F_2 region response to meteorological phenomena and geomagnetic disturbances: O (^{1}S) dayglow as a proxy to thermospheric dynamics

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OUTLINE

- Introduction
- F2 region response to geomagnetic disturbances
- F2 region response to meteorological phenomena
- F2 region response to earthquake events

Objective:

F2 region response to geomagnetic disturbances across Indian latitudes: O(^{1}S) dayglow as a proxy to thermospheric dynamics

Upadhayaya, A. K., S. Gupta, and P. S. Brahmanandam (2016), F2 region response to geomagnetic disturbances across Indian latitudes: O (^{1}S) dayglow emission, ***J. Geophys. Res. Space Physics***, *121, doi:10.1002/2015JA021366*

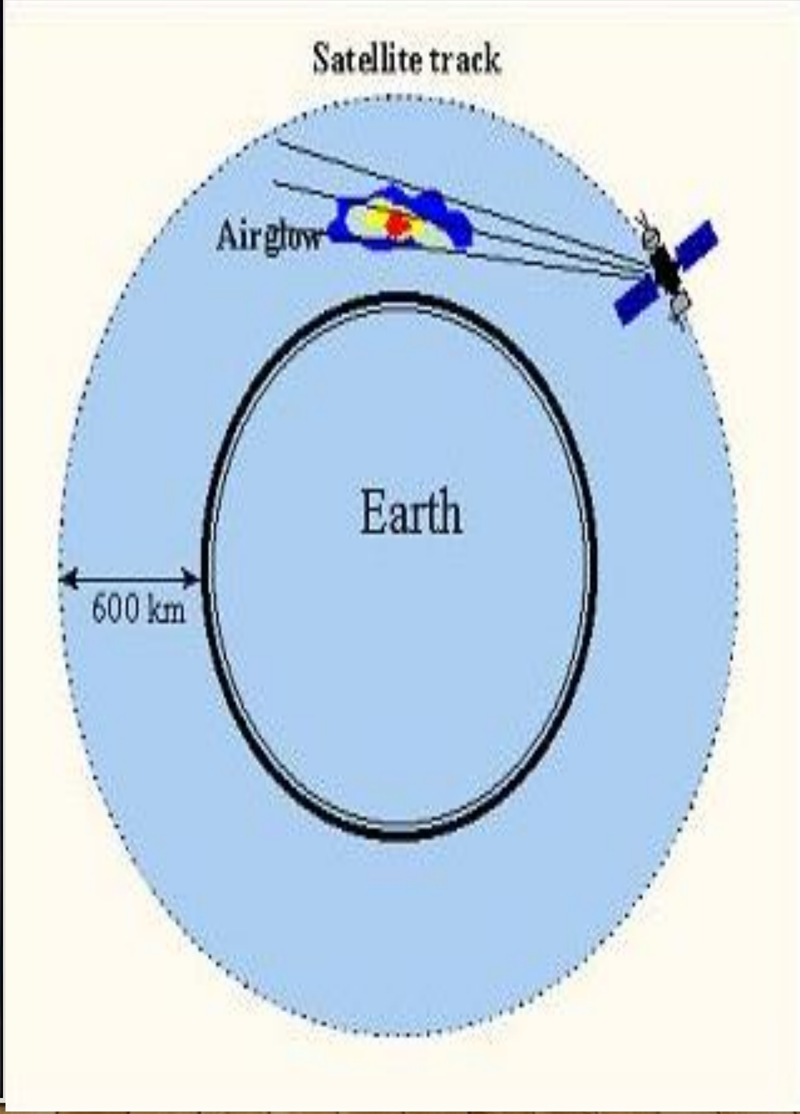
Introduction

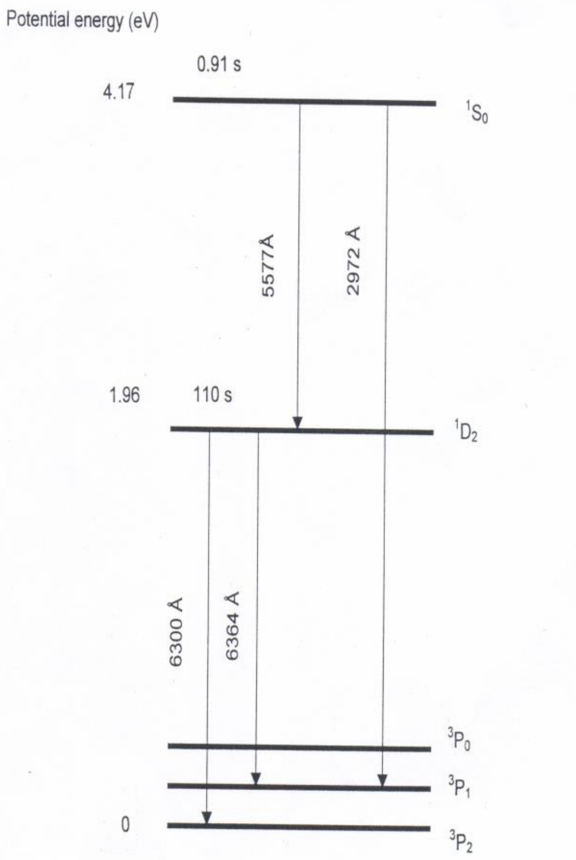
➢The responses of the upper atmosphere to geomagnetic activity have been studied for a long period of time to the present, using experimental techniques as well as theoretical models. Many reviews on this topic cover the subject in details (e.g., Abdu, 1997; Fuller-Rowell et al., 1997; Rees, 1996; Schunk and Sojka, 1996; Buonsanto, 1999, Danilov and Lastoviˇcka 2001; Kelley et al., 2011, Balan et al., 2011)..

➢ It is quite often seen that the normal ionospheric variability (which cannot be associated with an event) is at times even larger than the variability due to a transient (solar storm) or meteorological event. A good part of this unanswered reason for the variability could perhaps be related to possible changes in the neutral composition in thermosphere. While there are daily indices like F10.7 and Ap or Kp for solar ionizing radiation and magnetic activity respectively, there are none to represent daily changes in neutral atmosphere and electrodynamics. Briefly, this seems to be a major reason for the inability to explain the day-to-day and hour-to- hour variability seen in ionospheric F2- layer.

➢In the present study an attempt is made to examine the response of equatorial and low latitudes F-region ionospheric parameters (foF2 and h'F) during the disturbed periods of geomagnetic storms and to investigate the response of green line dayglow emission under quiet and strong geomagnetic conditions.

