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On the TEC variability during 24th solar cycle near northern anomaly crest

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Dedicated to Prof R G Rastogi,FNA

The dual frequency signals from the GPS satellites recorded at Rajkot (22.29 °N, 70.74 °E, geographic, 14.03 °N geomagnetic) near the Equatorial Ionization Anomaly (EIA) crest in India are analysed to derive the Total Electron Content (TEC) for the years 2006 to 2014 covering extremely low to high solar activity period during the 24th solar cycle. The subtle differences are found in diurnal variation pattern of TEC from low to high solar activity. The seasonal behaviour shows that TEC is maximum for equinox months. The winter anomaly is observed during the high solar activity period only for the year 2014. It is found that the EUV flux is most suitable for solar activity dependence of ionization with correlation coefficient of 0.83. The EUV flux and 10.7 cm flux also show the saturation in ionization production.

1 Introduction

The GPS based satellite control system and Navigational systems are now being standardized and used extensively. The GPS based navigational system has advantage of accurate, continuous and all weather three dimensional location measurements. The geographic position of user is derived using the time delay measurements done at GPS receiver. However, the accuracy in position is directly proportional to the Total Electron Content between the GPS satellite and receiver path [1]. The "carrier" and the "code" signals transmitted by GPS satellite undergo the phase advance and the group delay, respectively. These properties are directly proportional to TEC. For better accuracy, therefore the precise value of TEC under different geophysical and solar conditions is must for navigational use of GPS.

TEC varies with local time, season and solar activity and has been studied over few decades by now [2-9]. For the Indian sector of equatorial ionosphere, a good amount of knowledge on TEC variations under different conditions is available in literature. The low earth orbiting satellites and ATS-6 geostationary satellite were used to study the features of TEC variations [10-13]. With the advent of GPS satellites, GAGAN (GPS Aided Geo Augmented Navigation) network of stations monitoring TEC and scintillations in the Indian subcontinent has been possible. The characteristic features of GPS derived TEC are also studied at equatorial station like Waltair [14], and at anomaly crest region like Rajkot [9] and Udaipur [15].

The equatorial ionosphere is also controlled by another phenomenon known as equatorial ionization anomaly (EIA) having crest at ~15° magnetic latitude in both hemispheres. Using the ATS-6 measurements Rastogi and Klobuchar [16] showed that there is a large day to day variability in the location of the anomaly crest in the Indian sector and it is also dependent on the equatorial electrojet. Sethia *et al* [17] and Balan and Iyer [18] have shown that the equatorial electrojet has a pronounced influence on the development of EIA and TEC.

The present paper describes the TEC behaviour at Rajkot, in the anomaly crest region using the dual frequency GPS measurements. The importance of the present study is that it covers the extreme low solar activity period (2009-2010) and high solar activity period (2013-2014) of the 24th solar cycle in continuation.

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2 TEC measurements using dual frequency GPS signals

TEC is proportional to the ionospheric differential delay between the dual frequency transmissions from the GPS satellites viz. L_1 (1575.42 MHz) and L_2 (1227.60 MHz). These measurements lead to so called slant TEC estimation

$$STEC = \frac{1}{40.3} \times \left(\frac{1}{L_1^2} - \frac{1}{L_2^2} \right)^{-1} \times (P_1 - P_2) + TEC_{CAL} \tag{1}$$

Where P_1 and P_2 are pseudo ranges at L_1 and L_2, respectively. The TEC_{CAL} is the calibrated receiver bias supplied by the manufacturer as 0.793 TECU. The slant TEC (STEC) is converted to vertical TEC (VTEC) using the scheme as suggested by Klobuchar [19]

$$VTEC = STEC \times \cos[\arcsin (R_e \cos\theta / R_e + h_{max})] \tag{2}$$

Where R_e = 6378 km. , h_{max} = 350 km. , and θ = elevation angle at the ground station.

The details about the calibration constant and bias correction and further explanations are described by Mala *et al* [9] for the present station's observations. For the Indian sector, the IPP (Ionospheric Pierce Point) altitude of 350 km with elevation angle greater than 50° is valid as discussed by Rama Rao *et al* [14]. To derive the VTEC for Rajkot (22.29° N, 70.74° E, geographic) , we have used latitude- longitude grid of 2° × 2° with elevation cut-off at 50°.

3 Observation, results and discussion

The dual frequency GPS receiver is used to monitor TEC at Rajkot since 2005. The STEC at every 30 seconds is used to calculate the hourly mean VTEC values for given hour of the day. As we have used (2° × 2°) grid with elevation cut-off at 50° around observing site, sometimes on a given day none of the GPS satellites may have favourable orbit. Hence we have included only those days which met with the above criteria

3.1 Diurnal variation

A typical quiet day diurnal variation of TEC on 5 April 2009 during extreme low solar activity (monthly mean Rz = 2.2) is shown in Fig1. For comparison, diurnal variation of TEC on same date but during high solar activity (monthly mean Rz = 82) is also shown. The year 2009 observed extremely low solar activity such that it had 50 years low in solar wind pressure and 12 years low in solar irradiance. The UV dropped by about 6%. There were no sunspots on a large number of days. These facts are reflected in diurnal TEC variation also. There is about 20 TECU (1TECU = 10^{16} electrons/m^2) difference between the daytime peak and the night time minimum for the low soalr activity day of 5 April 2009.

