Nighttime enhancement of ionospheric parameters

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In the present work, ionospheric electron content (IEC) as well as critical frequency of F2 layer (foF2) data from three locations (low, mid and high latitudes) have been used to study the anomalous nighttime F-region during low to moderate solar activity period, i.e. from January 2006 to December 2010. The results show that at high and mid-latitude locations, there is maximum percentage of enhancement in IEC and foF2 during winter season, whereas at low latitude location, maximum percentage of enhancement in both the parameters is during equinox. The highest total number of enhancements in IEC parameter occurred at high latitude station Chilton, whereas in foF2 parameter, highest total number of enhancements occurred at low latitude station Kwajelin. Out of 1116 enhancements in IEC, 661 enhancements occurred during pre-midnight hours and 455 during post-midnight hours. Although out of 948 enhancements for foF2, 457 enhancements occurred during pre-midnight hours and 491 during post-midnight hours.

Keywords: Ionospheric electron content (IEC), F2 layer critical frequency (foF2)
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1 Introduction

In general, after nighttime (local time), ionospheric electron content (IEC) starts increasing and in post-noon period, it becomes maximum; after that it starts decreasing and attains a minimum or low value around 2200-2400 hrs LT. Simple theory suggests that after sunset when thermosphere is no longer bare to radiation from the Sun, electron content would decay steadily as recombination occurs. It is recognized that IEC does not decrease throughout the night as predicted by simple theory but shows anomalous enhancements under a broad range of geophysical conditions1-3. The various enhancement characteristics, such as frequency of occurrence, time of occurrence, amplitude and duration are found to depend on location, season and solar activity. Many researchers have studied the effect of season, solar and magnetic activity on nighttime enhancements in IEC for low, mid and high latitudes4-7. The maintenance of nighttime ionosphere is a matter of controversy14. One explanation, that has received much attention, is that the ionization is lifted up by an equatorward neutral wind or an eastward electric field to regions of small loss rate15. However, vertical drifts alone cannot fully explain the persistence of nighttime ionosphere16,17. The formation of pre-midnight peaks in winter is mainly due to heights with a lower recombination rate10,11. Large amplitudes during equinox may be associated with the highest efficiency in the interaction between the Earth and the solar wind that occurs during these periods18.

Nighttime enhancement (pre-midnight and post-midnight) is a unique phenomenon for the mid to low latitude F2 region which has long been observed in IEC. In the equatorial anomaly region, the most important source of such nighttime enhancement is the evening increase in the upward E×B drift at the equator12. At mid latitudes, the chief source has been identified as a downward flow of plasma from the protonsphere to the ionosphere5. In addition, neutral air winds modulate and these enhancements play an important role at all latitudes19,20.
Generally, during the nighttime, the post-sunset peak varies in the range 12-50%, while the post-midnight peak varies in the range 22-70% in all the seasons. These two peaks of variability can be attributed to steep electron density gradients that are caused by the onset and turn-off of solar ionization and superimposition of ionospheric F-region irregularities (spread-F) on the background electron density. Recently, Akala et al. studied the diurnal, seasonal and solar activity effects on the variability of ionospheric foF2 (critical frequency of the F2 layer) in the equatorial low latitude region and analyzed that foF2 is more susceptible to variability during the nighttime than the daytime, with two characteristics peaks, pre-sunset (12-50%) and post-midnight peak (22-70%). An overall statistical study of nighttime enhancement of NmF2 showed that both pre-midnight and post-midnight NmF2 peak demonstrate distinct variations under geophysical conditions, indicating different physical mechanisms responsible for their formation. Vyas & Pandey studied ionospheric drifts at low latitude station, Udaipur, in the nighttime F-region and daytime E-region during solar flares and reported that for nighttime F-region drifts, a reduced electric field coupling of sunlit and dark hemispheres is the possible cause.

Dashora & Pandey considered the total electron content (TEC) enhancements in the nighttime low latitude ionosphere in the Indian zone (Udaipur) near the crest of equatorial anomaly and reported that the enhancements in TEC are a local phenomenon and cannot be linked with equatorial spread-F. They have reported the first assessment of an isolated TEC enhancement at the anomaly zone latitude using GPS observations. An increase of about 5 TECU in less than 30-min interval cannot be recognized to changes in slant height, or to normal latitudinal variation in plasma density. The control of solar and magnetic activity on nighttime enhancement in IEC at Lunping, a station near the crest of northern equatorial anomaly, is studied using the IEC data for a period of 7 years from January 1981 to December 1987, which corresponds to descending phase of solar cycle 21. The occurrence of enhancements is more prominent in post-midnight hours than in pre-midnight hours and is more frequent during summer months, less during equinox and least during winter months.

