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GPS TEC variations under quiet and disturbed geomagnetic conditions during the descending phase of 24th solar cycle over the Indian equatorial and low latitude regions

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Abstract

The present study is focused to understand the geomagnetic storm effects on the short- and long-term variations of ionospheric Total Electron Content (TEC) over the equatorial and low latitude sectors. GPS-TEC observations over a near equatorial station Bangalore and low latitude stations Waltair and Hyderabad during the declining phase of the 24th solar cycle (2015–2019) is analysed. The TEC variations during quiet and disturbed conditions are individually analysed to understand the geomagnetic storm effects on the diurnal, seasonal and solar activity variations. The seasonal variations of disturbed time TEC are following the quiet time trend with equinoctial maximum and summer minimum in the moderate solar activity periods. But, during low solar activity periods, the seasonal dependence of disturbed time TEC is different than that of quiet time. The difference in TEC during disturbed and quiet times is higher during moderate solar activity than that of low solar activity conditions. The TEC difference between disturbed and quiet periods is found to be maximum during summer months of moderate solar activity periods. Further, correlation analysis between F 10.7 cm solar flux and TEC during quiet and disturbed conditions is carried out for three different locations. It is found that the correlation between TEC and F 10.7 cm solar flux is higher during quiet time compared to that during disturbed periods with more correlation at the equator than at low latitudes.

Keywords: Total Electron Content (TEC); Geomagnetic storms; Semi-annual variation; Equatorial Ionization Anomaly (EIA)

1. Introduction

The ionospheric Total Electron Content (TEC) vary significantly with time, day-to-day, season, latitude, longitude as well as with solar activity. The spatio temporal variability of ionospheric TEC have been studied extensively for past few decades by many authors (Abdu, 1997; Warnant 2000; Rama Rao et al., 2006; Bagiya et al., 2009; Galav et al., 2010; Venkatesh et al., 2014; de Abreu Alessandro et al., 2017; Patel et al., 2017; Singh et al., 2019). The ionosphere F-region electron density over the equatorial and low latitude regions is characterized by double-humped latitudinal distribution with a trough centered around the dip equator and two crests on either side of equator around ±20° dip latitudes. This phenomenon has been recognized as “Appleton anomaly” or “equatorial ionization anomaly” (EIA). It results in the formation of fountain which generates an enhanced TEC (crest) on either sides of the magnetic equator and a reduced TEC (trough) at the equa-

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tor (Appleton, 1946; Duncan, 1960; Liu et al., 2012). The TEC is used to estimate the propagation delays experienced by radio signals when they pass through the ionosphere. Among the different sources of GPS positional errors, the propagation delay, which is proportional to the ionospheric TEC, is the largest contributor. In the recent times, measurements and modelling of accurate values of ionospheric TEC have acquired a great importance particularly in the estimation of positioning and timing information of satellite based navigational and *trans*-ionospheric communication systems, as well as surface transportation systems. Therefore, it is necessary to have a meticulous knowledge on the variability of TEC at different geographical locations under different geomagnetic (quiet and disturbed) conditions in order to get better estimates of TEC for satellite-based communication and navigation applications.

Geomagnetic storms are the most prominent phenomenon of space weather during which the ionosphere can be greatly disturbed as compared with quiet time and cause remarkable variations in TEC. These variations can cause negative ramifications on space and ground-based communication and navigation systems (Akala et al., 2013). If the electron density increases as a result of storm dynamics, it is called as a positive ionospheric storm effect, while a decrease in electron density is called as a negative ionospheric storm effect (Fagundes et al., 2016). The positive storm effects at low latitudes occur mainly due to the intensified equatorial plasma fountain caused by the prompt penetration electric field (PPEF) induced eastward electric field enhancement. The positive effect can also happen due to rapid slowdown of both recombination processes and downward diffusion of plasma by the effects of storm time equatorward neutral winds (Kelley et al., 2003; Balan et al., 2009; Balan et al., 2010; Lissa et al., 2020). Negative ionospheric storm effects at low latitudes arise from the changes in neutral composition that leads to decrease in the O/N2 density ratio (Fuller-Rowell et al., 1994; Huang et al., 2005). Ionospheric TEC variations under geomagnetic disturbed conditions have been studied by several researchers using different methodologies by considering the single or set of geomagnetic storms (Migoya Orue et al., 2009; Fagundes et al., 2016; Blagoveshchensky et al., 2019; Lissa et al., 2020). The variation of ionospheric TEC in the Indian sector during different geomagnetic storms have been studied by Dashora et al., 2009 at Udaipur, Bagiya et al., 2009 at Rajkot and by Kumar and Singh 2010 at Varanasi.

While there exists, numerous studies addressing the effects of different geomagnetic storms on the ionosphere, it is very much necessary to compare the ionospheric variations during quiet and disturbed geomagnetic conditions using long term observations for a better understanding of space weather effects on the morphological features of ionospheric parameters. There are limited studies using long term observations on the variations of ionospheric TEC during geomagnetically quiet and disturbed conditions (Fuller-Rowell et al., 1997; Bhattacharya et al., 2008; Sanjay Kumar et al., 2012; Singh et al., 2019; Akala and Adewusi, 2020).

In this study, we try to understand the impact of geomagnetic storms on the short- and long-term variations of ionospheric TEC in the declining phase of 24th solar cycle. The GPS observations over three different locations in the Indian equatorial and low latitude sector, namely Bangalore, Waltair and Hyderabad are considered. Morphological features of TEC are analysed individually during quiet and disturbed conditions to understand the space weather effects on the ionospheric variability and the corresponding results are discussed in detail.

2. Data and methodology

Now a days, the dual frequency GPS receiver networks are providing an efficient way to compute the ionospheric TEC values with greater spatial and temporal coverage. In the present study, the dual frequency GPS observations are considered from three different locations namely, Bangalore (IISC, Geographic latitude 13°02′ N, Longitude 77° 57′ E, Geomagnetic latitude 4°61′ N), Waltair (WALT, Geographic latitude 17°73′ N, Longitude 83°37′ E, Geomagnetic latitude 8°87′ N) and Hyderabad (HYDE, Geographic latitude 17°41′ N, Longitude 78°55′ E, Geomagnetic latitude 8°89′ N) in the Indian sector are shown in Fig. 1. The GPS receiver at Waltair is GPStation–6 while the other two receiver locations Bangalore and Hyderabad correspond to International GNSS Network (IGS). The IGS data is downloaded from the webpage *ftp://cddis.gfsc.nasa.gov/pub/gps/data.* The GPS TEC observations have been considered for a period of five years during the descending phase of solar cycle 24 from 2015 (annual mean F10.7 is 117.7 s.f.u) to 2019 (annual mean F 10.7 is 69.7 s.f.u). The RINEX observation files obtained from Waltair station and the other stations in the IGS network are processed to get the vertical TEC values by using the GPS TEC analysis software developed by Gopi Seemala (Seemala and Valladares, 2011).

