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Variations of total electron content over high latitude region during the ascending phase of 24th solar cycle

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Abstract

The solar cycle variation and seasonal changes significantly affects the ionization process of earth's ionosphere and required to be monitored in real time basis for regional level refinement of existing models. In view of this, the present study has been carried out by using the ionospheric Total Electron Content (TEC) data observed with the help of Global Ionospheric Scintillation and TEC monitoring (GISTM) system installed at Indian Antarctic Research Station, "Maitri" [70°46′00″S 11°43′56″E] during the ascending phase of 24th solar cycle. The daily values of solar extreme ultraviolet (EUV) flux (0.1–50 nm wavelength), 10.7 cm radio flux $F_{10.7}$ and Sunspot number (SSN) has been taken as a proxy to represent the solar cycle variation to correlate with TEC. The linear regression results revels better correlation of TEC with EUV flux rather than $\mathbf{F_{10.7}}$ and SSN. Also, the EUV and TEC show better agreement during summer as compared to winter and equinox period. Correlation between TEC and EUV appears significantly noticeable during ten internationally defined quiet days of each month (stable background geophysical condition) as compared to the overall days (2010–2014). Further, saturation effect has been observed on TEC values during the solar maxima year 2014. The saturation effects are more prominent during the night hours of winter and equinox season due to transportation losses manifested by the equator-ward direction of meridional wind.

Keywords: High latitude ionosphere; Total electron content; EUV flux; Sunspot number; Correlation

1. Introduction

The ionosphere is the important part of the atmosphere, which is ionized by the solar radiation and play vital role in the atmospheric electricity. In general, ionosphere supports the sky wave radio signal propagation for establishing long distance wireless communication network. It also plays an important role in trans-ionospheric radio wave propagation. The propagation frequency and distance of target receiver has been managed by monitoring the state of ionosphere on real time basis. Now a day, various methods and types of modern/advanced instruments are available for real time monitoring of earth's ionosphere which is useful for monitoring agencies and community to estimate ionospheric charge density on real time basis. The measurement of ionospheric Total Electron Content (TEC) with the help of GPS receivers is one of the most popular techniques. The said TEC is the integrated value of total number of electrons present along the raypath between a satellite to a ground receiver.

The GPS based TEC measurements are widely used by scientific community for understanding of the long as well as short term ionospheric variability which is useful in

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ionospheric modeling for predication of ionospheric conditions. In view of this, many researchers studied the regular variations of solar radiation and its impact on Earth's ionosphere (Afraimovich et al., 2008; Chen et al., 2008; Huang and Cheng, 1995; Sethi et al., 2002). Basically, studies enriched the knowledge of scientific community about the global as well as regional behavior of earth's ionosphere and transform the same for societal and commercial utilization. The regional level ionospheric studies provided better insight and the acquired knowledge transformed for modification/updating of available ionospheric models. In line of this, Dabas et al. (2008) demonstrated an alternative regional level ionospheric predication tool which is effective for equatorial and low latitudinal ionospheric region. The study utilizes the multi-regression method between the various ionospheric parameters (foF2, hmF2 and MuF 3000), sunspot number and Ap index. Also linear dependency of TEC on the solar input (sunspot number) studied and reported by many researchers (e.g. Chakraborty and Hajra, 2008; Kouris et al., 1998; Lei et al., 2005; Rishbeth, 1993) and the same is observed in current study.

Apart from these studies, there are various global and regional ionosphere models which need quality input data for regional level refinements. The empirical models like International Reference Ionosphere (IRI) and Ne-Quick provided systematic ionosphere variation based upon the available historic data records. But these models have limitations to predict ionospheric parameters over high latitude region due to lack of observations. Many researchers (Coïsson et al., 2006; Bjoland et al., 2016; Liu et al., 2007, etc.) studied and validated the IRI and Ne-Quick models and noticed large deviation from the observed values. Lee et al. (2011) reported that the IRI models do not perform well for polar region because they were developed based originally on data from the non-auroral ionosphere. However, the parameterized models like PIM have limitation to replicate the particular ionosphereic conditions especially during the adverse geophysical conditions. Also, the PIM model does not produce the complete annual variation and gives most uncertain predations between equinoxes and solstices. It is also to be noted that most of the studies and models, which are defining the ionospheric behavior on different latitudes and solar activity levels were based on ground based observation i.e. by using ionosonde data (Rishbeth, 1998; Tsagouri et al., 2000; Yadav et al., 2011) and provided long term trend of F2 layer electron density. The said studies/models have limitation to provide the behavioral characteristics during the disturbed geomagnetic conditions. It has also been observed that very few studies performed for high latitude (especially over southern hemisphere) due to difficult logistic requirement. The high latitude regions are very sensitive to the changing near earth space environment system due to direct particle precipitation through the almost vertical geomagnetic field lines and hence difficult to predict and model.

In view of this, the presented work is an attempt for understanding the long-term behavior of high latitude ionospheric region which may lead to enhance the modeling capabilities of high latitude ionospheric region. The present research work describes the correlation between solar extreme ultraviolet flux (0.1–50 nm wavelength) and the ionospheric Total Electron Content during solar minima year 2010 to solar maxima year 2014 under different geomagnetic conditions.