The intent of the present work is to get some further knowledge about the anomalous nighttime increase (ANI) phenomenon using both the parameters, IEC and foF2, based on ionosonde records provided by the three receiving stations Chilton (52°N, 359°E), Athens (38°N, 24°E) and Kwajelin (9°N, 167°E) at low, mid and high latitude. To study the behaviour of IEC and foF2, hourly values of IEC and foF2 data for the period of 5 years, from January 2006 to December 2010, have been used. All the characteristics of nighttime enhancement, like time of occurrence of peak, mean peak amplitude and duration of enhancement have been analyzed considering solar and magnetic activity dependence. The main aim is morphological study of nighttime enhancement in foF2 and IEC during low solar activity period from January 2006 to December 2010. The detailed physical interpretation of the morphological features revealed will be attempted in near future.

2 Data and Analysis

IEC and foF2 data for this study, for the period January 2006-December 2010 for different latitude zones (low, mid and high), were obtained from National Geophysical Data Centre’s Space Physics Interactive Data Resource (http://ngdc.noaa.gov/). The values of Ap, AE and solar 10.7 cm flux (Sa) were obtained from World Data Center WDC Kyoto, Japan (http://wdc.kugi.kyoto-u.ac.jp/wdc).

Cases of nighttime enhancement were grouped into three seasons as winter (January, February, November, December), summer (May, June, July, August) and equinox (March, April, September, October). Nighttime enhancements for IEC and foF2 were also divided into pre-midnight (1900-2300 hrs LT) and post-midnight (0000-0600 hrs LT) period, depending on the time of prominent peak of the enhancement occurred. In the current study, the majority of the enhancements are found to have a single peak. Though, in few events, the enhancement having double or triple peak, the prominent peak is considered for statistical purposes.

In characterizing the nighttime enhancement, the criterion adopted by Unnikrishnan et al. (Ref. 28 and references therein) is applied. Therefore, nighttime IEC or foF2 enhancement, defined as the excess content or mean peak amplitude (ΔIEC or ΔfoF2), which remained behind the exponentially decaying background of the diurnal content, was subtracted from IEC and critical frequency of F2 layer. The maximum difference between the enhanced IEC or foF2 and the background content gave the excess content, which is called the amplitude of enhancement (1 IEC = 10^16 el m^-2).
In the present study, only those enhancements were taken into consideration, which had amplitudes greater than 20% of the background content.

Solar activity and magnetic activity are represented by the solar 10.7 cm flux (Sa) (in sfu, 1 sfu = 10^{-22} \text{ Wm}^{-2} \text{ Hz}^{-1}), AP/AE index (nT), respectively. In this study, 10.7 cm flux (Sa) is used as a better indicator of solar activity. In order to study the solar and magnetic activity dependence on the characteristics of enhancement like peak amplitude (\Delta IEC or \Delta foF2), duration of enhancement and time of enhancement, peaks have been obtained from daily plots of IEC and foF2, then the mean values of these enhancement characteristics have been calculated for each grouping of solar 10.7 cm flux, AP and AE index for different seasons. The daily values of Sa varies from 65 to 103 units during the period of consideration, while AE varies from 8 to 827 units, and AP from 0 to 94 units.

### 3 Results

Location-wise number of enhancements, occurred during the period of study, i.e. from January 2006 to December 2010, for both the parameters during pre-midnight and post-midnight hours, are shown in Table 1. It is clearly seen from the table that highest total number of enhancements in IEC parameter occurred at high latitude station Chilton, whereas in foF2 parameter, highest total number of enhancements occurred at low latitude station Kwajelin.

