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RESEARCH ARTICLE

Diurnal and seasonal variation of GPS-TEC during a low solar activity period at EIA region (Bhopal)

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Abstract

The ionosphere near the equatorial ionization anomaly crest region in the Indian ionospheric sector was studied from May 2016 to April 2017, a solar minimum period. Total electron content (TEC) recorded using the multiple frequency GPS receivers at Bhopal (23.2° N, 77.4° E & MLAT 14.2° N) is used for the study. The diurnal variation shows that the day minimum in TEC is attained around 06:00 hours LT, and the day maximum occurs at about 16:00 hours LT. A similar diurnal pattern was observed in all months across various seasons. During the period of study, it was observed that Seasonal variation of TEC was minimal in winter, whereas highest during equinox and summer months. The variation of TEC_{max} with EEJ shows a positive correlation between the parameters for all the months. The highest correlation (0.8398) was observed in January 2017, while it was lowest (0.4004) in March 2017 and the results were compared with earlier observations, and a possible mechanism was discussed.

Keywords: Total electron content, Equatorial ionization anomaly, Global positioning system, Solar indices, Electron electrojet.

Introduction

Earth's atmosphere contains a series of regions that have a relatively large number of electrically charged atoms and molecules. As a group, these regions are collectively called the ionosphere. The ionosphere consists of a sufficient number of ions and free electrons, which can affect radio signals. Ionospheric irregularities as a result of inhomogeneity in electron density lead to variations in the intensity of radio signals (Somoye, 2010; Ogwala *et al.*, 2018; Ogunmodimu *et al.*, 2018). Akala *et al.* (2011) reported that the variable nature of the equatorial and low-latitude ionosphere adversely affects communication and, navigation and satellite systems in the region. The equatorial and low-latitude ionosphere exhibits unique features such as the seasonal anomaly, semi-annual anomaly, equinoctial anomaly, noon bite-out, spread F, equatorial electrojet (EEJ) and equatorial plasma bubbles (Stankov, 2009; Maruyama *et al.*, 2004; Jee *et al.*, 2004; Codrescu *et al.*, 1999).

The diurnal and seasonal variations of most of the ionospheric parameters, such as the peak density of the F2 layer and ionospheric total electron content (ITEC), depend largely on the sun's declination and the phase of the solar cycle. The total electron content (TEC) is an important ionospheric parameter. The TEC is the total number of electrons in a vertical column of 1 m^2 cross-section from the height of the GPS satellite (~20,000 km) to the receiver on the ground. It is measured in TEC units (TECU), and 1 TECU is equal to 1×10^{16} el m^2. The study of temporal, spatial, and solar-induced variations in TEC is useful for users of satellite-based radio systems. Changes in TEC are of serious concern at low and equatorial latitudes. The ionospheric effects on satellite communication, tracking, and navigational control applications are directly proportional to the TEC. It is now well accepted that a GPS-based navigation system provides an accurate, continuous, all-weather, three-dimensional location of a user, and in recent years, the dependence on this navigation system has increased drastically. When the GPS signals propagate through the ionosphere, the carrier experiences a phase advance and the code experiences a group delay due to the total number of free electrons along the path of the signals from the satellite to the receiver. Therefore, the carrier phase pseudo ranges are measured to be too short, and the code pseudo ranges are measured to

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be too long compared to the geometric range between the satellite and the receiver. Many researchers have studied the morphological features of TEC at low and equatorial latitudes Ram Rao *et al.*, 2004-2005; Bhuyan *et al.*, 1992; Arvindan *et al.*, 1990; Bhuyan *et al.*,1992; Solar activity dependence of TEC been studied by a large number of researchers Balan *et al.*, 1993; Dabas *et al.*,1993; Ram Rao *et al.*, 1994; Chakraborty *et al.*, 2007. Rama Rao *et al.*,1980, Studied the diurnal variations in TEC at Waltair in India. They observed many characteristics typical of a low-latitude ionosphere, such as a short-lived pre-dawn minimum, a steep early morning rise followed by a broad mid-afternoon maximum, and a steep post-sunset fall. Dabas *et al.*, 1993, studied the variations in TEC with different solar indices, i.e., EUV, F10.7 solar flux, and smoothed sunspot number (SSN) for summer, winter, and equinoxes. They concluded that the general and linear variations with EUV and F10.7 solar flux. Rama Rao *et al.*, 1994 detected a good correlation of TEC with SSN (0.84) during the years 1978-1990. Chauhan *et al.*, 2011, studied the diurnal and seasonal variation of GPS-TEC during a low solar activity period as observed at low latitude station Agra in India. They studied the variations in TEC (max) with different solar indices, that is, EUV, F10.7 solar flux, and smoothed sunspot number (SSN) for the summer, winter, and equinox months. They concluded a good correlation of TEC (max) with F10.7 solar flux (0.84) during the years 1978-1990.