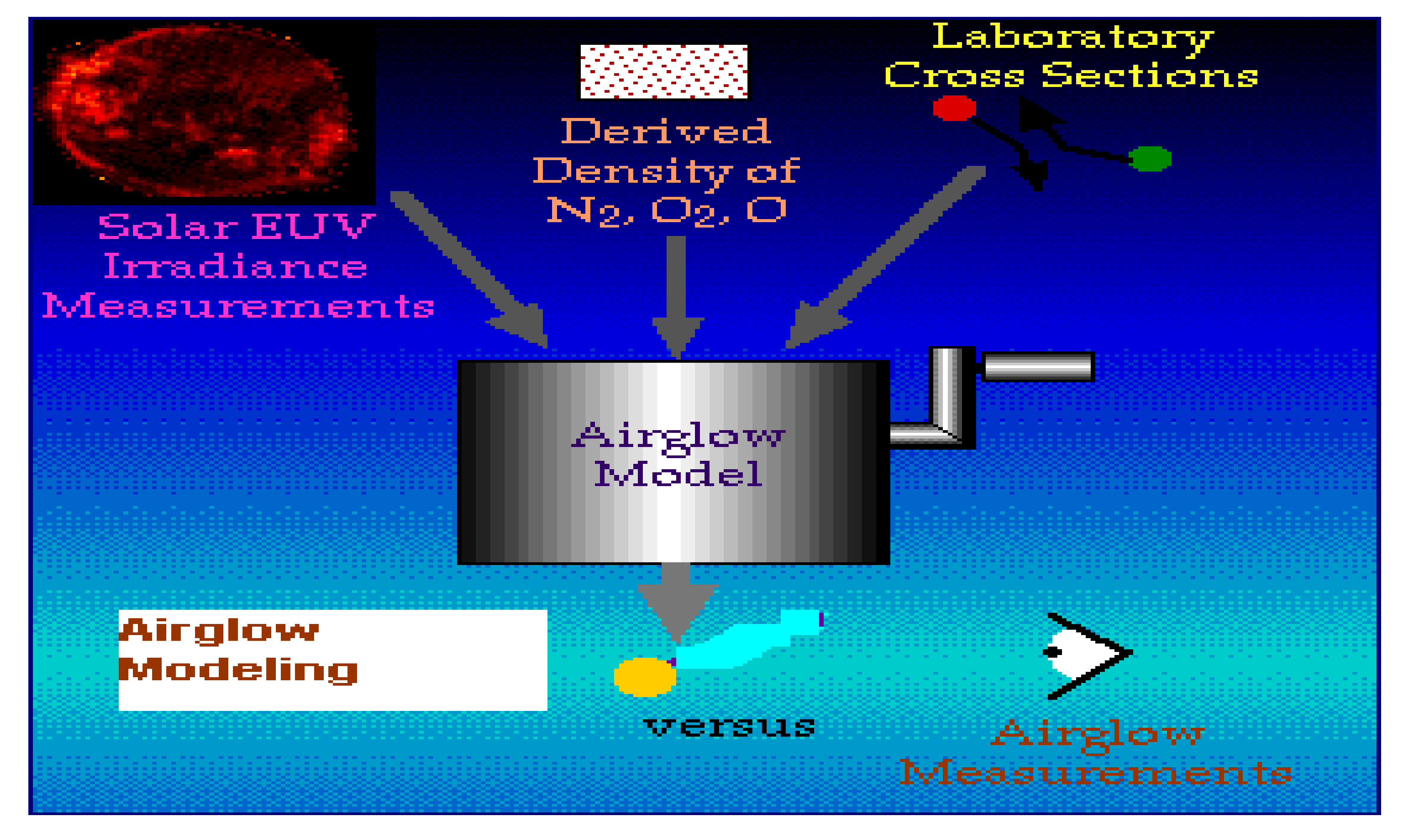
O(^{1}S) dayglow emission





The energy level diagram of atomic oxygen for 5577Å (O(^{1}S)) and 6300Å (O(^{1}D)) emissions.

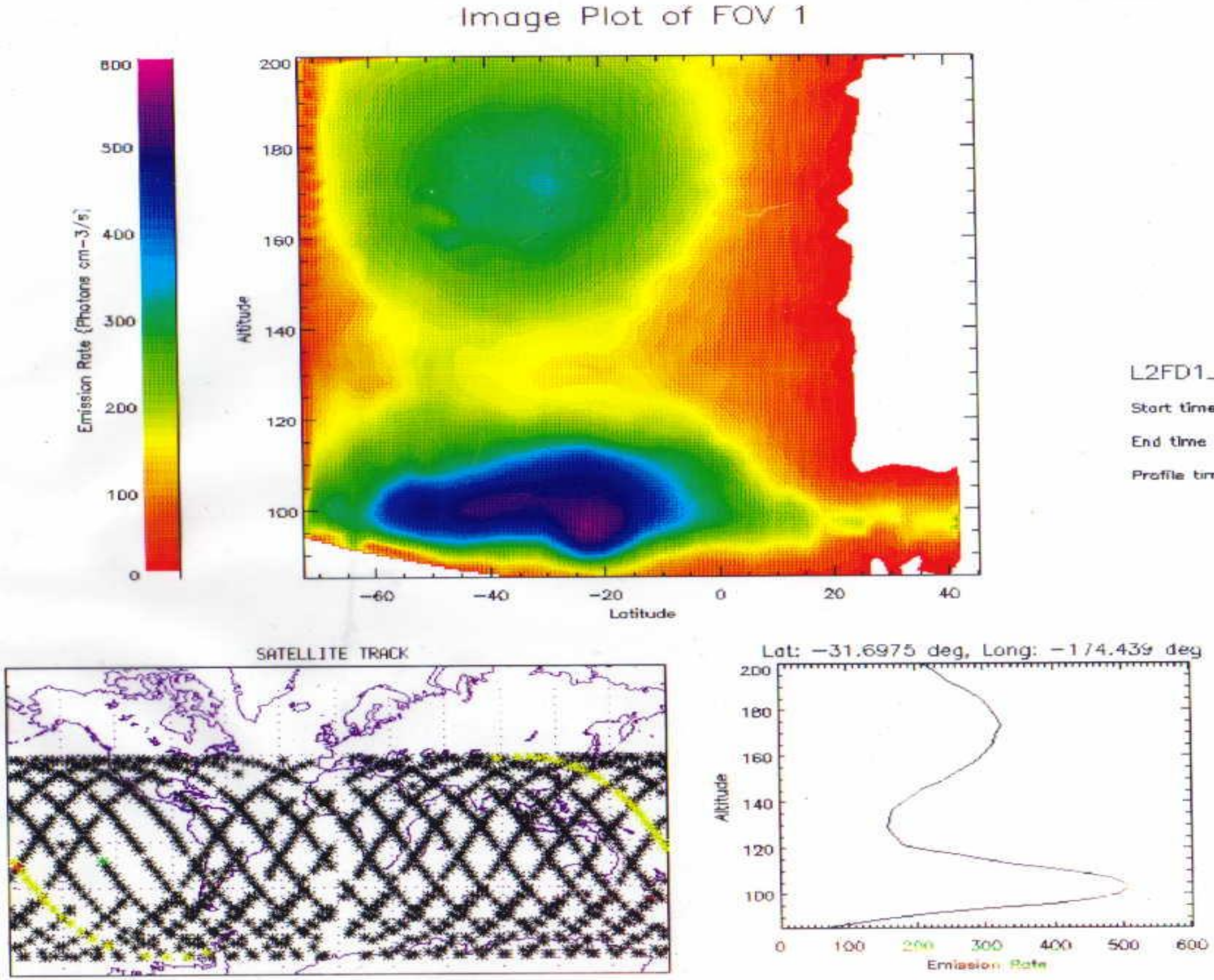
Modeling O(^{1}S) dayglow emission :



NRLMSISE-00 [Picone et al., 2002] &
IRI-2007 [Blitza and Reinisch, 2008] models are used for neutral atmosphere and electron density

HEUVAC solar flux model (Richard et al., 2006)

Ap = 20 (quiet) and Ap=200(strong) geomagnetic condition.
F10.7=130 (fixed)
Common solar ionizing condition for estimating VER.



L2FD1_0206.CDF;1

Start time :	04-APR-1992 19:36:17
End time :	04-APR-1992 20:28:56
Profile time:	04-APR-1992 20:10:37

Model: O(^{1}S) Emission

Production Processes

1. *Dissociative recombination*

$O_2^+ + e \rightarrow O(^1S) + O$

The production rate of O (^{1}S) due to this reaction is given by $R_{DR}[O(^1S)] = \beta_1 K_1 [O_2^+][e]$, where, β_1 and K_1 represents the quantum yield and reaction rate coefficient of the reaction, e represents an electron.

2. *Collisional deactivation of $N_2(A^3\Sigma_u^+)$*

$N_2 + ep_h \rightarrow N_2(A^3\Sigma_u^+)$, followed by reaction $N_2(A^3\Sigma_u^+) + O \rightarrow O(^1S) + N_2$

The production rate of O (^{1}S) due to the photoelectron impact on molecular nitrogen is calculated from, $R[N_2(A^3\Sigma_u^+)] = [N_2]\int_{E_{th}}^{\infty} \varphi(E_s, z, \alpha)\sigma_{N2A}(E_s)dE_s$, where $[N_2]$ is the density of molecular nitrogen, $\varphi(E_s,z,\alpha)$ is the photoelectron flux which is a function of photoelectron energy E_s at altitude z and solar zenith angle α, and $\sigma_{N2A}(E_s)$ is the effective excitation cross section for $N_2(A^3\Sigma_u^+)$ production. The production rate of O(^{1}S) emission due to energy transfer from $N_2(A^3\Sigma_u^+)$ from the subsequent reaction is given by, $R_{N2A}[O(^1S)] = \beta_2 K_2[N_2(A^3\Sigma_u^+)][O]$, where, β2 and K2 represents the quantum yield and reaction rate coefficient of the reaction.

3. *Photoelectron excitation*

$O + eph \rightarrow O(^1S) + eph$

The production rate of O (1S) due to this reaction is calculated using the expression $R_{ph}[O(1S)] = [O]\int_{E_{th}}^{\infty} \varphi(E_s, z, \alpha)\sigma_{O1S}(E_s)dE_s$ where $R_{ph}(O(^1S))$ is the production of O(^{1}S) due to photoelectron impact excitation , [O] is the density of atomic oxygen, $\varphi(E_s,z,\alpha)$ is the photoelectron flux which is a function of photoelectron energy E_s at altitude z and solar zenith angle α and $\sigma_{O1S}(E_s)$ is the electron excitation cross section of O(^{1}S) state.

4. *Photodissociation of O2 molecules*

$O_2 + h\vartheta(< 1332.5\ A^\circ) \rightarrow O + O(1S)$

The production rate of O(^{1}S) due to this reaction is $R_{pd}[O(1S)] = [O_2]\int F_{(h\ \lambda)}Q_\lambda\sigma_\lambda d\lambda$ where $[O_2]$ represents density of molecular oxygen, $F_{(h\ \lambda)}$ represents solar flux at altitude h for wavelength λ, Q_λ is the quantum yield at fixed wavelength λ and σ_λ is photo absorption cross section of molecular oxygen.

