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Solar EUV flux (0.1-50 nm), F10.7 cm flux, sunspot number and the total electron content in the crest region of equatorial ionization anomaly during the deep minimum between solar cycle 23 and 24

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The daily peak total electron content (TEC), recorded from Rajkot (22.29°N, 70.74°E, 31.6°N dip angle), is analyzed to investigate the combined roles of the solar cycle effect and neutral dynamical processes on the TEC variation over the equatorial ionization anomaly (EIA) crest region during the deep minimum between solar cycle 23 and 24. It is found that the mean peak TEC level decreases monotonically during 2005-2008 in accordance with the mean solar EUV (0.1-50 nm) and F10.7 cm (2800 MHz) flux (1 sfu = 10^{-22} Wm^{-2} Hz^{-1}). The mean peak TEC level over Rajkot seems to respond to the mean EUV flux (or F10.7 cm flux) level by simultaneously registering an increasing trend from February 2009 onwards. Most importantly, the rate of increase in the mean peak TEC level during 2009 over Rajkot is greater than the corresponding rates of increase in the mean EUV and F10.7 cm flux levels indicating the important additional roles played possibly by the residual (difference between annual averages) effects of the trans-equatorial winds, compositional changes, etc. over this time scale. It is verified that the inherent solar periodicity of around six months has no consistent causal connection with the semi-annual variation in TEC. A few spectral differences are also observed between the EUV flux and F10.7 cm flux. The annually averaged peak TEC value over Rajkot is found to be well correlated (R = 0.98) with the corresponding annually averaged F10.7 cm flux during 2005-2009. Statistical analyses also indicate that the time of occurrence of maximum TEC over Rajkot changes randomly during 2005-2009 indicating the possible role played by the processes related to the residual trans-equatorial wind over the years.

Keywords: Total electron content (TEC), Solar EUV flux, Solar F10.7 cm flux, Sunspot number, Equatorial ionization anomaly (EIA), Deep solar minimum

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1 Introduction

Solar cycle 23 is characterized by a minimum activity period that is unique in many ways. During this deep slumber phase of the sun, it went spotless for over 70% days (265 days) during 2008-2009. The various characteristics of this minimum from solar physics perspective are discussed in literature[1]. Apart from the sunspot number (SSN), which represents the solar activity fairly accurately, the solar EUV (0.1-50 nm) and F10.7 cm (2800 MHz, 1 sfu = 10^{-22} Wm^{-2} Hz^{-1}) fluxes are widely used to describe the variations in the solar extreme ultra violet (EUV) irradiance. Often, it is postulated that the relationship between EUV flux and F10.7 cm flux is invariant over different solar cycles, and therefore, F10.7 cm flux is used as a proxy for solar activity in the ionospheric models like International Reference Ionosphere (IRI)[2]. However, a recent study indicates that the relationship between the F10.7 cm flux and the solar EUV flux during the latest deep solar minimum is different from the previous minima, the decrease in the two parameters being ~5% in F10.7 cm flux and 15% in 1-50 nm EUV irradiance compared to the previous minimum[3]. The study also indicates that the F10.7 cm flux is not an ideal indicator of foF2 during the period 2007-2009. In another recent study, Luhr & Xiong[4] have shown that IRI-2007 model overestimates the electron density during the deep minimum between solar cycle 23 and 24. Considering the crucial dependence of the solar EUV photons in the production of ionization in the terrestrial ionosphere, it is, therefore, important to investigate the ionospheric variation during the deep minimum between the solar cycles 23 and 24, vis-à-vis changes in the EUV flux, F10.7 cm flux and SSN.

The production of plasma in the ionospheric F-region over low-latitudes is mainly due to the solar EUV radiation primarily in the 14.0-79.6 nm spectral range. F-region is also strongly dominated by the plasma transport processes. Over low latitudes, F-region is characterized by the enhanced plasma density (ionization crest) over ~±20° magnetic north and south with depleted plasma density (ionization trough) over dip equator. This essentially occurs due to the vertical E×B plasma drift over the dip equator[5-8] followed by ambipolar diffusion of plasma along the field lines in the meridional direction. This fountain-like plasma movement during daytime over low-latitudes was first reported by Appleton[9]. The "fountain effect" generates an anomaly in the plasma distribution over low-latitudes as ionospheric F-region over low-latitudes consist of more plasma than its counterpart over the dip equator although equatorial F-region should have contained more plasma in proportion to the solar radiation received. This equatorial ionization anomaly (EIA) is a hallmark feature of low latitude F-region ionosphere.

Several techniques are adopted to probe the F-region ionosphere. With the advent of the Global Positioning System (GPS) satellites, measurement of total electron content (TEC), which is derived based on the propagation characteristics of the L-band signals transmitted by the GPS satellites, is frequently used to investigate the F-region ionosphere. The ionospheric contribution of TEC mainly comes from the F2-layer which being a transport dominated region, ionospheric TEC is expected to respond to various geophysical events that change the plasma transport and associated chemical processes. On the contrary, the plasmaspheric component of TEC does not show much variability except during severe space weather events[10]. As a consequence, TEC is often used to investigate the F–region ionosphere over low latitudes. TEC in the vicinity of the anomaly crest region is known to depend crucially on the development of EIA.