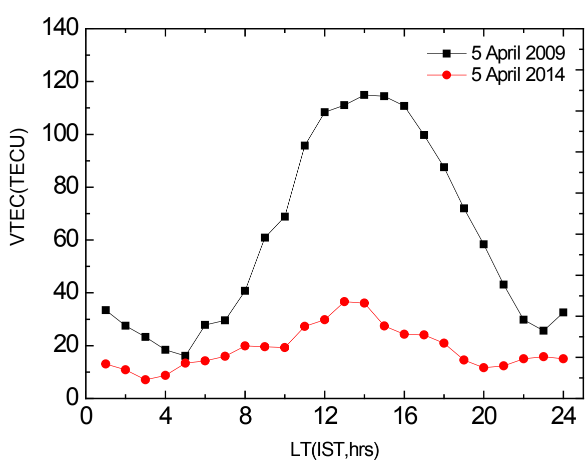

Fig 1. A typical diurnal variation of TEC during extreme low solar activity (2009) and high solar activity (2014).

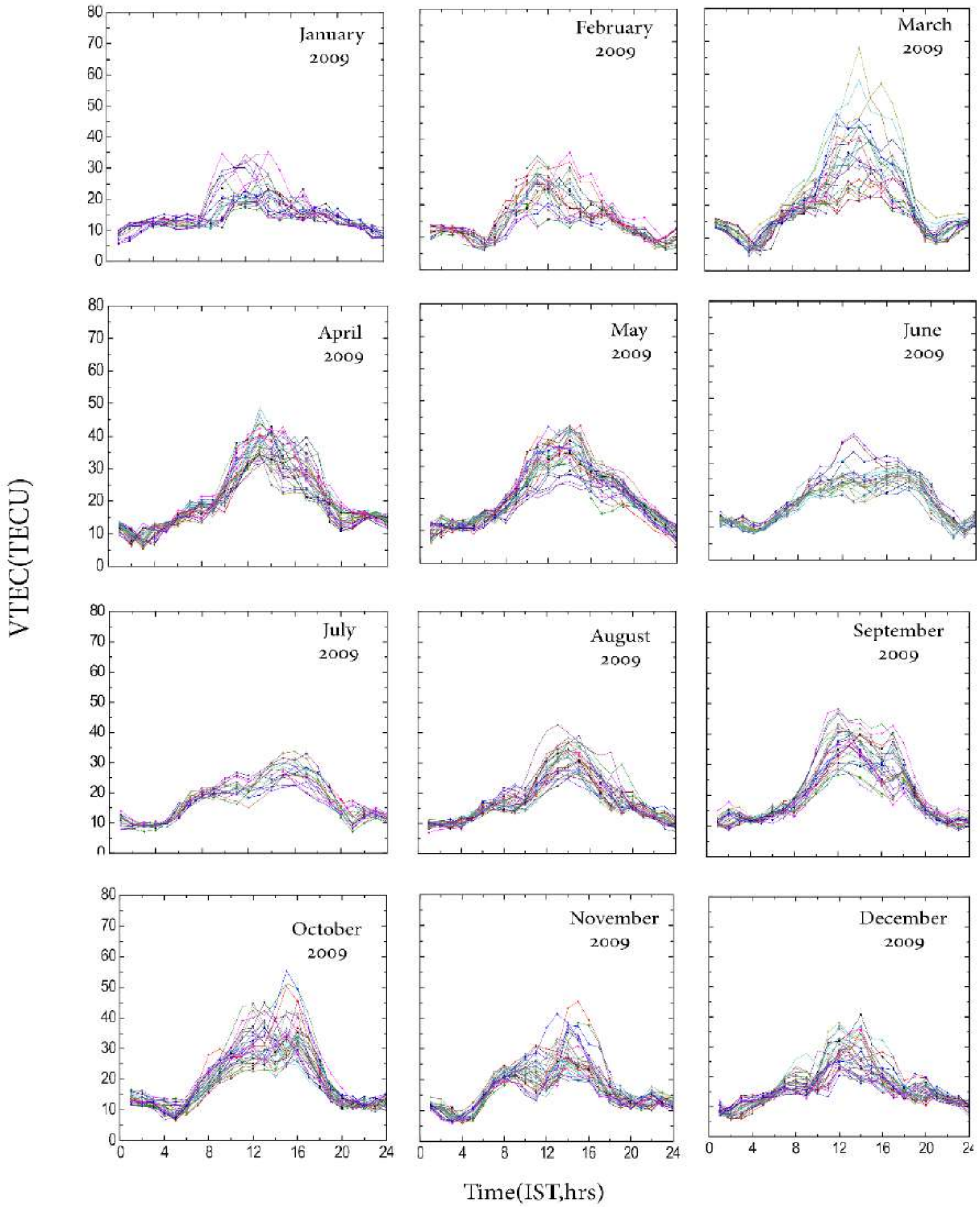

Fig 2(a). Mass plot of diurnal variation of total electron content at Rajkot for year 2009