5. *The three bodu recombination reaction*

$O + O + M \xrightarrow{\gamma k_5} O_2^* + M$, followed by $O_2^* + O \rightarrow O(^1S) + O_2$

γ, k represent the quantum yield and reaction rate coefficients of the reaction and O_2^* represents the excited state of molecular oxygen. $R_{TH}(O(^1S))$ represents production due to three body reaction. The total production rate $R_{TOT}[O(^1S)]$ of O(^{1}S) due to all these reactions is given by,

$R_{TOT}[O(^1S)] = R_{DR}(O(^1S)) + R_{N2A}(O(^1S)) + R_{ph}(O(^1S)) + R_{pd}(O(^1S)) + R_{TH}(O(^1S))$

The first three reactions are primarily responsible for the thermospheric peak (at an altitude of ~ 160 km) whereas the last two reactions are responsible for the mesospheric peak (~ 96 km) of the greenline dayglow emission.

Loss Processes

$O(^1S) + (O_2, O) \xrightarrow{K_7, K_8} O(^3P) + (O_2, O)$

$O(^1S) \xrightarrow{A_8} O(^1D) + h\nu(557.7\ nm)$

$O(^1S) \xrightarrow{A_9} O(^3P, ^1D) + h\nu(total)$

The quenching factor is given by $Q_s = \dfrac{A_7}{(A_9 + K_7[O_2] + K_8[O])}$

where [Z] denotes the number density of the corresponding species Z, A_8 and A_9 are the Einstein's coefficients; and K_7, K_8 are the rate coefficients for the reactions. The total volume emission rate of O (^{1}S) is obtained by following equation:

$$VER\ [O(^1S)] = Q_S \cdot R_{TOT}[O(^1S)]$$

Summary of magnetic storm events studied

Year	Month	Begin Day	SSC* (EMT(EMT=UT+5)	Minimum Dst (nT)
2001	04	11	1843	-271
2001	11	24	1000	-221
2001	10	1	0025	-148
2003	11	20	1700	-422
2006	04	14	0800	-98

*Storm sudden commencement

O/N_2 ratio is measured from GUVI instrument on TIMED satellite.

Intensity variation for $O(^1S)$ dayglow emission (557.7 nm) is simulated using GLOW model.

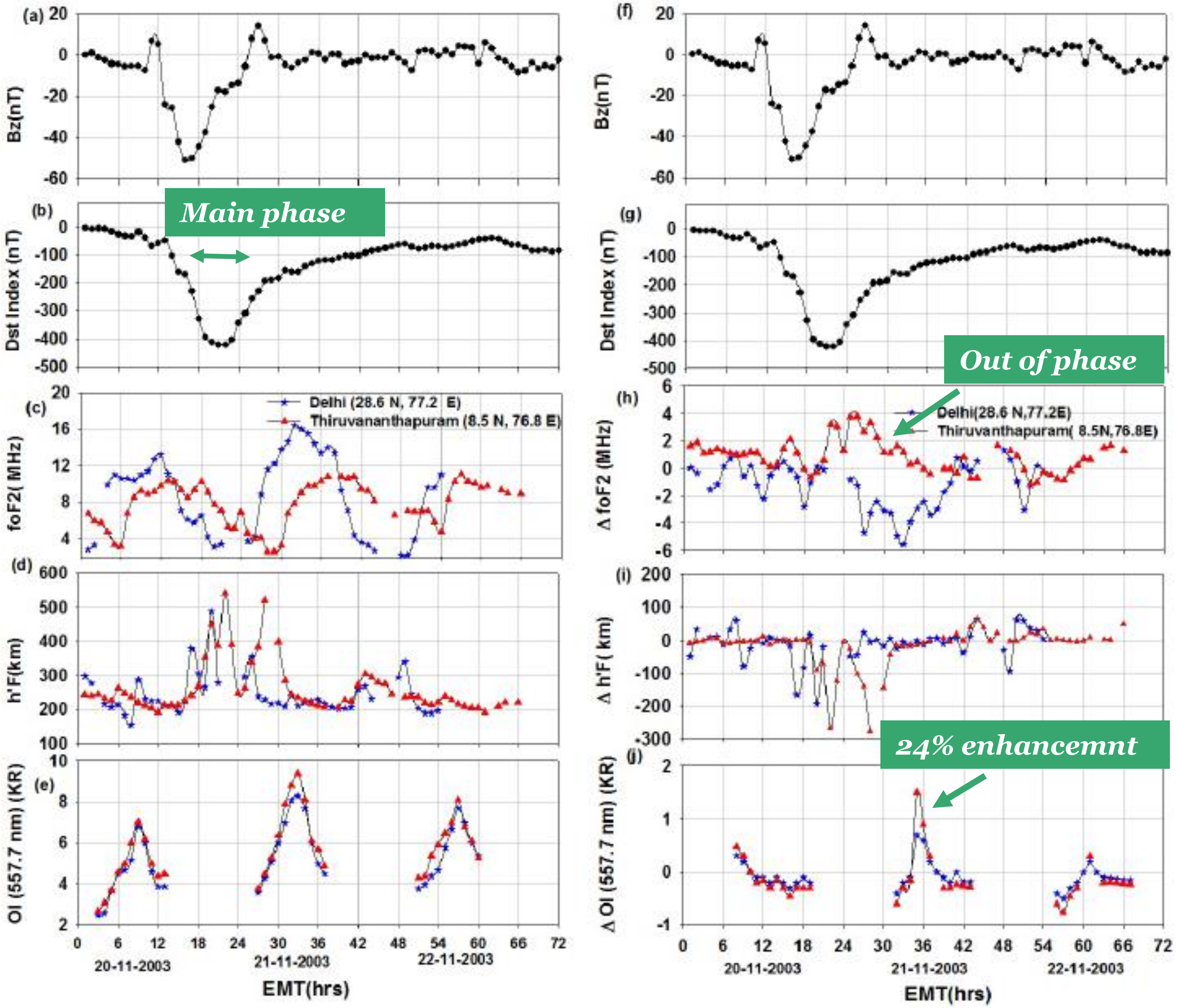
Ionosonde and IRI model are used to obtain ionospheric parameters for equatorial and low latitude stations.

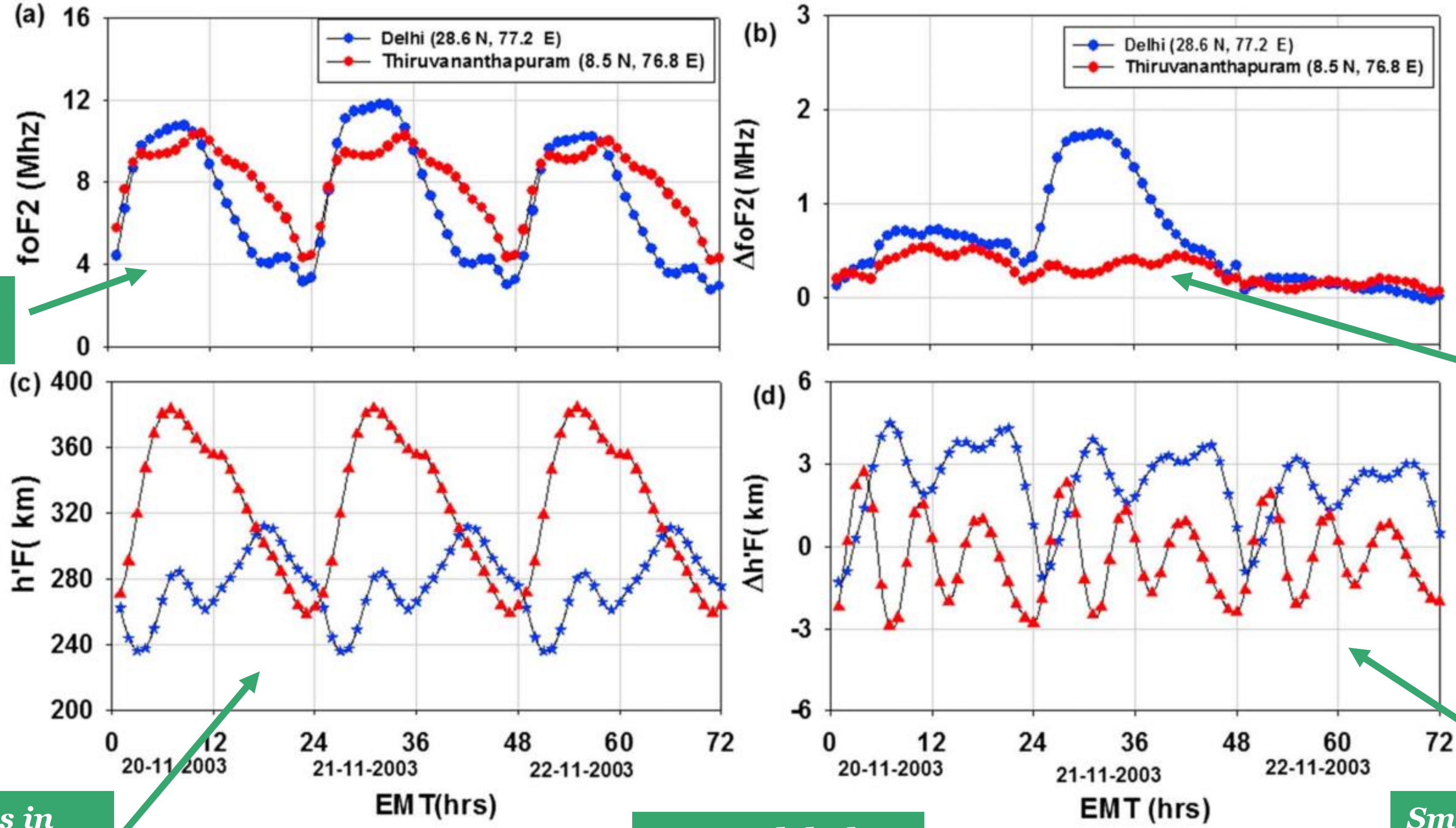
Station	Geographic Latitude	Geographic Longitude
Thiruvanthanapuram	8.5 °N	76.8 °E
Delhi	28.6 °N	77.2 °E

1. 20th – 22nd Nov 2003

International Quiet days (IQD)
(http://www.ga.gov.au/oracle/geomag/iqd_ form.jsp)

- Maximum deviation in foF2 during recovery phase.
- h’F variation shows large increase during main phase.
- Modelled greenline dayglow intensities show increase during main phase of the storm.





