On the day-to-day variability in the GPS TEC and its connection to the EEJ strength over India: Influence of neutral atmospheric dynamics from below

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In this paper, we present the analysis of magnetic and GPS data that suggests that there is a strong association between the equatorial electrojet (EEJ) strength and the modulations in the total electron content (TEC) as obtained from GPS observations during January to March 2006. It is well-known that zonal electric field over the EEJ region drives the daytime ionization to higher altitudes through vertical EXB drift and this ionization slowly descends to higher latitudes through diffusion along the magnetic field lines. The zonal electric field in turn produced through atmospheric waves mainly associated with tides. The recent IMAGE satellite observations suggest that atmospheric tides can influence the equatorial ionization anomaly (EIA) dynamics through modifying the zonal electric field over the dip equator that produce EIA. Recent observations also suggest that large scale waves like quasi-2-day wave, 5-day wave and 16-day wave do influence the low latitude ionospheric electrodynamics. In this context, we have performed a study to understand the association between the strength of the EEJ current and the variations in the TEC over Indian region at different stations. Wavelet and Fourier analysis suggests that the EEJ strength and the TEC variations have a periodicity of nearly 12-16 days. The observations further suggest that these large-scale modulations are prominently seen near to EIA region. It may be noted that possible sources for the changes in TEC are mainly due to (a) Solar flux, (b) Geomagnetic storms and (c) the vertical EXB drift. Since the TEC data which we have used for the present analysis belongs to magnetically quiet period and also the solar flux does not show any periodic variations, we are left with the sources which can influence the vertical EXB drift. Since we have identified almost similar periods in both EEJ strength and TEC during the same period, it is conjectured that these large-scale wave like modulations in TEC can be associated with atmospheric planetary scale wave phenomenon that is modifying the EEJ current and zonal electric field through atmospheric tides. Observations of electron density obtained using CHAMP satellite for the same period also indicate that large-scale periodic variations are seen in the electron density data.

1. Introduction

Day-to-day variabilities in the ionospheric E and F regions have been studied for several decades at various locations right from the equator to the auroral region using a variety of observations obtained through ground and space based instruments (e.g., Forbes et al., 2000; Rishbeth and Mendillo, 2001). Since the Earth's ionosphere has the influence of magnetospheric forcing from top and the influence of lower atmospheric waves originating from below, understanding and modeling the day-to-day variabilities in the ionospheric region is highly complicated (Rishbeth and Mendillo, 2001). The observational data base suggests that the sources for the day-to-day variability in the ionosphere could be characterized mainly as (a) Atmosphere-Ionosphere coupling, (b) Solar flux and (c) Geomagnetic storms (e.g., Forbes et al., 2000). While the geomagnetic storms do account for the variabilities in the ionosphere over equatorial and low latitudes, their influences are predominantly seen over high latitudes. However, the vertical coupling due to the neutral atmospheric wave or meteorological forcing due to solar radiative heating is the most important source for the variability in the equatorial and low latitude ionosphere (e.g., Forbes et al., 2000).

