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Analysis of Total Electron Content (TEC) Variations over Low-Latitude Indian Regions during a Low Sunspot Year of Solar Cycle 24

Sunil Kumar Chaurasiya[1*], Kalpana Patel[2], Nabin Sharma[3], Abhay Kumar Singh[4]

[1,2,3]Department of Physics, SRM Institute of Science and Technology, Delhi-NCR Campus, Modinagar, Ghaziabad, India.*
[4]Atmospheric Research Laboratory, Department of Physics, Banaras Hindu University, Varanasi, India.

Corresponding Email: [1]csunilchaurasiya@gmail.com*

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Abstract:** The Total Electron Content (TEC) measurements from two stations in the Indian sector, namely the equatorial station Bangalore (Geographic latitude 12°, 58' N, longitude 77°, 35' E) and the equatorial ionization anomaly (EIA) station Varanasi (Geographic latitude 25°, 19' N, longitude 82°, 59' E), are used to examine the variations of the TEC. In comparison to Varanasi, Bangalore has greater daytime TEC values. At the anomalous crest locations, significant daily changes in the TEC values are seen. Three distinct possibilities for the topside electron density present in the model (IRI-2001, IR01-Corr, and Ne-Quick) have been taken into consideration when comparing the observed GPS-TEC with the IRI-2016 model-derived TEC. While the TEC using the IRI01-Corr and IRI-2001 approach exhibits greater variances, the TEC obtained using the Ne-Quick options exhibits better agreement with GPS-TEC.

***Keywords:** Solar Cycle-24, Total Electron Content (Tec), Gps-Tec, Iri-2016 Model.*

1. INTRODUCTION

Within an altitude range of 50 to 1000 km, there is a space filled with charged particles called the ionosphere. It is evident that the ionosphere changes noticeably with altitude, latitude, longitude, time, season, solar cycle, as well as geomagnetic activity (Chaurasiya et al., 2023). The ionosphere's high density of free electrons has an impact on how electromagnetic radio frequency waves are transmitted. The primary contributors to this fluctuation include solar wind/magnetosphere-related phenomena, as well as those in the lower atmosphere. The Total Electron Content (TEC), a crucial ionospheric parameter provided by the Global Positioning

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System (GPS), is utilized significantly for the analysis of the ionosphere (S.N.V.S. Prasad et al., 2012; Chaurasiya et al., 2022a).

The GPS is a collection of 24 satellites that are arranged in six orbital planes and are in almost circular orbits above the surface of the planet. These orbits are inclined at an angle of 550 degrees to the equator and have an orbital period of about 11 hours and 58 minutes. The two L-band frequencies used by GPS satellites for signal transmission are L1 (1575.42 MHz) and L2 (1227.60 MHz), which are both generated from the fundamental frequency of 10.23 (f_0) MHz and have the values 154f0 and 120f0, respectively. Due to the ionosphere's dispersive properties, as these GPS signals travel through it, the carrier wave encounters a phase advance, which causes a group delay that varies with TEC. Consequently, the GPS receiver's positional accuracy is reduced (Hofmann et al., 1992; Rao et al., 2006). Therefore, it is essential to have a thorough understanding of the exact values as well as fluctuations of the TEC at various geographic regions under various geophysical circumstances to obtain higher positional precision. Numerous ionospheric models have been created during the past years to comprehend the physics that governs the dynamics of the ionosphere. There are three types of ionospheric models: experimental, analytical, and physical. The electron density (Ne-h) profiles in the IRI model are numerically integrated to derive TEC. (Singh et al.,2021; Chaurasiya et al., 2022b) state that the IRI model is incessantly improved as new data and modeling techniques are added.

Studies comparing TEC and the IRI model on low latitudes conducted by several scientists (McNamara and Wilkinson., 1983; Souza et al., 2003; Sharma et al., 2023) revealed where the data and the model agreed and disagreed. IRI-90 (Bilitza, 1990) overestimates in all seasons by roughly 180–320%, according to a collation of Faraday rotation data over New Delhi (28.60N, 77.20W) with IRI-90 throughout low solar activity (Singh et al., 1996). Iyer et al. (1996) at the equatorial anomaly station reported an overestimation of the expected TEC by IRI-90 at the time of low solar activity. The Ne-Quick topside option is used in the most recent version (IRI-2016) to get over the IRI-2007 model's constraints (Rao et al., 2006; Chaurasiya et al., 2022a).