The diurnal and seasonal variations of TEC are analysed individually for quiet and disturbed geomagnetic periods under different solar activity conditions during the considered 5-year period (2015 – 2019). For this analysis, the days with -20 nT $\geq$ Dst Index $>$ -250 nT are considered as disturbed days (Damaceno et al., 2020). The five geomagnetic quiet days in each month are considered to retrieve the quiet time TEC variations without any storm effects. The quiet days information is downloaded from the website *http://wdc.kugi.kyoto-u.ac.jp/qddays/index.html*. The Dst index and F 10.7 cm solar flux data was downloaded from the OMNI webpage *https://omniweb.gsfc.nasa.gov/form/omni_min.html.*

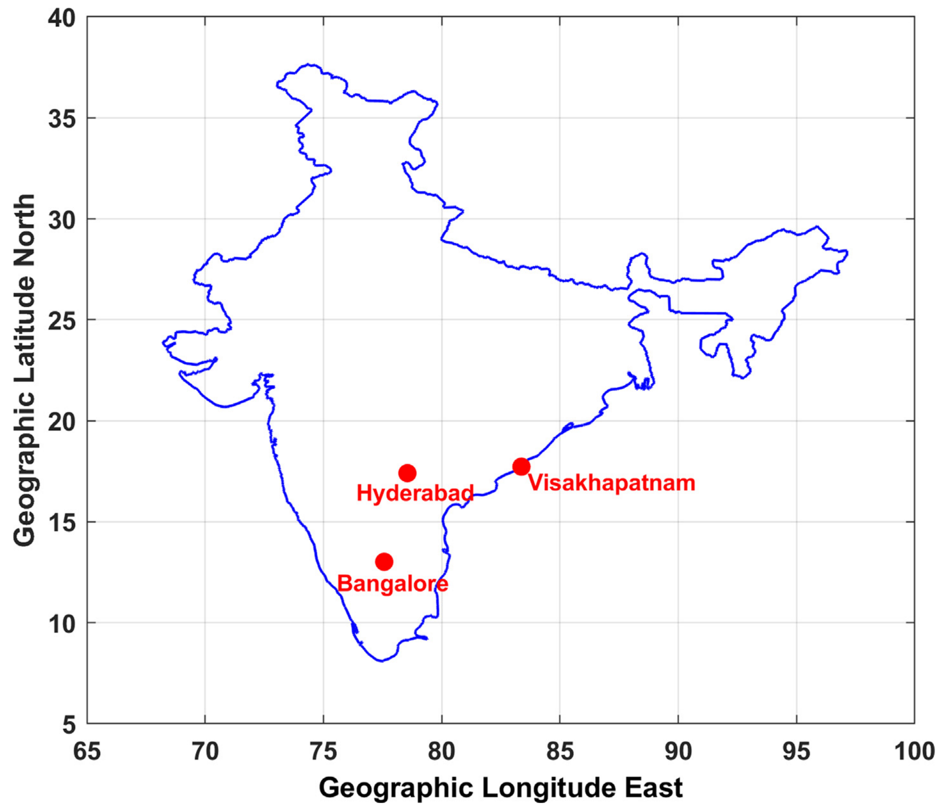

Fig. 1. Locations of the GPS receiver stations used in the present study.

3. Results and discussion

3.1. Seasonal and solar activity variation of GPS-TEC

The contour plots shown in Fig. 2 delineates the monthly mean variations of GPS TEC during the descending phase of solar cycle 24 from 2015 to 2019 over Bangalore, Waltair and Hyderabad. This plot is made by considering all quiet and disturbed days to briefly look at the general trend of TEC variations during the considered period. It is noticed that, the diurnal maximum in TEC is seen approximately between 12:00 and 16:00 UT at all stations. Day time TEC values are found to be higher in equinoctial months (March, April, September and October) followed by winter (November, December, January and February) and summer months (May, June, July and August) at all stations. The higher day maximum TEC values are observed over Waltair followed by Hyderabad and Bangalore, peaking in the equinoctial months of March, April and September, October and they are decreasing from moderate to low solar activity period. It is known that the seasonal variation of TEC is directly controlled by the thermospheric neutral composition. During day time, the equator is hotter than poles and therefore the meridional wind flows towards pole from the equator. The meridional wind flow changes the neutral composition and the ratio of atomic oxygen to molecular nitrogen (O/N2) increases at equatorial and low latitude regions, which will be maximum during equinox. Since the N_2 dissociation is the major process which removes the ambient electrons around 300 km, the increase in O/N_2 ratio will increase the electron density and leads to higher TEC values during equinoctial months (Bagiya et al., 2009). The magnitude of GPS derived TEC is evidenced higher for March equinox than the September equinox for all stations. Monthly mean variations in day time TEC shows a semi-annual periodicity which is diminished from moderate (2015–2016) to low solar activity (2017–2019). The observations revealed that the annual and semi-annual variations in TEC are mostly absent during night time hours for all the stations. The intensity of the semi-annual variation is found to be diminished with solar activity. Natali and Meza (2011) have studied the annual and semi-annual variations using GPS TEC during high solar activity and concluded that semi-annual variation is higher during March-April equinox than the September-October equinox over equatorial and low geomagnetic latitudes. Latitudinal comparison reveals that the TEC intensity is increased from near equator (Bangalore) towards low latitudes (Hyderabad and Waltair) during the descending phase of solar cycle 24.

These observations indicate general trend in TEC variations irrespective of the quiet and disturbed conditions. In the following sections, the TEC characteristics are individ-