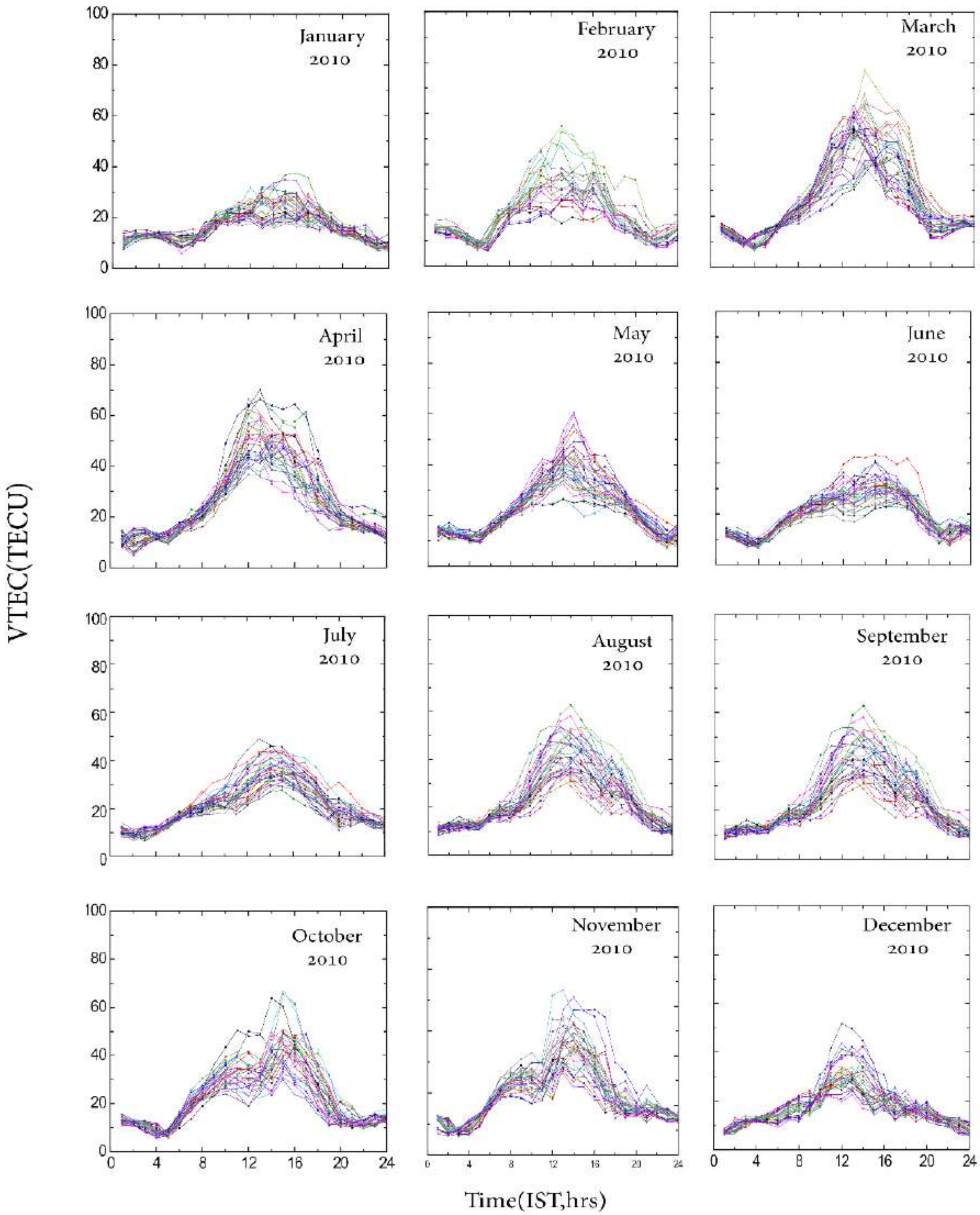

Fig 2(b). Mass plot of diurnaliurnal variation of total electron content at Rajkot for year 2010

