

Climatology of ionosphere over low-latitude (Kolkata) using FORMOSAT-3/COSMIC satellite observation

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We have analyzed the diurnal, monthly, and seasonal variation in NmF2, HmF2, and IECs parameters derived from the COSMIC-RO observation over the low-latitude (Kolkata) region during 2008–2012 and compared the result with the IRI-2007 model output. In general, during HSA period the seasonal averaged model outcome prominently overestimates the observed values throughout the day, except HmF2, while in LSA period it is confined to post-noon hours. The differences between diurnal-dip and diurnal-peak values of all these parameters are considerably higher in the model outcomes than those of observed values, especially during increasing solar activity. In addition, the monthly averaged NmF2, BIEC, and TIEC values at noon and midnight, obtained from the both options, exhibit semi-annual variation, which are in good agreement with some earlier studies, whereas HmF2 shows annual variability for all solar activity. Moreover, the similarities and dissimilarities observed in variation pattern, particularly during 2011 and 2012, can help the research community to understand the recent trends of ionospheric parameters and develop the IRI model with more efficiency to fit the observed profile in a better way.

1. Introduction

The ionosphere is a natural plasma medium surrounding the Earth. Its height, density, and other delicate characteristics are severely affected by the state of the Sun. Lower atmosphere and other layers of the space also have a vital relation with the ionosphere. The increasing dependencies of man and his different tools to utilize the presence of ionosphere have encouraged the research community to understand its variability on a long term (climatological) basis at different spatial zones. Additionally, the knowledge of climatological variation in different ionospheric parameters is essential to extract information about instantaneous changes in electron (Ne) concentration due to lower as well as upper atmospheric forcing. The International Reference Ionosphere (IRI) model continuously

provides us valuable information about the state of the instantaneous ionosphere throughout the globe (Bilitza and Reinisch 2008; Kenpankho *et al.* 2011). In this model, the input variables are incorporated from ground and space-based observations situated at different locations of the Earth. In that respect, equatorial ionosphere is the most important as occurrence of various irregularities in this region is prevalent. Some authors (Bhar *et al.* 1970; Chakraborty *et al.* 1999; Das *et al.* 2010; Paul *et al.* 2011) have extensively studied about different features of ionospheric irregularities over the Equatorial Ionization Anomaly (EIA) region using VHF scintillation technique in the recent past. Among these studies, Chakraborty *et al.* (1999) highlighted the trends of Total Electron Content (TEC) variability over the Indian EIA region due to the variation of solar activity, analyzing long-term

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(13 years) observational data, whereas Paul *et al.* (2011) established the necessity of differential grid size around the northern crest of EIA region owing to sharper TEC gradient towards the pole. To date, the availability of ionospheric parameters in the Indian equatorial region is limited. The Low Earth Orbiting (LEO) satellite measurement may be an alternative solution not only to this problem but also to the effort of modification of IRI model. However, a few research works about the ionospheric variability for large time scale over this region have been done, which encouraged us to study the ionospheric variability for long-time basis using LEO satellite observation during 2008–2012. It may be mentioned here that in 2008, the Sun was quieter than in recent years and thereafter, its raising phase continued till 2012. However, the Low Solar Activity (LSA) period is necessary to display the natural variations in atmosphere as well as ionosphere. Kawamura *et al.* (2002) have extensively studied the ionospheric variability during LSA condition.

Recently, Sripathi (2012) in his study has made several attempts to reveal the seasonal, diurnal, and latitudinal variations in ionospheric Ne concentration with variation in altitude over Indian longitude during LSA phase in 2008. This study indicated an important phenomenon that the Ne concentration gets higher during vernal equinox compared to autumn equinox.

Using the digital ionosonde measurements, Sethi *et al.* (2004), Sethi and Dabas (2006) observed that the HmF2 variability was greater at midnight in comparison to daytime, and the bottom side TEC (BTEC) increased by a factor of more than two from moderate to High Solar Activity (HSA) conditions, over Delhi. In this study, they have also reported that BTEC has exhibited large day-to-day fluctuation at any given Local Time (LT).

Das Gupta *et al.* (2007) in their seminal study on ionospheric Ne content observed that equatorial ionosphere sustained not only maximum ionization but high TEC also and the gradient of EIA was extended both in horizontal and altitudinal directions. Moreover, the trough and crest phenomenon in EIA were sharper, which resulted in large temporal and spatial variations of the ionospheric electron content.

The central point of the present paper is to analyze the diurnal, monthly, seasonal, and yearly variation of ionospheric peak parameters: the peak Ne density (NmF2) and the height of peak Ne density (HmF2), BIEC and Topside Integrated Electron Content (TIEC) over the region 15°–30°N and 80°–95°E, based on COSMIC satellite observations during 2008–2012, and comparison with IRI-2007 model output to validate our result. The data and method of analysis are mentioned in section 2.

Results and discussion are shown in section 3, and the conclusion is given in section 4.

2. Data and method of analysis

To examine the solar activity variation, the solar flux data at 10.7 cm ($F_{10.7}$) have been taken from World Data Centre website (<http://www.ukssdc.ac.uk>) and the $\sum Kp$ index data have been obtained from the Kyoto University website (<http://wdc.kugi.kyoto-u.ac.jp>) to analyse the geomagnetic activity from 1 January, 2008 to 31 December, 2012.