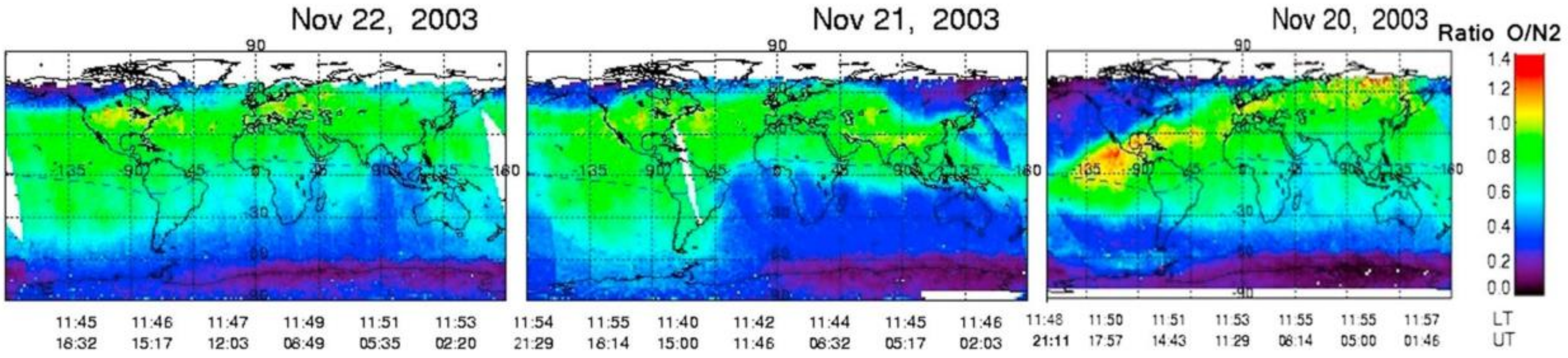
Well predicted by IRI model

Very little variation

Smaller variations in order of magnitude is predicted by IRI model

IRI Model Plots

Smaller variations as compared to the observations

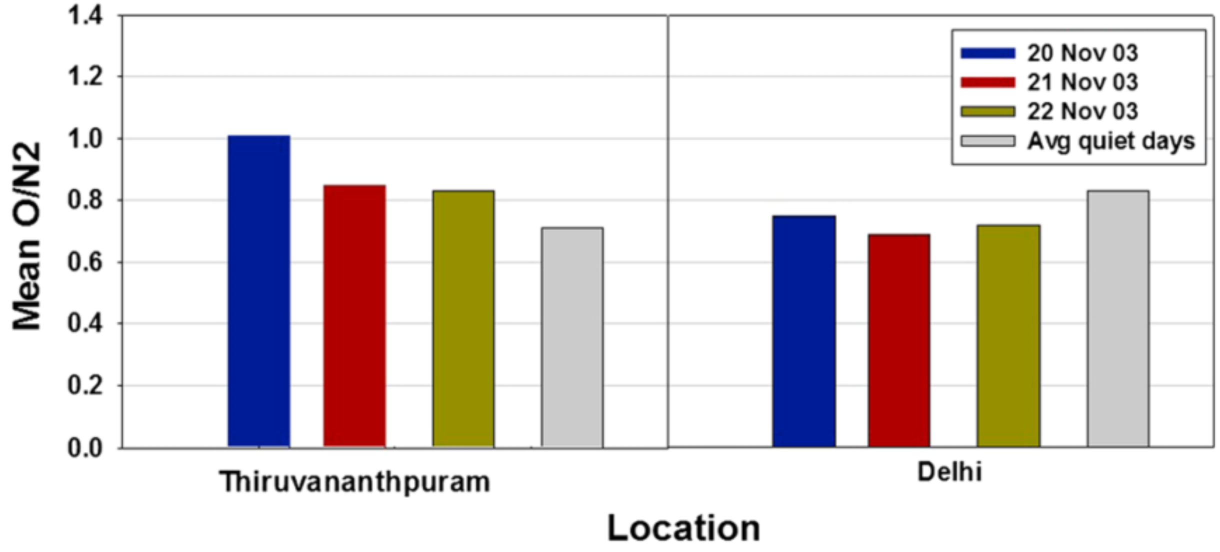


Global map of O/N2

- Significant changes in O/N2 occurred during this storm event with reference to the quiet time behavior.

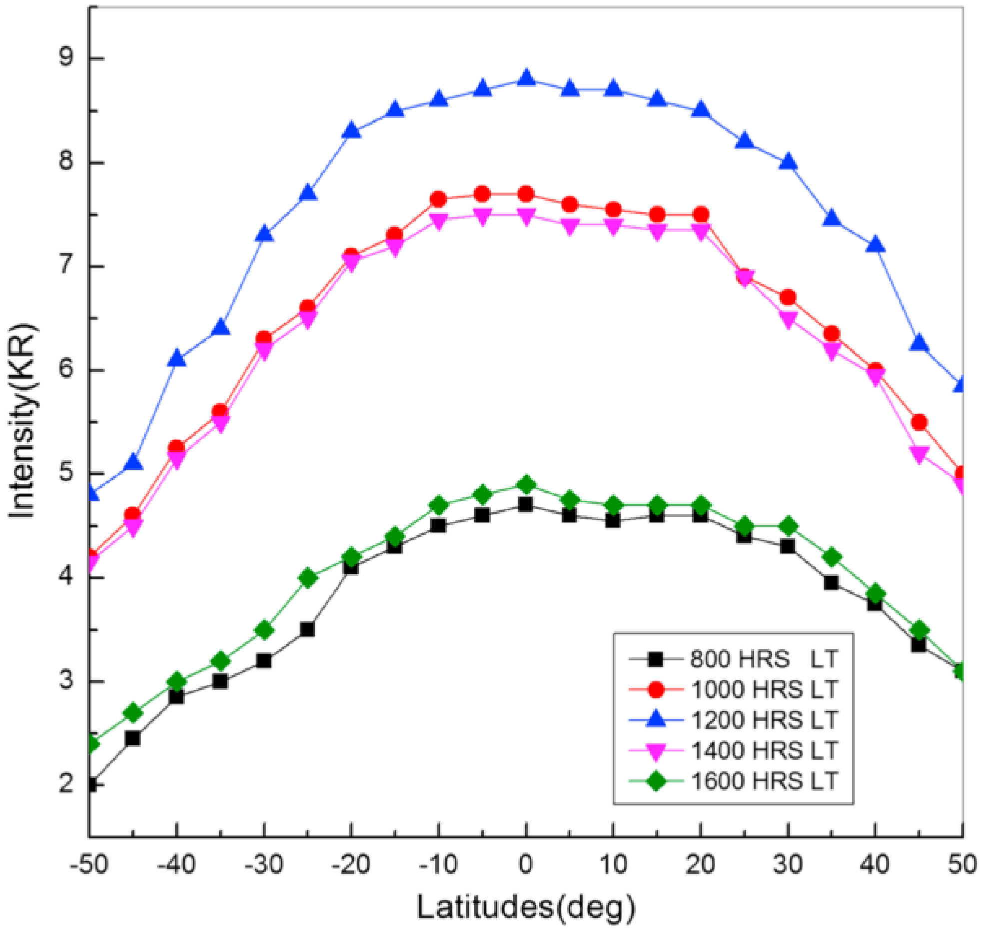
- A comparison of the O/N2 behavior for these three days with the deviation in foF2 from the quiet days for both stations, shows that they follow each other.

- A positive deviation in ΔfoF2 is associated with a rise in O/N2, and vice-versa.