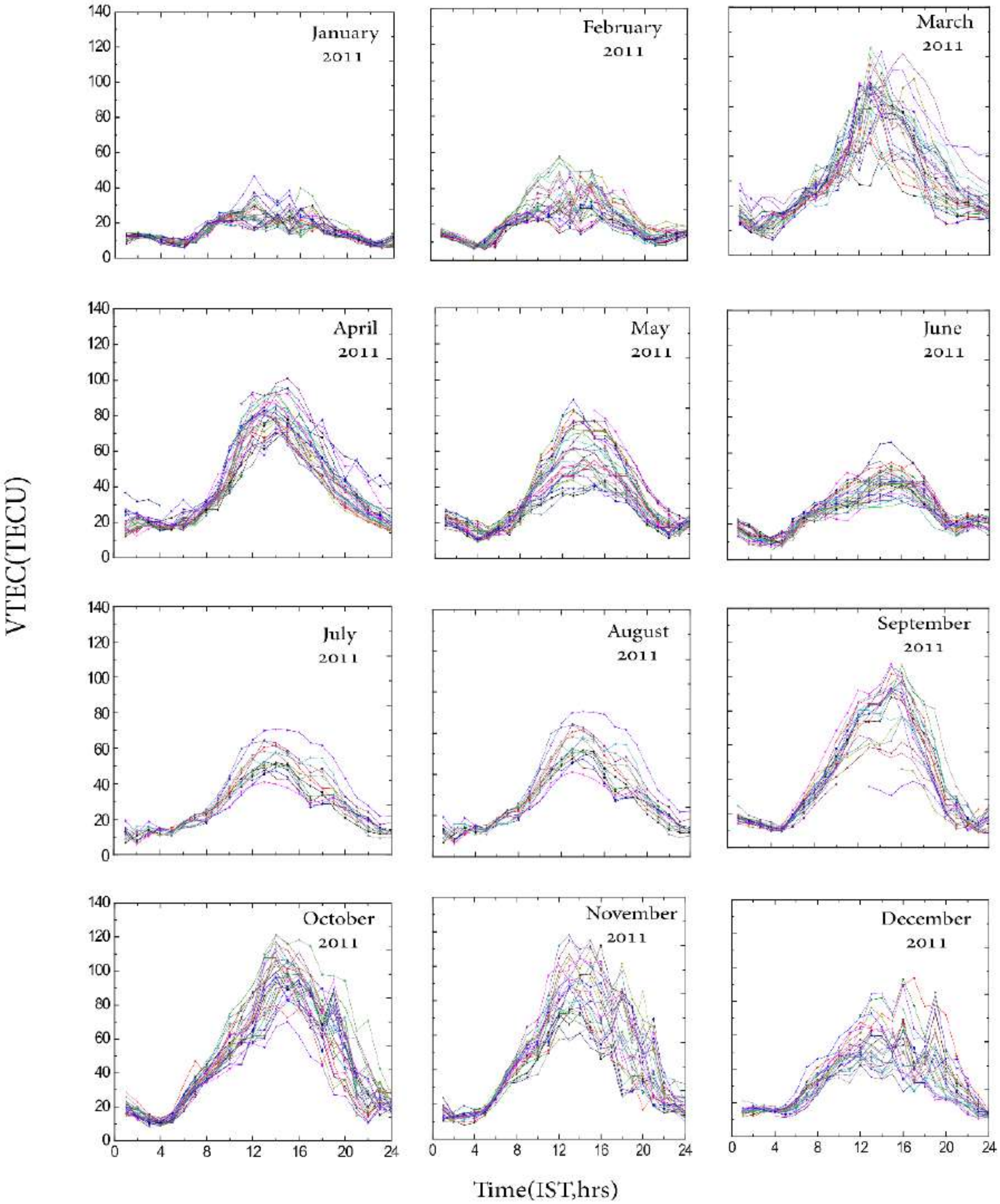

Fig 2(c). Mass plot of diurnal variation of total electron content at Rajkot for year 2011

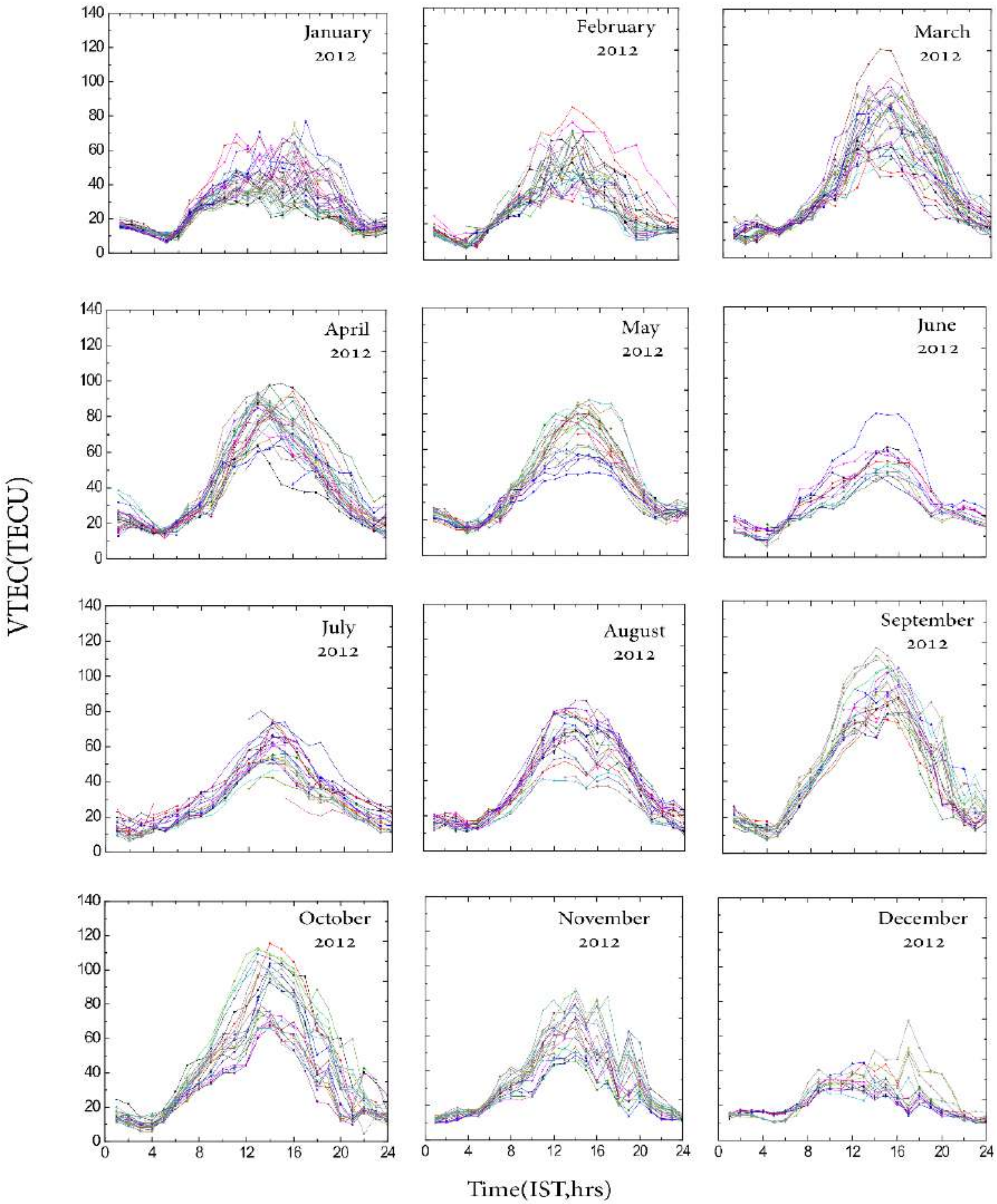

Fig 2(d). Mass plot of diurnal variation of total electron content at Rajkot for year 2012