#### 3.1 Percentage of nighttime enhancement in IEC and foF2

Figure 2 represents the average monthly variation of percentage of nighttime enhancement in IEC as well as foF2 from January 2006 to December 2010. It is seen

![Fig. 1 — Examples of nighttime enhancement](image1)

![Fig. 2 — Monthly variation of percentage of nighttime enhancement in IEC and foF2 during January 2006 – December 2010](image2)

<table>
<thead>
<tr>
<th>Station</th>
<th>IEC enhancements</th>
<th>foF2 enhancements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Pre-midnight</td>
</tr>
<tr>
<td>Chilton</td>
<td>525</td>
<td>212</td>
</tr>
<tr>
<td>Athens</td>
<td>329</td>
<td>229</td>
</tr>
<tr>
<td>Kwajelin</td>
<td>262</td>
<td>220</td>
</tr>
<tr>
<td>Total</td>
<td>1116</td>
<td>661</td>
</tr>
</tbody>
</table>
from the figure that at high latitude location Chilton (52°N, 359°E), percentage of enhancement is maximum in IEC and foF2 during the month of January and May, respectively. At mid latitude location Athens (38°N-24°E), percentage of enhancement is maximum in IEC and foF2 during the month of November and January, respectively; while at low latitude location Kwajelin (9°N-167°E), percentage of enhancement in IEC and foF2 is maximum during the month of April.

3.2 Seasonal variation of nighttime enhancement in IEC and foF2

Figure 3 represents the average seasonal variation of nighttime enhancement in IEC and foF2 from January 2006 to December 2010. It is seen that at high and mid latitude locations, percentage of enhancement in IEC and foF2 is maximum during winter, whereas at low latitude maximum percentage of enhancement in both the parameters is maximum during equinox.

3.3 Time of peak of enhancement in IEC and foF2

Figure 4 represents latitudinal and average seasonal variation of time of enhancement peak in IEC and foF2 for the period January 2006 to December 2010. It is clear from the figure that at high latitude location Chilton (52°N, 359°E), post-midnight events are dominating; whereas at mid latitude location Athens (38°N, 24°E) and low latitude location Kwajelin (9°N, 167°E), pre-midnight events are dominating. During winter months, average pattern of IEC and foF2 at high latitude shows that the maximum percentage of occurrence of enhancement peak occurred around 0100-0200 hrs LT, whereas at mid and low latitude, it is around 2000-2200 hrs LT. During summer months, all the locations (low, mid and high latitude) show maximum percentage of enhancement of peak just before midnight hours.
around 1900-2100 hrs LT. Although, during equinoxial months at high latitude location, percentage of enhancement is maximum during post-midnight hours around 0100-0200 hrs LT, whereas mid and low latitude show maximum percentage of enhancement peak during pre-midnight hours around 1900-2300 hrs LT.

3.5 Duration of nighttime enhancement in IEC and foF2

Figures (5 and 6) represent the average percentage of duration of enhancement during pre-midnight and post-midnight hours. It is seen from these figures that the duration of enhancement varies between 2 to 11 h for all the latitudes. At high latitude location Chilton (52°N, 359°E), maximum percentage of duration in IEC is of 3 h and in foF2 is of 9 h during pre-midnight hours. Whereas, during post-midnight hours maximum percentage of duration in IEC is of 3 h and in foF2, it is 5 h. In few cases at high latitude, it persists throughout the night. At mid latitude location Athens (38°N, 24°E), maximum percentage of duration is between 3 and 5 h for IEC and foF2 during pre-midnight as well as post-midnight hours. Although at Kwajelin (9°N, 167°E), maximum percentage of duration in pre-midnight and post-midnight hours is between 2 and 5 h for IEC as well as for foF2.

3.5 Monthly mean variation of peak size ($\Delta$IEC$_{max}$ and $\Delta$foF2$_{max}$)

Figure 7 represents the monthly mean variation average (January 2006 to December 2010) of peak size of nighttime enhancement in IEC ($\Delta$IEC$_{max}$) and
foF2 (ΔfoF2_{max}) separately for pre-midnight and post-midnight hours. It is seen that high latitude location Chilton (52°N, 359°E) has smaller peak size for pre-midnight and post-midnight events for both the parameters. At mid latitude location Athens (38°N, 24°E), peak size is almost smooth and constant for both the parameters whereas low latitude location Kwajelin (9°N, 167°E) shows a sharp increase in peak size in IEC for post-midnight events during the month of April.

3.6 Effect of magnetic activity on nighttime enhancement

The effect of magnetic activity (AE index) on peak size (ΔIEC_{max} and ΔfoF2_{max}), duration of enhancement and number of occurrences are presented in Figs (8 and 9). For this purpose, regression curves were drawn between the enhancement parameter and AE index. It is clear from Fig. 8 that at high latitude location Chilton (52°N, 359°E), number of occurrences and duration of enhancement shows negative correlation and peak size (ΔIEC_{max}) shows positive correlation with AE index. For mid and low latitude locations, number of occurrences are negatively correlated whereas duration of enhancement and peak size (ΔIEC_{max}) are positively correlated with AE index.