2. Data and methods

The present work has been performed by using TEC data acquired with the help of Novatel make dual frequency GPS receiver installed at Indian Permanent Research Base "Maitri", Antarctica (70°46′00″S, 11°43′56″E). The GPS receiver utilized for acquiring the ionospheric data is a state of art system and able to log ionospheric slant TEC remotely with the resolution of 1 min. The system measures the TEC using pseudorange measurements on the L1 and L2 frequencies in which C/A code measurements are used on L1, while semi-codeless P code measurements are used on L2. This may cause bias in TEC output values which are different for different GPS PRN. These biases have been estimated by using the data collected through the International GPS Service (IGS) network on daily basis and same has been available on website (http://ftp.aiub.unibe.ch/CODE/) for satellite bias calibration. The Novatel GPS receiver manufacturer provided a TEC logging algorithm written in C^{++} programming language to generate new raw data file every day. This program code has provision to remove these biases by updating (manually) differential code bias (DCB) value in the code line on regular basis. Here, in this case the code line was updated after every five days to avoid daily data gaps. However, during post processing, the corresponding days P1C1 bias values are manually supplied for re-calibration of pre-recorded TEC to make collected absolute TEC values more correct. Basically, recorded absolute TEC is measure of number of electron along the path from satellite to ground receiver which derived from Eq. (1).

$$TEC_{(absolute)} = [9.483 * (PR_{L2} - -PR_{L1} - \Delta_{C/A-P,PRN}) + TEC_{RX} + TEC_{CAL}]TECU \quad (1)$$

where

PR_{L2} is the L2 pseudo-range in meters,
PR_{L1} is the L1 pseudo-range in meters,
$\Delta_{C/A\text{-}P,\ PRN}$ is the input bias between considered GPS PRN C/A-code and P-code chip transitions in meters,
TEC_{RX} is the range delay offered by receiver and provided by the manufacturer,
TEC_{CAL} is the TEC offset estimated from P1C1 differential code biases.

The absolute TEC obtained from GPS receiver is then converted into vertical TEC with help of self-developed algorithm in C++ language. The first step of the said algorithm is to estimate the correction factor termed here as Obliquity Factor (OF) which is derived for each of single satellite at the height of Ionospheric Prices Point (IPP). The estimation of IPP height based upon the assumption on the basis of maximum electron density in the ionosphere. The point of intersection of this thin shell with the line of the sight from the satellite to the receiver is known as the ionospheric pierce point (IPP). The estimated obliquity factor (OF) is than utilized to convert each observed absolute TEC into the vertical TEC to remove the dependency of the elevation angle from the ray-path. The OF is than multiplied with absolute TEC to estimate the vertical TEC as shown in Eq. (2).

$$TEC_{(vertical)} = TEC_{(absolute)} * OF \quad (2)$$

where OF is obliquity factor.

An obliquity factor is a cos β, where β is the angle between the slant distance between satellite and receiver and vertical distance between receiver and assumed horizontal layer of ionosphere.

$$OF = \cos\beta \quad (3)$$

where

$$\beta = \sin^{-1}((\cos(elv) * RE)/(RE + hmF2)) \quad (4)$$

Here, the RE is the radius of the Earth in radian and hmF2 is the peak electron density of the Earth's ionosphere in km. A masking angle of 45° elevation angle for each satellite has been applied to filter out multiple path reflection noises, lower atmospheric perturbation (by minimizing travelling path through lower atmospheric region) and large spatial variation.

By multiplying cos β (OF) slant range is converted into vertical range and absolute TEC is converted into vertical TEC. This calculated vertical TEC (hereafter termed as TEC) at interval of each second is averaged hourly and then segregated as per the background geomagnetic condition i.e. for quiet and disturbed days. The background geomagnetic condition data for each month have been downloaded from world data center, Kyoto. Further, the GPS TEC data has been analyzed for four different hours i.e. 0000UT, 600UT, 1200UT and 1800UT of each of the considered days. On the other hand, the daily sunspot number, EUV and F10.7 has been downloaded from world data center (http://www.ngdc.noaa.gov/wdc/wdcmain.shtml).

After that a linear regression analysis has been performed between dependent variable TEC and the independent variable SSN by using Eq. (5) to explore the relationship. The same has also been repeated between TEC & EUV and TEC & F10.7 to examine which solar proxy gives better correlation.

$$TEC = A0 + A1 * R \quad (5)$$

where A0 is the TEC intercept of the regression line, A1 is the Slope and R is the independent variable i.e. SSN/EUV/F10.7.

The linear regression method provided correlation coefficients (CC) between TEC and different solar proxies for different hours of representative months of all the seasons.

3. Results and discussion

The main aim of the present work is to establish a relationship of Ionospheric TEC with EUV, SSN and $F_{10.7}$ over southern hemispheric sub-auroral region. The study divided into two parts i.e. (1) The long term dependency of sub-auroral region TEC over EUV, SSN and F10.7 during the ascending phase of 24th solar cycle (2010–2014) and (2) Correlation between TEC and $F_{10.7}$ and TEC and EUV over sub-auroral region during different seasons for the ascending phase of 24th solar cycle (2010–2014).

3.1. General picture of TEC, EUV, SSN and F10.7

Fig. 1 shows the long term diurnal variation of EUV, SSN, $F_{10.7}$ and TEC during ascending phase of 24th solar cycle (2010–2014) at four different representative hours i.e. 0000, 0600, 1200 and 1800UT. The observation shows similar trend of variation in all the four parameters i.e. TEC, EUV, SSN and $F_{10.7}$ but the annually averaged TEC shows better correlation with solar EUV as shown in Table 1. The observation shows good agreement with work reported by Liu and Chen (2009), in which they analyzed 11 years (1998–2008) of TEC data and shows strong correlation between TEC and solar variation over low, mid and high latitude regions. The observed trend of long term TEC variation with considered solar proxies is quite obvious because the solar EUV is the first source of ionization. However the regional existence of ionization depends upon the various loss factors manifested due to transportation, recombination etc. Such factors depend upon the neutral density, temperature and compositional changes, ionospheric chemistry, neutral winds (Liu et al., 2004) and the electric fields. These electro-dynamic changes are directly or indirectly depended on the transient behavior of solar driven parameters hence the trend of ionospheric TEC variation poorly matched with solar cycle especially during such transient activity periods. The impact of such transient activities has also been observed in terms of anomaly during the solar moderate year 2012, when an enhanced TEC has been observed as compared to the solar maxima year 2014. The enhanced value of TEC may directly be correlated with the enhanced geomagnetic activities during solar moderate year 2012 which can be explained in terms of sudden enhancement of EUV as shown in Figs. 2–4. Bhattarai et al. (2018) also reported the similar effects during the enhanced geomagnetic activity periods. Moreover,