In this study, we have used the LEO satellite Radio Occultation (RO) data. Six microsattellites termed Formosa Satellite 3 and Constellation Observing System for Meteorology Ionosphere, and Climate (FORMOSAT-3/COSMIC or F3/C in short) were launched from Vandenberg Air base, California at 0140UTC on 15 April, 2006. These satellites continuously monitor the globe with near about 2500 Vertical Electron Density (VED) profiles per day. The data used in this study (namely “ionPrf” data in COSMIC website, a level 2 vertical profile data) were obtained from the COSMIC website (<http://www.cosmic.ucar.edu>) for the time period from 1 January, 2008 to 31 December, 2012. The detailed description about this mission and its data processing techniques are presented in Aragon-Angel *et al.* (2009); Hwang *et al.* (2009); Chuo *et al.* (2011); and Sripathi (2012). However, a filtration technique to select suitable dataset has been imposed. As, the COSMIC is a LEO satellite with an orbital period of ~ 100 min, in order to detect the ionospheric variability at any specific location and time, the data from those orbital passes within a $15^\circ \times 15^\circ$ box centred at the point of location (Kolkata) are considered. First, the profiles, in which the geographic latitude (GEO_LAT) and geographic longitude (GEO_LON) of HmF2 lies within 15° – 30° N, 80° – 95° E are sorted out. Thereafter, those profiles, which are associated to $F_{10.7} > 150$ sfu and/or $\sum Kp > 30$ are discarded. The BIEC ($1\text{TECU} = 1\text{E}+16 \text{ el/m}^2$) and TIEC are calculated using the equation:

$$(\text{BIEC}, \text{TIEC}) = \int_{(\text{Balt}, \text{HmF2})}^{(\text{HmF2}, \text{Talt})} Ne(z) dz \quad (1)$$

where Balt is the mean sea level altitude (MSL_Alt) at the bottom point of the profiles; HmF2, the MSL_Alt of NmF2 in F layer; and Talt, the MSL_Alt at the top point of the profiles. For COSMIC satellite, Talt is generally greater than 700 km, whereas Balt has been taken as 70 km.

In the late 1960s, the IRI project was initiated by the Committee on Space Research (COSPAR)

and by the International Union of Radio Science (URSI) to avoid the uncertainties involving theoretical understanding of ionospheric processes and coupling to the regimes below and above. Detailed description about the IRI model, including information on the IRI newsletter and the IRI electronic mailer, can be found on the IRI homepage at <http://IRI.gsfc.nasa.gov/> (Kenpankho *et al.* 2011). The corresponding predictions of IRI parameters are calculated from the IRI-2007 model (Bilitza and Reinisch 2008) using the location, date, and period of time as inputs to the model. For our study, model output is taken for the time period 2008–2012 with Kolkata (22.56°N, 88.36°E) as geographic location within 70–700 km altitude.

In the end, to figure out the variability in the monthly averaged profile at noon and midnight time, all those profiles are considered in which the observation-time range lies between 10.00–14.00 and 22.00–02.00 hrs LT, respectively.

3. Result and discussion

3.1 Solar flux and $\sum Kp$ index variations

The solar flux at 10.7 cm ($F_{10.7}$) is a measure of solar activity, which has intimate relation to the

ionization in the ionosphere. In figure 1, actual $F_{10.7}$ solar flux data (figure 1a) and $\sum Kp$ index data (figure 1b) have been plotted over a period of 5 years (1 January 2008 to 31 December 2012). But, all available data, for which $F_{10.7} \leq 150$ sfu and $\sum Kp \leq 30$ have been taken into consideration for analysis. From the upper panel, one can observe that during the period 2008 to 2010, the solar flux values are mostly in the range of 65–92 sfu (1 sfu = 10^{-22} W m⁻² Hz⁻¹), which have been considered as LSA period, thereafter, flux increases gradually with rapid fluctuation in amplitude during the year 2011. Finally, in the year 2012, the flux varies between 87 and 183 sfu (figure 1a). So in that respect, the beginning of year 2011 may be considered as the transition from LSA to HSA period. Also, there are some occasions where sharp increase in upper limits of the range are found, which could be due to 27 days solar rotation (Sripathi 2012). The bottom panel shows the day-to-day variability in $\sum Kp$ index for the time range 2008–2012. However, for maximum days, $\sum Kp$ values are less than 30, which separates the days to be geomagnetically quiet or not. In 2011, ten days (maximum in comparison to other years) were attributed to geomagnetically disturbed days. Some earlier studies have reported that solar activity (Lee and Reinisch 2006, 2007)