It is suitable to conduct a comparative analysis amid the TEC data and those forecasted by the model because the Indian equatorial and low-latitude locations are both covered by the TEC provided by the IRI model as well as the GPS observations. Additionally, across low latitudes, the signal declination is possibly more probable due to the significant TEC variation near the peak of the Equatorial ionization anomaly caused by extremely high background TEC values. The International Reference Ionosphere (IRI) model and the TEC obtained from GPS satellite measurements have been compared by Rao et al. (2022). The IRI-TEC overestimates GPS-TEC for all seasons, according to Costa et al. (2004), who used GPS data from a low-latitude location to make this discovery. Therefore, it is crucial to conduct comparison research amid the model and the TEC data over low latitudes across the Indian regions to improve the model's ability to reflect TEC. This study examines the fluctuations in GPS TEC over two places in the Indian sector: Varanasi and Bangalore. Three different

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possibilities for the topside electron density, namely IRI01-Corr, IRI-2001, and Ne-Quick, are used to compare these results with those from the latest model, the IRI-2016.

Data

Throughout the low sunspot year of 2008 of the solar cycle 24, the vertical TEC (VTEC) data were acquired through the GPS receivers situated at two sites in the Indian region, specifically Varanasi and Bangalore. The three topside profile options (IRI01-Corr, IRI-2001, and Ne-Quick) offered by the IRI-2016 model (https://ccmc.gsfc.nasa.gov/models/iri2016_vitmo.php) are used to obtain the IRI model's forecasted values of TEC up to 2000 km altitude for the above-mentioned sites. The sunspot counts can be obtained at the webpage at http://sidc.oma.be/sunspotdata/dailyssn.php.

2. RESULTS AND DISCUSSION

Total Electron Content (TEC) fluctuations

The vertical TEC acquired at the two stations was analyzed in order to examine the temporal as well as spatial fluctuations in TEC. The monthly average TEC from January - December 2008 is presented in Fig. 1 together with the vertical TEC achieved at those two stations. This figure demonstrates that the TEC over Bangalore has a transient day minimum and broad day maximum that are not as noticeable over Varanasi. In all months at both sites, the day low in TEC is seen approximately at 0300-0500 h LT, whereas the day extreme is seen approximately at 1100-1300 h LT. The daytime maximum TEC values over Bangalore, which range between 20 and 33 TECU, are greater than those over Varanasi, which range between 9 and 30 TECU. The overnight TEC values over Bangalore range from 10 to 25 TECU, and there are considerable variances between the nighttime TEC values for various months. In contrast to Bangalore, the nighttime values of TEC over Varanasi vary by about 8 TECU and remain nearly constant throughout the year.

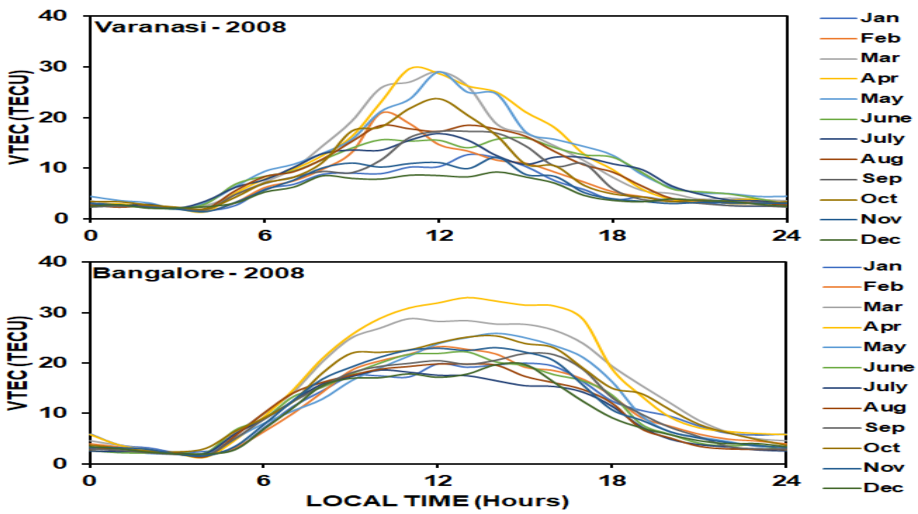

Fig. 1. Monthly average diurnal fluctuation of the TEC across Varanasi and Bangalore from January 2008 to December 2008.

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In contrast to Bangalore, the nighttime values of TEC over Varanasi vary by about 8 TECU and remain nearly constant throughout the year. The seasonal means for the three equinox seasons (March, April, September, and October 2004), winter (January, February, November, and December 2004), and summer (May, June, July, and August 2004) for both stations are shown in Fig. 2 to analyze the seasonal fluctuations in the TEC.