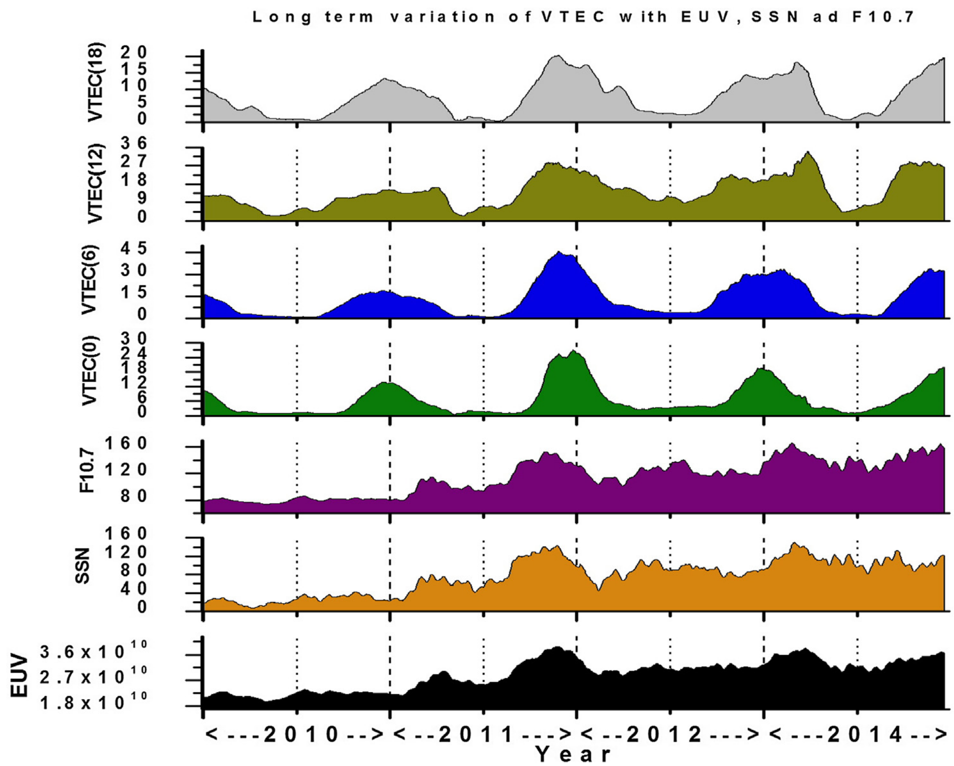

Fig. 1. The long term variation of EUV, $F_{10.7}$, SSN and TEC for the ascending phase of 24th solar cycle (year 2010–year 2014) at four different representative hours i.e. 0000, 0600, 1200 and 1800UT (from bottom to top in graph).

Table 1
Correlation coefficients between SSN, F10.7, EUV and TEC at four different representative hours i.e. 0000, 0600, 1200 and 1800UT.

Correlation coefficient	R (UTC = 0)	R (UTC = 6)	R (UTC = 12)	R (UTC = 18)
SSN:VTEC	0.240015	0.330034	0.462467	0.265331
$F_{10.7}$:VTEC	0.308865	0.408538	0.55384	0.345189
EUV:VTEC	0.410196	0.511184	0.645157	0.449864

an extraordinary agreement between TEC and EUV has been observed during solar minima year 2011 of 24th solar cycle as shown in Fig. 5. This is mainly due to the fact that the solar minima years are mostly quiet in terms background geomagnetic conditions. Hence, the ionization is mostly depended upon the solar the extreme ultraviolet

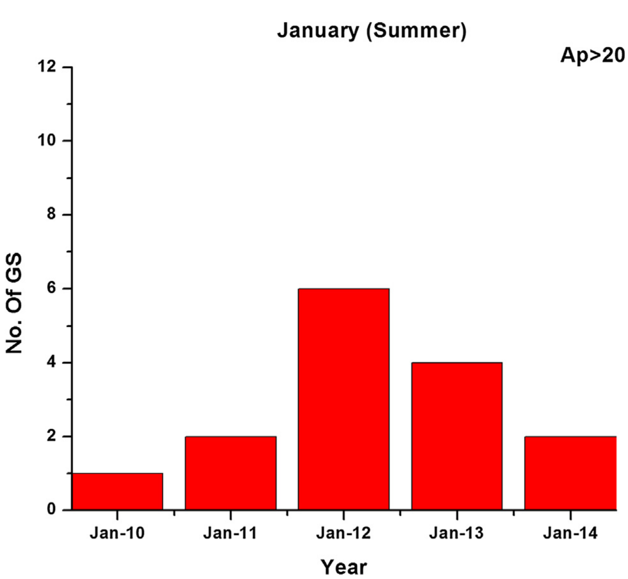

Fig. 2. The number of geomagnetic storms (Ap > 20) occurred each year (from solar minima year 2010 to solar maxima year 2014) during the Summer season of the year.

