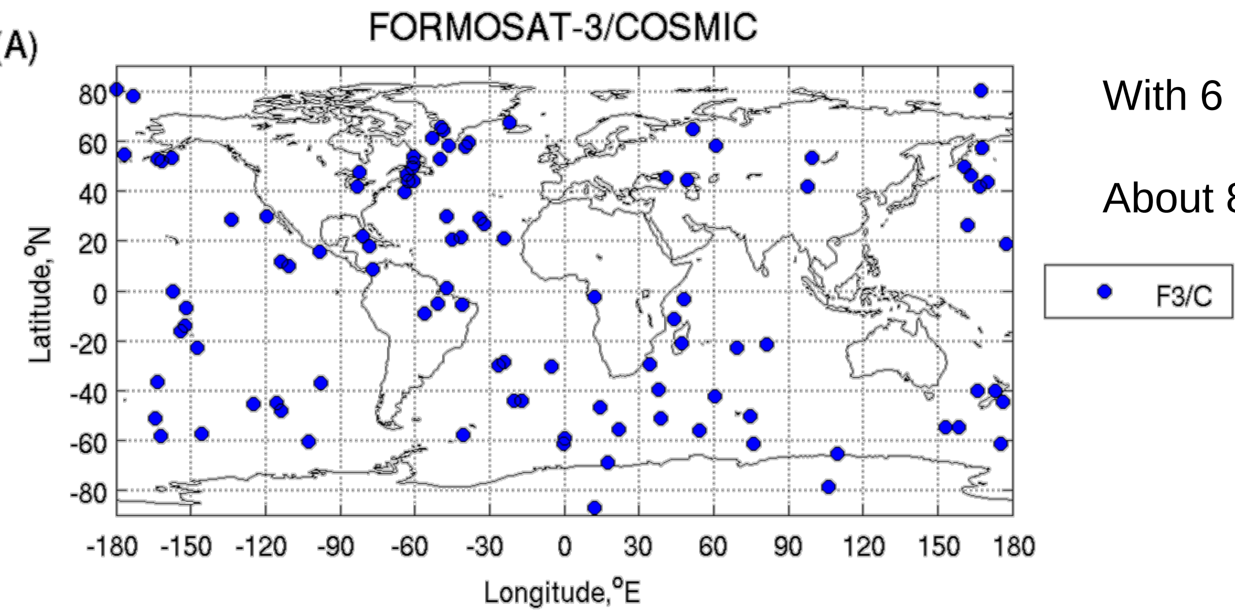


	FORMOSAT-3/COSMIC	FORMOSAT-7/COSMIC-2	
Exterior Design			
Sequence		1st Launch	2nd Launch
Constellation	6	6	6
Mission Orbit Altitude	800 km	520-550 km	720-750 km
Inclination Angle	72°	24-28.5°	72°
Mission Payload	GOX	TriG	
RO Signals	GPS	GPS, GLONASS, Galileo	
Launch Schedule	Launched in 2006	2016	2018

- Descriptions are provided by NSPO (http://www.nspo.org.tw).
- F7/C2 is illustrated by Surrey Satellite Technology LTD.

F7/C2 vs F3/C

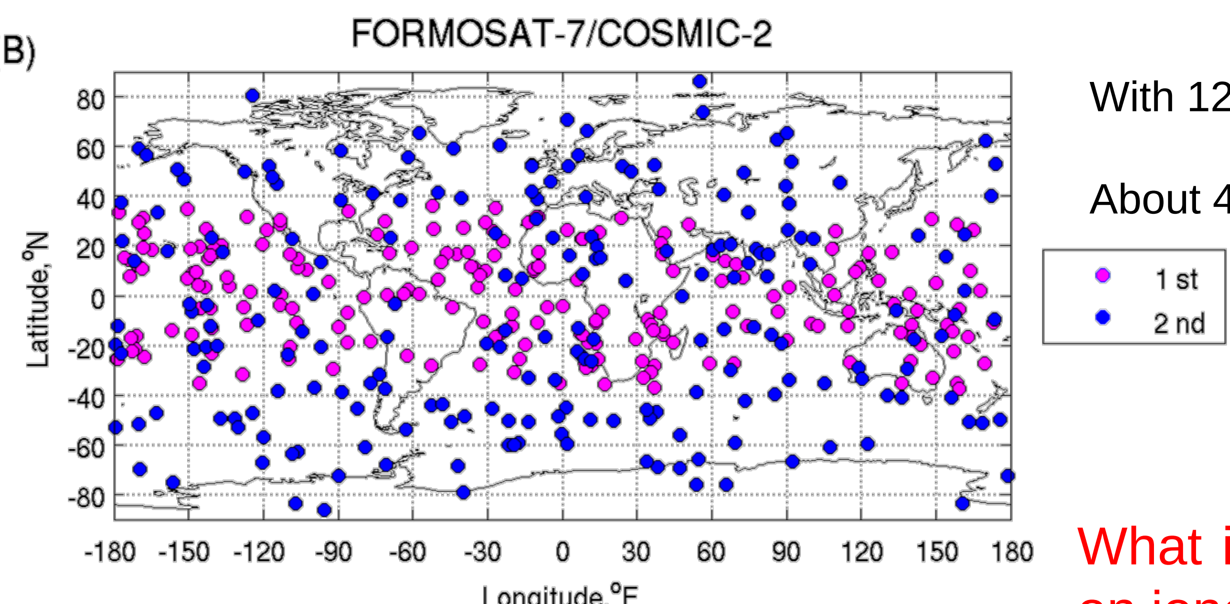
(A)