Gupta and Singh (2001) observed long-term ionospheric TEC variations over Delhi (geographic lat 28.36° N, long 77.13° E), India for the period 1975–80 and 1986–89. They concluded that the winter TEC anomaly appears only during high solar activity. They also found a positive correlation between the TEC and F10.7 solar flux. Rama Rao *et al.*, 2006, presented the temporal and spatial variations in TEC derived from the simultaneous and continuous measurements for the first time using the Indian GPS network of 18 receivers located from the equator to the northern crest of the equatorial ionization anomaly (EIA) region and beyond, covering a geomagnetic latitude range 1° to 24° N. in the analysis, they used 16-month data for the low sunspot activity period March 2004-June 2005. In their findings, along with the diurnal and seasonal variations in TEC, the day-to-day variability was also significant in all seasons, particularly during the daytime, with maximum variations in the EIA crest regions.

Chakraborty and Hajra (2007) analyzed TEC data at Calcutta, a station situated vertically below the northern crest of the equatorial ionization anomaly. They studied the dependence of TEC on EUV radiation from the sun and found that, in addition to day-to-day changes in TEC, the monthly mean TEC was very well correlated with F10.7 solar flux. Using a dual-frequency GPS receiver, Bagiya *et al.* (2009) investigated diurnal and seasonal TEC variations during a low solar activity period (2005–2007) at Rajkot, a station near the equatorial ionization anomaly crest in India. It was found that the TEC was maximum during the equinox months (March, April, September, and October) and minimum during the winter months (November, December, January, and February), with intermediate values during the summer months (May, June, July, and August). The equatorial electrojet is a narrow ribbon of current flowing eastward in the daytime equatorial region of Earth's ionosphere.

The equatorial ionosphere exhibits large spatial gradients in electron density due to the well-known equatorial ionization anomaly (EIA), with a trough at the equator and a crest at ~ 15 ° north and south geomagnetic latitudes. Rastogi and Klobuchar (1990), using ATS-6 TEC measurements from India, have shown a large day-to-day variability in the location of the anomaly crest in the Indian sector and its dependence on the equatorial electrojet and counter electrojet. Sethia *et al.* (1980) and Balan and Iyer (1983) have shown that the electrojet has a pronounced influence on the development of EIA in TEC based on the sparse data of previous satellites of opportunity.

Balan *et al.*, (1994), Ouattara *et al.*, (2009), Akala *et al.*, (2013), Ayorinde *et al.*, (2016), Ratovsky *et al.*, (2022), Zoundi *et al.*, (2021), have examined the dynamic of the ionosphere and its characteristics at all latitudes during different phases of the solar cycle under disturbed and quiet conditions. Some of them have highlighted the fact that the variability depends on the level of sun agitation, the season and the geomagnetic activity. Tsai *et al.*, (2001), Ogwala *et al.*, (2019), The seasonal variations of the total electron content in the regions of equatorial anomalies are the combined effects of the neutral trans-equatorial, sub-solar and towards the equator. Mukherjee *et al.*, (2010), studied the variability of TEC on the crest of the equatorial anomaly station in Bhopal (India) during the solar activity period (2005-2006) using GPS and observed a greater variability of the TEC on quiet days compared to disturbed days.

The present paper discusses the observations of the diurnal and seasonal variation of GPS-TEC during a low solar activity period (May 2016 to April 2017) at Bhopal (23.2° N,77.4° E & MLAT 14.2 °N), a station near the equatorial ionization anomaly crest region in India, using the data recorded by a multiple frequency GPS network of receivers at the above-mentioned station. The results were compared with earlier observations and a possible mechanism was discussed.