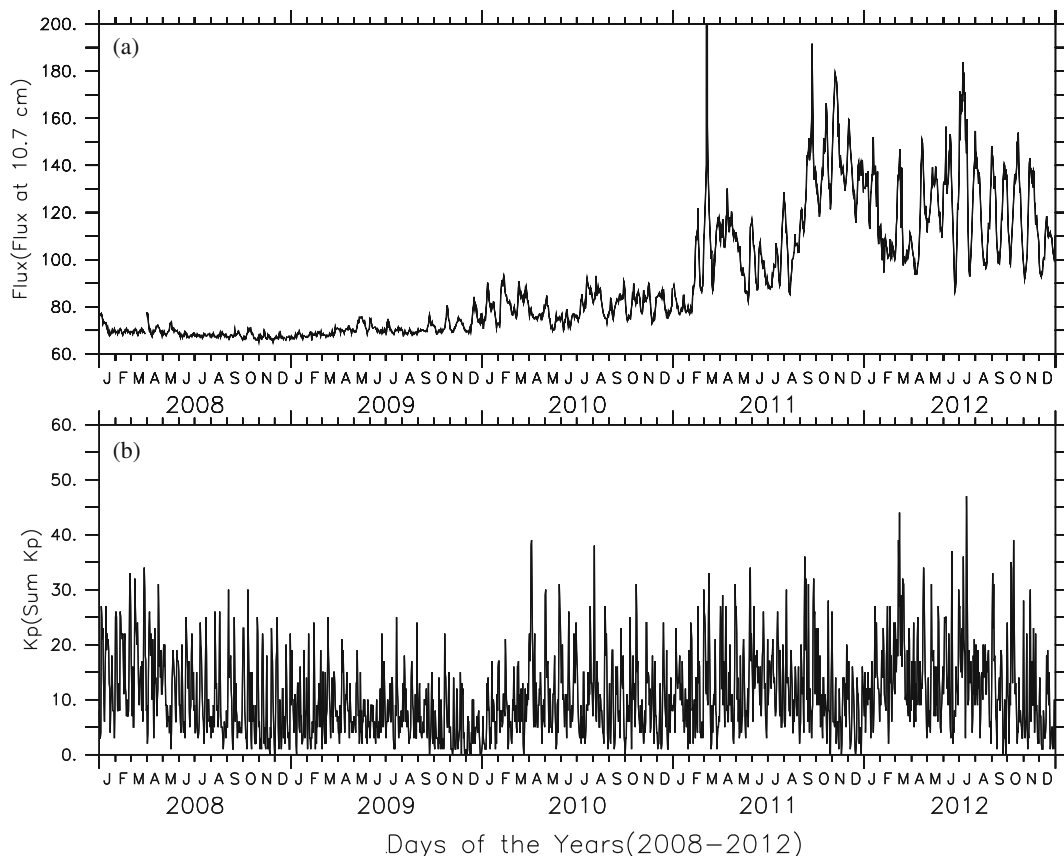


Figure 1. The variation of (a) daily solar flux ($F_{10.7}$) at 10.7 cm during 2008–2012 and (b) daily $\sum Kp$ index for the years 2008–2012.

and geomagnetic activity (Park *et al.* 2010; Sun *et al.* 2012) both have obvious association with ionospheric variability.

3.2 NmF2 and HmF2 diurnal and seasonal variations

The NmF2 and HmF2 are two crucial parameters in the study of ionospheric electrodynamics. Figure 2(a–j) displays the season-wise diurnal variations in NmF2, obtained from COSMIC satellite measurement and IRI-2007 model output,

for 2008–2012. The trend of diurnal variability is more or less similar for the both options with diurnal-dip during 05.00–07.00 hrs LT. Thereafter, NmF2 starts to increase and reaches the diurnal-peak at noon. The increase in NmF2, especially during 2011 and 2012, is due to high production rate at higher altitude in the presence of solar radiation during daytime compared to chemical losses (Su *et al.* 1998; Lee and Reinisch 2006; Sripathi 2012). However, the diurnal-peak values of NmF2 in IRI-2007 model are relatively peaky with higher standard deviation around

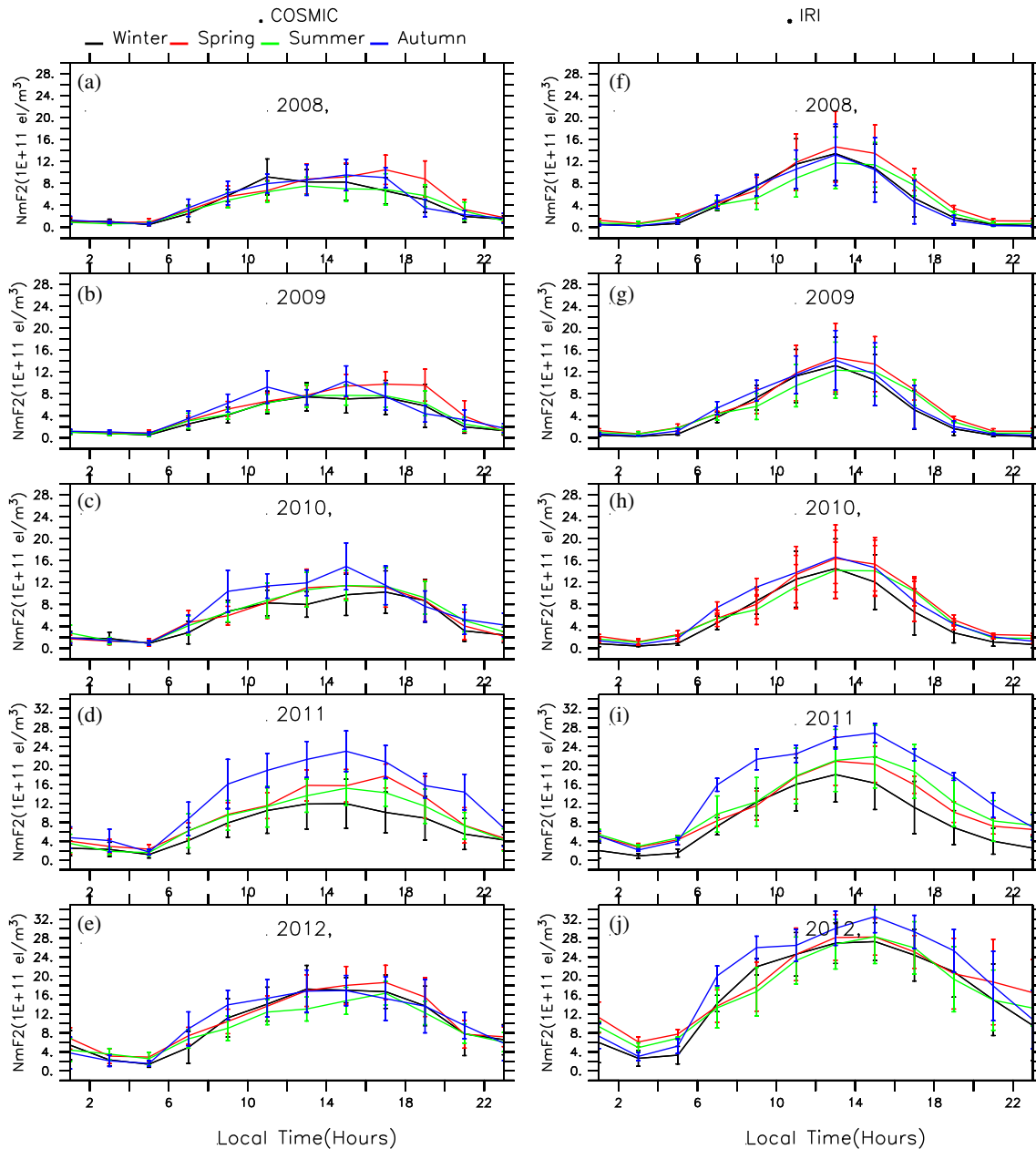


Figure 2. The diurnal variation in NmF2 using COSMIC-RO observations over low-latitude region (15° – 30° N, 80° – 95° E) and IRI-2007 model output at Kolkata. The left panels are for COSMIC-RO measurements for the years: (a) 2008; (b) 2009; (c) 2010; (d) 2011 and (e) 2012. The right panels are for IRI-2007 model output for the years: (a) 2008; (b) 2009; (c) 2010; (d) 2011 and (e) 2012. Different colours represent different seasons. Vertical bars denote the standard deviation.