With 6 satellites + GPS, 60 minutes

About 80-100 profiles per hour

(B)

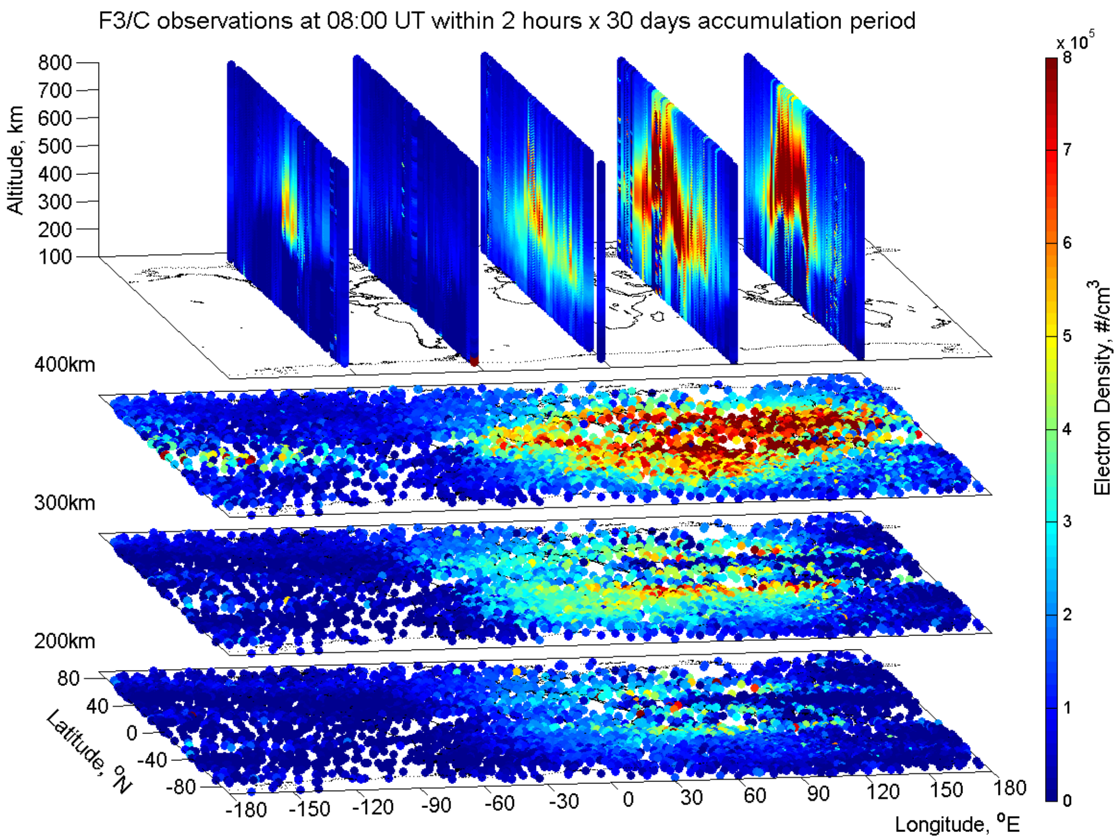


With 12 satellites + GPS, 60 minutes

About 400 profiles per hour

What is future impact of F7/C2 on ionospheric research?