Data and Method of Analysis

To study the diurnal and seasonal variation in TEC over the station near the crest of equatorial ionization anomaly, a multi-frequency receiver [L1(1575.42 MHz), L2 (1227.60 MHz), L5(1176.45 MHz)] has been installed at Govt. M.L.B Girls P.G College, Bhopal (Geog.23.2°N,77.4°E & MLAT 14.2°N) in 2016 with the collaboration of Space Physics Laboratory, VSSC Trivandrum. The receiver tracks signals from GPS, GLONASS, GALILEO, SBAS, COMPASS, &QZSS constellation of GNSS satellite system. The receiver generates and outputs 50 Hz phase and amplitude samples for all visible satellites and frequency bands. TEC data is generated every minute for all satellites cracked by the receiver. TEC, Amplitude scintillation and phase scintillation data along with satellite pseudo random number (PRN, i.e., unique sequence number of satellite), azimuthal angle and elevation angle is recorded automatically. In the present study we have used the GPS data for the period of May 2016 to April 2017 observed at Bhopal.

TEC is defined as the line integral of electron density on a given ray path. This slant TEC (STEC or simply TEC) corresponds to the total no of free electrons along a cylindrical path with a 1 m^2 cross-sectional area. The unit of TEC is equal to TECU where 1 TECU = 10^{16} electrons per meter square. When TEC is calculated on a vertical path in the local zenith direction, it is called vertical total electron content (VTEC). VTEC can be expressed as

$$VTEC = (STEC - [b_{R+} b_{s]}) / S(E) \quad ......(1)$$

Where STEC is the uncorrected slant TEC measured by the receiver, S(E) is the obliquity factor with zenith angle, z, at the ionospheric pierce point (IPP), E is the elevation angle of the satellite in degrees, and VTEC is the vertical TEC at the IPP. S(E) is defined by

$$S(E) = 1/\cos(z) = \{1- (R_E * \cos(E) / R_E + h_s)^{2}\}^{-0.5} \quad ......(2)$$

Where R_E is the mean radius of the Earth measured in km, hs is the height of the ionosphere from the surface of the Earth, which is approximately equal to 350 km for Bhopal station, z is te zenith angle of the satellite.

To remove multipath error the data has been filtered for elevation angles less than 30. In order to study the solar variation of TEC, the data of Solar flux (F10.7 cm), Kp, AP, sun spot number have been obtained from the internet through (http://omniweb. Gsfc.nasa.gov/from/dx1.html). To study the seasonal variation in TEC, we have grouped the data into three seasons as summer (May, June, July, August), winter (November, December, January, February) and equinox (September, October, March, April) months. The daily maximum value of TEC (TEC_{max}), solar radio flux (F10.7), sunspot number (SSN), KP index, and Ap index for the above-mentioned period has been plotted, and to study the diurnal variation in TEC, the data during the magnetically quiet period has been considering.

The proxy to the prompt penetration of the electric field can be the equatorial electrojet strength (EEJ), which is the difference of horizontal component (ΔH)off-e at the low latitude station. In the Indian region, Tirunelveli (8.42 ° N, 77 °.480 E, Geomag. Lat. 0.57° S) (ΔH)Tir and Alibag (18.63° N,72.87° E, Geomag. Lat.10.03° N) (ΔH)Ali are used to calculate the EEJ, provided by Indian Institute of Geomagnetism (IIG), Mumbai. Therefore an attempt have been made to study monthly and seasonal variations of $TEC_{(MAX)}$ with EEJ during the above-mentioned period.

Results and Discussions

Diurnal Variation in TEC

The variations in TEC were analyzed by creating mass plots of TEC for each month from May 2016 to April 2017. In order to find the quietest month during the period of study, we have observed that the ΣKp was lowest during December 2016 as compared to the rest of the months during the period of study. As an illustration, the diurnal variations of TEC for December 2016 are depicted in Figure 1. The figure indicates that the day minimum in TEC is attained around 06:00 hours LT, and the day maximum occurs near about 16:00 hours LT. A similar diurnal pattern was observed in all months. The diurnal variation of TEC exhibits a short-lived pre-dawn minimum, a steady early morning increase, followed by an afternoon maximum, and a gradual decline after sunset. The observations of diurnal variation in TEC reveal that the time at which TEC reaches its diurnal peak varies between 13:00-16:00 hours LT. Significant fluctuations in TEC were observed during daytime hours, whereas night-time variations were found to be relatively consistent.