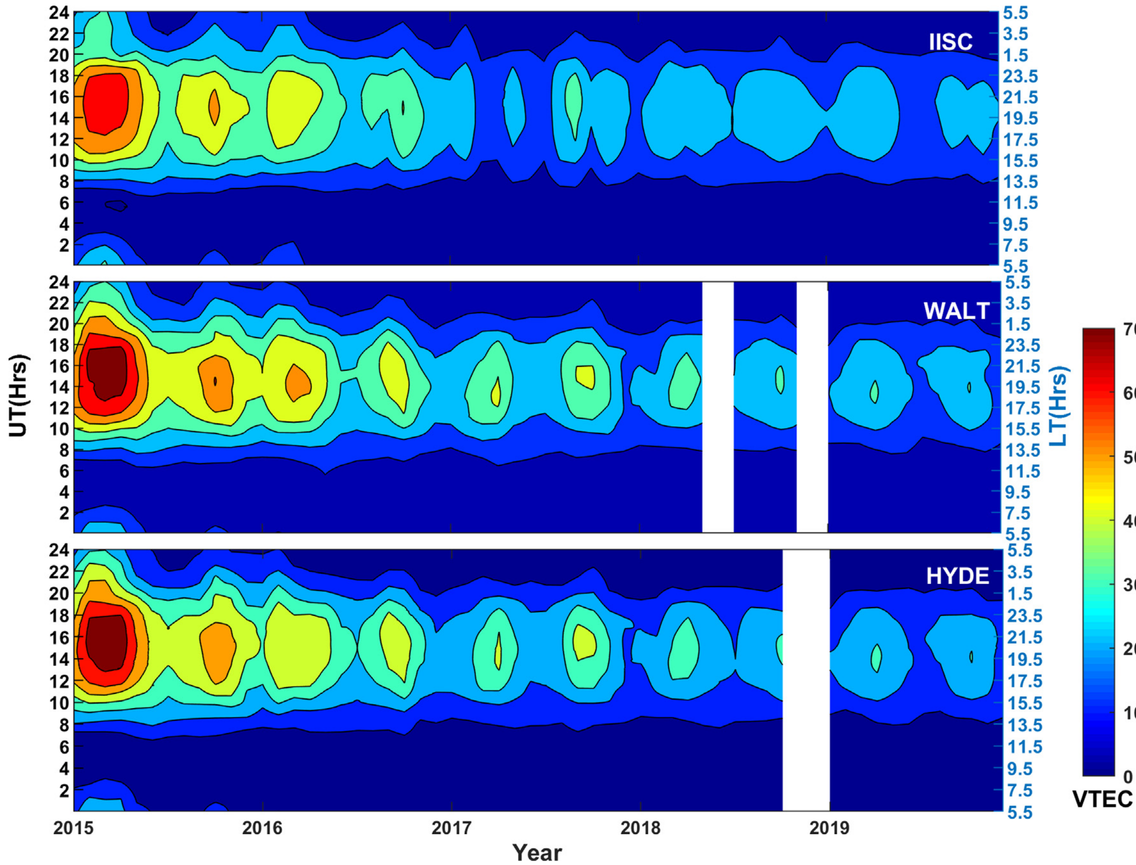

Fig. 2. Semiannual Variation in ionospheric TEC during the descending phase of 24th solar cycle (2015–2019).

ually analysed during quiet and disturbed conditions and the corresponding results are presented.

3.2. TEC variations during quiet and disturbed geomagnetic conditions

The following sections describe the similarities and differences of TEC characteristics between quiet and disturbed geomagnetic periods during different solar activity conditions.

3.2.1. Seasonal variations

To distinguish the seasonal TEC variations under quiet and disturbed geomagnetic conditions, the seasonal mean TEC variations are presented in Fig. 3. The quiet and disturbed periods in each year are considered as described in the data and analysis section. The seasonal mean day maximum TEC and seasonal mean standard deviation during quiet and disturbed geomagnetic conditions has been calculated for each season and the results are shown in Fig. 3. In this figure, three rows from top represents three stations IISC, WALT and HYDE respectively and the left column refers to disturbed time while the right column refers to quiet time.

Seasonal variation of GPS TEC indicates higher TEC values in equinoctial months followed by winter and summer during quiet time during all the years from 2015 to 2019 over the three stations following the general trend presented in Fig. 2. The quiet time day maximum TEC for each season is highest for the year 2015 and then decreases subsequently with the decreasing solar activity towards 2019. During disturbed periods, the seasonal variations indicate equinoctial maximum and summer minimum similar to that of quiet period during moderate solar activity years (2015 and 2016). However, it is interesting to observe that, the general trend is not retained during the disturbed days of low solar activity years (2017–2019). It is clearly seen that the TEC during equinox and summer are similar during the years 2018 and 2019; TEC during the three seasons is nearly comparable in the year 2018; and winter minimum is seen in the years 2017 and 2019. All these features of TEC indicate that the seasonal variations of TEC during disturbed conditions of low solar activity period do not follow the quiet time seasonal behavior. The diminished seasonal effect and dynamic seasonal mean standard deviation values during low solar activity period under disturbed geomagnetic conditions can be attributed to the geomagnetic storm effects on the ionospheric variability. The following section presents more detailed analysis on the TEC variations during moderate and low solar activity periods under quiet and disturbed geomagnetic conditions.

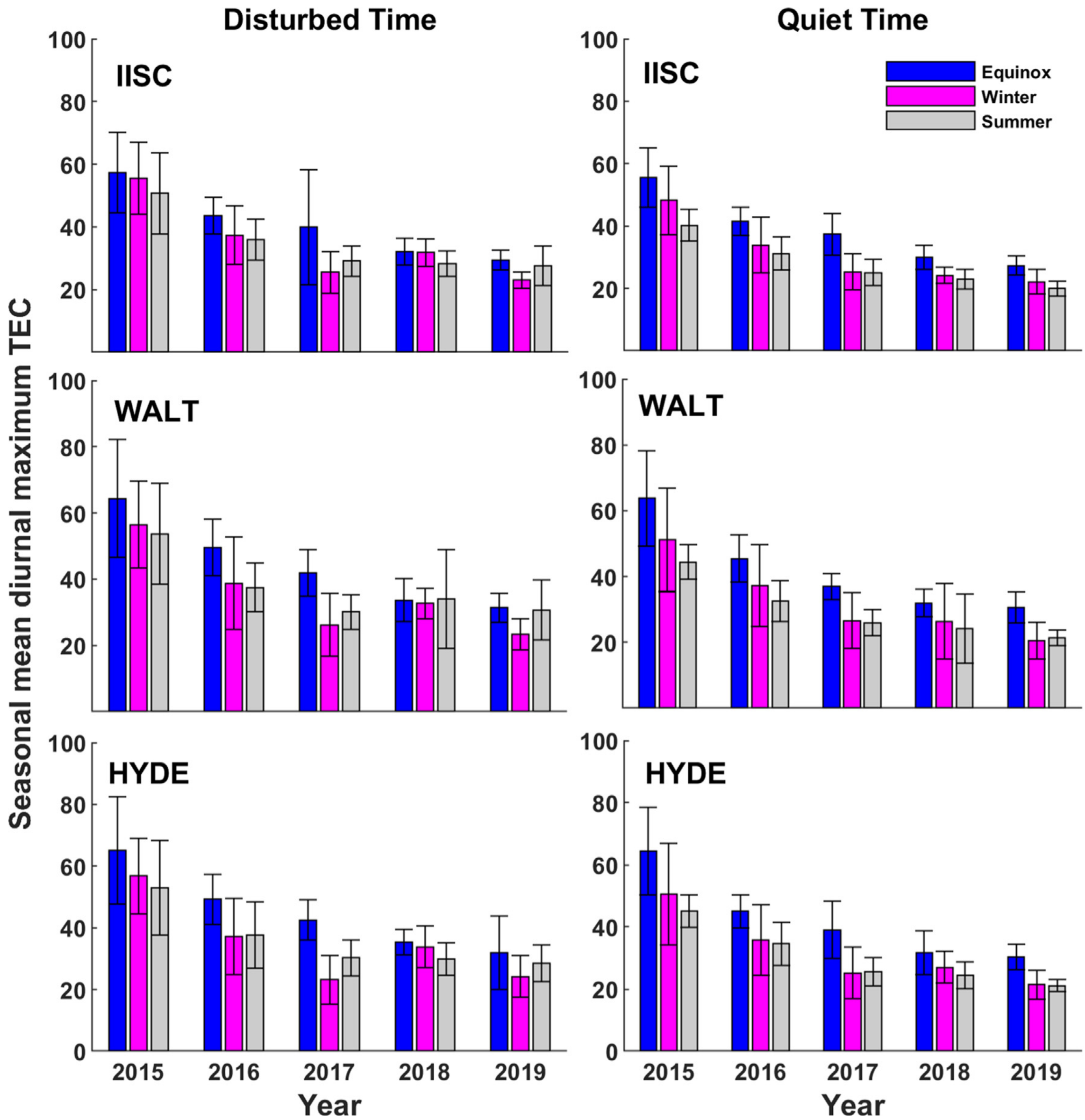

Fig. 3. Quiet and disturbed time seasonal mean day maximum TEC during the descending phase of 24th solar cycle (2015–2019).