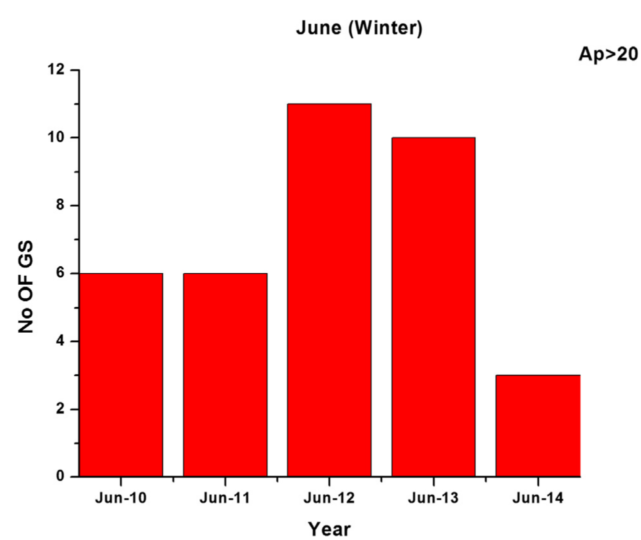

Fig. 3. The number of geomagnetic storms (Ap > 20) occurred each year (from solar minima year 2010 to solar maxima year 2014) during the Winter season of the year.

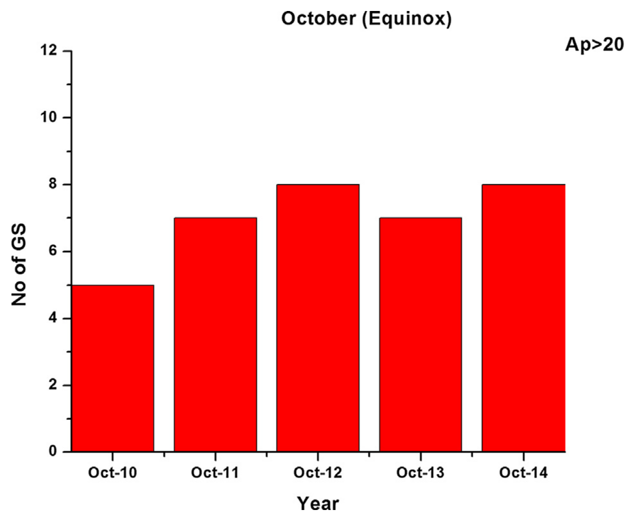

Fig. 4. The number of geomagnetic storms (Ap > 20) occurred each year (from solar minima year 2010 to solar maxima year 2014) during the Equinox season of the year.

irradiance. Hao et al. (2014) also reported the similar set of results for the solar minima year 2008 and 2009.

3.2. Correlation between TEC, $F_{10.7}$ and EUV

Figs. 6–8 show the association between TEC and solar activity ($F_{10.7}$ and EUV) during the representative month's of southern hemispheric summer (January), winter (June) and Equinox (October) seasons respectively. The results show a better linear agreement between TEC and EUV as compared to TEC and $F_{10.7}$ during minima to moderate level of solar activity. However, a saturation effect has been observed during the high solar activity periods. This might be due to the fact that the regional existence of ionospheric ionization directly/indirectly dependent upon the various loss factors manifested due to the regional level changes of electro-dynamic processes. These electro-dynamic processes are responsible for horizontal as well as vertical