The monthly variation in the diurnal mean of TEC is depicted in the contour plot of Figure 2, which reflects the diurnal and seasonal fluctuations. The figure confirms that the diurnal peak of TEC fluctuates between 13:00 and 16:00 hours LT, with the highest values recorded during the summer and equinox months, and the lowest values during the winter months. Notably, the winter anomaly is not present in this timeframe.

Due to the preponderance of recombination processes, the TEC values decrease between 00:00 and 06:00 hours LT, reaching its minimum. After 06:00 hours LT, the TEC values increase and reach their maximum between 13:00 hours and 16:00 hours LT. This is in agreement with previous studies Dabas *et al.*, (2003), Somoye *et al.*, (2011), Hajra *et al.*, (2016), and D'ujanga *et al.*, (2016). The increase in TEC during sunrise is attributed to the upward vertical drift of ExB plasma and the rapid filling of the magnetic field tube due to solar extreme ultraviolet (EUV) radiation, which causes an eastward electric field at the equator, lifting the plasma to high altitudes Ogwala *et al.*, (2019), Somoye *et al.*, (2011), D'ujanga *et al.*, (2016). Saranya *et al.*, (2015) after 18:00 hours

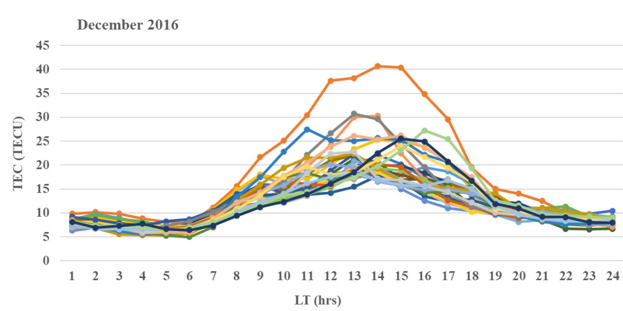

Figure 1: Diurnal (Hourly)Variation of TEC for December 2016, a lowest magnetic activity month

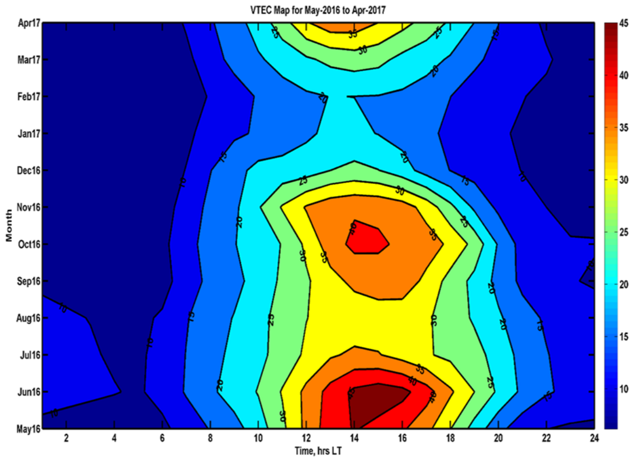

Figure 2: The monthly variation in the diurnal mean of TEC for period of May 2016 to April 2017

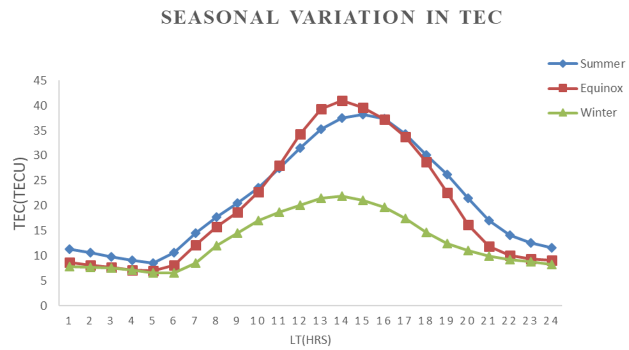

Figure 3: Seasonal variation in TEC for the May 2016-April 2017

LT, the TEC values show a decreasing trend until 23:00 hours LT, indicating a gradual decline in photo-ionization and an increase in recombination processes. Similar analyses were conducted by Bolaji *et al.*, (2012), Fayose *et al.*, (2012), Okoh *et al.*, (2015), and Eyelade *et al.*, (2017).