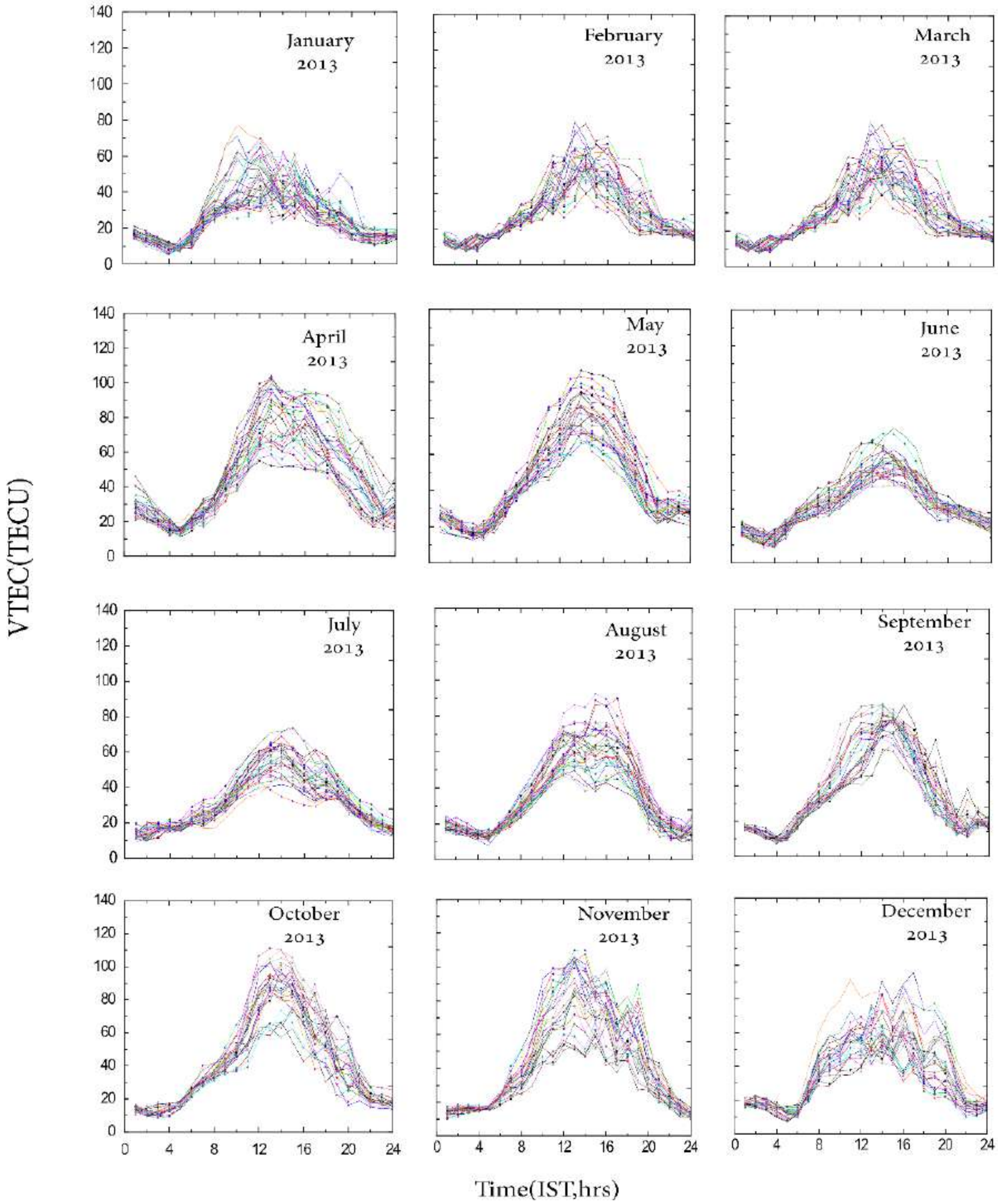

Fig 2(e). Mass plot of diurnal variation of total electron content at Rajkot for year 2013