There are many ionospheric and thermospheric factors that can modulate EIA and as a consequence, TEC over low latitudes. Prompt penetration[11] and over shielding effects[12] of interplanetary electric field (IEF) or substorm-related electric field perturbations[13] can alter the zonal electric field over dip equator resulting in the changes in the distribution of F-region ionization over low-latitudes through fountain effect[14]. Meridional winds are known to cause hemispherical asymmetry in the intensity (crest to trough ionization density ratio), as well as the location of the crest[7-8,15-17]. In addition, lower atmospheric tidal processes are now believed to generate standing wave patterns (in the global constant local time frame) in the F-region ionization around the EIA crest region[18]. Compositional changes[19] can alter the O/N_2 concentration ratio that can eventually change the TEC over the anomaly crest region[14,20]. In addition, solar flares[21-23] can also bring in transient changes in TEC over low latitudes by changing the input of EUV flux into the upper atmosphere.

All the above mentioned processes generally affect TEC at a time scale much smaller than the time scale characteristic of a solar cycle. It has been shown by various researchers[24-31] that changes in the TEC can take place over the years during a solar cycle owing to the changes in the EUV/F10.7 cm solar flux. Over the Indian sector, several investigations have been carried out to decipher the changes in TEC over the anomaly crest region[20,32-36] during low solar activity period in the solar cycle 23. As mentioned earlier, the deep minimum in the solar cycle 23 is a peculiar one in terms of its duration and the relationship between solar EUV flux and the F10.7 cm flux. In addition, the overestimation of electron density by the IRI model during the deep minimum at low-latitudes during daytime hours[4] is also particularly important highlighting the gap areas in our overall understanding. As the solar activity corresponding to the cycle 24 is stepping up, it becomes important to compare the variation of TEC over the anomaly crest region during the descending phase of the last cycle (cycle 23) and the newly started ascending phase of cycle 24 vis-à-vis the variations in the EUV and the F10.7cm solar flux during these periods. The present investigation addresses a few of these aspects.

2 Details of observations

The GPS system comprises of more than 24 satellites at an altitude of ~20200 km that transmits signals at L1 (1575.42 MHz) and L2 (1227.60 MHz) frequencies. As the GPS signals pass through the ionosphere, the carrier frequency experiences advancement in phase and the coding frequency undergoes a group delay owing to the presence of free electrons along the ray paths from the satellites to receiver. Therefore, the pseudo-ranges yielded by the carrier phase and the code become shorter and longer, respectively when compared with the geometric range between the satellite and the receiver. Although this poses a challenge to the positional accuracy, it offers a way to estimate TEC (Ref. 37). The GPS-TEC observations are carried out using a dual frequency GPS receiver from Rajkot (22.29°N, 70.74°E, 31.6°N dip angle), a station near the crest region of equatorial ionization anomaly (EIA). The number of days of observation is around 180 per year during the period 2005-2009 and encompasses all seasons for each year fairly well. The receiver bias is corrected using the values by calibrating the receiver against Wide Area Augmentation System (WAAS). The satellite bias values are periodically obtained from the site (http://aiuws.unibe.ch/spec/dcb.php#p1c1) and these values are used to correct the measured slant TECs. Most of the time, receiver bias is of the order of ~1-2 ns. Hence, the instantaneous TEC values can be considered to be accurate between ±3 TECU and ±6 TECU. Slant TEC values are then converted to vertical TEC values using an obliquity factor or mapping function[38], which is a function of the elevation angle of the satellite. For this study, an elevation mask of 30° is used to eliminate the multi-path and troposphere scattering effects both of which are more prominent at lower elevation angles[20]. The vertical TEC values, thus obtained, are used to construct the plots of diurnal variation of TEC over Rajkot. The daily mean peak TEC is determined by averaging the TEC data for one hour around the time of the peak value of TEC. The annual mean peak TEC data are obtained by averaging the daily mean peak TEC data for the available days in a year. As the time scales addressed in this investigation is much larger compared to a day and the geomagnetic activity is significantly less during this period[3], no attempt is made to classify the data according to the geomagnetic activity level.

The daily SSN and F10.7 cm flux data are taken from the Space Physics Interactive Data Resource (http://spidr.ngdc.noaa.gov/spidr/). The EUV flux (in units of 10^{10} photons cm^{-2} s^{-1}) data are obtained from the Solar EUV Monitor (SEM) on-board the SOHO satellite. The daily averaged EUV fluxes in the 0.1-50 nm spectral band (http://www.usc.edu/dept/space_science/OLD_WEB/semdata.htm) are used for the present study.