3.2.2. TEC variations during moderate and low solar activity conditions

In order to get better understanding on the effects of space weather events in the ionosphere during different solar activity conditions, we have studied the quiet and disturbed time TEC variations during moderate and low solar activity conditions. The monthly mean diurnal variations of TEC during quiet and disturbed conditions are individually obtained for low and moderate solar activity periods and the results are shown in Figs. 4, 5 & 6 for IISC, WALT and HYDE respectively. Monthly mean TEC variations during low (2017–2019) and moderate (2015–2016) solar activity periods has been shown in the top and bottom panels respectively for the three stations. The blue curve represents the quiet time monthly mean TEC and red curve represents the disturbed time monthly mean TEC for each month. As stated above, disturbed days are separated DST index as a proxy, and no disturbed days are observed during the January month of low solar activity period. It is seen from these figures that the day minimum in the diurnal variation of TEC is found between 05:00 IST and 06:00 IST for both quiet and disturbed periods during low and moderate solar activity conditions. The day maximum TEC values are observed between 13:00 IST and 15:00 IST under quiet and disturbed conditions for both low and moderate solar activity phase for all the stations. The day time peak TEC values depend greatly on the strength of the equatorial ionization anomaly in the low latitude regions (Bagiya et al., 2009).

The TEC variations over near equatorial station IISC presented in Fig. 4 indicate that the monthly mean TEC values are higher (nearly double) in all months during moderate solar activity period than the low solar activity period for both quiet and disturbed periods. It is seen that the

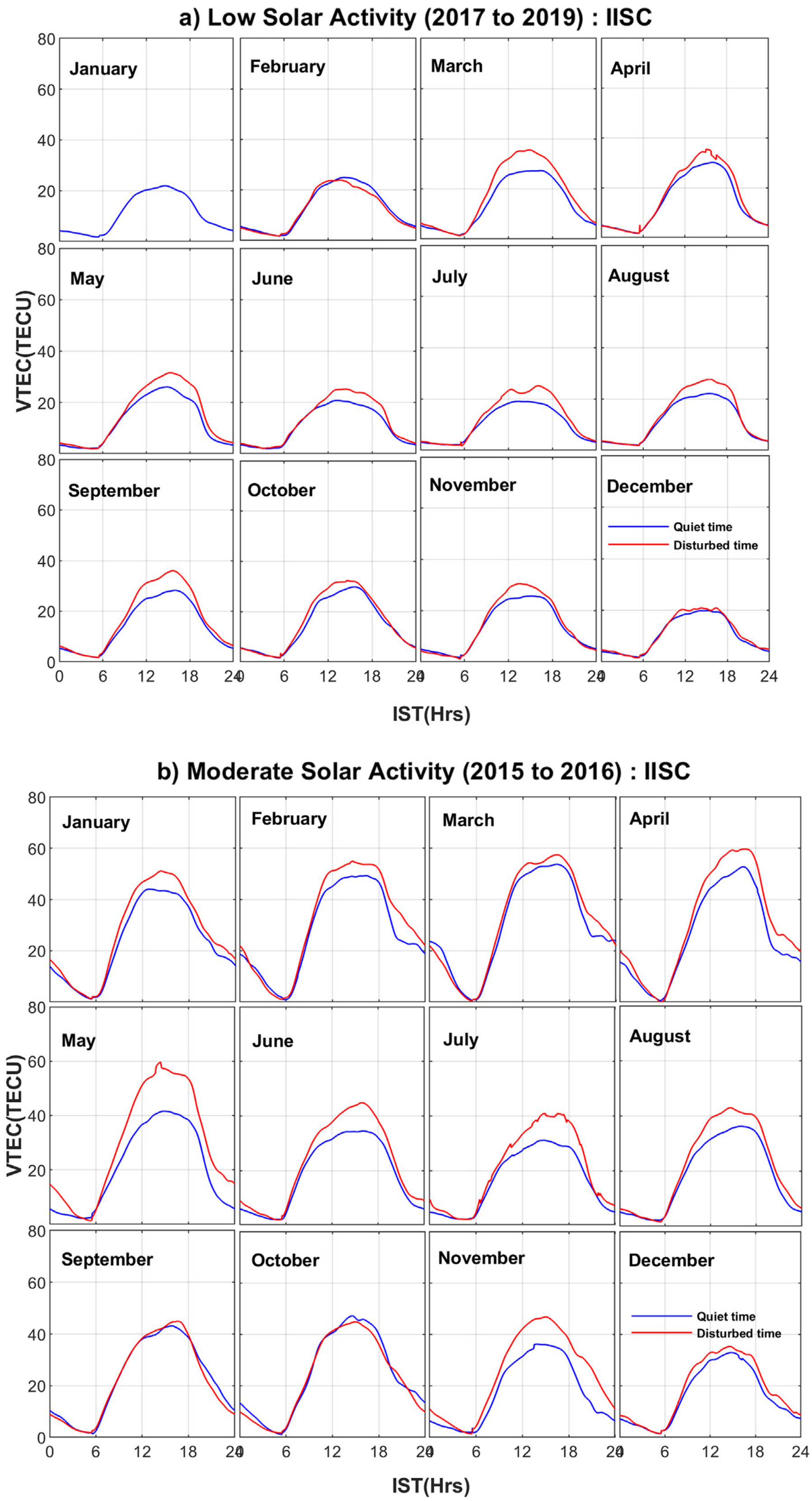

Fig. 4. Monthly mean TEC variation of quiet and disturbed time over Bangalore during (a) low solar activity (2017–2019) and (b) moderate solar activity (2015–2016) periods.