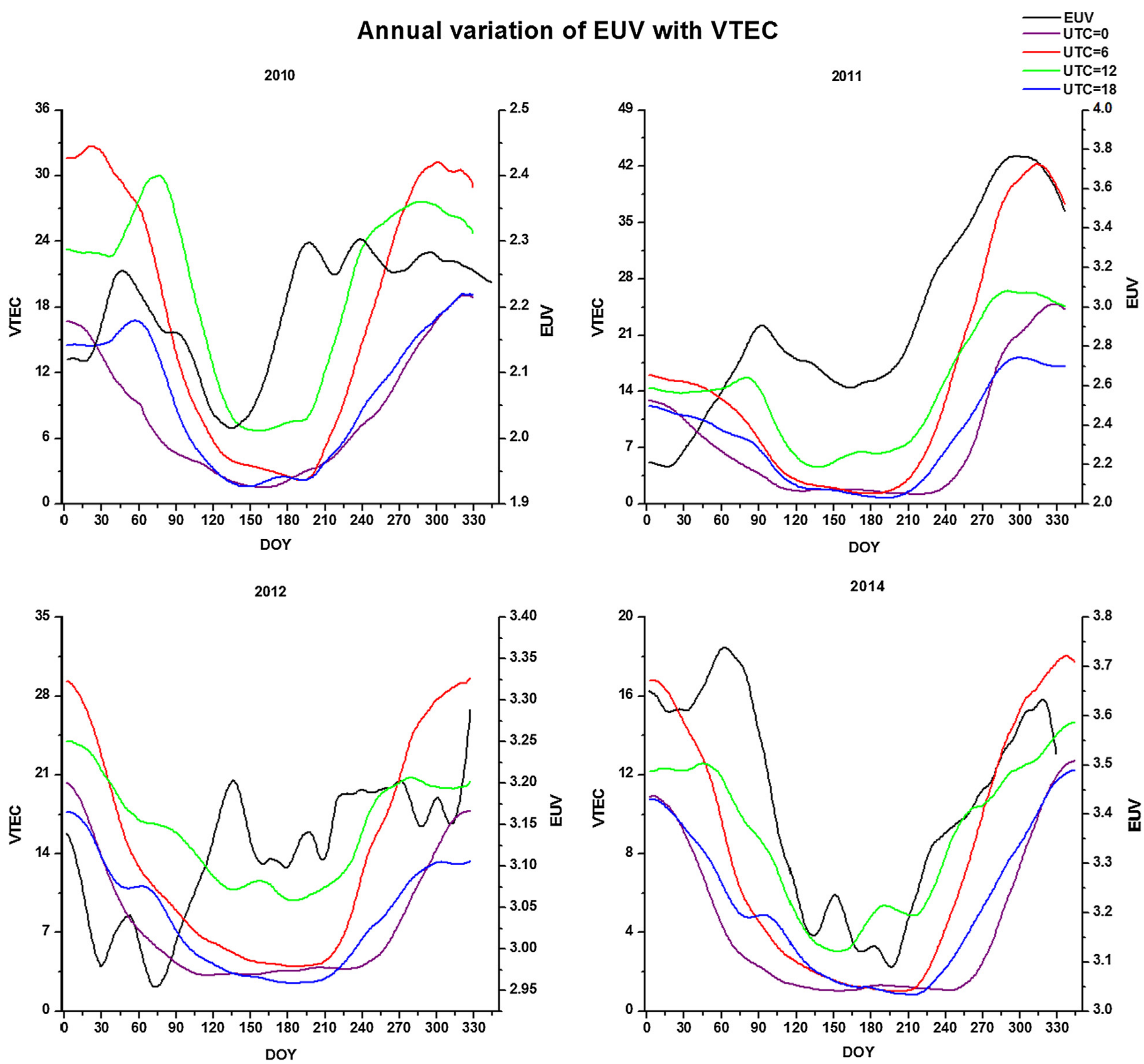

Fig. 5. Annual variation of TEC with EUV for 2010, 2011, 2012 and 2014at four different representative hours i.e. 0000, 0600, 1200 and 1800UT.

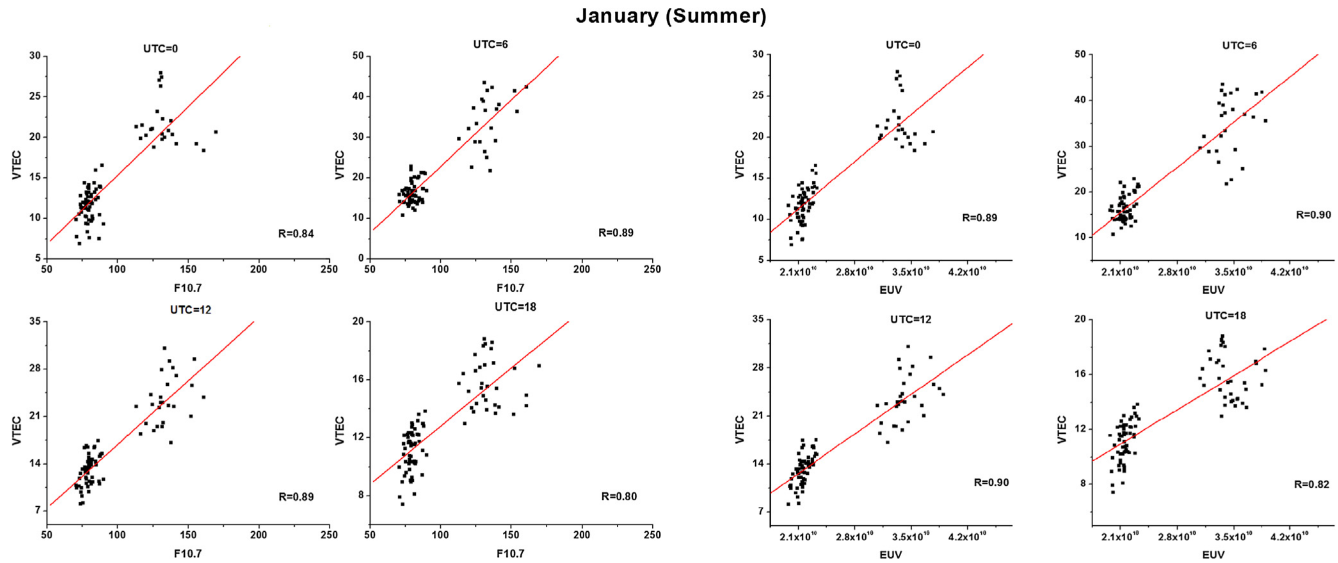

Fig. 6. Scatter plots of TEC values as a function of F10.7 (left four panel) and EUV flux (right four panel) for the summer season (January) of the year (black dots) at four different representative hours i.e. 0000, 0600, 1200 and 1800UT (from left to right and top to bottom in graph).