9.00–17.00 hrs LT than those obtained from COSMIC-RO, during all the seasons throughout the observation period. But, the COSMIC-RO measurement shows higher standard deviation during the post-noon hours. The autumn season, apparent in rising period of the Sun, shows maximum NmF2 concentration (figure 2) in comparison to other seasons, while winter seasons exhibit minimum concentration. The deviations in season-to-season diurnal values of NmF2, obtained from COSMIC-RO observations, with respect to winter have apparent trend to be larger during daytime (especially during post-noon hrs). In 2008 ($3.8\text{E}+11$ el/m³), 2009 ($3.8\text{E}+11$ el/m³) and 2012 ($1.9\text{E}+11$ el/m³), the maximum deviation occurred in spring, whereas in 2010 ($5.2\text{E}+11$ el/m³) and 2011 ($11\text{E}+11$ el/m³), it occurred during autumn. In comparison to COSMIC-RO measurements, the IRI-2007 model outputs interestingly display larger season-to-season deviations in NmF2 values. The significant solar flux fluctuations (figure 1a; Su *et al.* 1998; Lee and Reinich 2007; Chen *et al.* 2009) and the horizontal natural winds variability (Alken *et al.* 2008) in the low-latitude region play a sensitive role in ionospheric electrodynamics. So, noticeable differences between the observed results and model results have been detected in NmF2 variability.

In figure 3(a–j), the values of HmF2 obtained from COSMIC satellite measurement and IRI-2007 model output, for different LT are plotted for the years, 2008–2012. The vertical bars at each of the average points of HmF2 represent corresponding standard deviation. The diurnal variations in HmF2 exhibit almost similar pattern for the both options, with twin occurrences of diurnal-dips: one at post-sunrise (06.00–08.00 hrs LT) hours and another at sunset (18.00–20.00 hrs LT) time, whereas the two diurnal peaks are found to be at noon (12.00–14.00 hrs LT) and at midnight (22.00–02.00 hrs LT). In equatorial ionosphere, the HmF2 variation is intimately connected to the vertical $E \times B$ (E and B are electric and magnetic fields, respectively; both are vector quantities) drift velocity variation because of the horizontal geomagnetic field lines and ionization due to solar radiation (Sethi *et al.* 2004; Lee and Reinisch 2006; Chen *et al.* 2009; Ambili *et al.* 2012). During morning hours as solar radiation start to build, the rapid ionization in the lower F region causes a decrease in HmF2 values (Su *et al.* 1998; Ambili *et al.* 2012; Sripathi 2012). The HmF2 diurnal variations during post-noon hours are dominant for all the seasons and this characteristic was more prominent during 2011, may be due to rapid fluctuation in solar activities. The increase in PRE of (Sun *et al.* 2012) $E \times B$ drift velocity as well as decrease in ion production help the

plasma to be uplifted as well as transported to other latitudes, causing sudden enhancement in HmF2 during post-sunset (18.00–20.00 hrs LT) hours. Moreover, there is noticeable association between the appearance of sunrise undulation phenomenon in HmF2 produced by photochemistry (Ambili *et al.* 2012), and strong uplifted plasma at sunset (Ambili *et al.* 2013) around the magnetic equator. This association is more prevalent in COSMIC-RO observation than in IRI model output (see figure 3). During the autumn of 2010 (~ 287 km), 2011 (~ 420 km) and 2012 (~ 331 km) and the winter of 2012 (~ 338 km) this phenomenon noticeably occurred, but in the IRI-2007 model output, it is not visible. At noon, the so called ‘noon-bite-out’ phenomenon also plays a dominant role in ionospheric electrodynamics causing slight decreases in NmF2 (figure 2a–c) with fairly constant HmF2 (figure 3a–c) (Lee and Reinisch 2006; Sripathi 2012).

Also, during HSA (2011 and 2012) period, the noticeable enhancement (Chen *et al.* 2009) in magnitude of hour-to-hour seasonal averaged HmF2 values with respect to LSA period are prevalent to both IRI-2007 (up to 45 and 56 km) model and COSMIC-RO (185 and 96.5 km) observations.

3.3 TIEC and BIEC diurnal and seasonal variations

Figures 4(a–j) and 5(a–j) represent the diurnal variations in BIEC and TIEC, obtained from COSMIC satellite measurements and IRI-2007 model output, over the observation area for different seasons during 2008–2012. Both IECs (TIEC and BIEC) exhibit collateral trend in diurnal variations with larger spread (or standard deviation) in case of IRI-2007. However, the diurnal-dip occurred during pre-dawn hours for all the seasons and thereafter, both IECs started to increase, reaching maximum at noon (Chakraborty *et al.* 1999). The daytime peak values are almost 5–9 times higher than the diurnal-dip values in case of COSMIC satellite measurements, whereas for IRI-2007 model it is 5–50 for all seasons of 2008 to 2012, undergoing diminishing trend with increasing solar activity. In general, the autumn (spring) and winter correspond to maximum and minimum TIEC (BIEC) concentration along with the values of spring (autumn) and summer lies in between them (figures 4, 5; Kenpankho *et al.* 2011; Liu *et al.* 2006; Sethi and Dabas 2006), which partly support the report in Sripathi (2012). In comparison to yearly variability, 2011 shows the most significant evolution in IECs variation during daytime, with large positive deviations (figures 4d, 5d; up to 11TECU for BIEC and 25.13TECU for TIEC, considering all the seasons) in season-to-season

