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Low-latitude TEC variability studied from magnetically conjugate locations along 73°E longitude

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ABSTRACT

A comparative study on the variation of total electron content (TEC) was performed by using the observations from two GPS receivers located at magnetically conjugate stations near the equatorial ionization anomaly crests: Udaipur, India in the nortnern hemisphere and Diego Garcia in the southern hemisphere, located at approximately same geographic longitude. Our study reveals that the TECs at both stations shows the semi-annual variability being higher in equinoxes than in solstices. An important finding of the work is that in the northern hemisphere, during the declining phase of solar cycle 23, the amplitude of the winter crest is smaller than that in the summer whereas it is found to be comparable/higher (which is normally termed as "winter anomaly" in the mid latitudes) during the rising phase of solar cycle 24. Thus it is concluded that the so called "winter anomaly" at low latitudes is a phenomenon totally different from the one observed at mid latitudes. In fact its manifestation at low latitudes can be accounted for in terms of variation of the solar flux and/or the strength of the equatorial electrojet during different seasons.

1. Introduction

In the recent years, global positioning system (GPS) is being used for the satellite based navigation and ground positioning. Presently, a constellation of 32 satellites in six orbital planes, at a nominal altitude of 20,200 km, not only provide a wide spatial and temporal coverage but the accuracy of the measurements is also very high due to the use of the state-of-the-art GPS receivers that work at ultra high frequency. But, the measurements using the GPS receivers are critically dependent on the state of the ionosphere through which the satellite signals have to pass prior to their reception by the GPS receivers. This is because the range error in such measurements is directly related to the changes in total electron content (TEC) of the medium between a satellite-receiver pair. TEC is defined as the number of electrons contained in an imaginary cylinder of 1 m^2 cross section between a satellite-receiver pair and 1 TEC unit, called TECU equals 10^{16} electrons/m^2. Since TEC is heavily weighted by the electron density in the F-region of the ionosphere where it is highest both by the day and night, variations in F-region density are expected to be reflected in the TEC as well.

Electron density in the F_2 region, particularly the peak F_2 region density (NmF_2) is known to be associated with a number of anomalies and variabilities. Contrary to the prediction by the Chapman theory, early observations (Appleton and Naismith, 1935) revealed that the F_2 layer variations could not be explained merely in terms of changes in the solar zenith angle. This was thought to be anomalous. Since then, a number of ionospheric anomalies have been observed and studied; though Zhao et al. (2007) caution to distinguish an anomaly from the variation. A detailed account of previous works on various ionospheric anomalies has been recently given by Lee et al. (2011). The well documented anomalies in NmF_2 are seasonal, annual and semiannual. The most striking amongst these is the winter anomaly (also termed seasonal anomaly) wherein the winter NmF_2 is found to be higher than the summer NmF_2, especially at mid latitudes. A number of workers have reported different ionospheric anomalies using the TEC data at low latitudes. The most intriguing aspect of the TEC observations at low latitudes, that has been reported by a number of workers, is the presence of winter anomaly from regions other than India (Huang et al., 1989; Huang and Cheng, 1996; Tsai et al., 2001; Wu et al., 2004; Zhao et al., 2007; Huo et al., 2009; Liu et al., 2009; Olwendo et al., 2012). Seasonal variation of equatorial anomaly in terms of TEC spanning the period October 1985–September 1988 were given by Huang et al. (1989) in the east Asian sector around 120°E. Their result showed remarkable seasonal variation; with the anomaly crest being largest in the equinoxes, and slightly larger in the winter than in the summer. Huang and Cheng (1996) extended the study over a full solar cycle spanning September 1985–December 1994 at Lunping observatory (25°N, 121.7°E). They found that the strength of

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the EIA crest increases with the increase of the solar activity and exhibits winter anomaly with the strength of the winter crest being larger than the summer. Their result further showed that winter anomaly appears during high and medium solar activity periods. Earlier, using TEC data from transit satellite, Walker (1971) had also reported that the winter anomaly in the day time TEC was more apparent during high and medium solar activity periods. Based on the GPS observations of ionospheric TEC at YMSM (25.2° N, 121.7°E and 14°N geomagnetic latitude) and Diego Garcia (7.3°S, 72.4°E and 16.2°S geomagnetic latitude) during the solar minimum year 1997, Tsai et al. (2001) reported the presence of winter anomaly in the northern EIA region. However, the winter anomaly was not observed in the southern region by Tsai et al. (2001). Using a dense network of GPS stations clustered around Taiwan extending from 21.9°–26.2°N and 118.4°–121.6°E, Wu et al. (2004) reported presence of winter anomaly during the solar minimum period 1996–1997. Zhang et al. (2009) studied the TEC variation during the rising phase of the solar cycle 23 for the period 1998–2004. Instead of using the crest TEC values they employed crest-to-trough ratio (CTR) of TEC at 120°E longitude for both the northern and southern crests. They found that the TEC–CTR for the northern crest had a larger value in winter than in summer, whereas TEC–CTR in the southern anomaly did not show this winter anomaly effect.