3 Results

Figures 1(a, b and c) depict the variations in daily values in SSN, EUV flux and F10.7 flux during 2005-2010, respectively whereas Fig. 1(d) depicts the variations in the daily mean peak TEC over Rajkot from 2005 to the near-end of 2009. It is to be noted that TEC data after 2009 are not available. From the figure, it can be seen that the solar parameters show a gradual decrease during 2005-2008 (which is the declining phase of the solar cycle 23) and then enter into a slumber phase. This slumber phase of sun is an unusual characteristic which made the solar minimum of cycle 23 an ‘extended’ one. For F10.7 and EUV flux [Figs 1(b, c)], this phase is from April 2008 and continues up to February 2009. From February 2009, the parameters show an increasing trend, which may be considered as the beginning of the solar cycle 24. Interestingly, the SSN values show significant increase only from September [Fig. 1(a)]. In contrast to what is seen in the solar parameters, the TEC values over Rajkot, EIA crest region [Fig. 1(d)] did not show a slumber phase. Instead, they showed a continuously decreasing trend till February 2009. It is worthwhile to note that the mean level of TEC is still decreasing while the solar parameters have stopped decreasing. Even during the period when the EUV flux remains almost constant at a very low value (April 2008 to February 2009), the TEC does not remain so. Instead, the TEC variation continues to show the signatures of semi-annual and seasonal variations, and also a continuous linear decrease up to February 2009. Keeping these observations in mind, it can be seen that a linearly decreasing trend is applicable to the solar parameters only up to April 2008 (for EUV and F10.7 fluxes) and September 2008 (for SSN), whereas for the TEC, the linearly decreasing trend is applicable up to February 2009. Accordingly, the linear regression lines have been fitted. The linear regression lines are extended in such a manner that they capture the mean trend and do not deviate significantly from the observed values of the respective parameters at the end of the cycle 23 and the beginning of the cycle 24. When the mean trend is captured, one cannot extend the linear fits (with decreasing slopes) in Figs 1(a-c) beyond April 2008 as all the parameters reveal plateau regions (no slope) after that time. Under that situation, all the linear fits in Figs 1(a-c) will deviate significantly from the actual data points. This is not the case for Fig. 1(d), wherein the linear fit with decreasing slope can extend till February 2009 without getting deviated significantly from the actual variation. In each of these figures, these two linear regression lines are shown corresponding to the declining phase ($Y_{1SSN/1EUV/1SFU/1TEC}$ in red) of the solar cycle 23 and the slightly ascending phase ($Y_{2SSN/2EUV/2SFU/2TEC}$ in pink) of the solar cycle 24. The linear regression lines are extended in such a manner that they capture the mean trend and do not deviate significantly from the observed values of the respective parameters at the end of the cycle 23 and the beginning of the cycle 24. The intermediate slumber phase of the sun when SSN (April 2008 – September 2009), EUV (April 2008 – February 2009) and SFU (April 2008 – February 2009) are steadily low, is marked in cyan. It is important here to note that 11-year sinusoidal solar cycle is a trademark first order feature in SSN and F10.7 cm flux time series. The transition time of the respective parameters between the descending phase of the solar cycle 23 and the ascending phase of the solar cycle 24 can be determined fairly accurately based on the fitted curves. Based on Fig. 1, an attempt is made to establish a possible causal relationship between the variations in the sunspot numbers, EUV flux, solar F10.7 cm flux and the TEC variations over Rajkot during 2005-2009.

Figure 1(a) shows that there are many days during 2005-2009 when SSN is zero especially so during 2007-2009. It is also found that the mean SSN level monotonically decreases from 2005 to 2007, remains steadily low during 2007-2009 and shows an increasing trend from September 2009 onwards. On the other hand, the durations of steadily low EUV flux and the F10.7 cm flux, as revealed by Figs 1(b and c), seem to be shorter than that seen in the SSN. As Figs 1(b and c) suggest, EUV and F10.7 fluxes start increasing from February 2009 onwards. Figure 1(d) brings out the decreasing trend in the mean peak TEC over Rajkot during 2005 to a period close to February 2009. The peak TEC over Rajkot starts increasing from February 2009 onwards, which is a feature similar to the variation of EUV and F10.7 cm flux but not SSN. However, if the rate of increase in TEC is