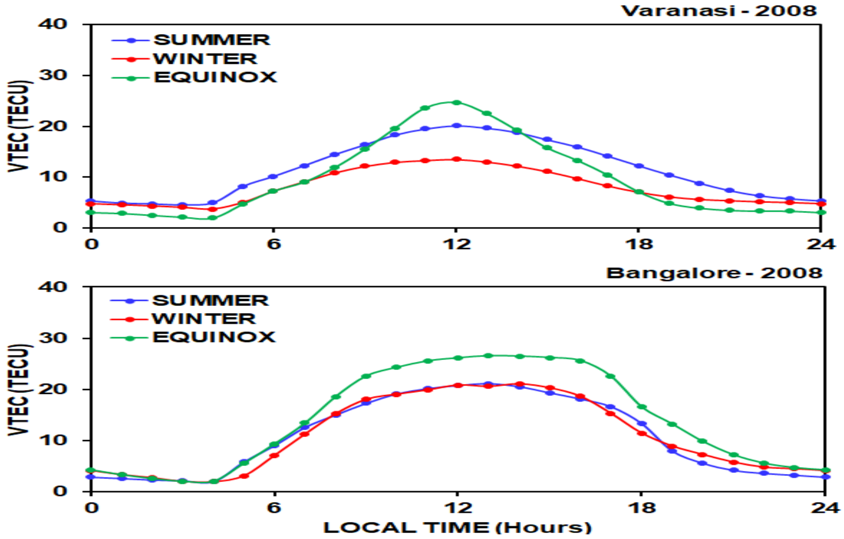

Fig. 2. The mean diurnal fluctuation of the temperature across Varanasi and Bangalore for the equinox, winter, and summer seasons from January - December 2008.

As can be observed from these data, TEC day maximum values at both locations are greater throughout equinoctial months and lower throughout summer and winter. Over Bangalore, the nighttime TEC values in the summer months are greater than those in the winter months, although they are equal in Varanasi during both seasons. According to Bagiya Mala et al. (2009), thermos-spheric neutral composition directly regulates the seasonal fluctuation of TEC. The meridional wind blows from the equator toward the pole because throughout the day the equator is warmer than the pole. At equatorial and low-latitude locations, this meridional wind flow alters the neutral composition and decreases O/N_2. This reduction will be at its greatest at the equinox. N_2 dissociation is the main process that eliminates atmospheric electrons at 350 km altitude (F_2 layer). As a result, the O/N_2 ratio will decline, leading to a higher electron density and a higher TEC at the equinox. The significant daily inconsistency of the F-region electron densities, as indicated in f_oF_2 and TEC, has an impact on the accuracy or consistency of any ionospheric parameter estimation. The daily changeability of TEC is depicted in Fig. 3 by the vertical TEC measured in Varanasi and Bangalore in the month of December 2008. As can be observed from this graph, the TEC levels vary significantly from day to day regardless of location. But at both stations, the TEC fluctuates differently from one day to the next.

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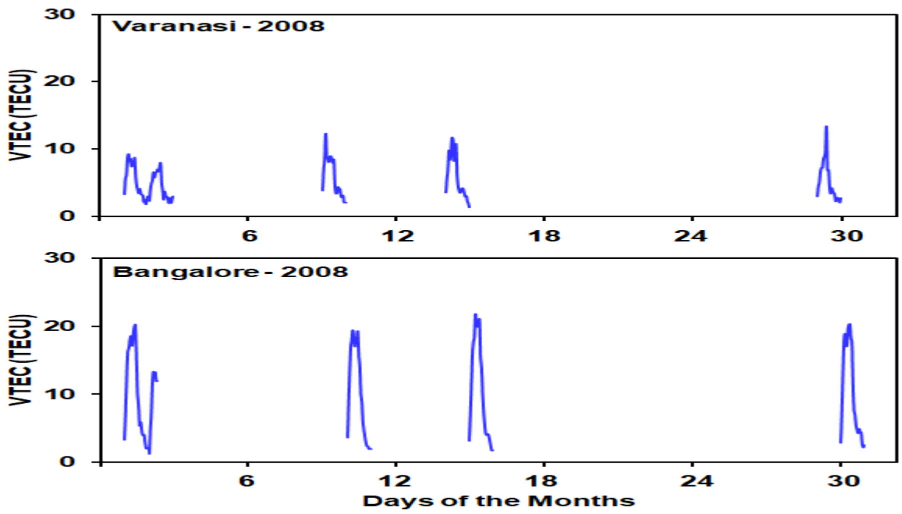

Fig. 3. The daily change of the TEC between Bangalore and Varanasi from December 1 to December 31, 2008.