Over the equatorial and low latitudes, the differential heating of the Earth's surface due to solar heating provides the main driving force for the production of atmospheric waves namely gravity waves (GW), atmospheric tides and planetary scale waves (PSW). While the GW has typical periods of about few tens of minutes to few hours, atmospheric tides have periods of diurnal (24-hours), semi-diurnal (12-hours) and ter-diurnal (8-hours). The PSWs have periods typically ranging from 2 days to 2 weeks. They are global scale oscillations commonly identified as the manifestations of the resonant or Rossby normal mode oscillations of the atmosphere (Salby, 1984). The horizontal and vertical scales of the normal modes are strongly affected by the background neutral wind and temperature structure through which they propagate (Salby, 1984). Once atmospheric waves are generated, they propagate to the higher altitudes where atmospheric density decreases exponentially with height and hence the amplitude of the wave keeps on increasing to maintain energy conservation. Using measurements of ΔH from a magnetometer station close to geomagnetic equator, it is also suggested that PSW activity may account for up to 75% of the total energy in quiet time ΔH values (Parish et al., 1994). Takahashi et al. (2005) have reported 2-4 day oscillations simultaneously in ionosonde h'F and mesospheric airglow emissions over equatorial region and suggested the existence of Rossby-gravity waves (or inertia-gravity waves) and ultra fast Kelvin waves in the equatorial ionosphere. A quasi-16 day oscillation is observed during winter at equatorial ionosphere which is related to the free Rossby mode excitation in the stratosphere (Forbes and Leveroni, 1992). In order to relate the PSWs to the quiet time ionospheric variability, several studies have been made using GPS TEC. Most of the observations suggest that large scale waves like quasi-2-day wave, 5-day wave and 16-day wave do influence the low latitude electrodynamics. In this context, we have performed a study to understand the day-to-day variabilities in the ionospheric TEC over Indian region under GAGAN project during January to March 2006 and also establish its correlation with variabilities in EEJ strength and link their sources to the PSW activity. While some studies indicate the existence of day-to-day variabilities in the ionospheric parameters in the Indian sector, due to lack of continuous observations the effect of PSWs on the ionospheric TEC has not been clearly identified. Now simultaneous measurements of GPS TEC using a chain of GPS receivers along with continuous observations of the geomagnetic field using ground magnetometers at Tirunelvali and Alibag stations provide an excellent opportunity to link the ionospheric variabilities to the variabilities in the middle atmosphere.

2. Experimental Details