Ionospheric Weather Monitoring



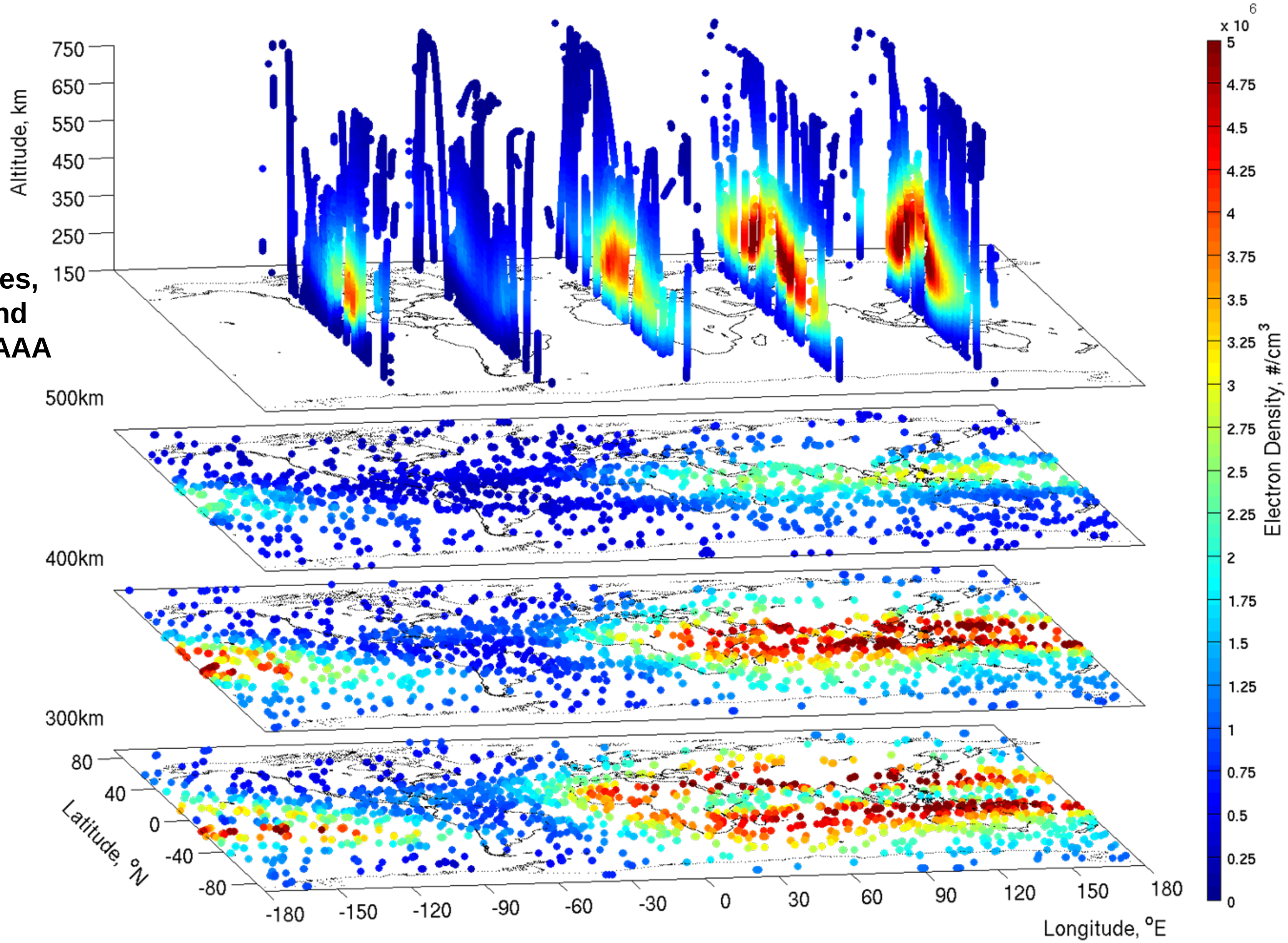
Latitudinal slices are at -120˚, -60˚, 0˚ 60˚ and 120˚ longitude with a interval of ±2.5˚.

- Solar activity variations
- Seasonal variations
- Monthly variations
- Tidal effects
- Diurnal variations
- Semi-diurnal variations
- Disturbed period effects
- Other temporal variations
- Irregularities

Could it be advanced by F7/C2 ?