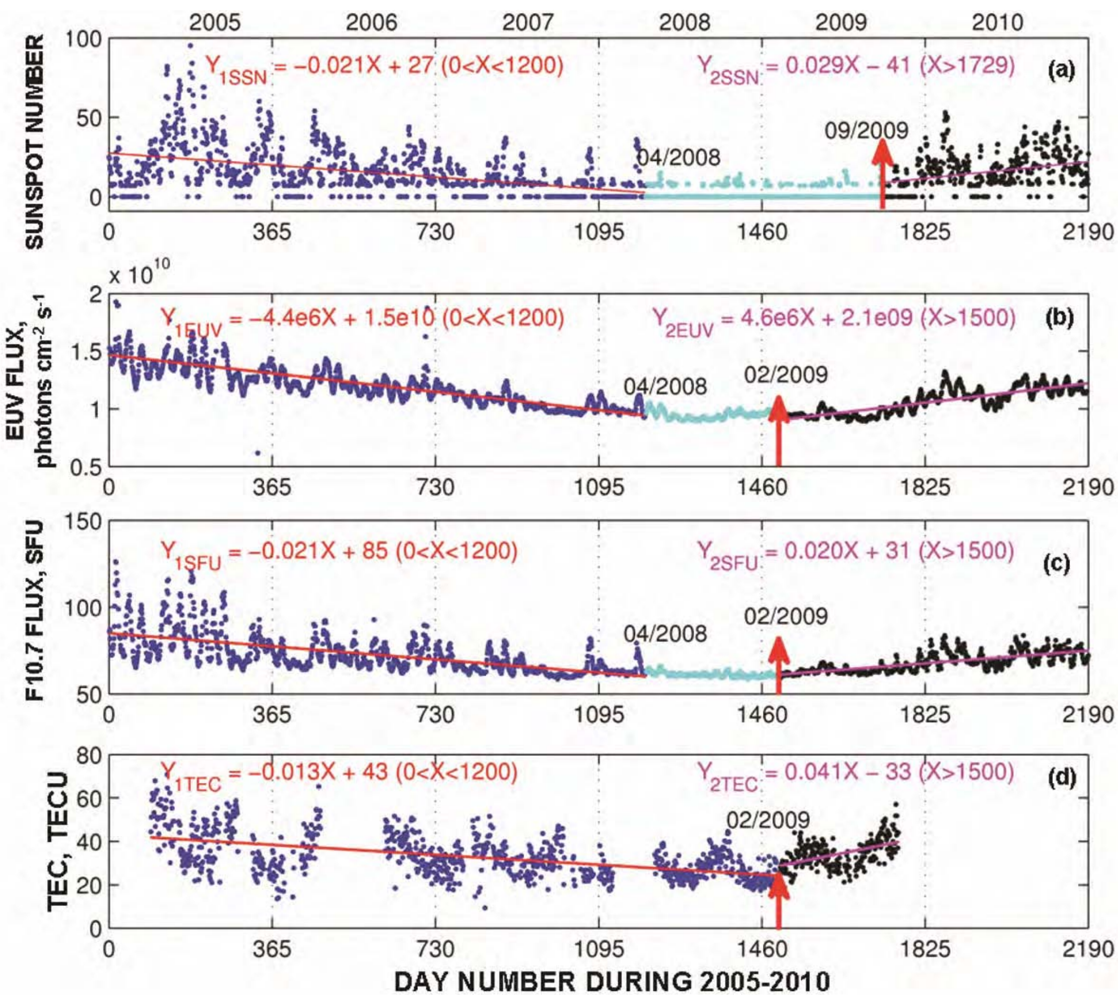

Fig. 1 — Variation of: (a) daily sunspot number; (b) EUV flux; (c) F10.7 cm flux along with (d) the diurnal maximum TEC at Rajkot [separate linear regression lines are overlaid on the actual variations for the descending phase (red) of the solar cycle 23 and the beginning of the ascending phase of (pink) solar cycle 24; cyan color in (a), (b) and (c) depict the interval when SSN, EUV flux and the F10.7 cm flux remain steadily low; red arrow represents the onset of enhancements in the respective parameters in the solar cycle 24]

compared with those of the EUV and F10.7 cm flux in 2009, it is evident that the former is conspicuously greater than the corresponding rates of increase in the EUV and F10.7 cm flux. In addition, during 2005-2010, the slopes of the decreasing and increasing trends in the mean SSN (-0.021 and 0.029, respectively), EUV flux (-4.4×10^6 and 4.6×10^6, respectively) and F10.7 cm fluxes (-0.021 and 0.020, respectively) are comparable. This is in stark contrast with the mean TEC level wherein the magnitude of the slope corresponding to the increasing trend (0.041) is almost three times more than the slope corresponding to the decreasing phase (-0.013). The possible reason for this anomalous behaviour is discussed later.

In order to investigate the small-scale (periods less than 1.5 year, following the Nyquist criterion) periodicities in the solar EUV flux, F10.7 flux and peak TEC data over Rajkot during the descending phase of the solar cycle 23, the linear trends (mean levels) in EUV, SFU and peak TEC are removed for the period between 2005 and 2008 based on the linear regression curves shown in Fig. 1. The de-trended residuals (high-frequency fluctuations) in EUV flux, F10.7 cm flux and peak TEC are then subjected to harmonic analyses using an algorithm[39] based on Lomb-Scargle-Fourier-Transform and Welch-Overlapped-Segment-Averaging procedure that can provide consistent spectral estimates for unevenly spaced time series data. As there are gaps in the peak TEC time series [Fig. 1(d)], this technique is ideally suited for the present investigation. The harmonic analyses generate normalized periodograms from the residual time series. The spectral power contained in each spectral element is normalized with respect to the total power contained in all the spectral elements taken together. This procedure makes the relative distribution of the spectral power independent of the spectral windowing (that reduces spectral leakage) used in the algorithm. The normalized periodograms for the residuals in EUV flux, SFU and peak TEC are depicted in Figs 2(a, b and c), respectively where the X-axis is period in days. Significant periodic components in the time series exceed the critical levels (marked by dotted lines) determined by the Fisher's test (tests only for the presence of a single periodic component) and the Siegel's test (extension of Fisher's test in which up to three periodic components can be tested). The necessary details on these tests are available[39]. For the present study, the higher critical level is taken as the reference beyond/around which the spectral peak will be considered significant. Inspite of the higher threshold, Figs 2(a, b and c) reveal significant periodic components in EUV flux, SFU and peak TEC, respectively. Figures 2(a and b) suggest that a number of significant and common periodicities are present in