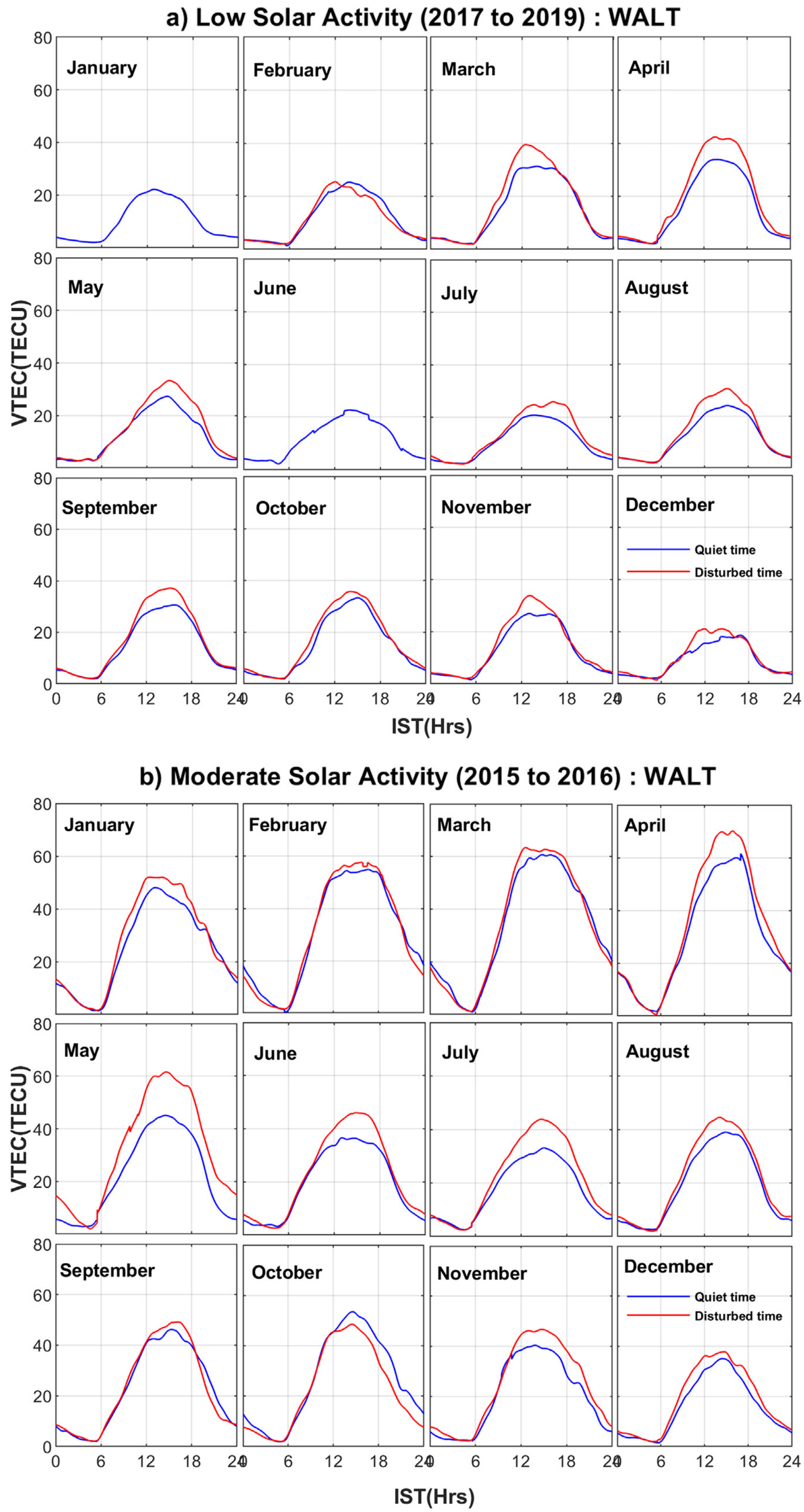

Fig. 5. Monthly mean TEC variation of quiet and disturbed time over Waltair during (a) low solar activity (2017–2019) and (b) moderate solar activity (2015–2016) periods.

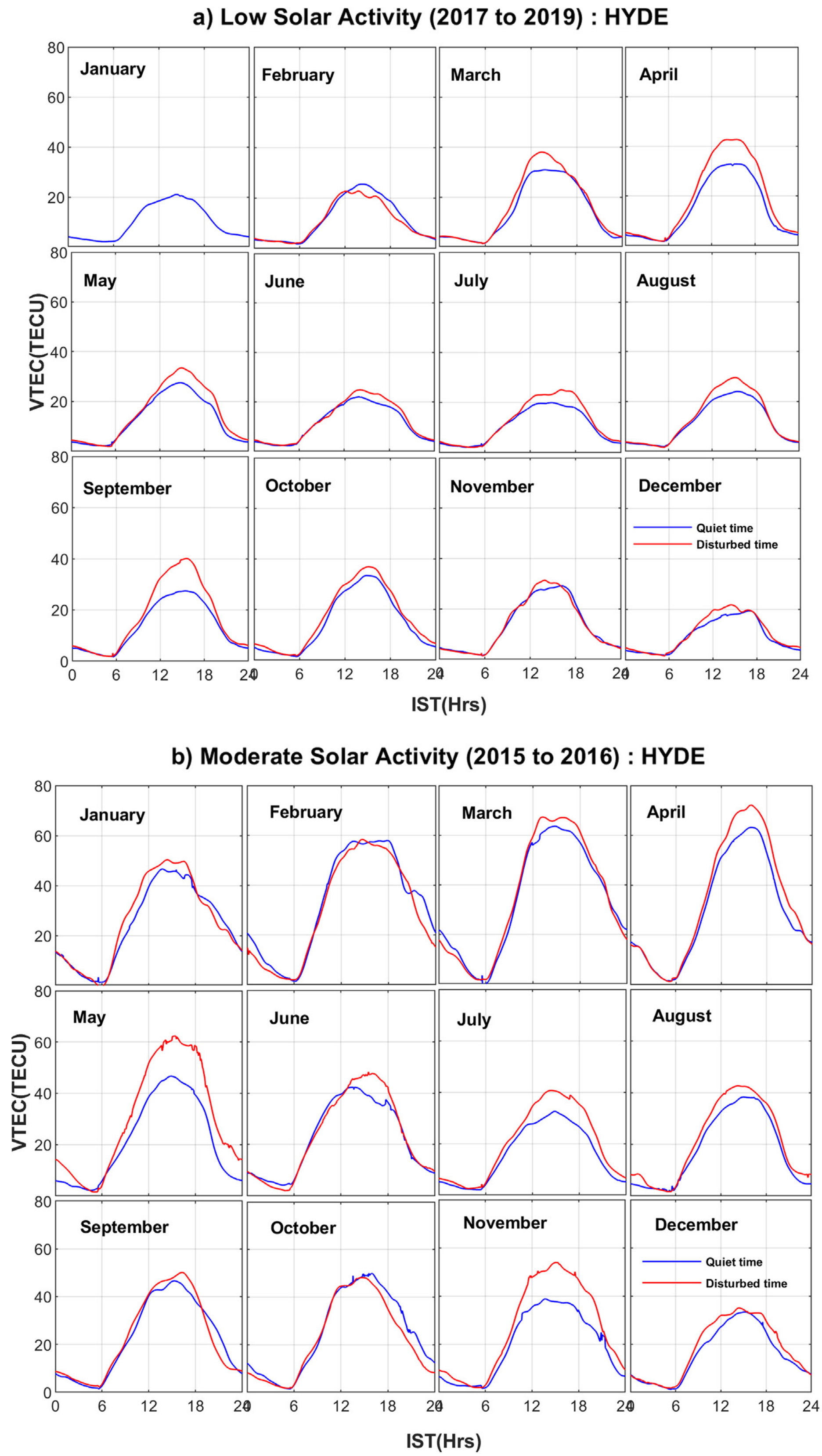

Fig. 6. Monthly mean TEC variation of quiet and disturbed time over Hyderabad during (a) low solar activity (2017–2019) and (b) moderate solar activity (2015–2016) periods.