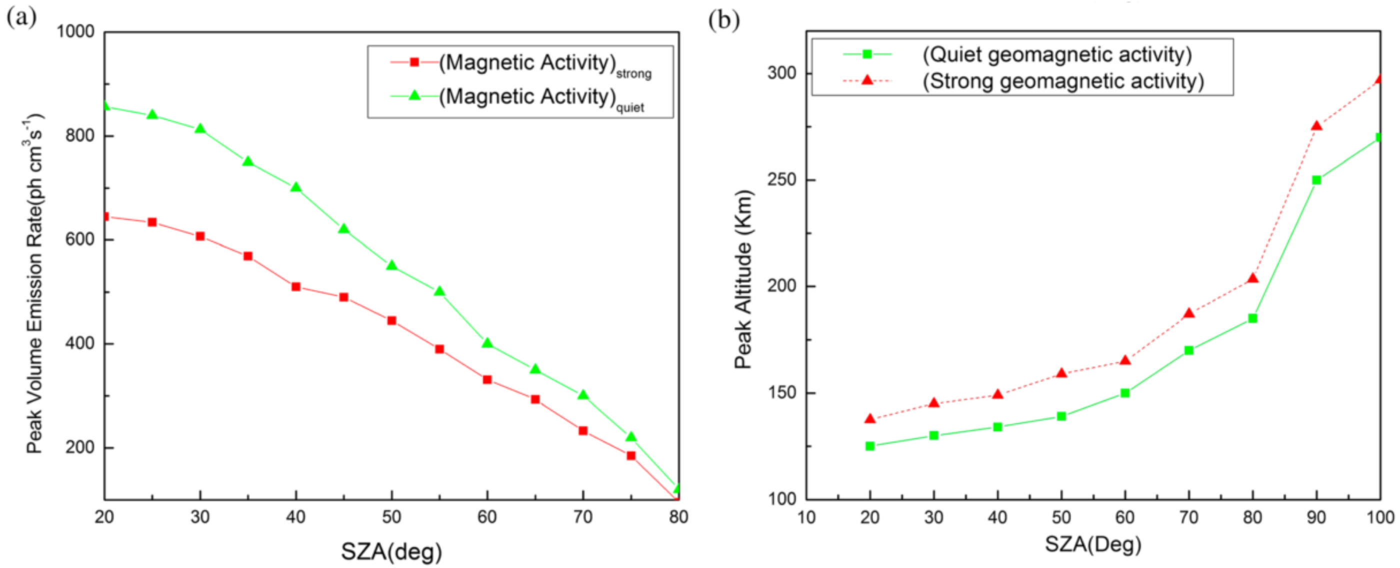


GUVI mean O/N2 values for average quiet day and 20–22 Nov 2003

The changes in O (^{1}S) thermospheric peak is simulated to examine its response during varying geomagnetic condition as it will be an indicator to the changing neutral composition.

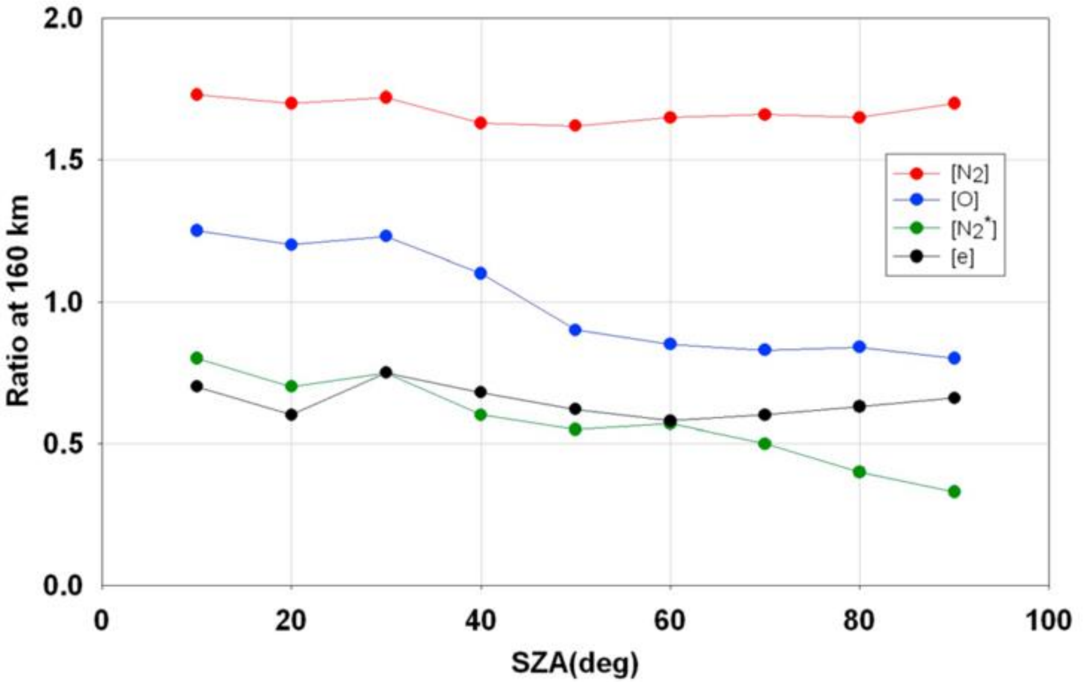


Averaged latitudinal variation of intensity of 5577Å dayglow emission under vernal equinox conditions (March/April 2013) at various local times.



(a) The volume emission rate of O(1S) as a function of solar zenith angle (SZA) with updated GLOW model run under quiet and strong geomagnetic condition. (b) The peak altitude of O(1S) as a function of solar zenith angle (SZA) with GLOW model run under quiet and strong geomagnetic condition.

- Decrease of about 30–40% in peak VER with SZA
- Increase of about 8 to 10% in peak altitude with SZA.
- This decrease in VER causes a corresponding decrease in intensity during the storm time at thermospheric peak heights.



Ratios of concentrations of [N2], [O], [N2 *], and [e] during strong magnetic activity to that during the quiet magnetic activity of $O(^1S)$ at peak thermospheric height (160 km).

At thermospheric peak heights, the concentrations of [N2] and [O] along with SZA, will be important factors in deciding the emission rates and in turn the ionospheric behavior observed at particular latitude and longitude.

Upadhayaya, A. K (2016), ***J. Geophys. Res. Space Physics***

RESULTS

- The responses of foF2 and h′F to geomagnetic storm at equatorial and low-latitude stations are anticorrelated. The reaction at different ionospheric stations may be quite different during the same storm depending on geographic and geomagnetic coordinates of the station, storm intensity and storm onset time.
- The modulation in foF2 at low (Delhi) and equatorial (TRV) Indian latitudes during geomagnetic disturbance of 20–23 November 2003 is fetched by the storm-induced changes in O/N2, but not during 14–16 April 2006 storm.
- The IRI 2012 model predicted foF2 and h′F parameters at both stations during the disturbed days reasonably well, with magnitude relatively smaller.
- The variation in modeled green line dayglow intensity at both the stations during these five storm events by and large showed an increase coinciding with the onset of the storm, with maximum variation in the $O(^1S)$ intensity seen for the severest of the storms considered.
- The updated GLOW model results show that thermospheric peak of green line dayglow emission shows a decrease and hence responds to changing geomagnetic activity and therefore updated GLOW model can be used to study the upper atmosphere response to geomagnetic activity and hence can be a possible candidate for a proxy to thermospheric dynamics .

(B) Response to Meteorological phenomena of Sudden Stratospheric Warming (2010 to 2016 events)

- The possibility of links between the meteorological phenomena and the upper atmosphere have been discussed very profoundly during the last two decades (***e.g. Forbes and Leveroni,1992; Hagan et al.,2001; Abdu et al., 2006; Lastovicka ,2006 ; Fuller-Rowell et al.,2008***) .

- One of the well known meteorological phenomenon which could be an important agent in this link is the large meterological variation in the winter time polar stratosphere, called the sudden stratospheric warming (SSW). During a SSW there is a sudden increase in stratospheric temperature, (**which could be as large as 70 K**), the polar vortex shifts off the pole and the zonal wind (U) become weak. This type of warming is designated as minor. However, if the vortex breaks up, and the zonal wind (U) changes direction then the event is designated as a major SSW.

- Although there have been some early attempts for identifying any ionospheric response to meteorological events like the sudden stratospheric warmings from theory, as well as from measurements (**e.g. Liu and Roble 2002, Kazimirovsky et al., 1971 , Danilov and Vanina 2003**), the field has seen relatively a vigorous activity only recently.

Most of these studies have been confined to the western hemisphere, particularly the 75ºW meridian. In view of the large longitudinal dependence of the equatorial electrodynamic perturbations during SSWs, we have attempted to examine ionospheric effects following SSW events of 2009 to 2016 in the Asian zone by using ionosonde data from six different stations. These stations cover a broad latitude range from 23º N to 45º N.

We find there are some perceptible changes in the ionosphere following these warmings at these stations.