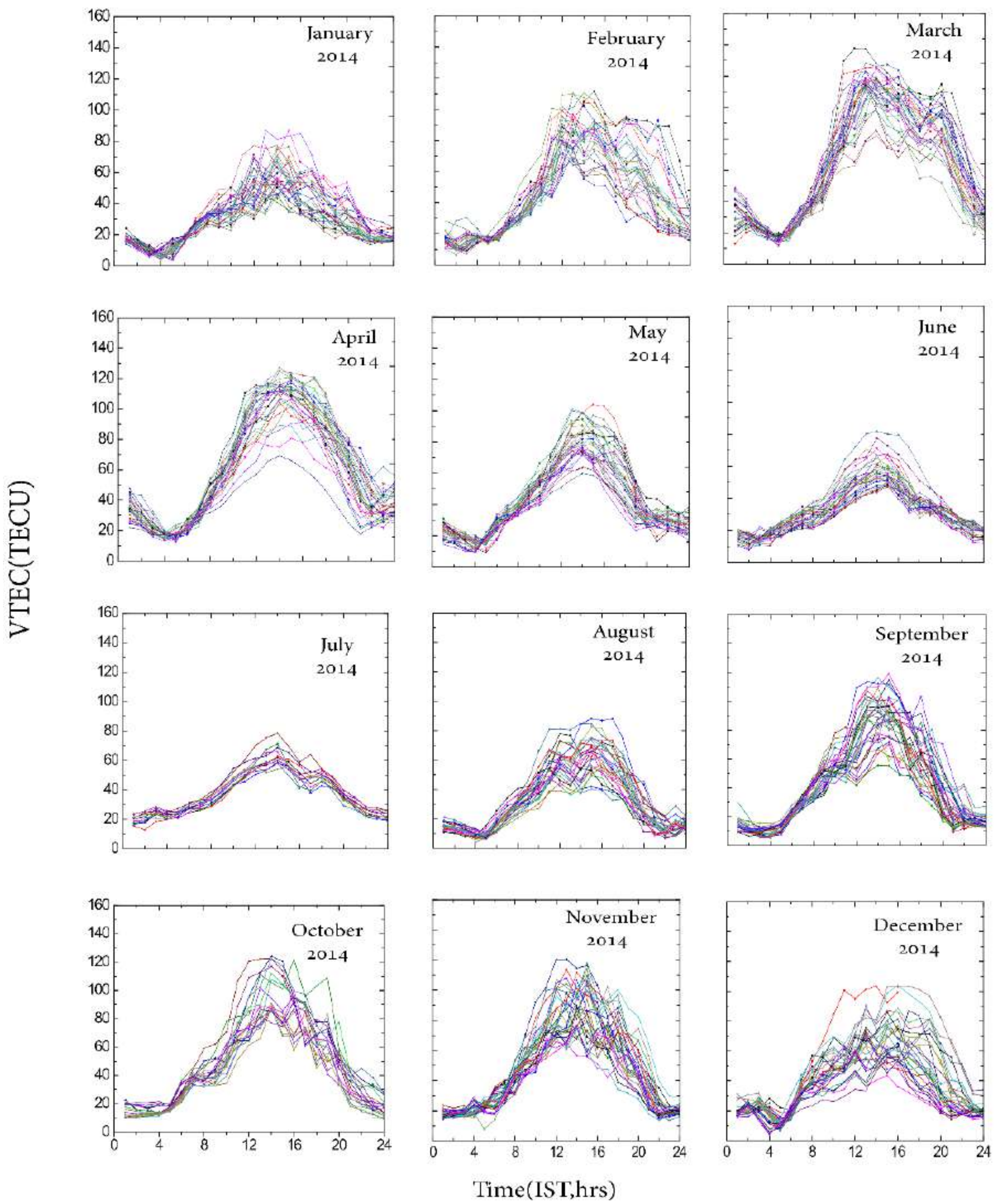

Fig 2(d). Mass plot of diurnal variation of total electron content at Rajkot for year 2014

The daytime peak has no broadening. During 2014, the difference between the daytime peak and the night time minimum is as large as 100 TECU. The daytime peak has a broadening of ~ 4 hours. Also the stiff rise and fall are observed compared to low solar activity periods. It is also interesting to note that the diurnal peak is around 1400 hrs (IST; 82.5° E) during all seasons and regardless of solar activity.

Figure 2 (a through f) show the mass plot of TEC diurnal variations for each months of the years 2009 to 2014. The day to day variability of TEC is contributed by the various parameters like EUV flux, geomagnetic activity [20], electrojet strength and local atmospheric conditions in the thermosphere [21].

3.2 Seasonal variations

The hourly mean values for three different seasons viz. summer, winter and equinox for the years 2007 to 2014 are shown in Fig 3. TEC maxima are seen during the equinox season throughout the period