Seasonal Variation in TEC

The mean seasonal variation in the TEC from May 2016 to April 2017 is shown in Figure 3. In this figure, the variation in TEC at local time during the equinox, summer, and winter months are shown. From the mean seasonal variation plot (Figure 3) it was clear that the variation during equinox and summer are almost similar whereas it is winter different in winter months. Our results support the result presented by Tyagi & Gupta (1990), Bagiya *et al.* (2009) and Chauhan *et al.* (2011), as studied the diurnal and seasonal variation of GPS-TEC during a low solar activity period as observed at a low latitude station Agra (geographic lat 27.12°. N, long 78.89° E, dip 41.1°), India.

Tyagi and Das Gupta (1990), in their review paper, presented the seasonal variation of TEC for low, moderate and high solar activity periods for Delhi station (geographic lat 28.36° N, long 77.13° E,) and find the absence of winter anomaly at low latitude during the low solar activity period. The same absence of winter anomaly was also reported by (Bagiya *et al.* (2009 and references therein) during low solar activity period.

Rishbeth and Setty (1961), suggested that the seasonal changes result from changes in the ratio of the concentration of atomic oxygen and molecular nitrogen in the F-region. On the basis of the calculation of scale height of the observing gas, it was found that in equinoctial months, the solar radiation is absorbed mainly by atomic oxygen; this is the reason of high value of TEC_{max} during equinoxes. During low solar activity, the lowest value of TEC max is observed in winters which rise to annual variation in TEC_{max} Gupta and Singh (2001).

TEC Variation During Varying Solar Conditions

Solar radiation affects the ionosphere, as it emits a wide range of spectrum. Therefore, in order to study the variation of TEC during varying solar condition, we have used the four solar indices: Solar radio flux (F10.7), sunspot number (SSN), K_p index, and A_p index for low solar activity period May 2016 to April 2017.

The Figure 4(a) – (e) depicts the the variation of Kp , Ap, F10.7, SSN and daily maximum value of TEC respectively during the period of study. It is observed that TEC_{max} was high during the beginning of May 2016 then it starts falling till end of the June 2016. Once again its stats increasing and reaches to max value between Aug and OCT 2016 , then fall off from oct 2016 to feb 2017 then starts increasing again. The solar flux, SSN, Ap and KP parameters have a pattern of increasing and decreasing together. However, the SSN pattern shows a drastic sharp increase in some months, while for solar flux was no so sharp. The Ap and Kp parameters have a pattern of increasing and decreasing together. Solar flux and Kp shows the value of the super from Oct 2016 to Feb 2017. Such inconsistencies in the variation of the solar flux and the SSN index have been reported by Chakrabarty *et al.* (2012) and Florence *et al.* (2017) (As they studied for period of 2010 to 2013), who observed discrepancies in these parameters over the anomaly crest region and reported a 7-month delay between onset of enhancement of SSN and that of the solar flux. As we are studying for low solar activity period, this might be the reason for observing the suppressed value of TEC_{max}, Ap, and Solarflux from Oct 2016 to Feb 2017.

Figure 5(a) displays a scatter plot of TEC_{max} in relation to magnetic parameters Ap and Kp. Additionally, Figure 5(b) displays a scatter plot of TEC_{max} relative to solar parameters F10.7 and SSN for three distinct seasons, and the correlation coefficient between the two parameters is also depicted in the figure. For each season, the data from the four months was combined. As illustrated in Figure 5(a), the Ap index ranged from 1 to 70 units, and the ΣKp index ranged from 3 to 57 units. For both parameters, TEC_{max} was highest for the winter months (with a negative correlation), followed