In the Indian region, the GPS–TEC measurements were initiated much later and results on TEC variability have been reported mainly during the second half of the solar cycle 23 (e.g., Rao et al., 2006; Galav et al., 2010; Kumar and Singh 2012; Chakrabarty et al., 2012; Sharma et al., 2012). Of these authors, Galav et al. (2010) were the first to emphasize the occurrence of lowest TEC during winter, measured during the declining phase of the solar cycle 23, for the years 2005–2009 near the crest of the equatorial ionization anomaly at Udaipur. These results implied the absence of the winter anomaly (in TEC) over Udaipur, a station in the northern hemisphere near the crest of the ionization anomaly and were at variance with the observations in the East Asian sector. But the moot point is whether any significance should at all be attached to the so called winter anomaly phenomenon at low latitudes! This has prompted us to have a critical view on the use of the term "winter anomaly" at low latitudes. This is because while the production of ionospheric plasma is expected to be dependent on the incoming solar flux at all the latitudes, but at low latitudes the redistribution of the plasma is known to be dominated by the equatorial plasma fountain and its variability. The present work, therefore, aims firstly, at determining and comparing variations in TEC during rising phase of the solar cycle 24 for the years 2009–2011 in the northern and southern equatorial ionization anomaly (EIA) zones. Secondly, variation of crest TEC obtained from the receivers located at two magnetically conjugate stations lying in nearly same longitude is compared for the period 2005–2011. This period encompasses the declining phase of the solar cycle 23 and rising phase of the cycle 24. Since the two stations are magnetically conjugate (Udaipur-Geomag. Lat. = 16.08°N and Diego Garcia-Geomag. Lat. = 15.36°S; reference year 2010), located on nearly same geographic longitude (~73°E) this would eliminate any longitudinal bias in TEC.

2. Observations

In the present study we investigate the behavior of low-latitude ionospheric TEC around 73°E longitude in the northern and southern hemispheres encompassing the crest of the EIA. TEC data for the Northern hemisphere was obtained from a dual frequency GPS receiver installed at Udaipur, UDPR (Geog. Lat. 24.6°N, Geog. Long. 73.7°E Geomag. Lat. 16.08°N). The GPS receivers provide the slant TEC along the line joining a satellite-receiver pair, which were corrected for satellite and receiver biases. The slant TEC (STEC) thus obtained were converted to vertical TEC (VTEC) by assuming ionosphere as a thin shell centered at an altitude $h_{\max}$, using the following formula (Ma and Maruyama, 2003)

$$VTEC = STEC \times \sqrt{1-\left(\frac{R_e\ \cos\theta}{(R_e+h_{\max})}\right)^2} \quad (1)$$

Here R_e is the radius of the earth and θ is the elevation angle of the satellite. For the present study the value of $h_{\max}$ has been taken as 350 km. The STEC includes the receiver bias and inter-frequency bias errors. The errors were taken care of during the post processing of the data. For TEC in the southern hemisphere, data from the IGS station Diego Garcia, DGAR (Geog. Lat. 7.27°S, Geog. Long. 72.37°E, Geomag. Lat. 15.36°S) has been used. It is important to note that UDPR and DGAR are not only nearly magnetic conjugate stations; they are also located on nearly same longitude. Thus the local time corresponding to a UT hour at the two stations is nearly same. The data downloaded from the IGS website are in RINEX format and to retrieve the TEC from this data indigenously developed computer codes (Sharma et al. 2011) have been used. Since main source of ionospheric plasma is the solar radiation, dependence of TEC on the absolute F10.7 cm solar flux has also been evaluated.

3. Results and discussion

3.1. Semi-annual variation in TEC in the EIA zones:

We have studied the variation of ionospheric TEC over the northern and southern hemispheric stations for the years 2009–2011. This period coincides with the rising phase of solar cycle 24. For this study we give contour plots of TEC for these years for the two stations as shown in Fig. 1. The upper panel of Fig. 1 corresponds to the northern station, UDPR and the lower one is for the southern station, DGAR. In each contour plot the TEC has been averaged over each hour of the day in a given month; only those months were considered which had data for more than 15 days at least. Hence the plot for February 2009 in the southern hemisphere (lower panel) is shown blank. Similarly, January and March 2009 are also partly filled as data of 23 days for these months each was available. As can be seen from Eq. (1), conversion from slant to vertical TEC depends upon the elevation angle, θ of the GPS satellite with respect to the receiver. The conversion errors are known to be higher for low elevation angles and also the data for very low elevation angle may suffer from multipath and line of sight obstructions (Galav et al., 2010). Therefore, Fig. 1 has been obtained by computing mean VTEC only in those cases when the elevation angle of the satellite was more than 50°. Thus the contour plot gives nearly the overhead variation of TEC at the two stations. The abscissa is the month of a given year, and ordinate is the universal time, UT. Value of VTEC has been shown by a color scale on the right side of the figure. It must be emphasized here that while May, June and July are the summer months in the northern hemisphere, these are winter months in the southern hemisphere. Similarly, winter months of the northern hemisphere are the summer months of the southern hemisphere. In short, what is summer solstice in the northern hemisphere is the winter solstice of the southern hemisphere and vice-versa.

It can be seen from Fig. 1 that throughout the years the TEC maximizes between 0830–1030 UT (LT~UT+0500 h). In a given year, from January onward the value of TEC in the northern EIA zone (upper panel) steadily increases to a high in the months of March–April. The TEC then decreases in the following months till