The TEC values are found to alter significantly near the crest of the anomalous peak (Varanasi), but not much at the equatorial station in Bangalore. The plots of the diurnal fluctuation of TEC for all the months of January-December 2008 across Varanasi and Bangalore are provided in Figs. 4 and 5, respectively, to help the reader comprehend the daily inconsistency in TEC over various stations in various months.

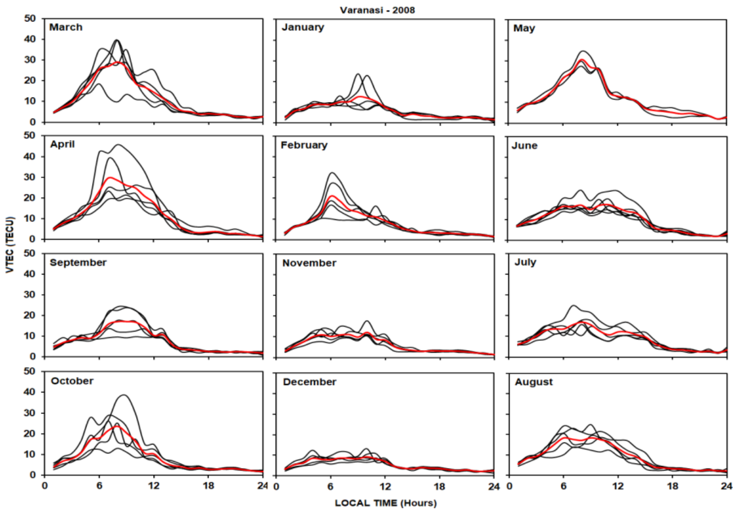

Fig. 4. Mass plots of the diurnal fluctuation of TEC across Varanasi for various months in 2008.

At both locations, it is noted that the day-to-day fluctuation is higher throughout the equinoctial months than it is during the other seasons. From the equator (Bangalore) to the low latitudes of Varanasi, TEC value and fluctuation rise. This can be as a result of the stations further than from the magnetic equator are typically located nearer to the Appleton anomaly crests, which are dense and display significant seasonal and daily change. In

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comparison to Bangalore, Varanasi experiences less daily variation throughout the three seasons. The TEC values at night over Bangalore are nearly flat and do not exhibit any daily variations. The inconsistency of TEC over the Indian low-latitude region was examined by Dabas et al. (1984), Rastogi and Alex (1987), and Aravindan and Iyer (1990) using information from Faraday rotation measurements. The daily variations in TEC in the Indian region are observed as single-day irregularity, alternate-day irregularity, as well as long-term periodic fluctuations of 27 and 45 days, all of which are reportedly measured by the equatorial electrojet and not always correlated with solar as well as magnetic changes, according to Dabas et al. (1984).

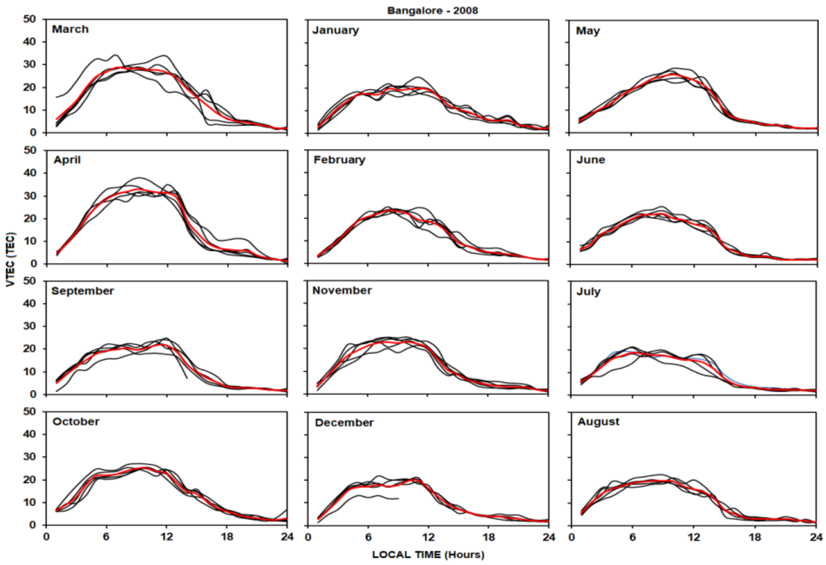

Fig. 4. Mass plots of the diurnal fluctuation of TEC across Varanasi for various months in 2008.