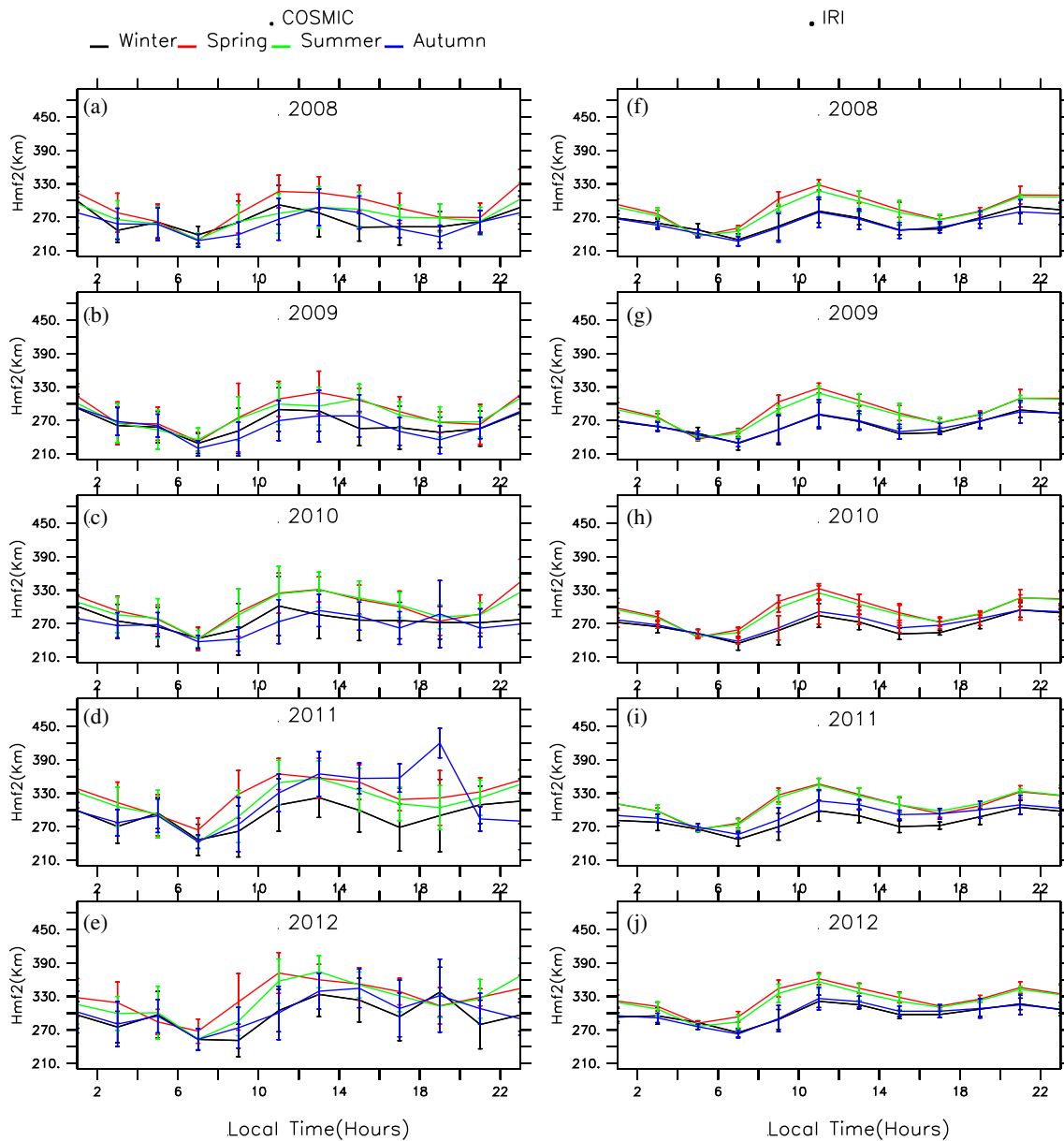


Figure 3. The diurnal variation in HmF2 using COSMIC-RO observations over low-latitude region (15° – 30° N, 80° – 95° E) and IRI-2007 model output at Kolkata. The left panels are for COSMIC-RO measurements for the years: (a) 2008; (b) 2009; (c) 2010; (d) 2011 and (e) 2012. The right panels are for IRI-2007 model output for the years: (a) 2008; (b) 2009; (c) 2010; (d) 2011 and (e) 2012 respectively. Different colours represent different seasons. Vertical bars denote the standard deviation.

values with respect to winter. But, in the case of remaining years, these deviations are comparatively small, with large fluctuation in the summer of 2012, when IRI-2007 model output shows relatively more diffusive trend in seasonal averaged IECs. During prolonged solar minimum in 2008, the ratio between seasonal averaged TIEC and BIEC values at different LT lies in between 1.33 and 3.10 for COSMIC satellite measurements, whereas for IRI-2007 it varies from 1.2 to 3.5. This ratio (graph not shown) always remains less than 3.1 and 3.5 for both options, respectively, with least values (1.1–2.1) at noon. The height difference between top and bottom side of the ionosphere

is, on an average, 100 km. The Ne concentration in this extra height definitely helps to account for this excessive TIEC in comparison to BIEC, except at noon, when the Ne concentration in bottom side ascend to the decisive level due to longer persistence of intense solar radiation and achieves relatively higher BIEC in comparison to TIEC.