TEC difference between quiet and disturbed periods is marginal during low solar activity period. But during the moderate solar activity period, the difference in TEC between quiet and disturbed periods is much higher except for the months September, October, December and March. Quiet time monthly mean TEC is more as compared with disturbed time TEC in the month of February during low solar activity phase and the same is not reflected in the moderate solar activity phase. The difference between quiet and disturbed time monthly mean TEC is higher in the month of May during moderate solar activity, which is not seen during the low solar activity period. During moderate solar activity period, the disturbed time TEC is higher in the equinoctial months followed by winter and summer. The higher TEC values in the winter than in summer for moderate solar activity period (2015–2016) shows the winter anomaly and the same is not seen during low solar activity period (2017–2019). During low solar activity period, the disturbed time TEC is higher in the equinoctial months and is more or less same for both winter and summer months.

Quiet and disturbed time monthly mean TEC variations during low and moderate solar activity periods over the low latitude station, Waltair are shown in Fig. 5. Over Waltair, quiet and disturbed time TEC is almost same during low and moderate solar activity periods except for the months April, May, June and July of moderate solar activity period. It is also seen that the disturbed time TEC is lower than quiet time TEC for the month of October during moderate solar activity and the same is observed in the month of February during low solar activity. Quiet and disturbed time monthly mean TEC values are higher for moderate solar activity period as compared with low solar activity period. During low solar activity period, disturbed time TEC is higher in the equinoctial months and is more or less same for both winter and summer months. During moderate solar activity period, the disturbed time TEC is higher in the equinoctial months followed by winter and summer.

Fig. 6 depicts the quiet and disturbed time monthly mean variations during low and moderate solar activity periods over another low latitude station, Hyderabad. During low solar activity period, disturbed time TEC is higher than quiet time for the months of April and September and the difference is not significant for other months. During moderate solar activity period, the disturbed time TEC is higher than quiet time TEC for the months of April, May, July and November. Disturbed time TEC is lower than time TEC for the month of October during moderate solar activity and for the month of February during low solar activity. Quiet and disturbed time monthly mean TEC values are higher for moderate solar activity period as compared with low solar activity period. During low solar activity period, the disturbed time TEC shows higher

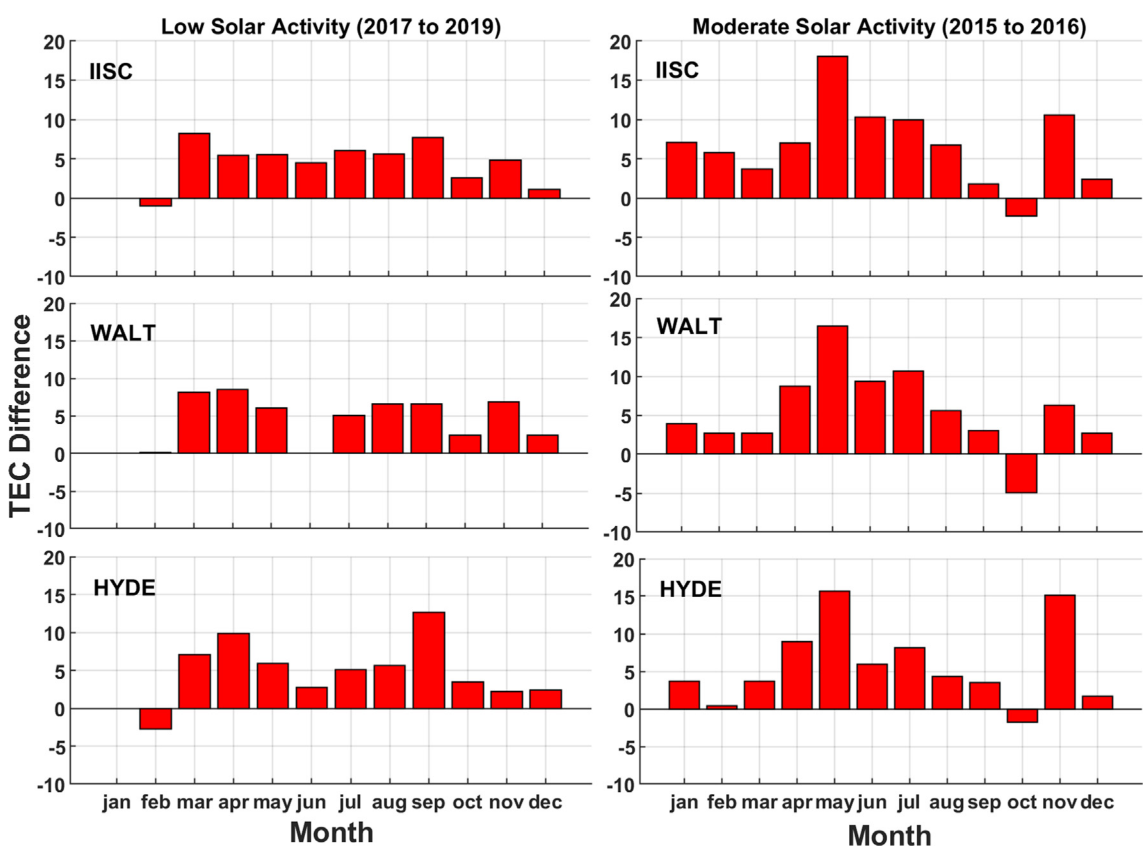

Fig. 7. Difference between quiet and disturbed time monthly maximum TEC during low and moderate solar activity periods.

values in equinox and nearly similar values in winter and summer. During moderate solar activity period, the disturbed time TEC shows a general trend with equinoctial maximum followed by winter and summer.

3.2.3. Difference between disturbed and quiet time TEC

In order to understand the variations in the magnitude of difference between quiet and disturbed time TEC, the differences in monthly mean TEC maximum between quiet and disturbed conditions are computed for all months in low and moderate solar activity phases at all the stations. Fig. 7 shows the difference in monthly mean TEC maximum between quiet and disturbed periods during low (left column) and moderate (right column) solar activity phases over the stations IISC, WALT and HYDE from top to bottom respectively. In these plots, the positive (negative) values indicate positive (negative) storm effect, i.e., the disturbed (quiet) time TEC is more than that of quiet (disturbed) time TEC. It is clearly seen from this figure that the positive storm effect is more significant as compared with negative storm effect during low and moderate solar activity phases at all three stations. The strength of the positive storm effect is more during moderate solar activity period than that of the low solar activity period. The monthly trends in TEC difference are varying with solar activity conditions. All the stations following the almost same trends of difference TEC particularly during moderate solar activity phase. The difference in TEC is higher in summer months and lower in winter months during moderate solar activity phase. During low solar activity phase, the TEC difference is nearly similar during summer and equinox and it is lower in the winter months. Negative TEC difference values are observed in the months of October and February during moderate and low solar activity phases respectively.

The strong positive storm effect is evidenced in the month of May with TEC difference around ~ 18 TECU over Bangalore during moderate solar activity period. During low solar activity, the strong positive storm effect is seen for September month around ~ 13 TECU over Hyderabad. The strongest negative storm effect is spotted out in the month of October around ~ 5 TECU at Waltair for moderate solar activity and in February around ~ 2.5 TECU at Hyderabad for low solar activity period. Higher positive storm effect is seen in all stations in the month of May during moderate solar activity phase and such type variation is not seen during low solar activity phase.