Simulated F7/C2 observations at 08:00 UT within 1 hour x 1 day accumulation period

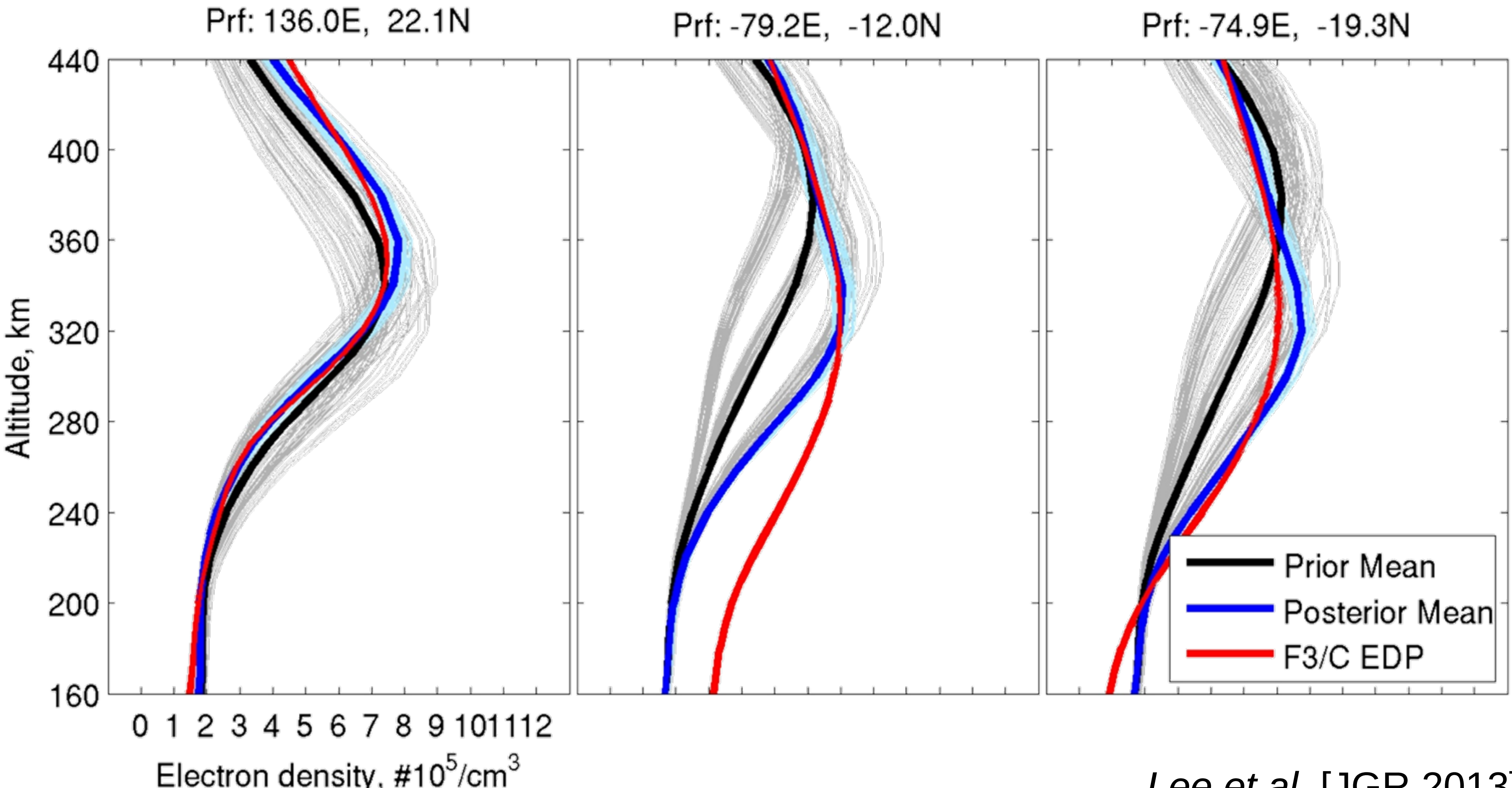