3.4 NmF2, HmF2, BIEC and TIEC annual variations

Figure 6(a–d) shows the plot of monthly averaged NmF2, HmF2, BIEC, and TIEC obtained

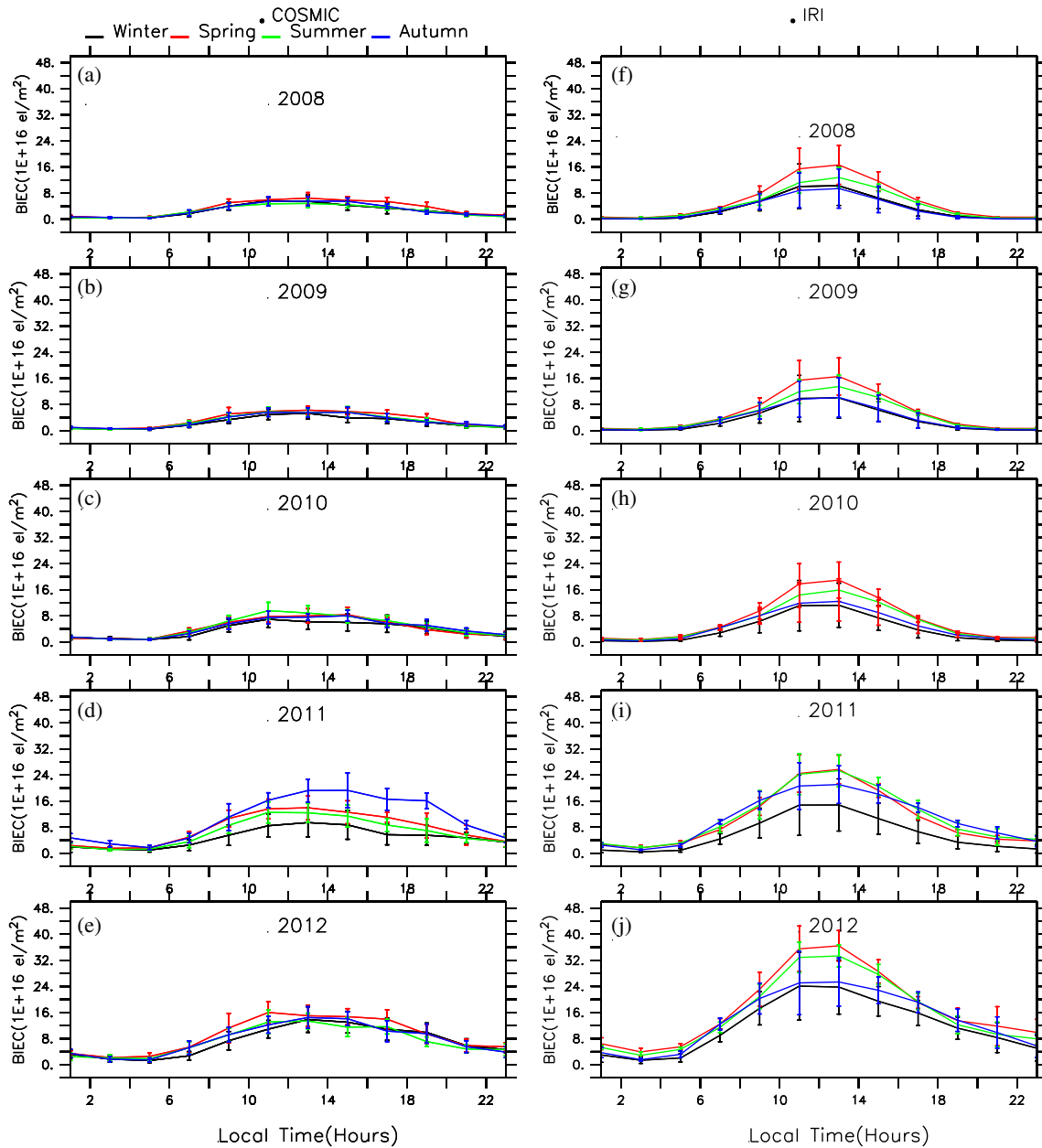


Figure 4. The diurnal variation in BIEC using COSMIC-RO observations over low-latitude region (15° – 30° N, 80° – 95° E) and IRI-2007 model output at Kolkata. The left panels are for COSMIC-RO measurements for the years: (a) 2008; (b) 2009; (c) 2010; (d) 2011 and (e) 2012. The right panels are for IRI-2007 model output for the years: (a) 2008; (b) 2009; (c) 2010; (d) 2011 and (e) 2012. Different colours represent different seasons. Vertical bars denote the standard deviation.

from COSMIC-RO (cross symbol) measurements and IRI-2007 (dash symbol) model output in the observation area for the time period 2008–2012. The gap in each panel (during midnight) is due to non-availability of data during the period 22.00–02.00 hrs LT. It may be seen from this figure that during March–April and September–November, there are two strong peaks in NmF2, BIEC, and TIEC values with larger spread from mean, which are represented using vertical bars. The monthly averaged values of HmF2 show single yearly-peak during May–June (figure 6)

for all the years, except 2012. In 2012, monthly averaged values of HmF2 (379 and 348 km at noon-time and midnight, respectively) exhibit yearly-peak during July–September. Also, in case of yearly-dip, monthly averaged values of NmF2, BIEC, and TIEC exhibit the occurrence of twin-dips associated to the months: December–January and June–July, whereas HmF2 values exhibit the yearly-dip in the month of December. It is now observed that the NmF2, BIEC, and TIEC values have persistent semi-annual variation. But the HmF2 has annual variation under LSA as well as