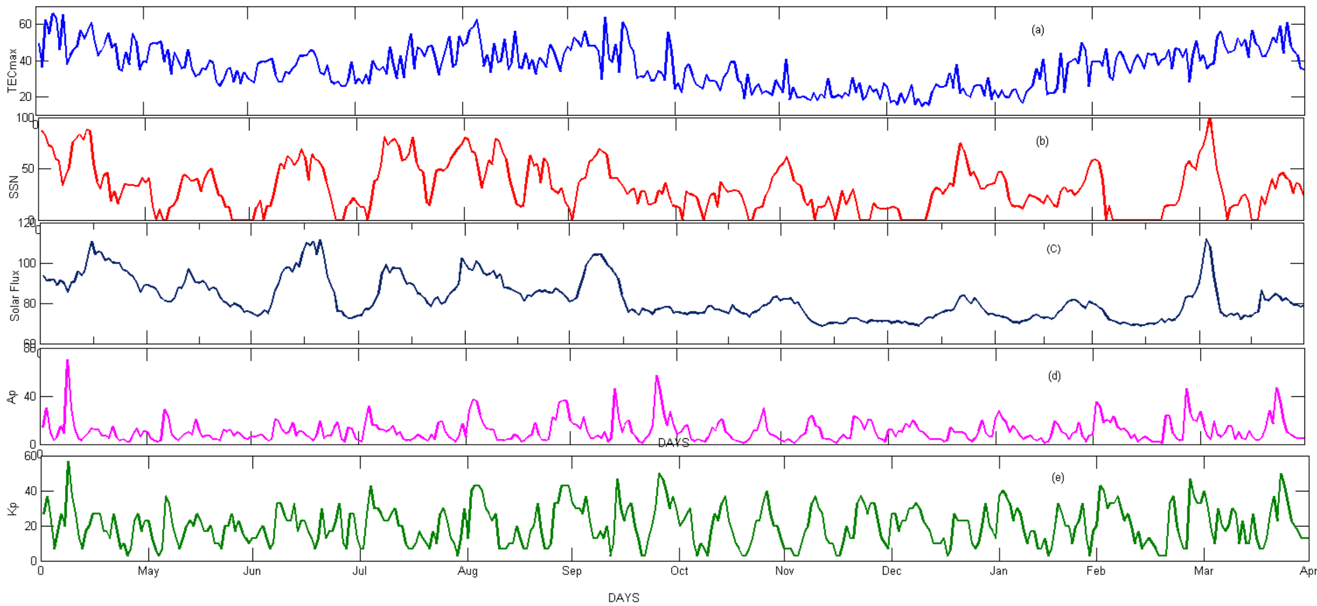

Figure 4: (a) – (e) Depicts the monthly variation of TECmax, SSN, F10.7, Ap and Kp respectively during the period of study at Bhopal