Figure 9 represents that at high latitude location Chilton (52°N, 359°E), the number of occurrences and duration of enhancements are negatively correlated whereas peak size (ΔfoF2_{max}) is positively correlated with AE index. For mid latitude location Athens (38°N, 24°E), all the enhancement parameters are positively correlated with AE index, whereas at low latitude location Kwajelin (9°N, 167°E), number of occurrences and duration of enhancement are positively correlated, whereas peak size (ΔfoF2_{max}) is negatively correlated with AE index.

Figures (10 and 11) represent the effect of magnetic activity (Ap index) on different parameters like peak size (ΔIEC_{max} and ΔfoF2_{max}), number of occurrences and duration of enhancements. For this purpose, regression curves were drawn between the
enhancement parameters and Ap index. Figure 10 shows that at high latitude location Chilton (52°N, 359°E), number of occurrences, duration of enhancement and peak size ($\Delta IEC_{\text{max}}$) are negatively correlated with Ap index. At mid latitude location Athens (38°N, 24°E), number of occurrences, peak size ($\Delta IEC_{\text{max}}$) show negative correlation with Ap index whereas duration of enhancement is positively correlated. Although, at low latitude location Kwajelin (9°N, 167°E), all enhancement parameters are positively correlated with Ap index.

Figure 11 represents that for high latitude location Chilton (52°N, 359°E), Ap index shows negative correlation with number of occurrences, duration of enhancement and $\Delta f_{oF2_{\text{max}}}$ At mid latitude location Athens (38°N, 24°E), number of occurrences shows negative correlation while duration of enhancement and $\Delta f_{oF2_{\text{max}}}$ shows positive correlation with Ap index. Although, at low latitude location Kwajelin...
(9°N, 167°E), number of occurrences and peak size ($\Delta f_{oF2_{max}}$) are negatively correlated and duration of enhancements are positively correlated with Ap index.

3.7 Effect of solar activity on nighttime enhancement

Figures (12 and 13) represent the effect of solar activity ($Sa$ index) on number of occurrences, peak size ($\Delta IEC_{max}$ and $\Delta f_{oF2_{max}}$), and duration of enhancement. For high latitude location Chilton (52°N, 359°E), number of occurrences and peak size ($\Delta IEC_{max}$) show negative correlation with solar activity, whereas duration of enhancement show positive correlation with solar activity (Fig. 12). At mid and low latitude, all the enhancement parameters are positively correlated with solar activity.

Figure 13 represent that at high latitude location Chilton (52°N, 359°E), number of occurrences and duration of enhancements are negatively correlated, whereas peak size ($\Delta f_{oF2_{max}}$) is positively correlated with solar activity. At mid latitude location Athens (38°N, 24°E), all enhancement parameters are negatively correlated with solar activity. Although, at low latitude location Kwajelin (9°N, 167°E), number of occurrences are negatively correlated with solar activity, whereas duration of enhancement and peak size ($\Delta f_{oF2_{max}}$) are positively correlated with solar activity.

4 Discussion

The present study investigates the morphology of nighttime enhancement of both the parameters (IEC and $f_{oF2}$). The results obtained provide a convincingly comprehensive picture of the effects of solar activity, magnetic activity, seasonal and local time variation of IEC and $f_{oF2}$, on various characteristics of nighttime enhancement at three locations of low, mid and high latitude during low to moderate solar activity period i.e. from January 2006 to December 2010. Balan et al. observed that there is little latitudinal variation in the time of occurrence of peak enhancement in IEC during summer. But in winter and equinox, the time of peak enhancement occurrences show latitudinal variation. At low latitude, pre-midnight occurrences and at mid-latitude, post-midnight occurrences are predominant. At the entire latitudes, peak occurred around midnight. The present results that post-sunset (pre-midnight) enhancement is dominant at low latitude, agree with earlier studies. In contrast to this, at lower mid
latitude Tokyo (23.10°N), a clear dominance of post-midnight enhancement was observed\textsuperscript{30}. Time of occurrence of peak enhancement is predominant in post-midnight at middle latitude\textsuperscript{31}, which disagree with present results for mid latitude because of drifting of E×B drift during very low solar activity period. At low latitude, the electrodynamics E×B drift are very effective in transporting ionization in the ionosphere. It has also been established that at low latitude, atomic oxygen is enhanced by transport from higher latitude for the upwelling in the auroral oval. This combined with the upward lifting of the ionized and neutral air winds, give prolonged enhancement in electron density and IEC\textsuperscript{32}.