The observations reported here were obtained from 18 dual frequency GPS receivers setup under the GAGAN (GPS and Geo-Aided Navigation) project. The GAGAN project is aimed at continuously monitoring the Equatorial and low latitude ionosphere and modeling the ionosphere in this region for use in aviation over Indian region. The data collected is used to obtain for every 1-min interval statistical parameters like S_4 index, which is the standard deviation of normalized intensity of the signal, standard deviation of phase, receiver lock time etc. for each satellite being tracked. The GPS satellites basically transmit radio signals at two frequencies namely L1 (1.575 GHz) and L2 (1.227 GHz). The dispersive nature of the ionosphere causes the two radio signals to propagate at different velocities, provides a time delay for each signal by a certain amount. This time delay, which is normally much smaller than the total transit time, is proportional to the total electron content along the line of sight to the satellite. Using the time delays for the two signals and also the more accurate phase information, the slant TEC (STEC) is obtained. VTEC, on the other hand, is obtained using appropriate mapping function,

$S_f = \cos\chi$, i.e. VTEC=STEC* $\cos\chi$

where $\chi = \sin^{-1}[R_E \cos\alpha / (R_E+h)]$, α is the elevation angle, R_E= Earth's radius, h = 400 km. Ground magnetometer data from Tirunelveli (8.7°N, 77.8°E, dip latitude: 0.4°N) and Alibag (18.5°N, 72.9°E, dip latitude: 13.0°N) during January to March 2006 are also used in addition to the TEC observations to obtain the ΔH variations that may be attributed to the equatorial elctrojet (EEJ) (e.g., Rastogi and Klobuchar, 1990). Solar flux at F10.7 cm and Ap index for the same period are also used in the present study.

3. Results and discussion

To study the day-to-day variabilities in TEC and EEJ strength over India, we have plotted in Figure-1(a-b) the diurnal variation of the latitudinal distribution of GPS TEC along with the EEJ strength obtained on (a) 05 January 2006 which is a case of normal electrojet strength event and (b) 14 January 2006 which is a case of counter electrojet event for inter-comparison. It may be noted that both these days are geomagnetically quiet days. From Figure-1a (bottom), it can be seen that during morning hours, ΔH slowly increases to higher values as time progresses and finally reached as high as 50 nT at about 11:45-12:00 noon. But soon after that, ΔH starts decreasing rapidly and goes to almost zero value at about 17:00 IST and same trend almost continued till next day morning 06:00 IST. The corresponding TEC map plotted in Figure-1a (top) as a function of latitude and local time suggests that in the morning hours TEC does not show any increase, however, as time progresses TEC slowly starts increasing and EIA starts building up at about 09:00 IST. As time progresses further, EIA tends to develop fully at about 15:00 IST and the latitude of the EIA crest is found to be 23°N. Since we have very few stations over equatorial locations, TEC plot has little information for equatorial locations. But as one goes to higher latitudes, as can be seen in the Figure-1a, the TEC data is evenly distributed due to the increase in number of stations. It may also be noted that the elevation angle of GPS signal path is above 30°, the latitude bin of 2°, time bin is of 15 min and longitude bin is of 75-85