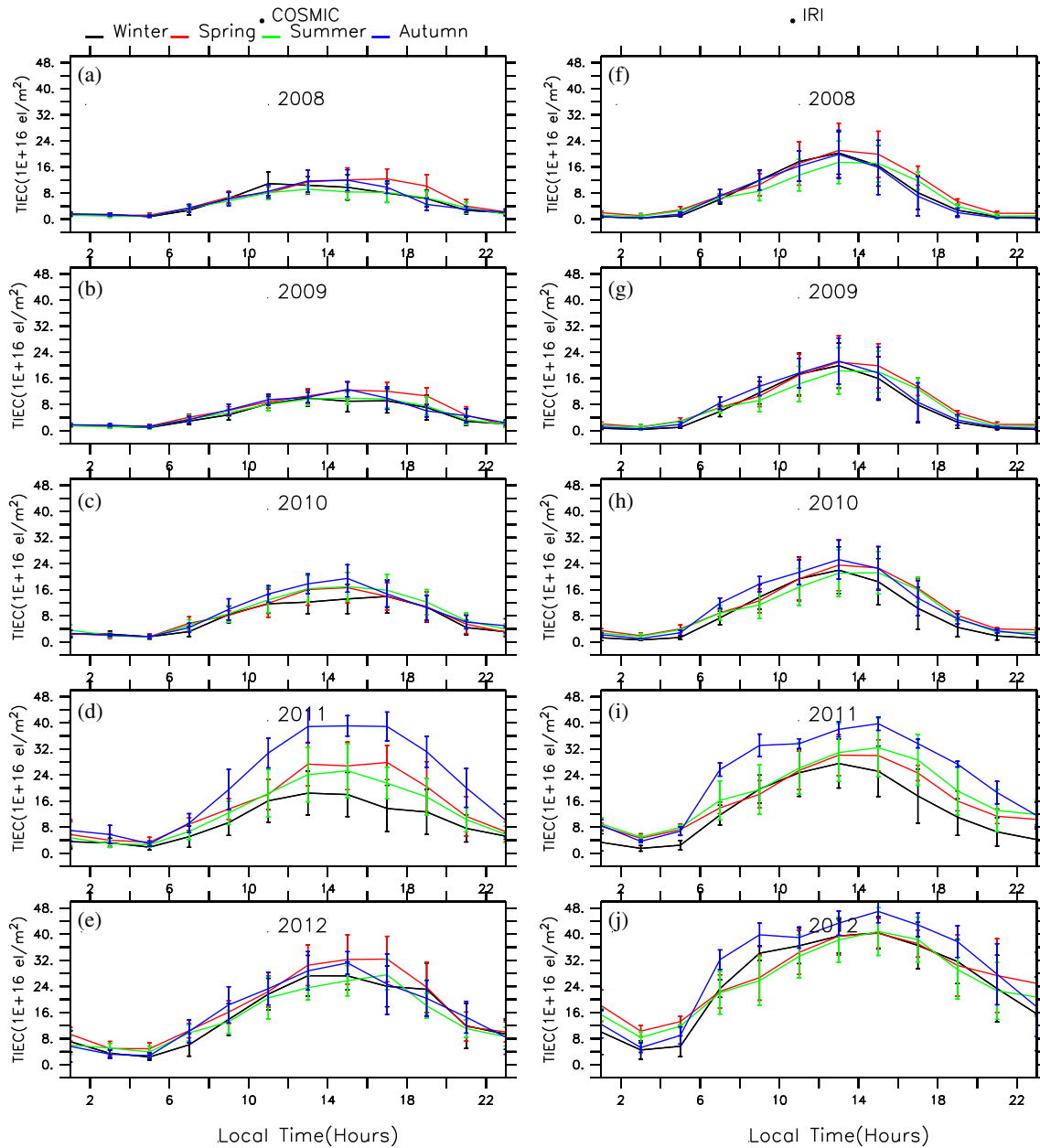


Figure 5. The diurnal variation in TIEC using COSMIC-RO observations over low-latitude region (15° – 30° N, 80° – 95° E) and IRI-2007 model output at Kolkata. The left panels are for COSMIC-RO measurements for the years: (a) 2008; (b) 2009; (c) 2010; (d) 2011 and (e) 2012. The right panels are for IRI-2007 model output for the years: (a) 2008; (b) 2009; (c) 2010; (d) 2011 and (e) 2012 respectively. Different colours represent different seasons. Vertical bars denote the standard deviation.

HSA conditions over this region. Some earlier studies have reported that over equatorial region, the ionosphere exhibits annual (in case of HmF2) and semi-annual (in case of NmF2, BIEC, TIEC) variations (Kawamura *et al.* 2002; Sripathi 2012), which are constrained by the solar zenith angle, photochemistry (Ambili *et al.* 2012, 2013), meridional neutral winds (Alken *et al.* 2008), and the ratio between [O] and [N2] (Su *et al.* 1998; Chen *et al.* 2009) variation. Generally, at midnight, monthly averaged values of all the parameters, except HmF2 (minor enhancement occurred during LSA), differ

by nearly 2.1–8.3 times less than that of noon-time values in case of COSMIC satellite observation, whereas for IRI-2007 model output, those values are periodically diffusive for month-to-month (1.3–42 in case of TIEC and NmF2 and 3–61 in case of BIEC) with minimum in June and maximum in November. This difference has significantly decreased during rising solar activity for both options. Additionally, a robust ascent in all the parameters during 2011 may be attributed to the significant change in solar activity (figure 1a), which proves the Sun's control over ionosphere