The mechanisms which are important at high latitude are corpuscular ionization and movement of the mid latitude ionospheric trough. The mid latitude ionospheric trough is manifestation of plasma pause and is a region of low electron density under magnetically quite conditions where the Earth's plasmasphere extends to L= 4 to 5. The lower edge of the latitude range corresponds to the position of minimum nighttime IEC enhancement observed under magnetically quiet solar minimum condition. IEC enhancement occurring in the trough region are due to corpuscular ionization\textsuperscript{33}, the intensity of which increases with increasing latitude. This mechanism is supported by the simultaneous observation of IEC enhancement and precipitation of soft electrons (<400 ev) in European sector\textsuperscript{33}. During magnetic storms, the plasmasphere is compressed causing the mid latitude trough to move to lower latitude. This movement causes the position of minimum nighttime enhancement seen at higher latitude to move to lower latitude\textsuperscript{3}. On the either side of the trough, IEC enhancements are strong on equatorward side due to magnetospheric compression and on the poleward side due to enhanced corpuscular ionization.

Previous studies indicate that the electrodynamic drifts and plasma motion due to the neutral wind is the apparent processes behind the nighttime enhancement in IEC. The accepted mechanism for low latitudes is related to the post-sunset increase in the vertical E×B drift which strengthens the equatorial fountain and the neutral winds which modulate the fountain\textsuperscript{12,19}. The seasonal and solar activity variations of the enhancements at equatorial anomaly latitudes are related to those of the post sunset increase in the F-region vertical plasma drift velocity at the equator. Also, the solar cycle variations are such that the increase in upward E×B drift velocity becomes greater with an increase in solar activity. This could be the probable reason for the observed increase in amplitude with 10.7 cm solar flux during the winter weak storms\textsuperscript{3,7,34}.

The direction of the meridional neutral air wind, in general, is poleward during the day and equatorward during the night. At low latitudes, the maximum velocity of the equatorward wind occurs during pre-midnight hours\textsuperscript{35,36}. The interactions between an equatorward neutral air wind and the ionospheric plasma raises the ionizations so that the extra ionization added to the topside ionosphere by enhanced fountain effect can exhibit enhancement in TEC. Since plasma motion due to neutral winds is one of the mechanisms behind the nighttime enhancement, this could explain why the most probable local time of maximum enhancement and highest value of enhancement parameters occur during pre-midnight hours.

Positive correlations between solar activity and ionospheric parameters at low latitude particularly for quiet nights have been observed by Unnikrishnan et al.\textsuperscript{28} and concluded that the mean peak amplitude (IEC) during winter and the mean half-amplitude duration (τ) for winter, summer and equinox have a general positive relationship with solar activity\textsuperscript{28}. However, the occurrence frequency of IEC enhancement does not show such a correlation. The observation that the time of occurrence of peak enhancements are during pre-midnight hours for all seasons during quiet nights are also consistent with earlier results\textsuperscript{3}.

5 Conclusion

The outcome presented in this study provides a comprehensive picture of the effect of season, solar activity and magnetic activity on different parameters of enhancement for the ionospheric parameters IEC and foF2. The main results are summarized as:

- Enhancements are more frequent in winter season at high and mid latitudes, whereas at low latitude, these are maximum during equinox.
- Sharp increase in different characteristics is obtained at low latitude while high and mid latitudes have smaller peak size both during pre-midnight and post-midnight hours.
- At high latitude enhancement peak occurred at post-midnight hours, while it occurred at pre-midnight for mid and low latitude locations.
- At all locations, pre-midnight is of shorter duration and post-midnight is of longer duration. There are some cases at high latitude which persists throughout the night. Also, foF2 parameter had longer duration of enhancement as compared to IEC.

- At high latitude, enhancements are of longer duration, smaller peak size and occurred later at night as compared to mid latitude whereas at low latitude, it shows a sharp increase in peak size during post midnight hours.

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