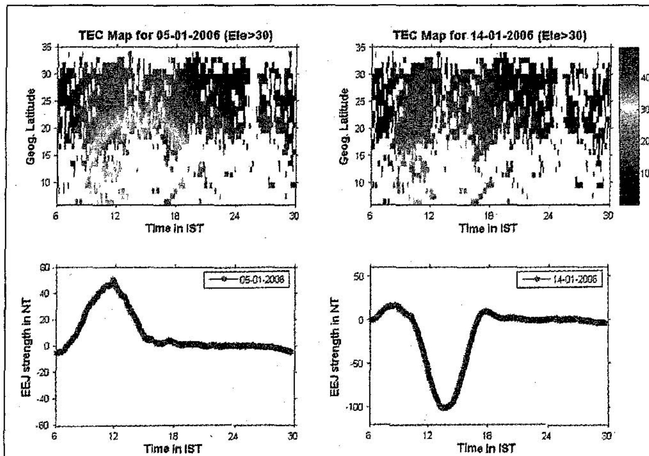

Fig.1(a-b). *Shows the day-to-day variability in the EEJ strength and its associated changes in the GPS TEC obtained on 05-01-2006 and 14-01-2006.*

degrees for generating the TEC map presented here. Figure-1b (bottom) shows that ΔH starts slowly increasing initially in the morning after 06:00 IST. However, as time progresses, ΔH abruptly decreases to as low as -110 nT at about 13:00 IST but later on, ΔH again increases gradually and ΔH reached its original value at about 17:00 IST. The TEC map plotted in Figure-1b a (top) show that in the early morning TEC is almost below 10 TEC units, but as time progresses, TEC map shows some increase in TEC to value of ~30 TEC units at 11:00-12:00 IST. But later on, no increase in TEC is found and similarly no EIA is found to develop on this day. So, from the Figure-1(a-b), it is clear that day-to-day change in the EEJ strength is well represented by variations in the TEC.

While the maximum TEC observed is about 40 TEC units at latitude of about 18-20^{0}N and is extended for longer hours (~6 hours) on 05 January 2006, the maximum TEC observed on 14 January 2006 is about 30 TEC units and occurring only for short duration in the time interval of about 11:00 to 12:00 IST.

Now in order to understand further about the day-to-day variabilities in the EEJ strength and their relation to TEC, we have plotted the daily EEJ strength averaged for every 5 min interval during 06:00 to 20:00 IST for January to March 2006 in Figure-2a as a contour map. Also plotted along with EEJ strength is TEC obtained at Trivandrum, Hyderabad and Bhopal averaged for every 5 min interval for the same period as shown in Figure-2(b-d). Here it may be noted that while horizontal axis represents the time in IST, vertical axis represents the Julian day number. The color bar represents the strength of EEJ current in nT and TEC in TEC units. It may be noted that the white gaps in the Figure represents data gap either due to non-availability or due to the elevation threshold used. The Figure-2a shows that EEJ strength is found to be high in the initial period of observations and as Julian day number progresses, EEJ strength is found to modulate in the form of highs and lows. The TEC observations plotted in Figure-2(b-d) for the stations Trivandrum, Hyderabad and Bhopal also represents such modulations in TEC in accordance with EEJ strength, with the strength of modulation is being strongest over Bhopal as shown in Figure-2(d). It may be noted that steady –ve slope in the y-axis in the TEC map in the Figure-2(b) can be due to the satellite movements.