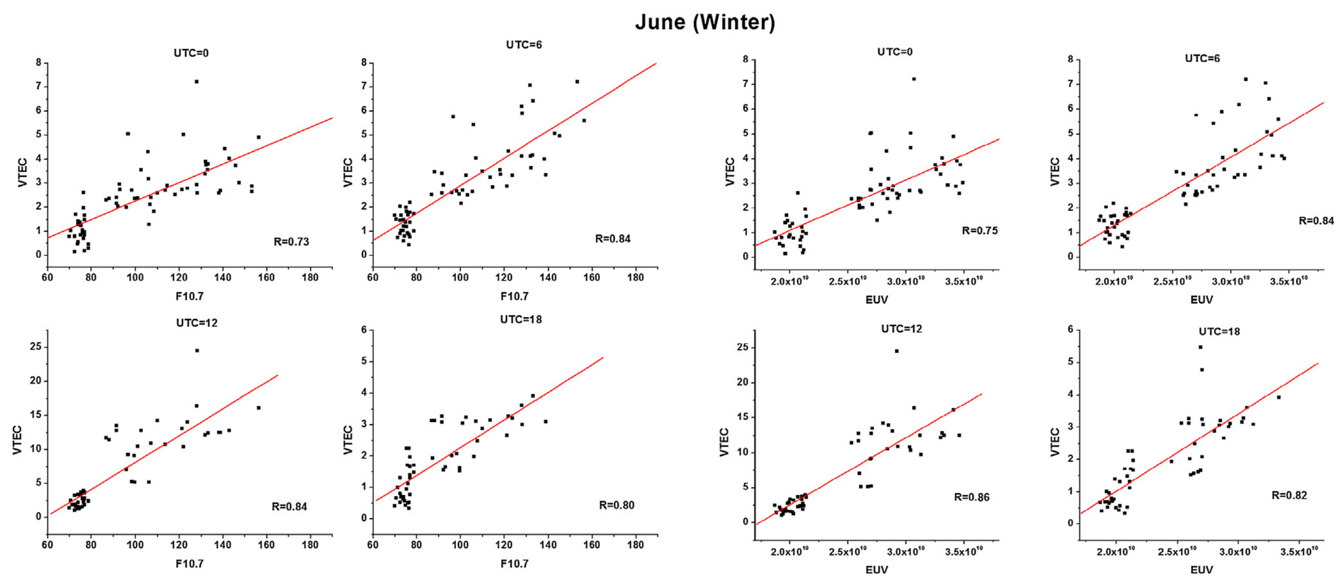

Fig. 7. Scatter plots of TEC values as a function F10.7 (left four panel) and EUV flux (right four panel) for the winter season (June) of the year (black dots) at four different representative hours i.e. 0000, 0600, 1200 and 1800UT (from left to right and top to bottom in graph).

transportation of ionization and are more prominent during the high solar activity period. Hence, such saturation effects have been observed during solar maxima period. Liu et al. (2006) also investigated saturation effect of electron density and they found that EUV changes are not solely feature of saturation effect; the atmospheric consequences as well as the dynamical effects also contribute to the solar activity changes in electron density. Such saturation effect are globally observed and reported by various workers (Balan et al., 1993; Balan et al., 1994; Kane, 1992; Liu et al., 2003; Belehaki et al., 2000). They find a nonlinear relationship between the solar EUV and $F_{10.7}$ and consider the saturation of ionization to be caused by the saturated production of ionization due to nonlinear increase of solar EUV fluxes.

It is also observed that the estimated correlation coefficient of summer is higher than the equinox and winter as shown in Table 2. This may be due to the changing nature of ionospheric convection pattern over high latitude which is responsible for horizontal transportation of ionized particles either pole-ward or equator-ward. As reported by various workers (Foster, 1993; Burns et al., 1991; Fuller-Rowell et al., 1994) that the pole-ward convection causes a positive ionospheric effect while the equator-ward convection cause negative type of ionospheric response over high latitude region. The scientific investigation carried out by

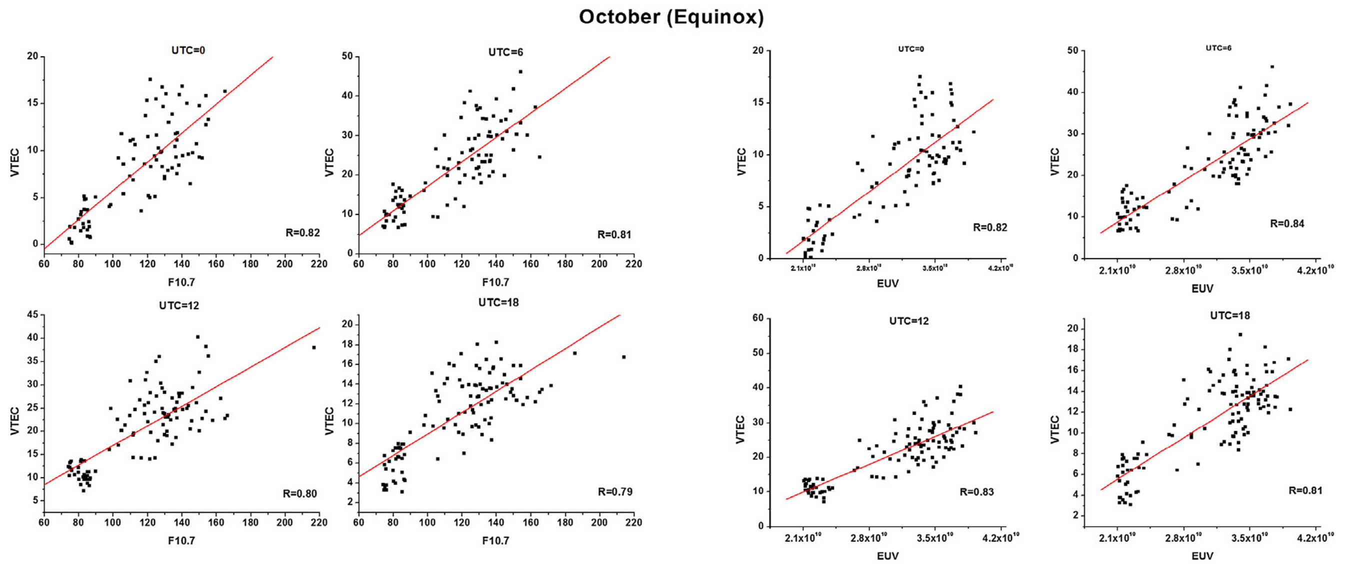

Fig. 8. Scatter plots of TEC values as a function of F10.7 (left four panel) and EUV flux (right four panel) for the equinox season (October) of the year (black dots) at four different representative hours i.e. 0000, 0600, 1200 and 1800UT (from left to right and top to bottom in graph).

Table 2
Correlation coefficients between EUV and TEC at four different representative hours i.e. 0000, 0600, 1200 and 1800UT for all three seasons.