Even though there have been numerous studies conducted on this topic from numerous perspectives, they are still significant because they are based on the investigation of data collected instantaneously from various latitudes in the Indian regions, adding to our understanding of low latitude morphological features that are crucial for the development of satellite-based navigation and communication systems and their applications.

Assessment of GPS-TEC with IRI model-derived TEC

As a result of the topside dispersion having a significant influence on TEC (Bilitza et al., 2006), the modern accessible and reorganized version of the IRI model, IRI-2016, has developed with three possibilities for topside electron density distribution. This is due to the inconsistencies revealed by numerous scientists and modeling exertion by many employees.

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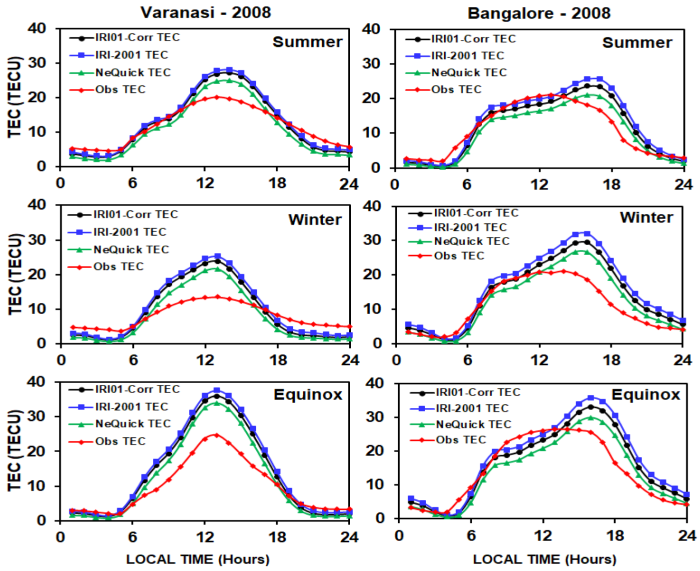

Fig. 6. Diurnal fluctuation of GPS TEC as well as IRI-2016 predicted TEC using three possibilities for topside electron density (IRI01-Corr, IRI-2001, and NeQuick) for the three distinct seasons of summer, winter, and equinox across Varanasi and Lucknow in 2008.

Fig. 6 depicts the diurnal fluctuation of GPS-TEC and IRI-forecasted TEC over Bangalore and Varanasi for various seasons using all three options offered by the IRI-2016 model. This figure shows how the TEC values from the IRI01-Corr, IRI-2001, and NeQuick techniques were lower than the GPS-measured TEC values over both stations at night. More than NeQuick TEC, the IRI01-Corr TEC, and the IRI-2001 TEC underestimated GPS TEC. For the three different techniques, deviations are greater throughout equinoctial months and lower throughout winter months. In the absence of large-scale depletions, Sobral et al. (1997) compared rocket flight observations of the OI 6300 A air-glow/electron density to electron density estimated from the IRI model at the Brazilian equatorial region. According to their findings, there may be differences between IRI-predicted as well as observed electron densities of at least 10% and, for certain altitude levels, a startling divergence of up to 112%. Based on a comprehensive statistical investigation that concentrated on the geomagnetic anomaly region, The extremely fluctuating height distribution of the electron density may always make it impossible to accurately portray the electron density profiles in the equatorial area when ionospheric bubbles are present.

3. CONCLUSIONS

The diurnal, daily, and seasonal characteristics of TEC are investigated using GPS-derived TEC data over the equatorial stations Bangalore and Varanasi in the Indian region. Over Bangalore, the diurnal trend of the TEC has exhibited a short-term day minimum and a broad day maximum with the ionization remaining stable at night. When compared to Varanasi, Bangalore has higher TEC day maximum values. In comparison to Varanasi, the daytime maximum TEC values are greater than in Bangalore. At both locations, the TEC values are greater during the months that coincide with the equinoxes and lower during the winter and summer. It is shown that there is a significant day-to-day changeability, with the equatorial station showing more of it than the EIA station. The TEC obtained via the IRI-2016 model using all three methods (IRI01-Corr, IRI-2001, and Ne-Quick) and the GPS-TEC have demonstrated good agreement for both stations, while the TEC obtained from the IRI01-Corr and IRI-2001 method exhibits significant differences. It should be identified that the IRI-2016 model's Ne-Quick for topside density provides improved predictions over both Indian stations.

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