To study the latitudinal variation of TEC for a given time by combining all 18 stations of TEC data, latitudinal distribution of TEC as a function Julian day number is plotted in Figure-3a. Also plotted in Figure-3(b-c) are the max TEC and its corresponding latitude for each day as a function of day number. Here the blue color represents the 3-point running average. From the figure, it can be noted that in the initial period of observations TEC has undergone large scale day-to-day variability in the maximum TEC and its corresponding geographic latitude.

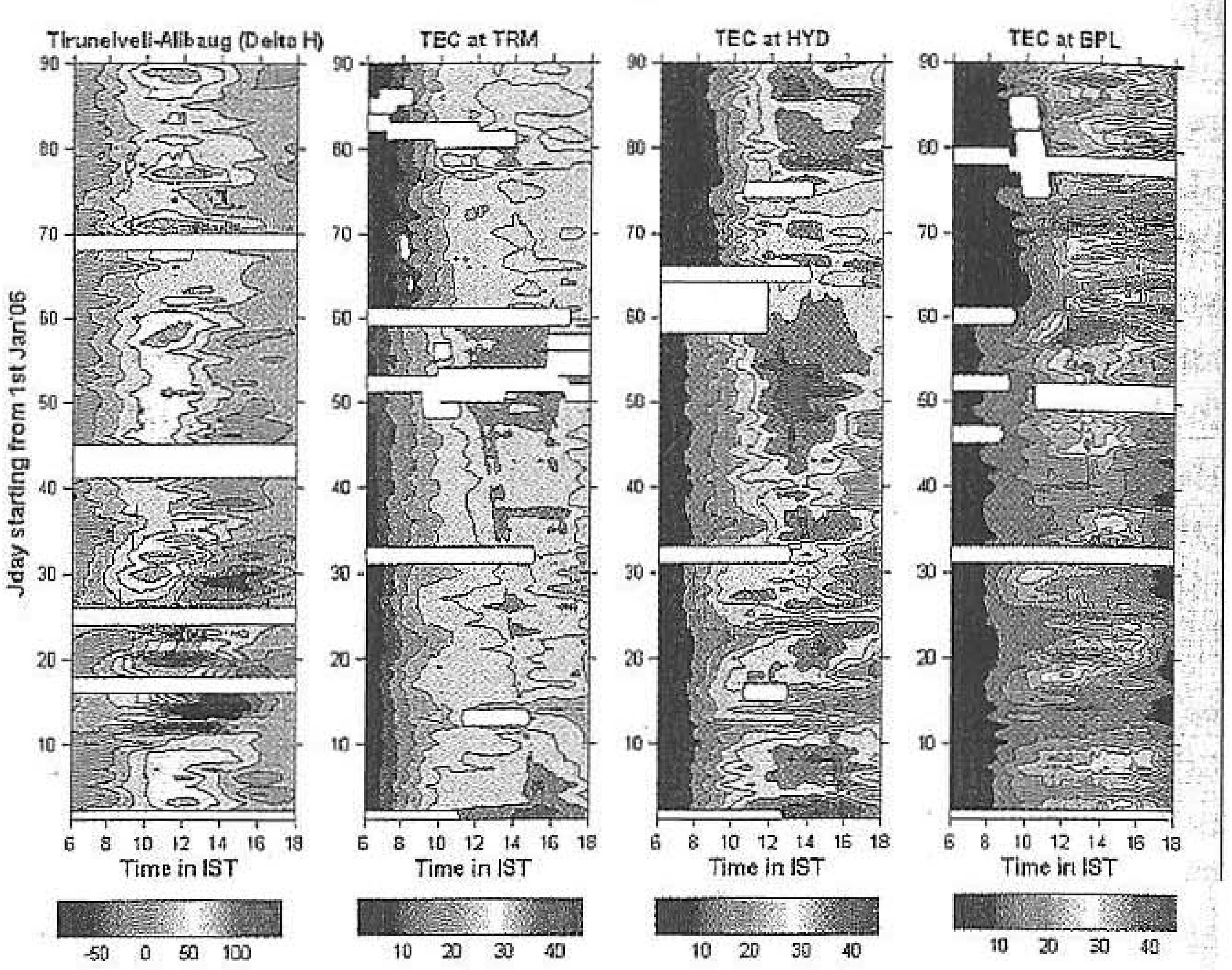

Fig.2. *Shows the a) EEJ strength and TEC over b) Trivandrum, c) Hyderabad and d) Bhopal during January to March 2006.*