12 satellites,
28 GPS and
24 GLONAAA



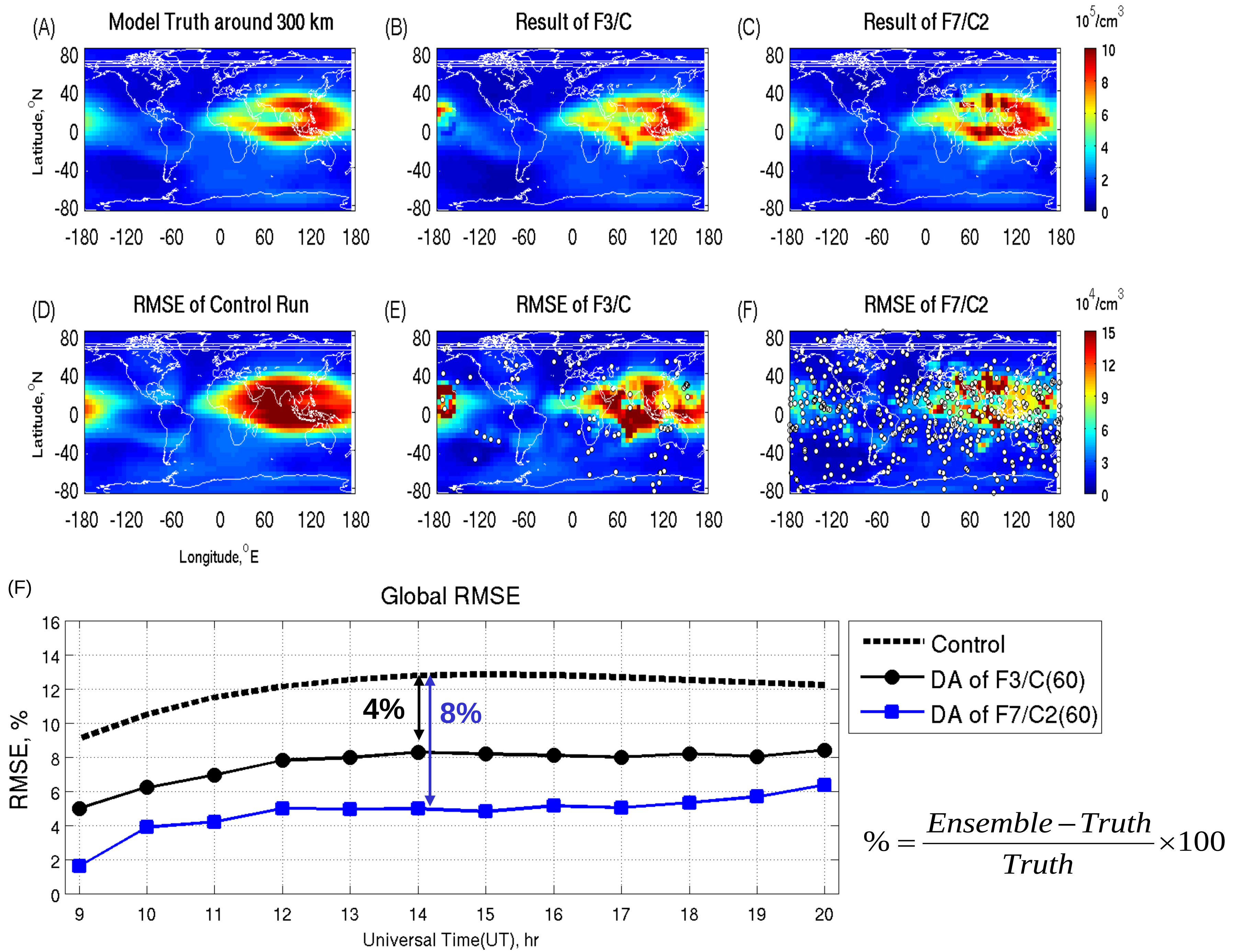
Lee et al. [2013]