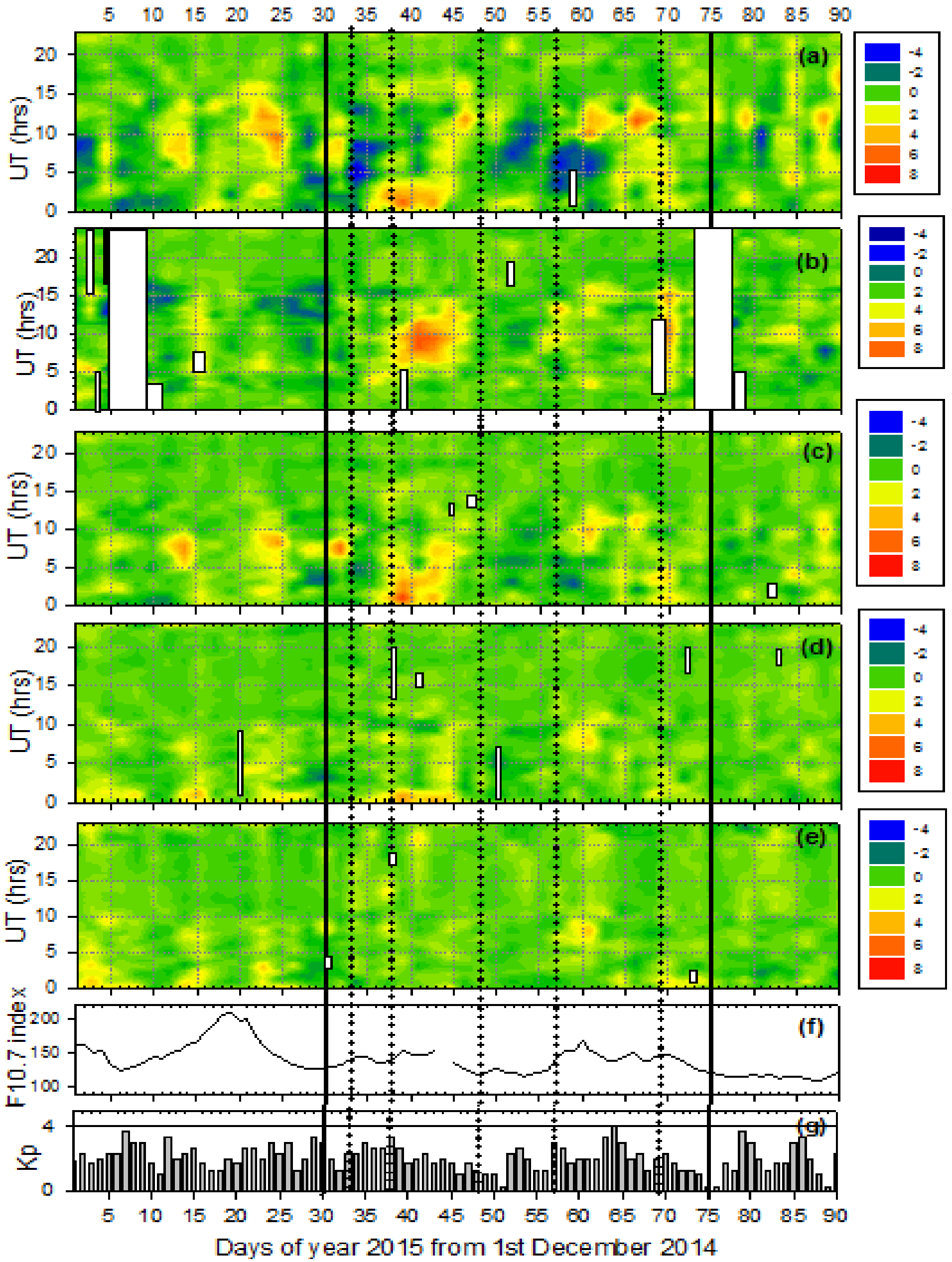
We then compare the magnitude of these changes with the normal day-to-day and hour-to-hour variability which exists in the ionospheric F2 region even at times when there are no SSWs and solar and magnetic indices are quite stable and close to their lowest values.

We examined ionospheric response to the following SSW events.

Winter of 2009-2010
Winter of 2010-2011
Winter of 2011-2012
Winter of 2012-2013
Winter of 2013-2014
Winter of 2014-2015
Winter of 2015-2016

Station	Geographic Latitude	Geographic Longitude	Geomagnetic Latitude	Dip
Okinawa	26.6°N	121.8°E	17.0°N	36.8°
Delhi	28.2°N	77.6°E	19.2°N	42.4°
Yamagawa	31.2°N	130.6°E	21.7°N	43.8°
Kokubunji	35.71°N	139.49°E	26.8°N	49°
Wakkanai	45.1°N	141.7°E	36.4°N	59.3°

To study **SSW** response, Delhi (digisonde) and Japanese ionospheric data is used: (NICT - World Data Centre, http://wdc.nict.go.jp/IONO/wdc/index.html)