Since the TEC and EEJ strength data belongs to Jan-Mar period which is local winter season, we tried to study any large scale periodic oscillations that could originate from MLT region during winter. In order to find out the periodic oscillations that might exist in our data, we have applied Fourier analysis techniques to TEC and EEJ strength data obtained at 16:00 to 16:30 IST. Figure-4 shows the amplitude spectrum obtained for EEJ strength and TEC data obtained at Trivandrum, Hyderabad and Bhopal stations. Interestingly, we have obtained the periods which are nearly close to 16 day period in both EEJ strength and TEC data. Here it may be noted that

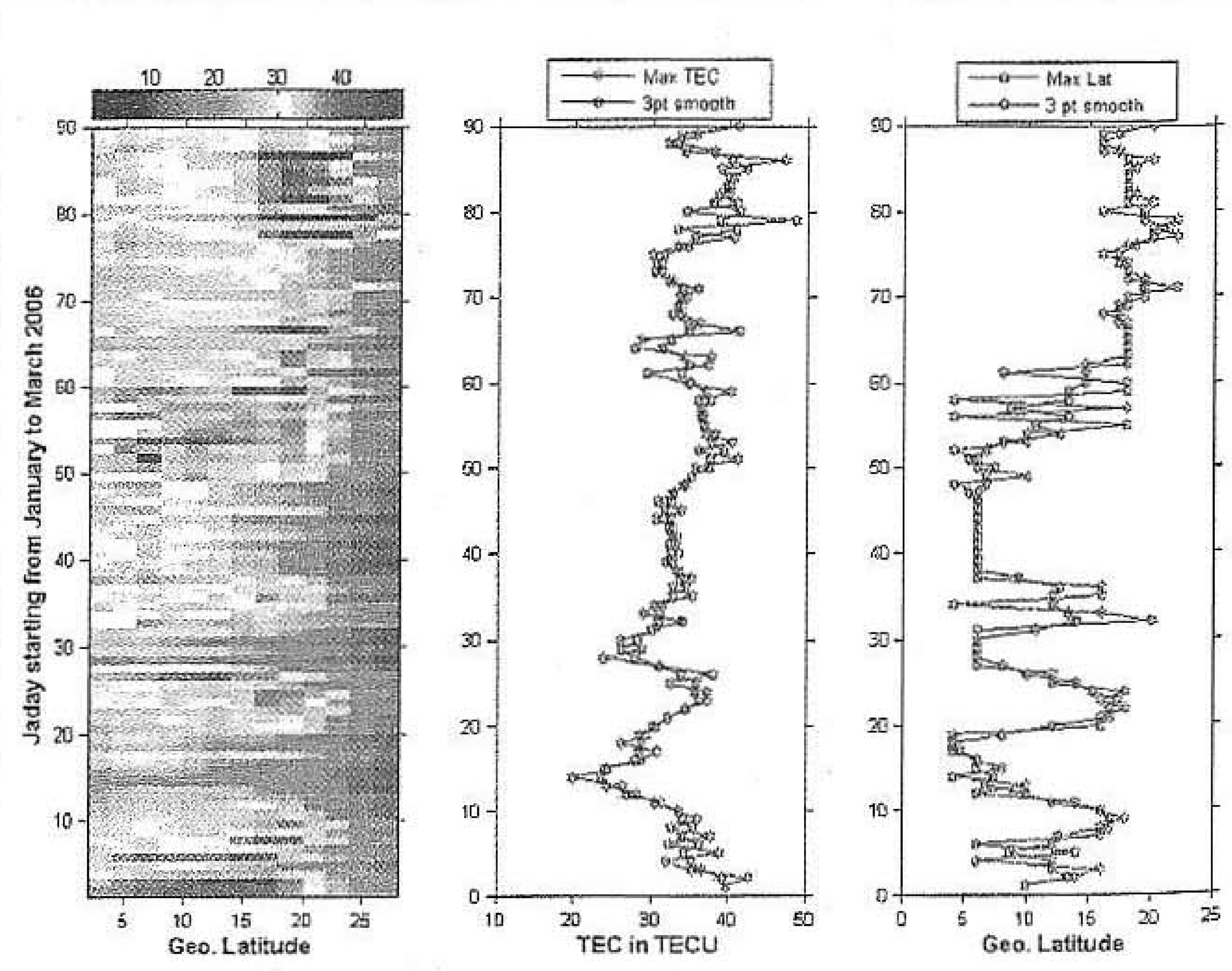

Fig.3. *Shows the a) daily latitudinal distribution of TEC obtained using 18 stations data during 14-16 IST as a function of day number and b) its max TEC and corresponding latitude during Jan-Mar'06.*