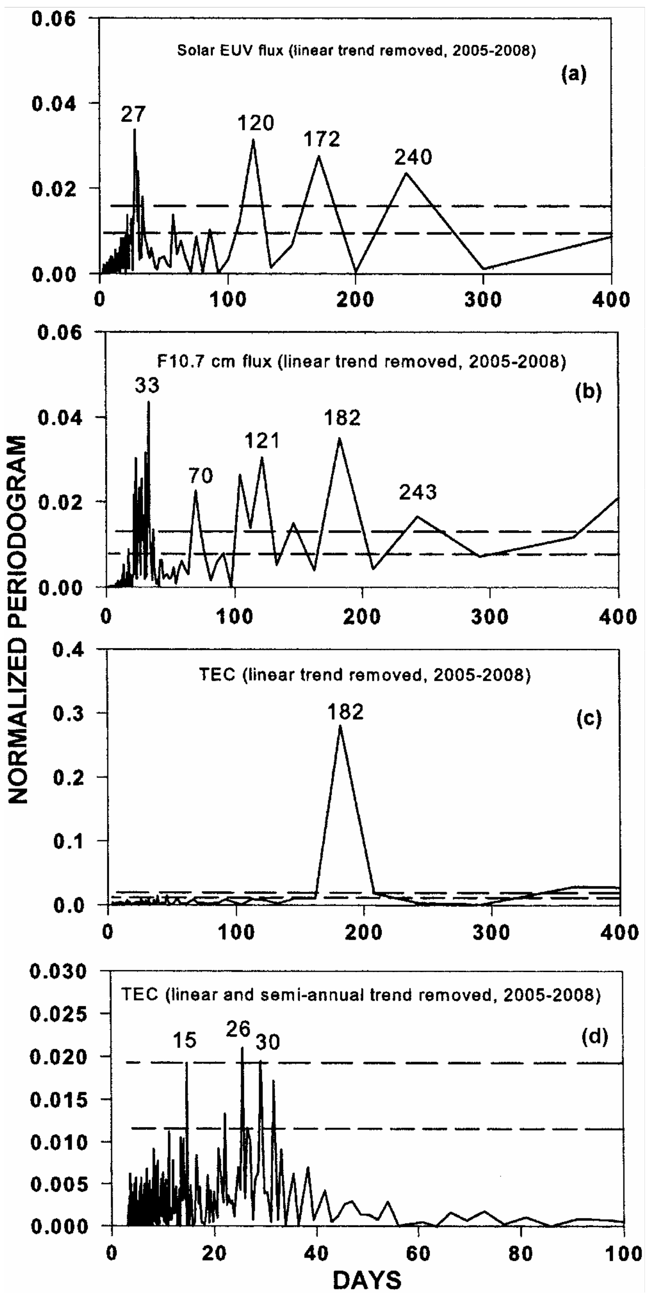

Fig. 2 — Normalized Lomb-Scargle periodograms for the residuals in: (a) EUV flux; (b) F10.7 cm flux; (c) mean peak TEC with linear trend removed; and (d) mean peak TEC with the linear and semi-annual trends removed for the years 2005 to 2008 [note that the scales of (d) are kept different for better visualization]

EUV and SFU which includes periods ~27, 120, 172, 240 days. A few differences are also noticed between the significant spectral peaks in EUV and F10.7 cm flux. For example, the 70-day period is found to be significant in F10.7 cm flux but not in EUV flux. Most importantly, the semi-annual (period 182 days) periodic component is found to be the most dominant in TEC. It is remarkable that although periodicities of 172 days and 182 days are present in EUV flux and SFU, the corresponding spectral powers in the solar parameters are one order less than that in TEC. In order to verify whether there is any causal connection between the semi-annual periodic component in TEC and EUV flux, a cross spectrum analysis[39] (not shown here) is performed. The cross-spectrum analysis reveals the absence of any stable and consistent phase relationship between the semi-annual variations in TEC and the semi-annual periodic component in the solar EUV flux. As the spectral power content in the semi-annual variation in TEC is very high, further detrending (filtering) is done to remove the 182 days periodicity from the TEC time series and a time-domain reconstruction is done. This reconstructed TEC data, where the linear as well as semi-annual trends are removed, are subjected to further harmonic analysis. The results obtained from this harmonic analysis are depicted in Fig. 2(d). It is seen that periods ~15, 26 and 30 days are present in TEC data. The spectral peaks, particularly the 26 day period in TEC, are similar (in terms of spectral power) to the peaks obtained from the solar parameters (EUV and F10.7 flux) clearly indicating the direct solar influence.

Figure 3 brings out the changes in the annual mean peak TEC values (along with $\pm 1\sigma$ bars) over Rajkot corresponding to the annual mean SFU based on the available data (180 days or more) for each year during 2005-2009. A linear regression curve can be obtained between these two parameters with a correlation coefficient (R) of 0.98.

Figure 4 shows the histograms of the percentage of occurrence of peak TEC over Rajkot from 2005 (at the top) to 2009 (at the bottom). It is seen that the occurrence of peak TEC over Rajkot is the highest during 1400-1500 hrs IST during both 2005 and 2006 that changes to 1300-1400 hrs IST during 2007. The occurrence of peak TEC over Rajkot seems to have shifted towards a later time with almost equal percentage of occurrence during 1400-1500 hrs IST and 1500-1600 hrs IST during 2008. During 2009, the occurrence of peak TEC takes place at an earlier time (1300-1400 hrs IST), which is similar to 2007.

In order to investigate the local time variation of the seasonally averaged TEC, Fig. 5 is introduced wherein equinoctial (March, April, September, October), summer (May, June, July, August), and winter (November, December, January, February) months during 2005-2009 are considered. This figure reveals that the maximum, minimum and intermediate TEC occur during equinoctial, winter and summer months eliciting a semi-annual variation. TEC values maximize around 1500 hrs IST in the equinoctial months during 2005-2006, around 1300 and 1500 hrs IST during 2006-2007 (double peaks are seen), around 1300 hrs IST during 2007-2008 and 2008-2009. Therefore, the time of occurrence of the maximum TEC shifts towards an earlier local time during equinoctial months as one reaches 2009 starting from 2005. On the other hand, the time of occurrence of the maximum in TEC occurs at the same time (around 1400 hrs IST) during both summer and winter months in 2006-2007 as well as 2007-2008. However, maximum TEC occurs at a later time during summer (than in winter) in 2005-2006 and 2008-2009.

4 Discussions

As mentioned earlier, the production of ionization in the low latitude F-region is mainly governed by the solar EUV radiation. It is known that the intensity of the solar EUV radiation waxes and wanes during a solar cycle in a manner similar to the solar magnetic activity. The magnetic activity and the solar EUV

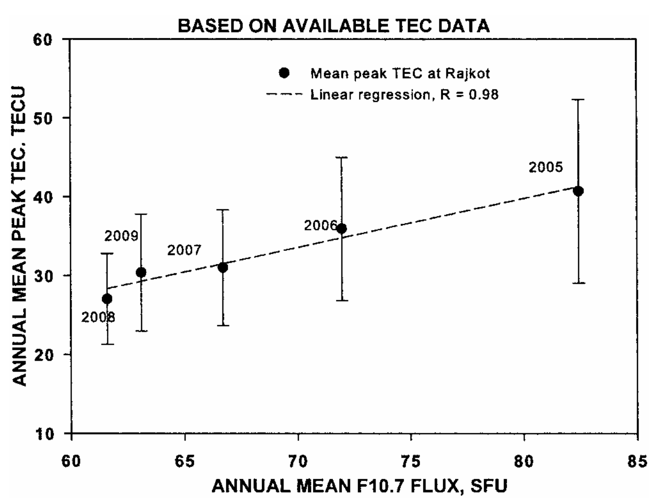

Fig. 3 — Correlation between the annual mean F10.7 cm flux and annual mean peak TEC for the years 2005-2009 (annual mean values are obtained based on the available data on each year)