Month (seasons)	Correlation coefficient	R (UTC = 0)	R (UTC = 6)	R (UTC = 12)	R (UTC = 18)
January (Summer)	EUV:VTEC	0.89	0.90	0.90	0.82
June (Winter)	EUV:VTEC	0.75	0.84	0.86	0.81
October (Equinox)	EUV:VTEC	0.81	0.84	0.83	0.81

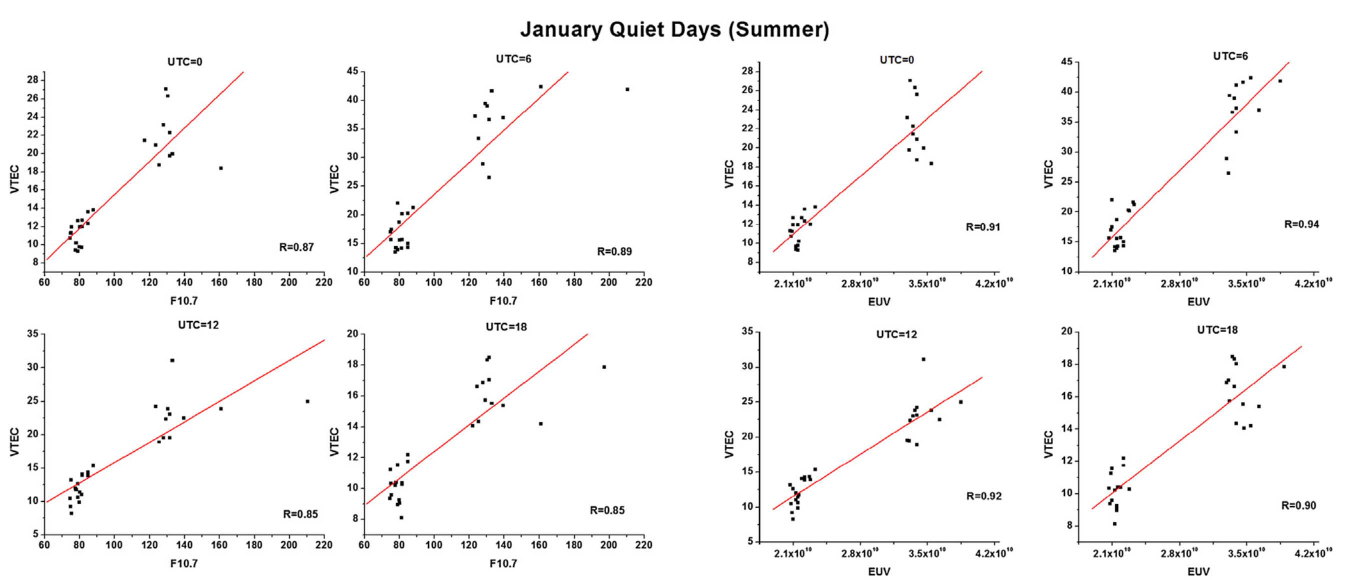

Fig. 9. Scatter plots of TEC values as a function of F10.7 (left four panel) and EUV flux (right four panel) during the quiet days of the months for the summer season (January) of the year (black dots) at four different representative hours i.e. 0000, 0600, 1200 and 1800UT (from left to right and top to bottom in graph).

Holt et al. (1987), De La Beaujardiere et al. (1991) and Koustov and Fiori (2016) shows that the solar activity and TEC observed at different locations follows different agreement for different seasons. In order to explore the dependency of TEC over $F_{10.7}$ and EUV under stable background geomagnetic condition, the observed TEC data during ten internationally defined quiet days for above said three months have been considered for four different hours i.e. 0000, 0600, 1200 & 1800 UTC (see Figs. 9–11). The observation shows similar results i.e. the correlation

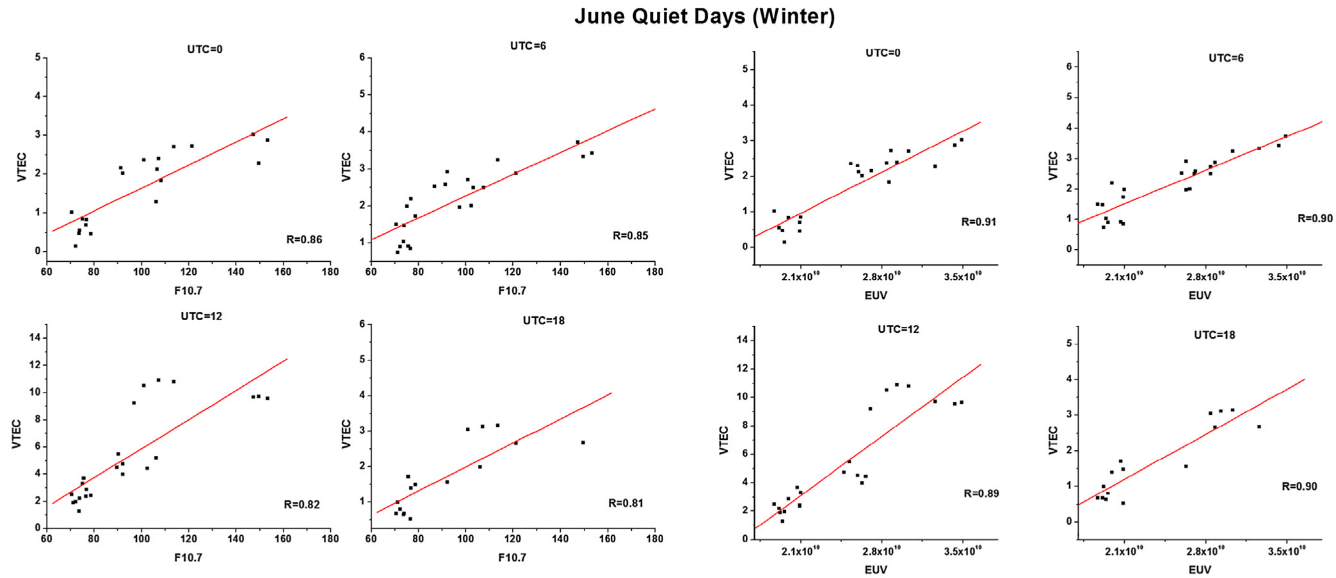

Fig. 10. Scatter plots of TEC values as a function of F10.7 (left four panel) and EUV flux (right four panel) during the quiet days of the months for the winter season (June) of the year (black dots) at four different representative hours i.e. 0000, 0600, 1200 and 1800UT (from left to right and top to bottom in graph).