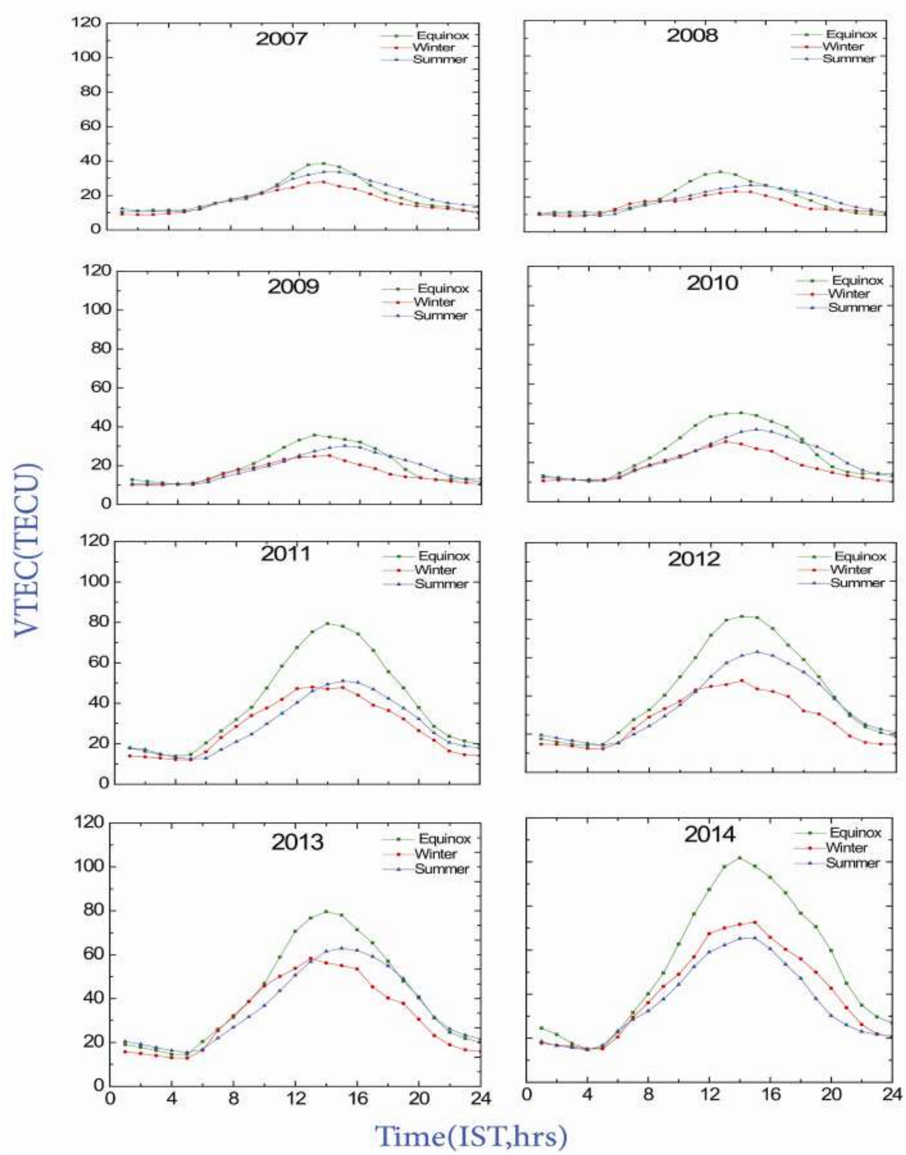

Fig (3). Seasonal mean diurnal variation of TEC for each year during 2007 to 2014.

of observation. This is as expected because of meridional wind, flowing from equator to pole, changes the neutral composition decreasing O/N_2 ratio. The decrease in the O/N_2 ratio is maximum at 350 km (F2 peak) during equinox. The present observing site at low latitudes shows the maximum TEC during equinox season as the decrease in O/N_2 leads to increase in TEC. The summer months show slightly higher values of TEC during the years 2007-2013. For the year 2014, the winter shows higher TEC than summer indicating the presence of winter anomaly at the observing latitude. The mass plot of TEC in Fig 2(F) also clearly shows that during June-July, 2014, TEC is lower compared to winter months of the same year. Huo *et al* [22] studied the global scale winter anomaly of TEC during the year 2002 (high solar activity) and found that the winter anomaly extends up to the latitude band of 15°- 30° N due to the joint effects of the meridional neutral wind and the seasonal changes of the sub solar point. Our observation of presence of winter anomaly during 2014 (high activity) confirms their observation.

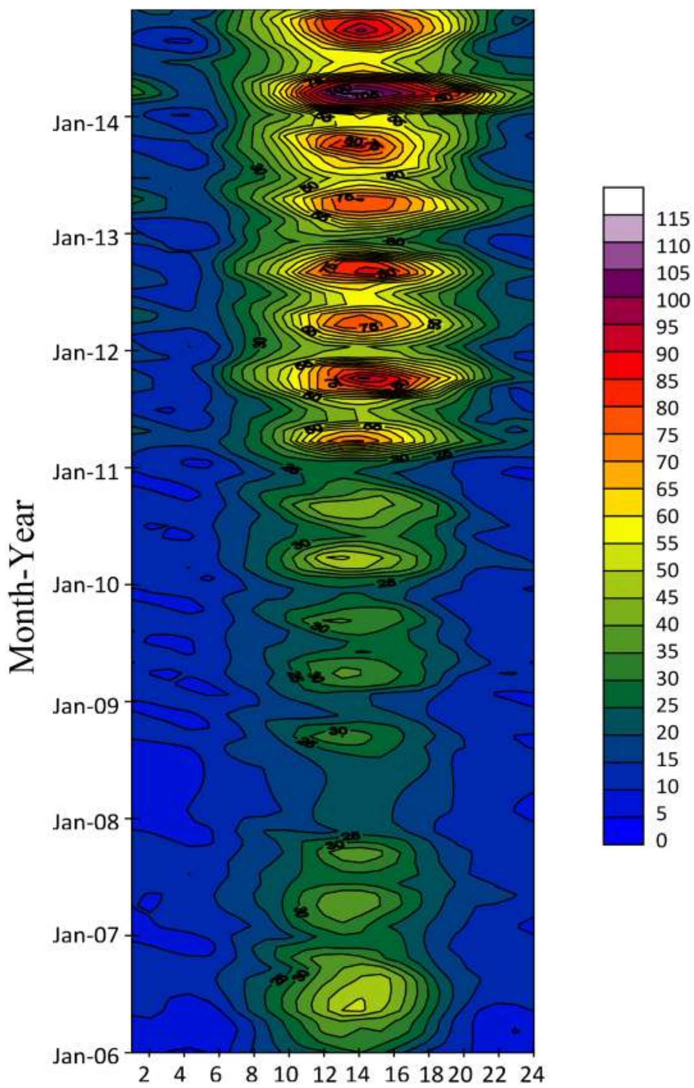

Fig (4). Contour plot of the monthly mean diurnal variation of TEC for the period of January 2006 to December 2014.