Ionospheric Data Assimilation

TIE-GCM + F3/C EDPs + DART

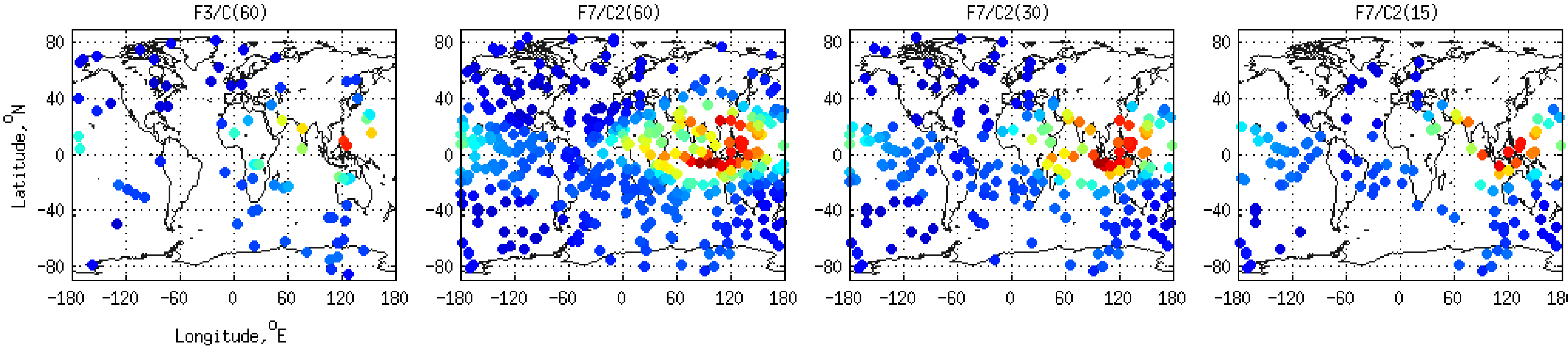


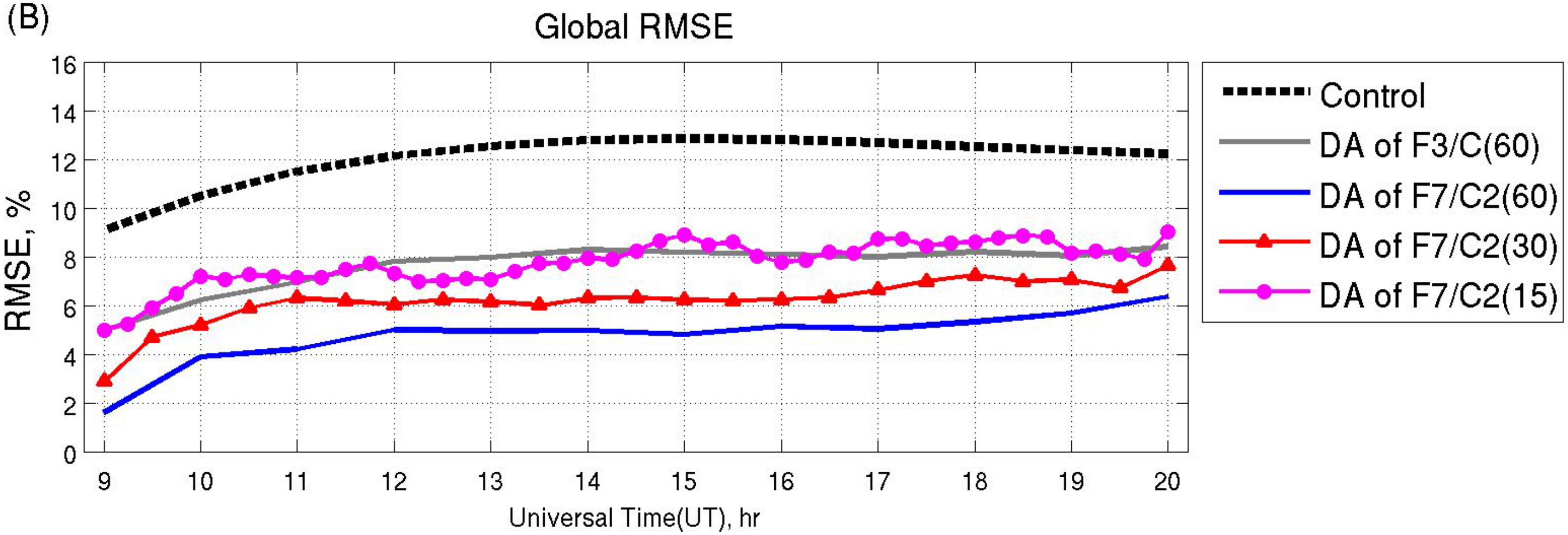
Lee et al. [JGR 2013]



(A)
Model Truth around 300 km
(B)
Result of F3/C
(C)
Result of F7/C2
10^5/cm^3
(D)
RMSE of Control Run
(E)
RMSE of F3/C
(F)
RMSE of F7/C2
10^4/cm^3
Latitude, °N
Longitude, °E
(F)
Global RMSE
Control
DA of F3/C(60)
DA of F7/C2(60)
4%
8%
RMSE, %
Universal Time(UT), hr
% = (Ensemble − Truth) / Truth × 100

Shorted assimilation window





Lee et al. [JGR 2013]

The F7/C2 data latency might not be less than 15 minutes for operational assimilation.

Conclusion

- FORMOSAT-7/COSMIC-2 could reconstruct 3D electron density structures for ionospheric space weather monitoring within a rather short data accumulation period.
- F7/C2 comparing to F3/C could yield reliable results within an assimilation window of less than 30 minutes.
- F7/C2 shall have significant impacts on ionospheric weather monitoring and researches.

Thank you