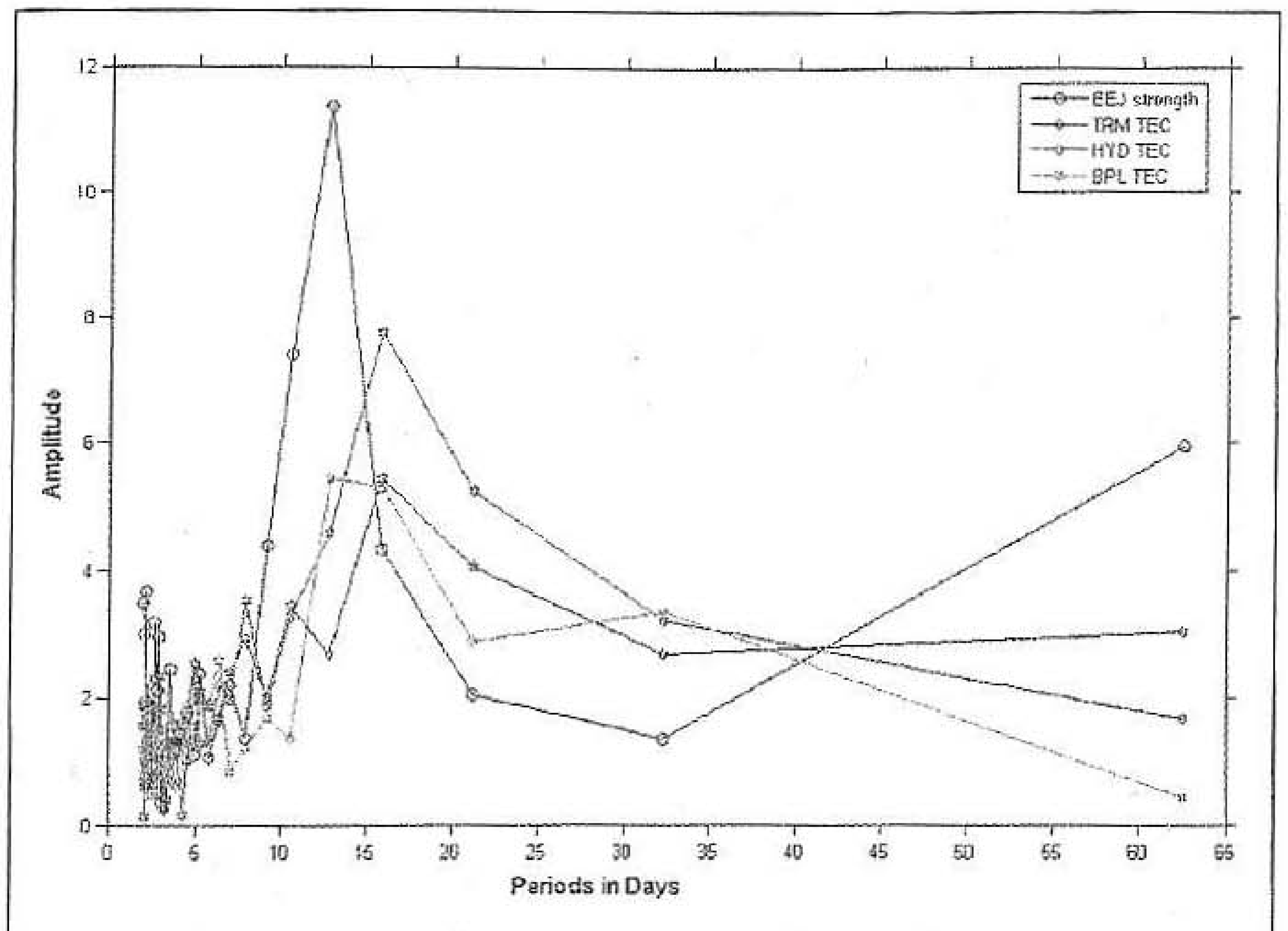

Fig.4. *Shows the amplitude spectrum of FFT of a) EEJ strength and TEC at b) Trivandrum, c) Hyderabad and d) Bhopal during 16:00-16:30 IST.*

we have also observed 16-day period at other timings as well. Further, we have seen from Figure-2(d) that this 16 day wave period is clearly seen as one go close to an EIA crest region over India. We have also applied wavelet analysis technique to study the temporal variation of amplitude of each period in our data sets as shown in Figure-5(a-d). The observations suggest that 16-day wave period is more dominant in the initial period of our observations and as time progresses, its strength weakens. As we don't expect periodic oscillations at 16-day period in solar flux and Ap index, we are left with sources which can influence the dynamics of the ionosphere. For the equatorial and low latitude region, it is the lower atmospheric wave phenomenon which can propagate to upper atmosphere and can lead to the variabilities in the EEJ strength and in turn lead to the changes in TEC observations. Also our observations belong to winter season during which stratospheric warming events can lead to the generation of large scale wave oscillations like PSWs and these waves propagate to MLT region due to decrease in the atmospheric density. These waves may also interact or modulate the diurnal/semi-diurnal tides and gravity waves over MLT region and may lead to the changes in the ionospheric currents, vertical drift or vertical transport through ionospheric dynamo system which could act as a source for the ionospheric variability. Recent observations made using Lidar observations over low latitude station, Gadanki, indicates the existence of PSWs during Jan-Feb'06 period ascertaining our view point (Sridharan et al., 2009)