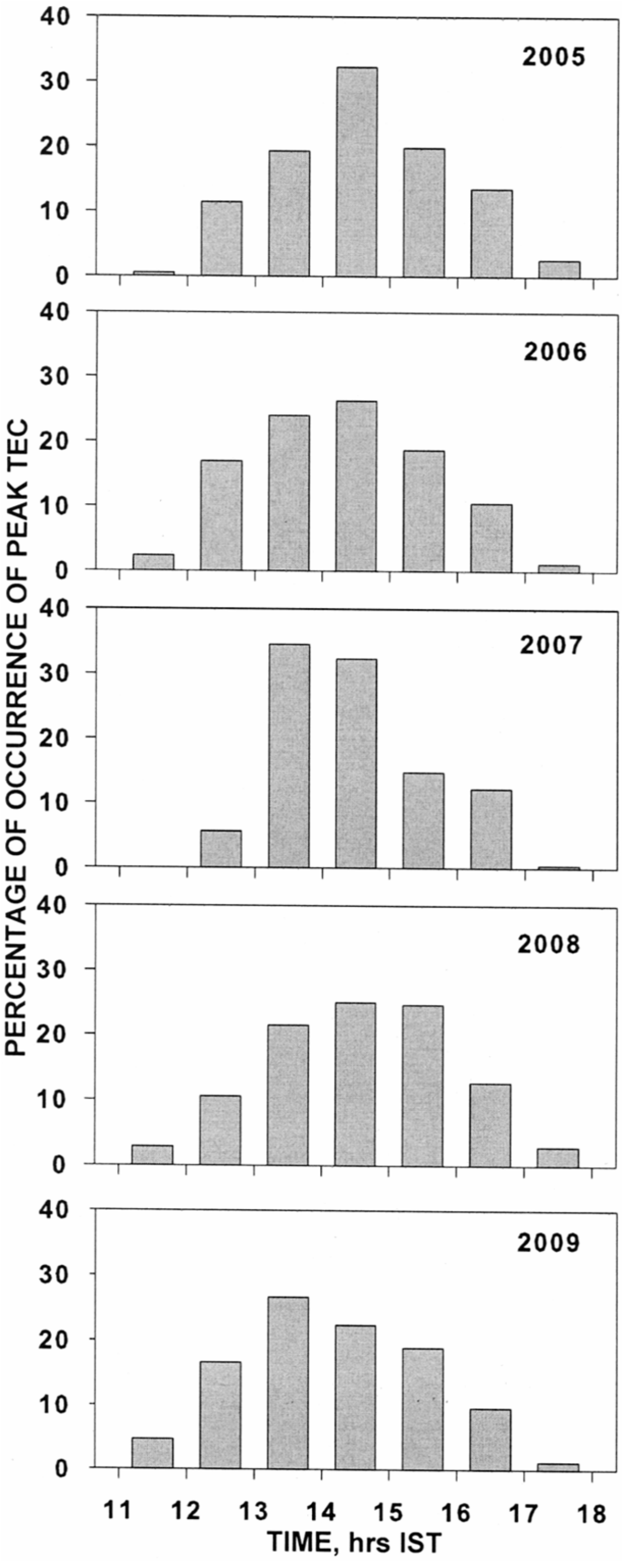

Fig. 4 — Histograms showing the time of the diurnal maximum of TEC from 2005 (top) to 2009 (bottom)

emission are very high in and around the solar active regions. However, EUV emission can also originate substantially from the rest of the solar disc that is devoid of sunspots or solar active regions. During a solar active phase, when the active regions are high in number, the total EUV emission is mainly contributed by the active regions. Interestingly, in the present case, the slopes in the mean SSN and the solar fluxes (EUV and F10.7 cm fluxes) during the descending phase of the solar cycle 23 are found to be similar in comparison with their counterparts during the ascending phase of the cycle 24. However, discrepancies (in terms of the duration) between the variations in SSN and solar fluxes arise during the slumber phase of the sun during 2007-2009 when the active regions are really sparse. This argument gets strengthened by the fact that even though the increase in F10.7 cm and EUV fluxes started from February 2009, the ascending phase of the SSN started only from September 2009. Kane[40] pointed out that there can be inherent delays between the variations in the solar EUV radiation and F10.7 cm solar flux. However, the onset of the enhancements in the EUV