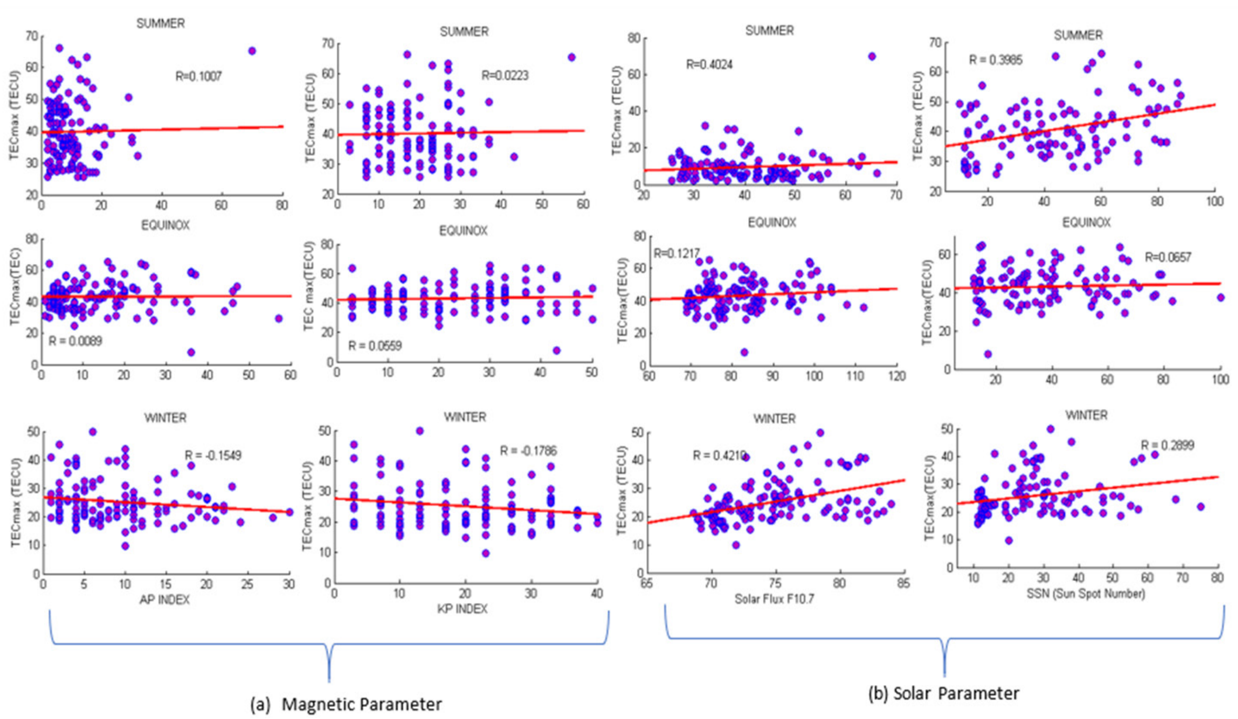

Figure 5: Seasonal variation in TECmax and its corresponding solar and magnetic activities

by summer and equinox. The correlation coefficients for the Ap and Kp indices were found to be very poor for all three seasons.

Figure 5(b) indicates that the solar flux (F10.7) varies between 68 and 111 units, while the sunspot numbers range from 10 to 100. The highest correlation between TEC_{max} and SSN was observed during the summer months, followed by winter and equinox. In contrast, the TEC_{max} for the solar flux (F10.7) was highest during winter months, followed by summer and equinox. The correlation coefficient (R) values for SSN were found to be 0.3984, 0.2903, and 0.0655 for the summer, winter, and equinox seasons, respectively. The values of R for F10.7 were 0.4024, 0.4209, and 0.1216 for all three seasons, respectively. These findings are displayed

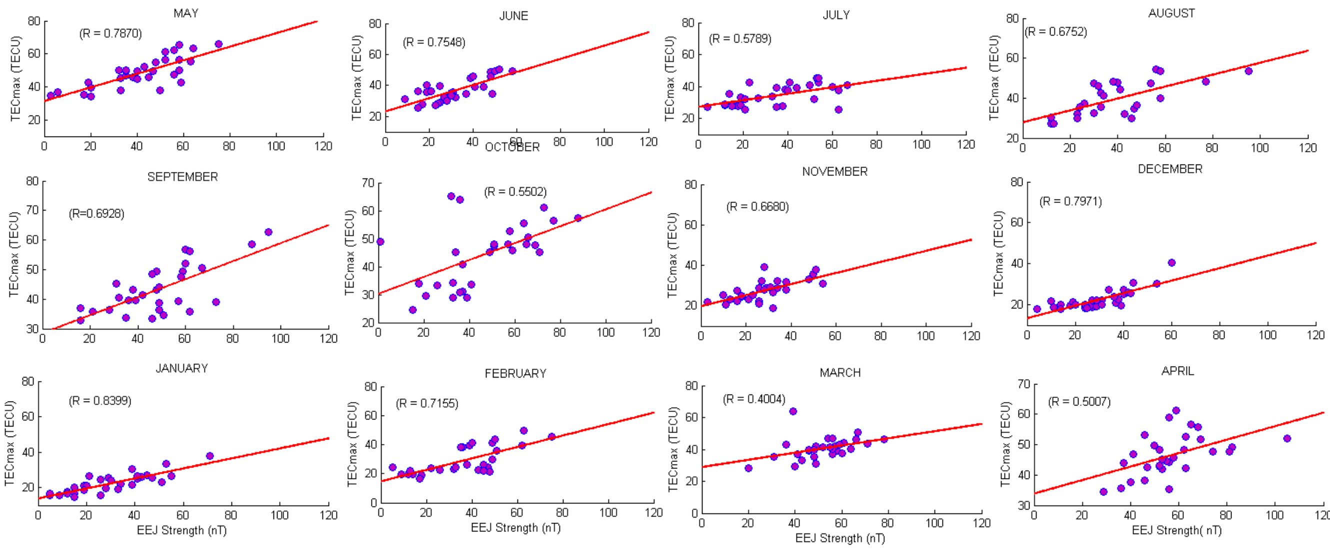

Figure 6: Monthly plots of daily TEC_{max} Vs EEJ STRENGTH (nT) for period May 2016 to April 2017