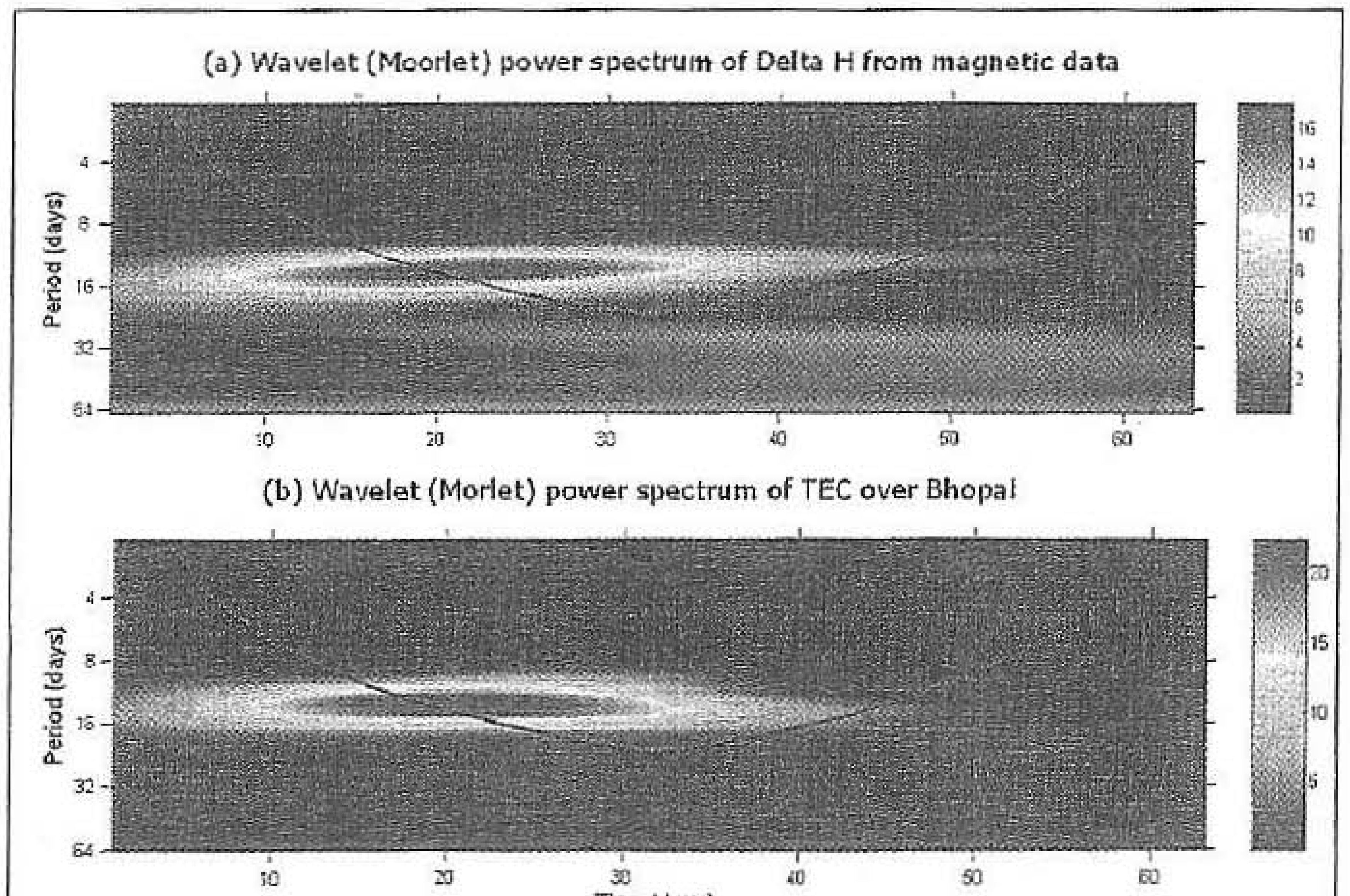

Fig.5. *Shows the wavelet analysis of a) EEJ strength and b) TEC over Bhopal obtained during 16:00-16:30 IST. Here the black line indicates 95% significance level.*

4. Summary and conclusion

From the observations, we summarize the following points: (a) there exists a day-to-day variability in the EEJ strength and TEC (b) large scale wave like oscillations (16-day period) exist in the EEJ strength and TEC observations. Since the observations presented here belong to winter season, there is a possibility that stratospheric warming events lead to the generation of PSWs which propagate to MLT region and cause changes in EEJ and TEC through modulating the diurnal/semi-diurnal tides over MLT region and may lead to the changes in the ionospheric currents, vertical drift or vertical transport through ionospheric dynamo system. Hence PSWs may act as a source for the ionospheric variability.

References

Forbes and Leveroni, GRL, vol. 19, pp: 981-984, 1992.

Forbes et al., JASTP, vol. 62, pp: 685-693, 2000.

Parish et al., JGR, vol. 99, pp: 355-368, 1994.

Rastogi and Klobuchar, JGR, 95, pp: 19045-19052, 1990.

Rishbeth and Mendillo, JASTP, vol. 63, pp: 1661-1680, 2001.

Salby, Rev. Geophy., vol. 22, pp: 209-236, 1984.

Sridharan et al., Anneles Geo. Phys., 27, 373-379, 2009.

Takahashi et al., GRL, vol. 32, doi: 10:1029/2004GL022318, 2005.