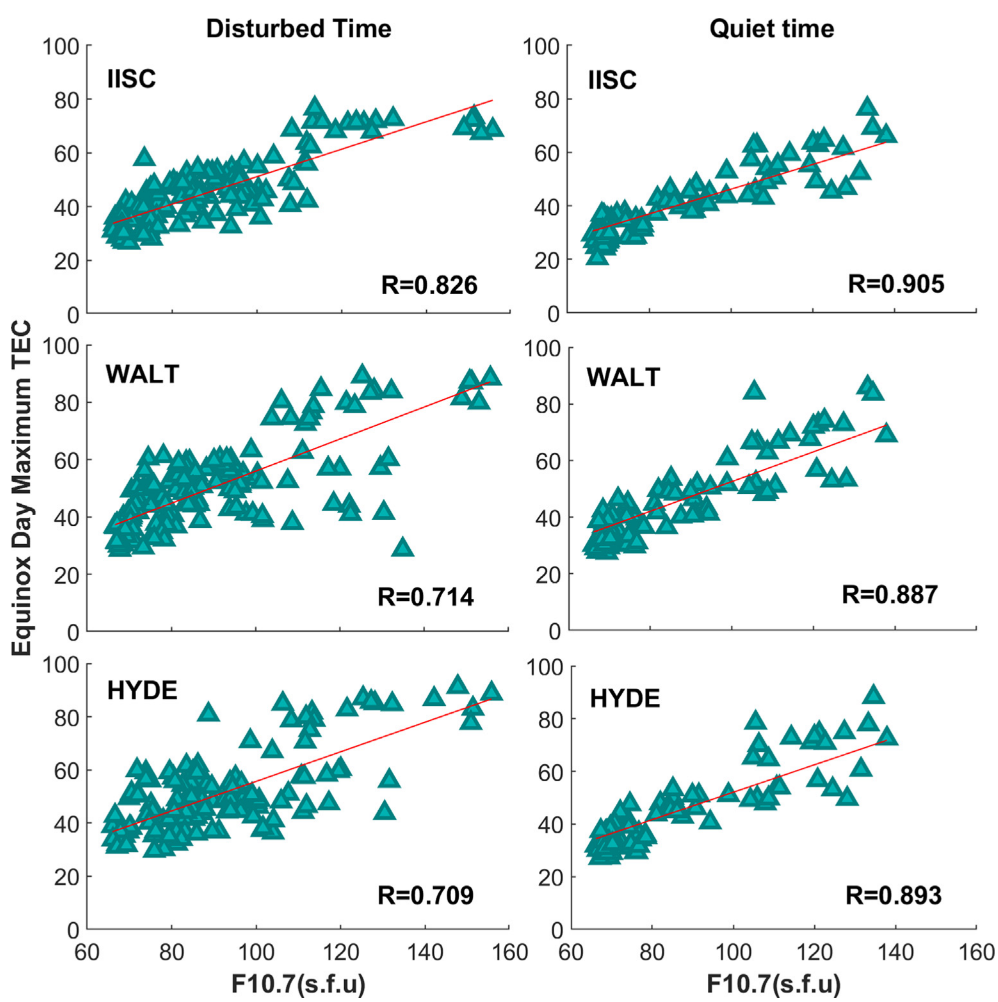

Fig. 8. Correlation of equinox day maximum TEC with F 10.7 solar flux during quiet and disturbed periods.

In general, it can be noted that the difference between disturbed and quiet time TEC is higher during moderate solar activity compared with low solar activity periods. During the moderate solar activity periods, the geomagnetic storms could occur more with comparably higher intensity than those during the low solar activity. This could have resulted more differences in TEC between disturbed and quiet periods during the moderate solar activity period.

3.2.4. Solar flux dependence of TEC

In order to check the solar flux dependence of TEC during quiet and disturbed periods, we obtain the statistical correlation between seasonal day maximum TEC and F 10.7 cm solar flux for the three stations from 2015 to 2019. The Figs. 8, 9 and 10 depicts the statistical correlation between seasonal mean day maximum TEC and F 10.7 cm solar flux during quiet and disturbed periods for equinox, winter and summer seasons respectively. The left column shows the correlation in the disturbed time while the right column shows the correlation in the quiet time. Correlation coefficient values between seasonal mean day maximum TEC and F 10.7 cm solar flux during quiet and disturbed conditions for all seasons at three stations are consolidated and presented in Table 1.

It is in general seen from these plots that the correlation coefficient values are higher during quiet time (vary between 0.73 and 0.90) compared to disturbed time (vary between 0.60 and 0.85) for all the seasons and stations. Higher correlation coefficient values are observed over the equatorial station Bangalore during both quiet (r = 0.905) and disturbed (r = 0.858) periods for all seasons as compared with those at Waltair and Hyderabad. During the quiet time period, the correlation is higher for equinox followed by winter and summer at all the three locations. Considering both quiet and disturbed days, Prasad et al., (2011) reported that the correlation coefficients of TEC with F10.7 are higher near the equatorial stations compared to the anomaly crest locations with equinoctial maximum and summer minimum. Correlation analysis results in the present study during quiet conditions are in agreement with those reported by Prasad et al., (2011). It is interesting to note that, during disturbed conditions, the correlation is found to be higher in winter months followed by equinox and summer. Also, comparison of correlation between quiet and disturbed periods in the present study