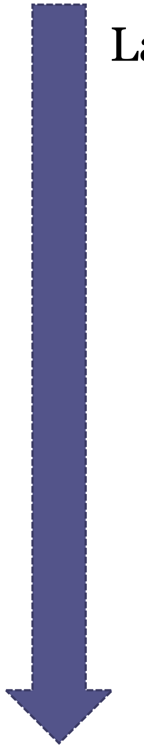
(a)Okinawa

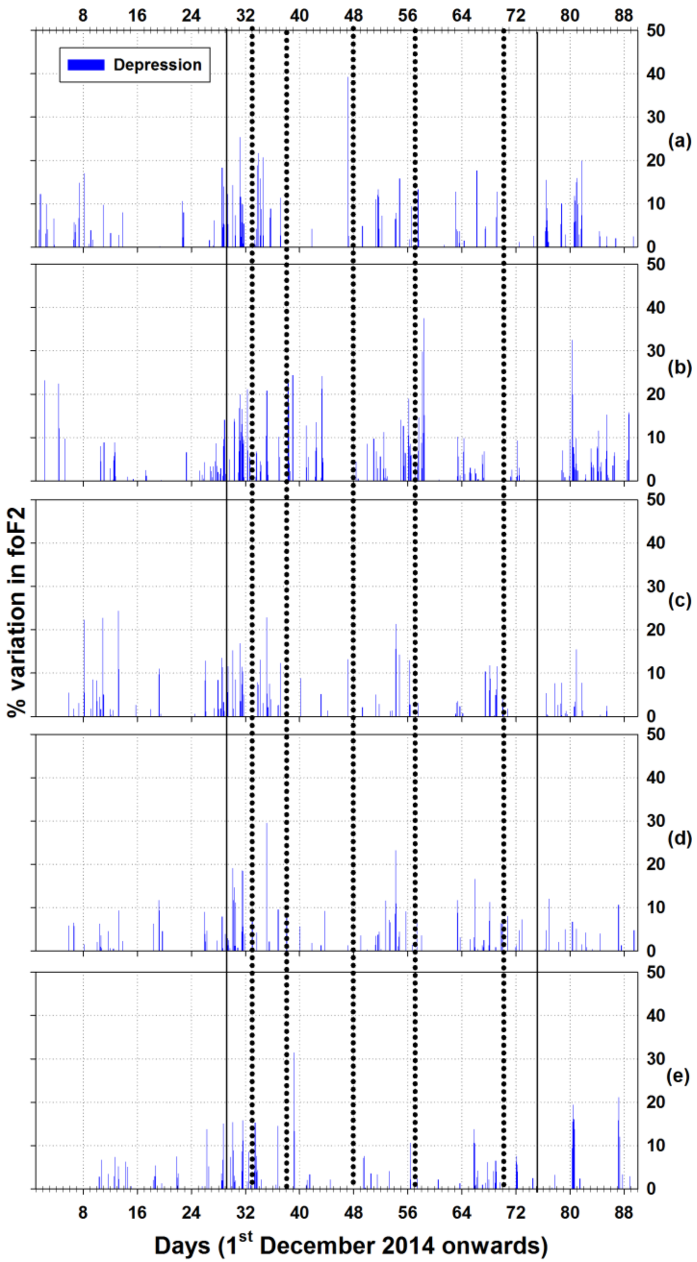
(b)Delhi

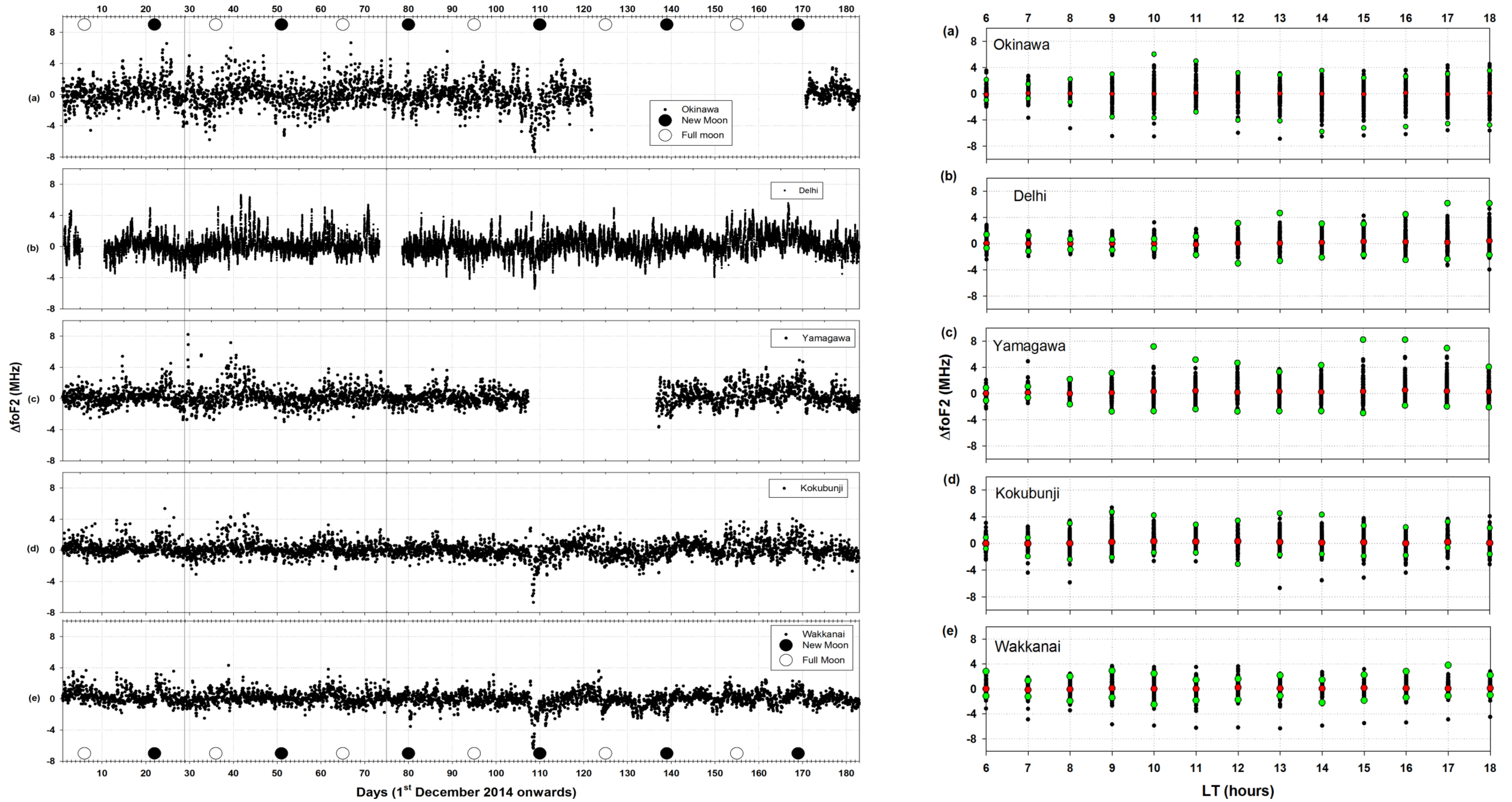
(c)Yamagawa

(d)Kokubunji

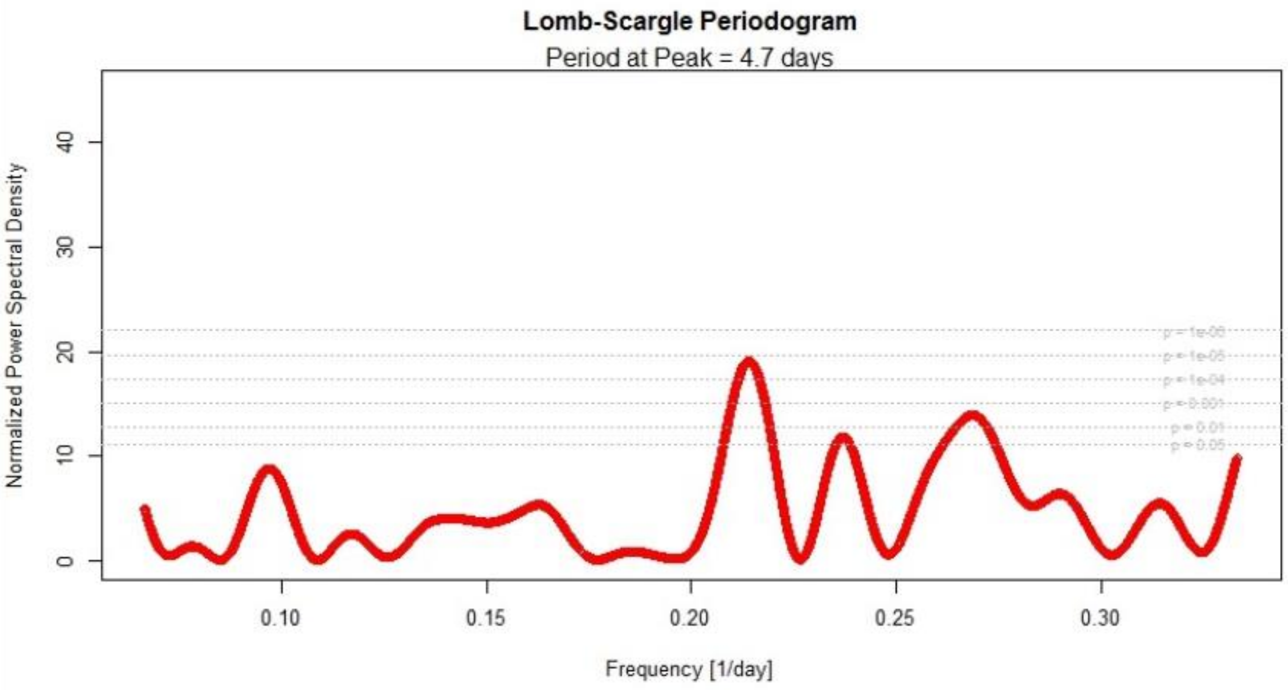
(e)Wakkanai







Okinawa
New Moon
Full moon
Delhi
Yamagawa
Kokubunji
Wakkanai
New Moon
Full Moon
ΔfoF2 (MHz)
Days (1st December 2014 onwards)
(a) Okinawa
(b) Delhi
(c) Yamagawa
(d) Kokubunji
(e) Wakkanai
LT (hours)



Summary

SSW event		ΔT (°K)	Electron density max % enhancement during SSW period
2010	Major	20.07	210.2%
2011	Minor	18.72	110.8%
2012	Minor	33.36	174.9%
2013	Major	37.34	185.2%
2014	Major	32.07	113.1%
2015	Minor	26.16	228.3%
2016	Major	49.12	150.95%