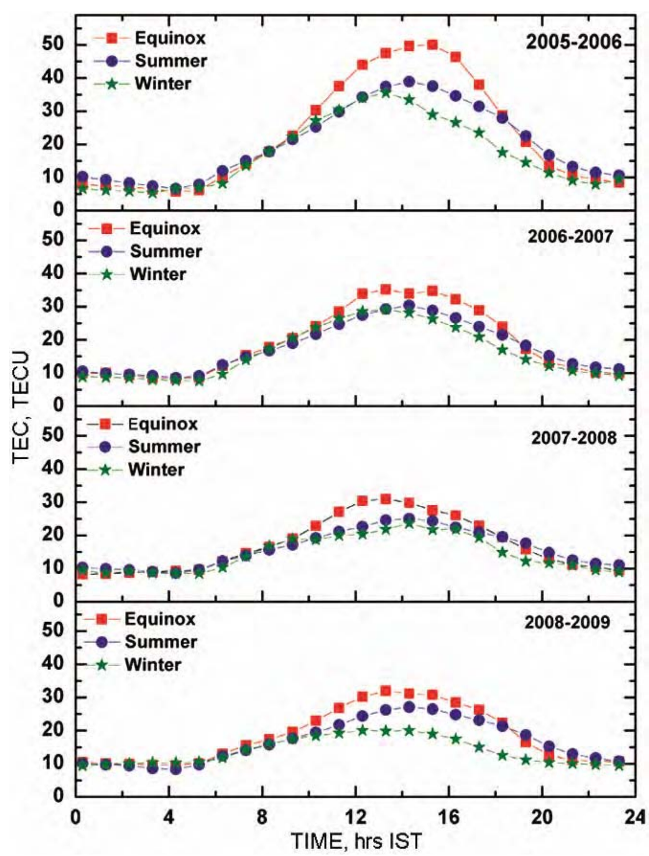

Fig. 5 — Local time variation in the seasonally averaged TEC over Rajkot during 2005-2009

and F10.7 cm flux during the ascending phase of the solar cycle 24 seems to be concomitant although there is seven month delay of the onset of enhancement of SSN.

The mean TEC level over Rajkot also starts increasing from February 2009 indicating the dependence of the TEC at the anomaly crest region on the solar EUV flux. Interestingly, although the time of the onset of the enhancements in EUV flux, F10.7 cm solar flux and the TEC are similar, the rate at which the mean TEC level increases after February 2009 is greater in comparison with the corresponding rate in the descending phase of the solar cycle 23. Liu & Chen[41] showed that the solar activity dependent rates of change of TEC in the equatorial and low latitude regions have a minimum around the dip equator and maxima near the crest of EIA which may appear to support the larger rate of increase of TEC over Rajkot as the solar activity starts increasing gradually since 2009. However, the present investigation elicits that there is a discrepancy between the rate of change of EUV/F10.7 cm solar flux and the TEC over the anomaly crest region when it comes to the year 2009.

In view of the discrepancy in the magnitude of the rate of change (slope) in TEC during the descending phase of the solar cycle 23 and the ascending phase of the cycle 24, two possible scenarios are envisaged.

4.1 Change in the solar EUV flux vis-à-vis F10.7 flux during 2009

Chen *et al.*[3] have reported that the F10.7 cm flux and the solar EUV flux decrease from the last solar minimum to the recent one with different amplitudes. The decreases are ~5% in F10.7 cm flux level and ~15% in 0.1–50 nm EUV flux level, and this effect is more prominent in the years 2008 and 2009. In other words, for the given F10.7 cm flux level, solar EUV irradiance is lower during 2007-2009 compared to the previous solar minimum. In the absence of the TEC data over Rajkot during the last solar minimum, the EUV fluxes and TEC levels for approximately similar F10.7 cm flux values occurring in 2007 and 2009 are compared. Thirty five days are selected with similar flux levels from 2007 (wherein F10.7 cm flux values varied from 59.8 to 61.9 SFU) and 2009 (wherein F10.7 cm flux values varied from 59.9 to 61.7 SFU). The average EUV fluxes for these two periods were 9.8×10^{10} photons cm^{-2} sec^{-1} and 9.6×10^{10} photons cm^{-2} sec^{-1}, respectively. The average TECs obtained were ~34 TECU and 24 TECU in 2007 and 2009, respectively. Therefore, although the EUV flux does not decrease much in 2009 as compared to 2007, the average TEC level (for a given EUV/F10.7 cm flux) is significantly lower in 2009 compared to 2007. This indicates towards the possible role of neutral dynamics.

The present observations also indicate another interesting fact, i.e. during 2009 (the expected ascending phase of the solar cycle 24), TEC over the anomaly crest region increases more rapidly than the corresponding rate in the F10.7 cm flux. This requires a more rapid increase in EUV flux compared to the F10.7 cm flux, which does not seem to be consistent as can be seen from the average values of these parameters presented earlier. In view of this, the anomalous rate of increase of TEC cannot be attributed to any anomalous behaviour in the production of ionization (represented by EUV flux) in this period. Hence, this anomalous rate of increase of TEC compared to the previous years could be associated with the EIA variability over the Indian sector by the transport (through trans-equatorial wind) or chemical processes.

4.2 Possible role of transport and chemical processes during 2009

Though the strength of the EIA depends on many factors, the location of the EIA crest is only dependent on the E×B drift of plasma over the dip equator. It is shown that the daytime equatorial electric fields do not undergo significant changes with solar activity[42]. Moreover, the time of occurrence of peak TEC over the crest location depends on the ambipolar diffusion of plasma along the field lines and the meridional wind. The residual (difference between the annual averages) change, if any, in the ambipolar diffusion of plasma within the same solar epoch is expected to be unidirectional (either increases or decreases) as it is dependent on plasma temperature and ion-neutral collision frequency. However, the residual change, if any, in the trans-equatorial wind over the years can be bidirectional (can increase and decrease) within the same solar epoch. As reported by Bagiya *et al.*[20], the daily peak in TEC occurs around 1400 hrs IST over Rajkot during the low solar activity period in the descending phase of the solar cycle 23. However, as shown in Fig. 4, the time of occurrence of peak TEC over Rajkot changes in a random manner over the years during 2005-2009. The time of occurrence of peak TEC is maximum during 1400-1500 hrs IST in 2005 and 2006, 1300-1400 hrs IST during 2007, 1400-1600 hrs IST in 2008 and again 1300-1400 hrs IST in 2009. This pattern reveals that the time of occurrence of peak TEC over Rajkot is random during 2005-2009. This may possibly be due to the combined effects of the differences in the local time occurrences of the maximum TEC in the equinoctial, summer and winter months during 2005-2009 as revealed by Fig. 5. It is to be noted here that the ionospheric component of TEC critically depends on the thermospheric composition ([O]/[N_2] ratio) which can change with different seasons owing to the altered meridional circulation pattern over low latitudes. Therefore, it is possible that the transport processes related to the trans-equatorial/meridional wind contribute significantly towards the changes in the time of occurrence of peak TEC over Rajkot during 2005-2009 and the larger rate of increase of mean TEC over Rajkot during 2009.