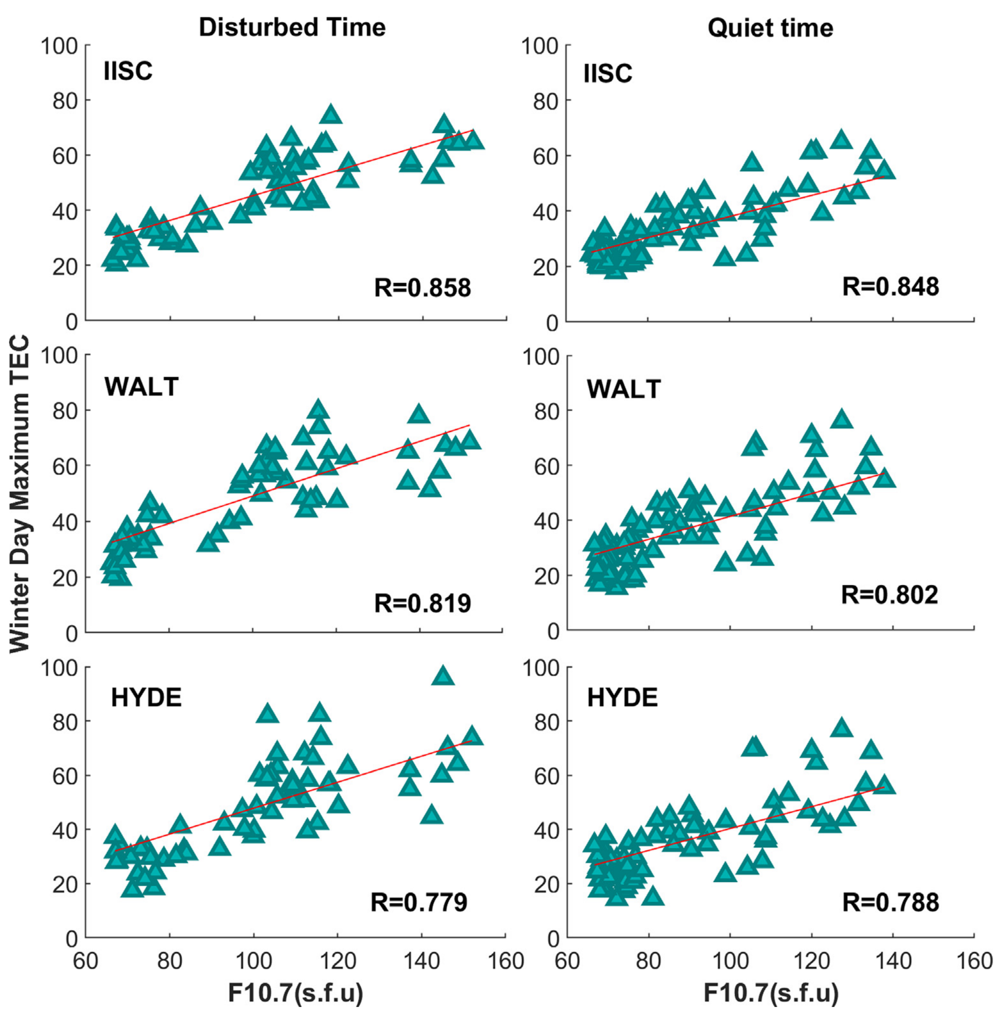

Fig. 9. Correlation of winter day maximum TEC with F 10.7 solar flux during quiet and disturbed periods.

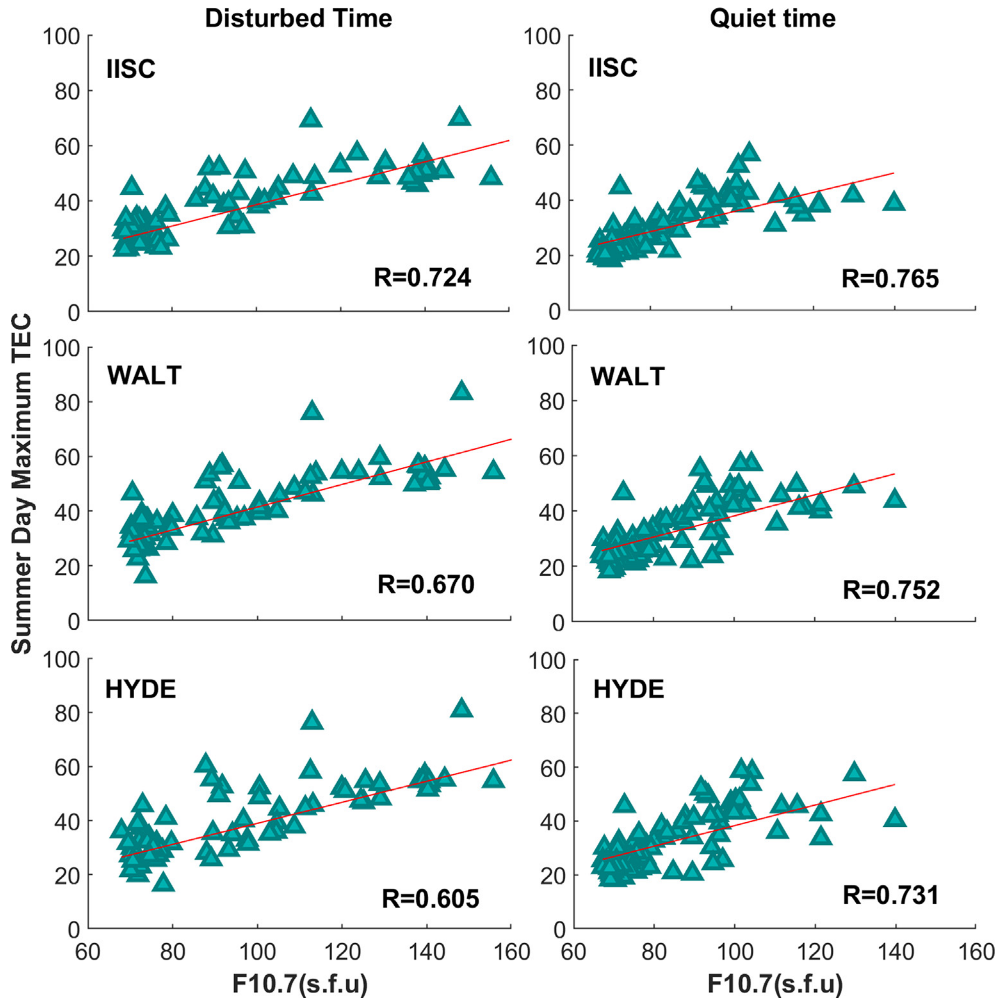

Fig. 10. Correlation of summer day maximum TEC with F 10.7 cm solar flux during quiet and disturbed periods.

Table 1
Correlation between Seasonal day maximum TEC and F 10.7 cm Solar Flux during Quiet and Disturbed Conditions.

Station Name	Correlation between Seasonal Mean Day Maximum TEC and F 10.7 cm					
	Equinox		Winter		Summer	
	Disturbed Time	Quiet Time	Disturbed Time	Quiet Time	Disturbed Time	Quiet Time
Bangalore	0.826	0.905	0.858	0.848	0.724	0.765
Waltair	0.714	0.887	0.819	0.802	0.670	0.752
Hyderabad	0.709	0.893	0.779	0.788	0.605	0.731

reveals reduced correlation of TEC with F 10.7 during the disturbed conditions. While the F10.7 solar flux indicates the intensity of the solar ionizing radiation, during active space weather conditions effects due to geomagnetic storm induced electric fields and winds also impact the low latitude ionospheric variability. This would have caused lower correlation of TEC with F10.7 during disturbed periods when compared to quiet time.

4. Summary

A detailed analysis has been carried out to understand the space weather effects on the short- and long-term variations of TEC over the equatorial and low latitude stations in the Indian sector. The GPS-TEC observations at three stations during the declining phase of the 24th solar cycle (2015–2019) is considered. The salient results of the present study are summarized here under:

1. General trend in TEC variations (considering both quiet and disturbed days) shows maximum TEC values in equinoctial months followed by winter and summer months.
2. Winter anomaly in day maximum TEC variations is seen during moderate solar activity and the same is not reflected in the low solar activity period.

3. The quiet time seasonal trend (equinoctial maximum and summer minimum) is seen during disturbed periods only in the moderate solar activity conditions. A mixed behaviour of seasonal trend is seen during disturbed conditions of low solar activity period.
4. The difference between disturbed and quiet time TEC is found to be higher during moderate solar activity compared with low solar activity periods.
5. During moderate solar activity, the TEC differences between disturbed and quiet time are maximum in summer months. During low solar activity the TEC differences are similar in summer and equinoctial months with minimum in winter months.
6. During disturbed time, the correlation between TEC and F 10.7 is maximum in winter followed by equinox and summer, whereas during quiet time maximum correlation is seen in equinox.
7. It is found that the correlation of TEC and F 10.7 is reduced during disturbed conditions compared to quiet time period.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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