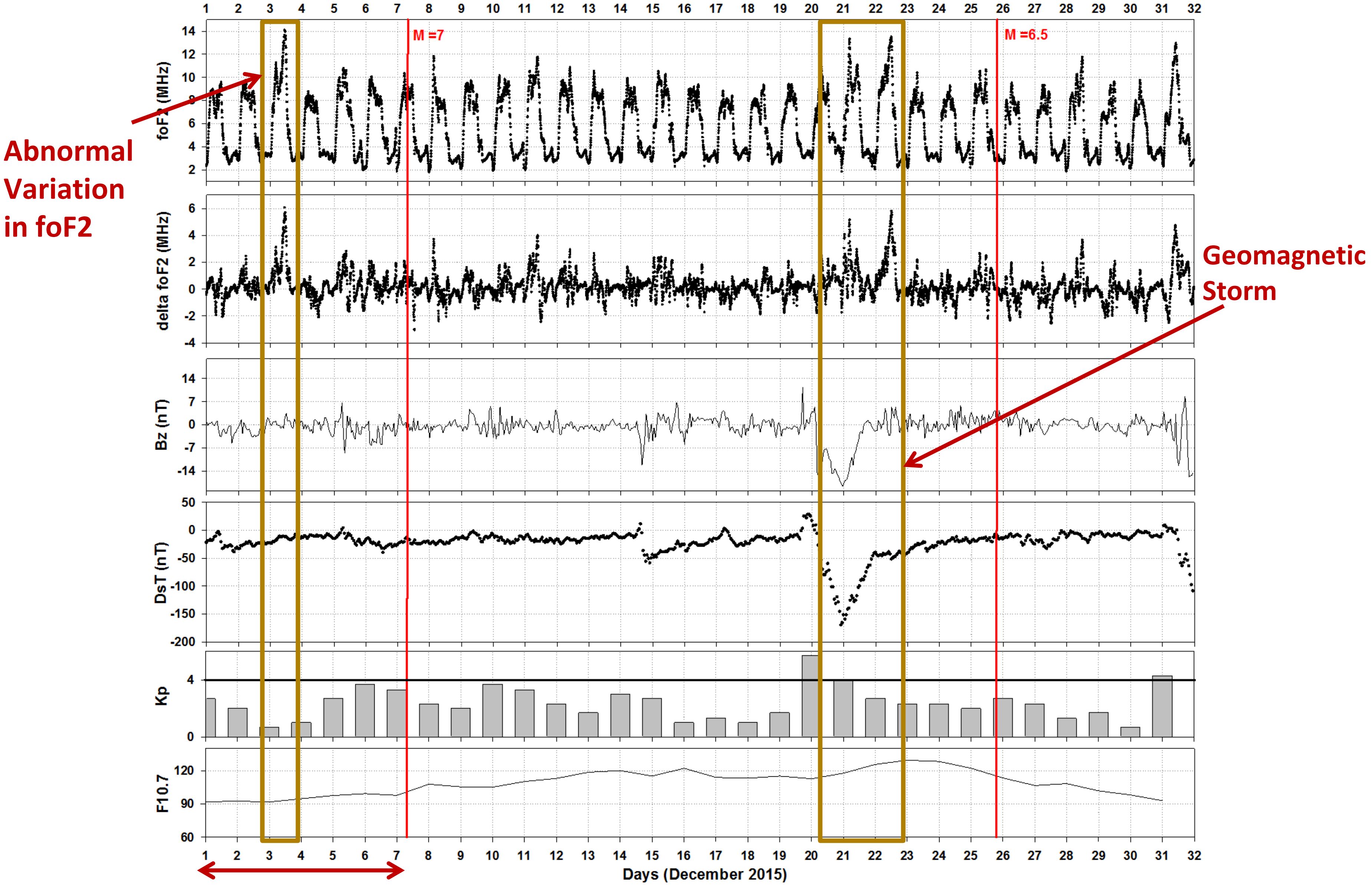
RESULTS

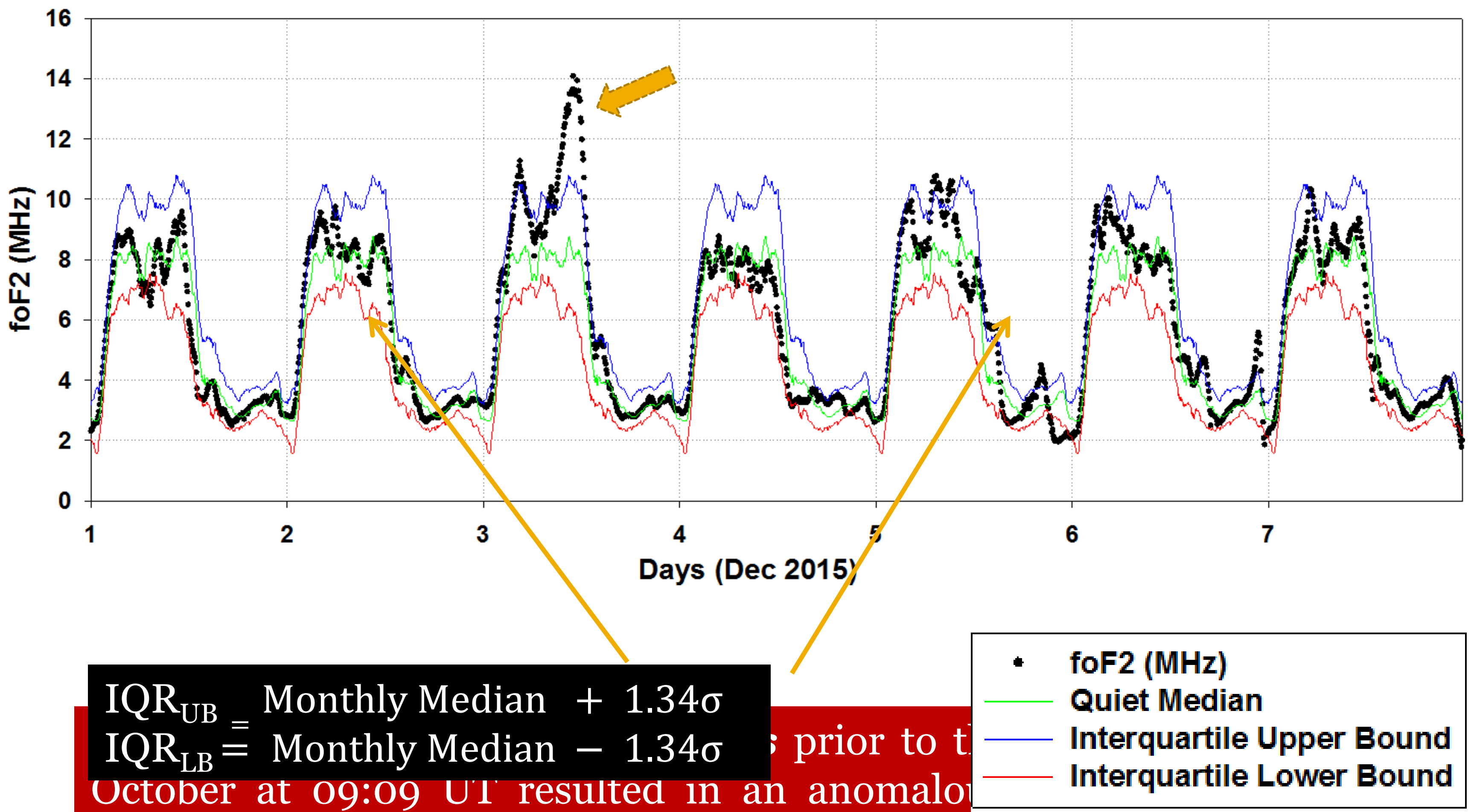
- It is found that by and large, ΔfoF2 varies semidiurnally during SSW period, with morning enhancement and afternoon depression
- Mostly, depression is seen during the SSW peak days.
- Such variations for low mid latitude station, Okinawa, seem to be correlated with the equatorial electrojet strength (EEJ) and total electron content (VTEC).
- Analysis of periodicity of these ionospheric perturbations during SSW periods shows a 4-5 day .
- The ionospheric response to SSW decreases in intensity and extent as the latitude increases.
- It is also found that there are days (including quiet days) when variations in foF2 values are comparable and at times even larger than the values seen during SSW period.

(C) Response to Earthquake events of 2015 and early 2016

S.No.	Date	Time (UT)	Magnitude (M)	Epicentre	Location		Radius of Earthquake Preparation Zone (km)	Distance from Delhi (km)
					Latitude (°N)	Longitude (°E)	$\rho = 10^{0.43M}$ Dobrovolsky et.al. (1979)	
1.	7 Dec 2015	07:50:02	7.0	Tajikistan	38.1	72.9	1023.3	~1105*
2.	26 Oct 2015	09:09:31	7.5	Hindu Kush, Afghanistan	36.5	70.8	1678.8	~1005
3.	12 May 2015	07:05:19	7.3	Nepal	27.7	86.0	1380.4	~875
4.	25 & 26 Apr 2015	06:11:25 07:09:08	7.9 6.9	Nepal	28.1 27.6	84.6 85.9	2187.7 933.3	~702 ~857
5.	3 Jan 2016	23:05:16	6.7	Tamenglong, Manipur	24.8	93.5	760.3	~1670.6*

* Observing station lies outside the earthquake preparation zone as given by *Dobrovolsky et al.* [1979].


Abnormal Variation in foF2
Geomagnetic Storm
M =7
M =6.5
foF2 (MHz)
delta foF2 (MHz)
Bz (nT)
DsT (nT)
Kp
F10.7
Days (December 2015)



$$IQR_{UB} = \text{Monthly Median} + 1.34\sigma$$
$$IQR_{LB} = \text{Monthly Median} - 1.34\sigma$$

… prior to t… October at 09:09 UT resulted in an anomalo… electron density at ionospheric monitoring station Delhi

Summary

Under review JGR-Space Physics

S.No.	Earthquake event	Anomaly seen prior to the event (days)	Electron density variation (%)	
			Max Enhancement	Max Depression
1.	7 Dec 2015	4	207.2	72.7
2.	26 Oct 2015	5-3	137.5	56.4
3.	12 May 2015	5	136.98	49.31
4.	25 & 26 April 2015	2,3,6	85.91	31.87
5.	3 Jan 2016	1,6	184.12	57.8

Results & Conclusion

- Perceptible ionospheric perturbations indicating towards possibility of seismo-ionospheric coupling. Maximum peak electron density observed **~207%.**
- By and large significant enhancement in foF2 observed **3-4 days** prior to the earthquake events.
- The maximum effect of the earthquake is seen for cases when the observing station was **outside** the earthquake preparation zone [*Dobrovolsky,* 1979]. Mostly, maximum depression is observed on the earthquake event day.
- The magnitude of variation in electron density as observed because of meteorological phenomenon of SSW event of 2015 is **comparable** to the variation seen due to the earthquake events in 2015 and both of these variations are reasonably similar in magnitude to that what has been seen during geomagnetic storm at these stations .

Acknowledgement : We are thankful to NICT Japan World data centre for making ionospheric data available on web Site. We are also thankful to the World Data Center, Kyoto University, Kyoto, Japan for geomagnetic indices data Dst. The Z component of interplanetary magnetic field Bz in Geocentric Solar Magnetospheric (GSM) coordinate downloaded from National Space Science Data Center, NASA/Goddard.

Thanks for your time.