The diurnal amplitudes of the neutral winds could be very high in moderate low solar activity levels as pointed out by other researchers[34]. The very prominent semi-annual variation in TEC indicates the importance of trans-equatorial winds (dependent on season) on determining the plasma density over this region. It may be remembered that composition changes due to large scale dynamical effects in the thermosphere is often considered as a cause for the observed semi-annual oscillation in the ionosphere[19,43]. Hence, it may be conjectured that these effects are more prominent when the rate of change of mean TEC level is considered even though the time of onset of enhancement in the mean TEC level matches quite well with that in the mean F10.7 cm flux and EUV flux levels during 2009. It is also reported that the thermosphere was cooler and lower in density than expected due to the extremely low EUV irradiance during this deep solar minimum period[44]. However, since the net plasma density at the EIA crest location is not just determined by the production and loss processes, but also by the transport processes (both electric field and meridional neutral winds). So, any simplistic approach considering only production and loss processes would not suffice to explain the density variation at these latitudes. In view of the fact that the data are only for ~10 months in 2009, it is presently not possible to comment on whether these effects will be remarkable throughout the ascending phase of the solar cycle 24, or whether these effects will be smoothed out on longer time scales. Another important question that arises is the quantitative roles of chemistry and transport processes in determining the variability of these time scales. These aspects need to be investigated comprehensively, with a larger database from different low-latitude stations.

In addition to the discrepancy in the rate of enhancement of TEC over the anomaly crest region, the present investigation also brings out the characteristic seasonal feature of the variation in TEC over low-latitudes. The semi-annual variation in TEC over low-latitude region is known for quite some time[20,32,35,36]. In the present investigation, the semi-annual variation in TEC is demonstrated to be dominant (maximum spectral power content) during 2005-2008 which is consistent with the earlier reports. In addition, the present investigation also reveals that the semi-annual variation in TEC has no consistent causal connection with the inherent solar periodicity of around six months as no stable and consistent phase relationship could be established between the semi-annual variations in TEC and the semi-annual periodic component in the solar EUV flux. Millward *et al.*[43] and Rishbeth *et al.*[19] explained the ionospheric semi-annual variability (maximum F2 layer ionization in equinox and minimum in summer and winter) based on the variations in the solar EUV input and composition disturbances due to the global thermospheric circulation. The ionospheric electron density is determined by the ratio [O]/[N2], where [O] and [N_2] are the concentrations of atomic oxygen and molecular nitrogen, respectively. This ratio is larger during winter and smaller during summer because of the thermospheric circulation from the summer to the winter hemisphere. The effect of this compositional change on the electron density is opposed by the effect of the solar zenith angle which makes the production rate larger in summer and smaller in winter. Such an optimized effect of the [O]/[N_2] and solar zenith angle produces two maxima in the plasma density at equinoxes giving rise to the semi-annual variation of the ionospheric F2-layer density. It is also important to note that the spectral power in the semi-annual component of the solar EUV flux is at least an order less compared to that in TEC [note the scales of the y-axis in the Figs 2(a and c)]. However, this is not the case as far as the 26-day periodicity is concerned. The spectral power in TEC for this periodic component is comparable [note the scales of the y-axis in Figs 2(a and d)] with that in the solar EUV flux. Therefore, the direct impact of the solar radiation on the modulation of TEC over the crest region in this time scale is evident.

Last but not the least, the present investigation also reveals that the correlation coefficient is still very high when it comes to the overall linear relationship between the annual mean F10.7 cm flux and the annual mean peak TEC during 2005-2009. This extends the results of Bagiya *et al.*[20] wherein similar linear relationship based on the TEC data from Rajkot during 2005-2007 has been shown.

5 Summary

The present investigation reveals that the rate of increase of the mean TEC level over the anomaly crest region is greater in the beginning of the solar cycle 24 compared to the rate of decrease during the declining phase of the solar cycle 23. It is argued that this anomalous behavior is not associated with the changes in the solar EUV flux but associated possibly with the residual (difference between annual averages) effects of the trans-equatorial winds, compositional changes, etc. over this time scale. The random changes in the time of occurrence of the diurnal maximum of TEC over Rajkot during 2005-2009 support this proposition. Spectral analyses are performed on the de-trended (linear trend removed) EUV flux, F10.7 cm flux and TEC data during 2005–2008 reveal that the semi-annual (182 days) periodicity is significant in TEC whereas a number of periodicities (~27, 120, 172, 240 days, etc.) are significant in both EUV and F10.7 cm flux. A few spectral differences are observed between the EUV flux and F10.7 cm flux. For example, the 70 day period is found to be significant in F10.7 cm flux but not in EUV flux. TEC data show signature of solar control in the form of ~27 day periodicity. It is verified that the semi-annual variation in TEC has no consistent causal connection with the inherent solar periodicity of around six months. Further, the annually averaged peak TEC value over Rajkot is found to be well correlated (R = 0.98) with the corresponding annually-averaged F10.7 cm flux during 2005-2009.

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