The contour plots of the monthly average diurnal variation of TEC during the period of 2006 to 2014 are shown in Fig (4) plotted in the grid of local time versus months. The presence of winter anomaly is also reflected in Fig (4). Broad day time peaks during high solar activity years are also clearly visible.

3.3 Solar activity dependence on the daytime peak TEC

The sun is the major source producing ionization in the ionosphere. Various agencies routinely monitor three solar indices viz. Sunspot number, 10.7cm solar flux and EUV flux along with other parameters. All these parameters show a good correlation with the peak ionization produced.

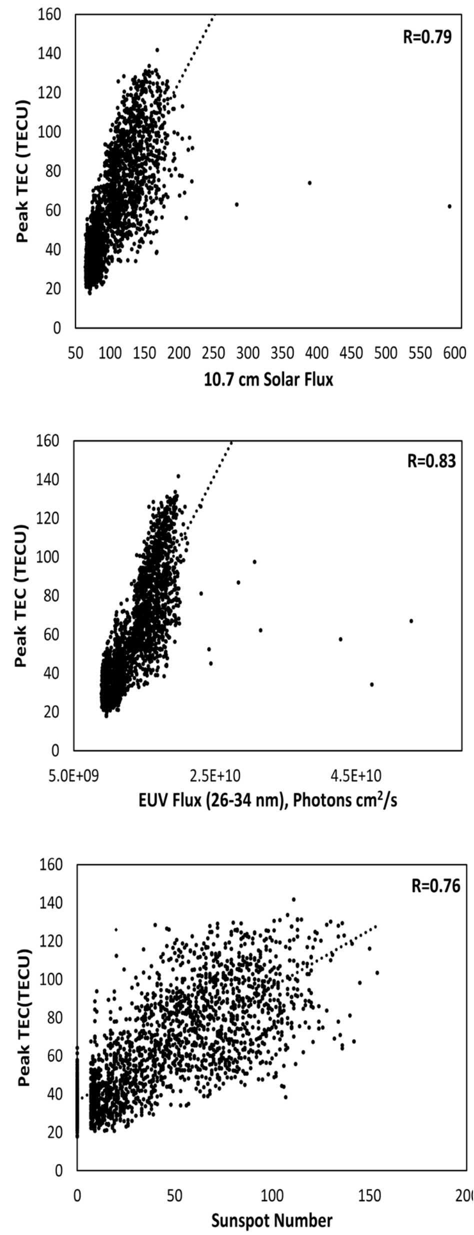

Fig 5. The daytime peak TEC dependence on various solar activity indices.

We consider in the present study the daytime peak TEC for the period from January 2006 to December 2014 covering extremely low to highest solar activity. Figure 5 shows the correlation between daytime peak TEC and the three solar indices. The daytime peak TEC shows a correlation coefficient of 0.76 with sunspot number. A good correlation of 0.83 is found with the EUV flux (26-34 nm). Note that the EUV flux values higher than 2.4×10^{10} are not considered while calculating the correlation, as the peak TEC shows the saturation for this and higher values of EUV flux. Similarly, the 10.7 cm flux also shows saturation for 200 and higher values of flux. The correlation between TEC and 10.7cm flux is found to be 0.79. The flux values higher than 200 are not considered while calculating the correlation. Thus it is found that the EUV flux is the most suitable index to relate the solar activity with the ionization.

4 Summary

The present study describes the TEC variability observed at Rajkot (22.29° N, 70.74° E, geographic, 14.03° N geomagnetic) in the anomaly crest region of Indian sector. The large data base of GPS derived TEC during 2007-2014 is used which is a unique as it covers the extremely low to highest solar activity period of 24th solar cycle. There are, so far no detailed reports are available on the GPS derived TEC during high solar activity period in the Indian region. The diurnal TEC variation has subtle differences depending on the solar activity. It is found that the diurnal TEC variability has smooth transition from day to night sector during the low solar activity, whereas, during the high solar activity, the same is observed to be very sharp. The daytime broad peak is observed during high solar activity. The seasonal behaviour shows the maximum TEC values during equinox with small differences between summer and winter. Hazarika and Bhuyan [23] also observed that the difference between summer and winter during 2005 (low solar activity) is small for Ahmadabad (72.5°E, 23.0°N). They also found that winter anomaly is absent. Our observations at Rajkot show that during the high solar activity i.e. 2014, the winter anomaly is observed indicating that the winter anomaly extends up to the observing latitude of 22.29° N during high solar activity only. The solar indices dependence shows that the EUV flux (26-34 nm) has a better correlation of 0.83 compared to 0.76 and 0.79 with sunspots and 10.7 cm solar flux, respectively. The EUV flux and 10.7 cm flux indicate the saturation in the ionization production which is not seen in the case of sunspots. Thus the EUV flux is the most suitable of the solar indices to study the correlation between ionization and the solar activity.

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