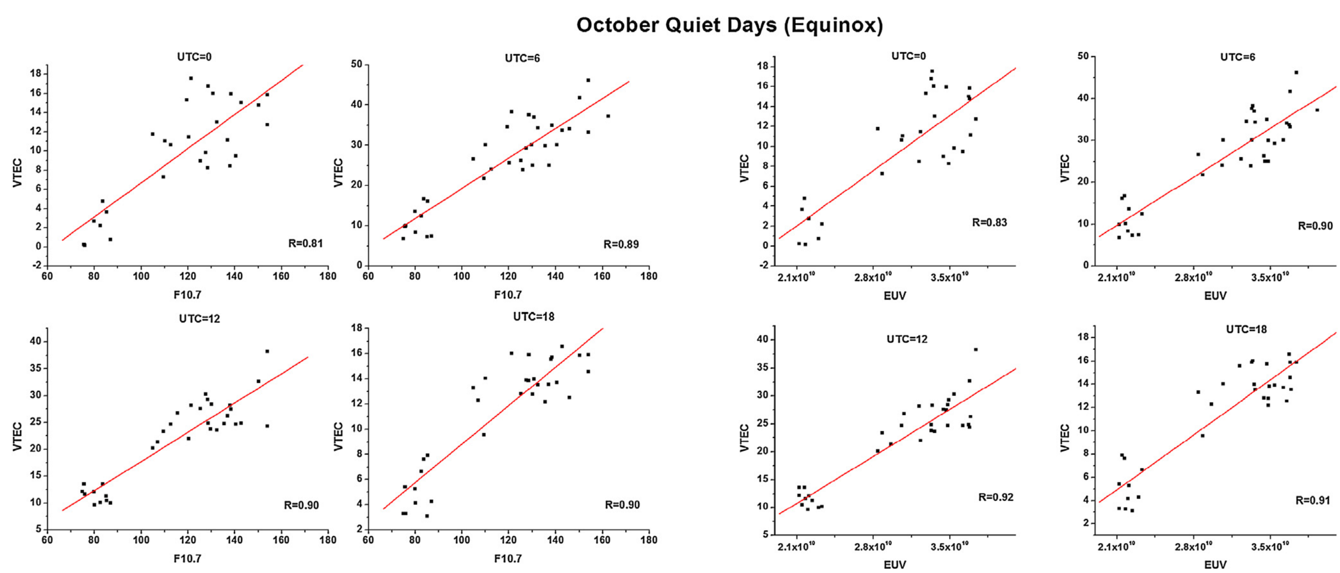

Fig. 11. Scatter plots of TEC values as a function of F10.7 (left four panel) and EUV flux (right four panel) during the quiet days of the months for the equinox season (October) of the year (black dots) at four different representative hours i.e. 0000, 0600, 1200 and 1800UT (from left to right and top to bottom in graph.

Table 3
Correlation coefficients between EUV and TEC at four different representative hours i.e. 0000, 0600, 1200 and 1800UT for all three seasons during the quiet days.

Month (seasons)	Correlation coefficient	R (UTC = 0)	R (UTC = 6)	R (UTC = 12)	R (UTC = 18)
January Quiet Days (Summer)	EUV:VTEC	0.91	0.94	0.92	0.90
June Quiet Days (Winter)	EUV:VTEC	0.91	0.90	0.89	0.90
October Quiet Days (Equinox)	EUV:VTEC	0.83	0.90	0.92	0.91

coefficients of summer are higher than that of winter and equinox (see Table 3). Also, the results show that the saturation effect is more prominent during 0000 & 1800 h. The above results suggested that the transportation of ion due to the meridional wind is one of the key driving forces for existence of regional level ionization. As reported by Lei et al. 2003 through a model study that the predominantly meridional winds are equator-ward in summer and pole-ward. Hence, the saturation effect is more prominent during the night-time &summer. However, in winter and most part of the equinox, the meridional winds mainly blow towards the poles from the geographic equator at daytime which minimizes the transportation losses, hence a better linear correlation has been observed during the equatorial day hour. While at nighttime of winter and equinox the direction of meridional wind is reverse i.e. from pole to equator. Hence, the transportation losses are maximum and show saturation effect. So by observing these results, it can be stated that at linear ionospheric TEC variation, EUV could be the solar index to model ionosphere satisfactorily.

4. Conclusion

The investigation of solar cycle variation of ionospheric TEC during different seasons over the sub-auroral region by using the long-term database of ascending phase of 24th solar cycle shows following interesting results.

(1) EUV is the better solar index parameter than the F10.7 and SSN to characterize solar activity variation because it showed highest correlation with the TEC.
(2) EUV and TEC follow better agreement during summer seasons and extraordinary agreement during minimum phase (during the year 2011) of the solar cycle.
(3) Correlation between TEC and EUV appear significantly noticeable during ten internationally defined quiet days of each month (stable background geophysical condition) as compared to the overall days (2010–2014).

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