in the corresponding figures. Due to the low solar activity period during which this study was conducted, the range of solar indices was insufficient to obtain a reliable correlation. However, it is suggested that these results be compared with data from a high solar activity period in future studies. Florence *et al.* (2017) reported a high correlation for the solar indices during the period of high solar activity in 2011.

The Figures 5 (a) and (b) illustrate the seasonal variation in TECmax and its corresponding solar and magnetic activities. These figures also display the correlation coefficient (R) for reference.

Monthly and Seasonal Variation of TECMAX with EEJ

Equatorial electrojet (EEJ) is an intense eastward current flowing in the equatorial ionospheric E-region at about a 105 km altitude. As it is already mentioned in the introduction, EEJ controls the strength and latitudinal extent of equatorial ionization anomaly. In this section, we have tried to study the monthly and seasonal variation of TEC_{max} with EEJ. Figure 6 shows the monthly variation of TEC_{max} with EEJ for the period of May 2016 to April 2017. It can be seen from the figure that all month's shows a strong positive correlation of TEC_{max} with EEJ. The highest correlation with TEC_{max} was observed in January 2017, the value of correlation coefficient (R) for EEJ have been found to be 0.8398, respectively. The lowest correlation with TEC_{max} was observed in March 2017. The value of the correlation coefficient (R) for EEJ have been found to be 0.4004, respectively. The remaining months also show a significant correlation of TEC_{max} with EEJ.

The correlation of TEC_{max} with EEJ for summer, winter and equinox months has been calculated. For each season, the data of four months are grouped together. It can be observed that the highest correlation with TEC_{max} in observed winter months (R = 0.6994) which is followed by summer (R = 0.6723) and equinox months (R = 0.5445).

The transport of the low-latitude ionospheric plasma controls the TEC distribution which is originated by the vertical EXB drift and electrojet, as both of these are driven by the eastward electric filed. Dabas *et al.* (1984) reported that the equatorial electrojet has a pronounced influence on TEC over a large latitudinal belt starting from the equator to 25°N dip latitude, Rama Rao *et al.* (2005) and Bagiya *et al.* (2009) have shown that equatorial electrojet controls the altitude of the lifted plasma and the location of the crest of the equatorial ionization anomaly, the higher the EEJ strength the higher the altitude to which plasma is lifted as the equator and the further the location is of the crest of the equatorial ionization anomaly. Khadka *et al.* (2016) has studied the mutual relationship of the EEJ with TEC for West America for the solar minimum period 2008. They observed a positive correlation between EEJ and TEC. Our results support the results presented by Rama Rao *et al.* (2005), Dabas *et al.* (1984), Bagiya *et al.* (2009) and Khadka *et al.* (2016).

Conclusion

In the present paper an attempt has been made to study the diurnal, season and solar activity variation of TEC for a low solar activity period for May 2016 to April 2017. The salient features of the above study may be summarised as:

- The diurnal variation shows that the day minimum in TEC is attained around 06:00 hours LT, and the day maximum occurs about 16:00 hours LT. The diurnal variation of TEC exhibits a short-lived pre-dawn minimum, a steady early morning increase, followed by an afternoon maximum, and a gradual decline after sunset.
- During the period of study, it was observed that seasonal variation of TEC was almost similar during equinox and summer months, whereas the variation during the winter differs markedly from rest of the two periods.

- The correlation of TEC with the solar and magnetic indices, namely solar radio flux (F10.7), sunspot number (SSN), K_p index, and A_p index and, found the least correlation as this study is carried out for a low solar activity period, the range of solar indices is too small to obtain reliable correlation.
- The study of monthly variation of TEC_{max} with EEJ shows a significant positive correlation between two parameters for the month. The highest correlation coefficient (0.8398) was observed in January 2017, while the lowest correlation coefficient (0.4004) was observed in March 2017.

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