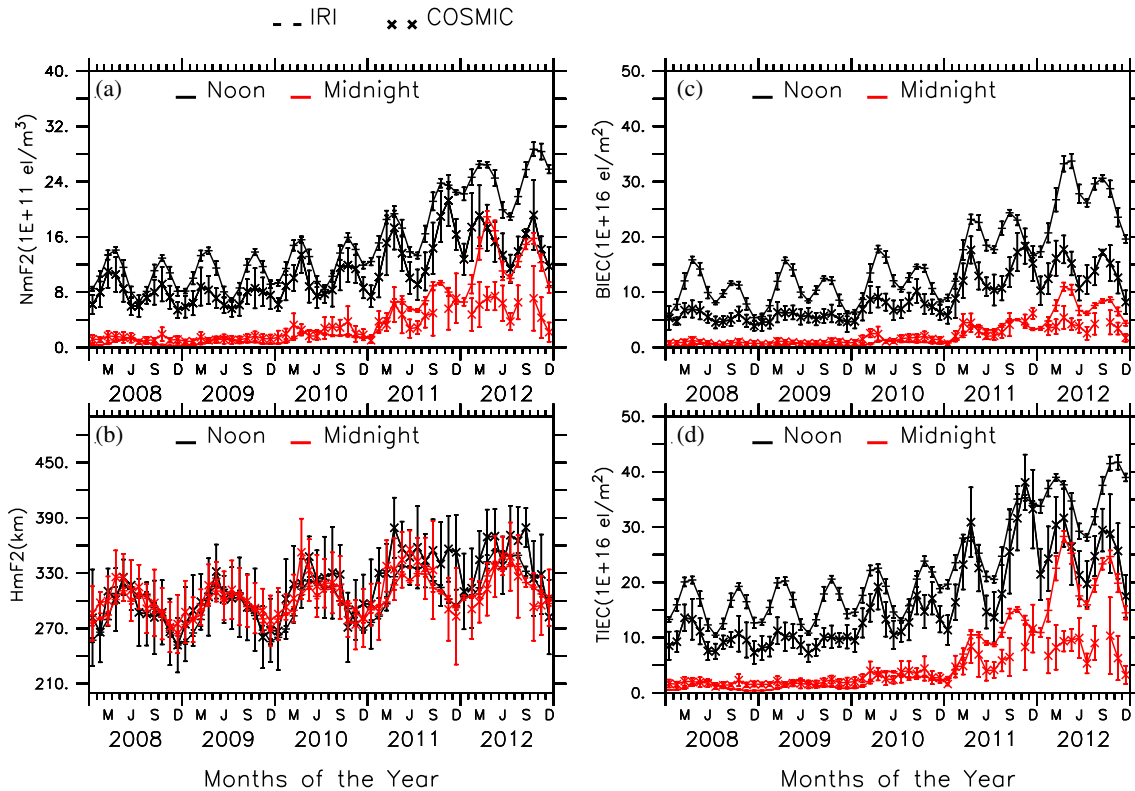


Figure 6. Time series plot of monthly averaged (a) NmF2; (b) HmF2; (c) BIEC and (d) TIEC using COSMIC-RO (cross symbols) observations over low-latitude region (15° – 30° N, 80° – 95° E) and IRI-2007(dash symbols) model output at Kolkata during 2008–2012. The black and red lines represent the noontime (10.00–14.00 hrs LT) and midnight (22.00–02.00 hrs LT) time outputs. Vertical bars denote the standard deviation.

(Rishbeth and Muller-Wodarg 2006; Chen *et al.* 2009; Sripathi 2012). It may be mentioned here that the HmF2 variation over equatorial region is dependent on vertical $E \times B$ drift velocity and over low latitude it is dependent on the meridional neutral winds (Su *et al.* 1998; Lee and Reinisch 2006; Alken *et al.* 2008; Sripathi 2012) below it, where both of these phenomena have diurnal (Ambili *et al.* 2012, 2013) and seasonal variations (Chen *et al.* 2009). At noon (10.00–14.00 hrs LT), the rate of ion production (in bottom and topside ionosphere) due to solar radiation and at midnight (22.00–02.00 hrs LT) the late PRE upward velocity are the dominating factors for rising HmF2 level, especially during LSA period (Lee and Reinisch 2006). The monthly averaged HmF2, NmF2, BIEC, and TIEC values obtained from both options have shown large differences (in 2012) at noon (58 km, $14.12E+11$ el/m³, $18.53TECU$, and $21.5TECU$) in comparison to midnight (46 km, $11.81E+11$ el/m³, $6.22TECU$, and $19TECU$). Till 2010 December, at midnight, monthly averaged HmF2 values, particularly at the yearly-dip, tended to be slightly higher than that of noontime values. During noon and midnight, the variations in observed IECs exhibit high level (86.4% and 85%) of collateral propensity, which is consistent with the model result (83% and

98%) also. Here it may be observed that the TIEC accumulates higher values, in 53–57% cases, than BIEC for both observed and model result.

4. Conclusion

To study the climatology of low-latitude ionosphere at Kolkata, we have analyzed the COSMIC-RO VED profiles over the region 15° – 30° N and 80° – 95° E and compared the result with IRI-2007 model output. This type of study using LEO satellite based information has not been done in recent times over this region. The diurnal, monthly, seasonal, and yearly variations of NmF2, HmF2, BIEC, and TIEC were investigated for the time period 1 January 2008 to 31 December 2012. The seasonal mean values of NmF2, BIEC, and TIEC have shown more or less similar trends in diurnal variation with diurnal-peak around noon to post-noon hours and diurnal-dip around pre-sunrise hours for both model and observed profiles. In addition, the post-noon discrepancies imparted in the observed and model profiles are indeed more intense during all the seasons. The night-time evolutions in all the parameters are more prominent than those of daytime as one moves from LSA

to HSA conditions. The monthly averaged NmF2, BIEC, and TIEC have sustained higher values in March–April and September–November (autumn) months, while that of HmF2 achieved higher values during May–June (spring) months. Therefore, the Ne concentration in spring and autumn seasons are significantly dominant in the climatological behaviour of ionosphere over this region. Our analysis also indicates that HmF2 exhibit annual variation with yearly-dip during winter, while others (NmF2, BIEC, and TIEC) exhibit semi-annual variation (figure 6). The major discrepancies observed between COSMIC-RO observation and IRI-2007 model outputs are:

- The differences between diurnal-dip and diurnal-peak values in all the parameters are considerably higher in IRI-2007 model output in comparison to COSMIC-RO observation, especially during rising solar activity.
- The sudden enhancement of observed HmF2, occurring in the autumn seasons (figure 3c–e) of 2010–2012 and the winter season (figure 3e) of 2012, is inconsistent with the model result.
- In case of monthly averaged NmF2 and IECs, the model outcomes markedly overestimate (nearly in 73% cases) the observed values, especially during rising solar activity period and for monthly averaged HmF2 it underestimates (nearly in 76% cases) the observed value.

Also, the ratio of TIEC and BIEC decreased rapidly towards noon, which helps to advocate that the Ne concentration in the bottom side of ionosphere attained higher values, due to longer persistence of intense solar radiation, in comparison to topside part. The significant evolution in variation of all the parameters during 2011 may be due to transition of solar activity from one stage to another. In 2012, the level of monthly averaged peak and dip values have increased by significant amounts (figure 6), which could be due to HSA. Moreover, the discrepancies observed in variation pattern, obtained from both options, can help the research community to understand the recent trends of ionospheric parameters, especially over this region and develop the IRI model in a more effective way for better fitting to the observed profiles.

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