Midlatitude nighttime enhancement in $F$ region electron density from global COSMIC measurements under solar minimum winter condition

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[1] Ionospheric electron density profiles retrieved from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) satellites measurements from 6 November 2006 to 5 February 2007 are used to study the ionospheric nighttime electron density enhancements under winter, solar minimum, and geomagnetically quiet conditions. In this work, the peak electron densities of $F_2$ layer ($N_mF_2$) derived from COSMIC measurements are found to be in reasonably good agreement with ionosonde observations during the night. Therefore the morphology of nighttime enhancements is investigated at geomagnetic midlatitudes (MLAT 20–60$^\circ$) in the northern hemisphere using COSMIC observations. The enhancements of electron density are evident near the $F_2$ layer peak at most latitudes and longitudes; however, significant variations in the latitudinal dependence of the occurrence time and net magnitudes of the enhancements are found in different regions. The characteristics of enhancements in the North Atlantic Ocean sector are distinctly different from those in the eastern part of the North American sector and also from those at longitudes from Europe to Asia, in the Pacific Ocean, and in the western part of the North American sectors. The longitudinal variations of the morphology of the electron density enhancements during nighttime are possibly caused by different downward plasma flux, meridional winds, and electric field drifts under the effect of the geomagnetic field.


1. Introduction

[2] Nighttime enhancements of the ionospheric $F_2$ region electron density have been observed by ionosondes, incoherent scatter radar (ISR), GPS total electron content (TEC) and also tomographic techniques [e.g., Evans, 1965; Balan and Rao, 1987; Bailey et al., 1991; Balan et al., 1991; Su et al., 1994, 1995; Mikhailov et al., 2000a, 2000b; Farelo et al., 2002; Dabas and Kersley, 2003; Pavlov and Pavlova, 2007]. The peak electron density ($N_mF_2$) of the ionospheric $F_2$ layer and the TEC have been found to increase after sunset in all seasons. This phenomenon is called anomalous enhancement/increase of electron density, since the solar EUV radiation as the major source of ion production is absent during the nighttime. Strong local time, seasonal and solar cycle variations are found in these enhancements. The nighttime enhancements can occur during either the premidnight/postsunset period or the postmidnight period or during both periods. Under solar minimum, winter conditions, the local time of the peak enhancements is around 2100–2200 LT for the premidnight enhancements and around 0300 LT for the postmidnight ones [Farelo et al., 2002]; and the enhancements of $N_mF_2$ after midnight are reported to have the highest relative amplitudes and occur on over 90% of the days [e.g., Farelo et al., 2002; Mikhailov et al., 2000a].

[3] Several mechanisms have been proposed to explain the observed nighttime enhancements of the electron density. At midlatitudes, the enhancements are mostly considered to be the result of the net increase of electron density from the downward plasma fluxes relative to the loss from the recombination [e.g., Mikhailov et al., 2000b; Farelo et al., 2002; Dabas and Kersley, 2003]. At equatorial anomaly latitudes, an upward $\mathbf{E} \times \mathbf{B}$ drift in the evening raises the equatorial $F$ region to higher altitudes and the subsequent downward movement of plasma at later hours gives rise to the postsunset/premidnight enhancements of TEC [Balan et al., 1991; Su et al., 1994, 1995; Balan and Bailey, 1995; Balan et al., 1995]. Neutral meridional winds can also contribute to the enhancements of electron density by transporting the plasma to higher altitudes where the recombination rate of ions is small. It is suggested that the relative balance between the downward plasma flux and the recombination determines the characteristics of the enhancements, and in turn affects the seasonal and solar cycle variations of the nighttime enhancements [Bailey et
The postmidnight enhancements of electron density have been found to be contributed by larger downward plasma flux during the enhancement periods at midlatitudes in winter at solar minimum condition. Several simulation studies have taken efforts to explain how and why this larger downward plasma flux source occurs at midlatitude over stations in the North American sector [Bailey et al., 1991; Mikhailov et al., 2000b; Richards et al., 2000a].

Analysis of data from multiple stations has revealed distinct geographic variations in the morphology of $N_{m}F_2$ and TEC nighttime enhancements. Strong latitudinal dependence of the enhancement characteristics has been reported [Balan and Rao, 1987; Balan et al., 1991; Mikhailov et al., 2000a; Farelo et al., 2002], but there are disagreements about this latitudinal dependence. Balan et al. [1991] showed that the minimum amplitude of TEC enhancements occurred at the magnetic latitudes around 25 and 60 degree at solar minimum in winter, whereas Farelo et al. [2002] found a relative minimum around 35 degree for the amplitude of the $N_{m}F_2$ enhancements. This difference may be partly due to the scarcity of observations between 30 and 40° in the study of Balan et al. [1991]. In addition, all of these investigations used data combined from different longitudinal sectors, and thus their results might also suggest that there were longitudinal as well as latitudinal variations of the nighttime electron density enhancements. The latitudinal variations of these enhancements have been poorly investigated, especially at midlatitudes. Farelo et al. [2002] found that there was a distinct longitudinal dependence for the occurrence time of the postmidnight enhancements, but their results were based on data from all latitudes (15–60°). In addition, significant longitudinal differences in the frequency of the occurrence of the enhancements have been reported at geomagnetic low latitudes and also on the geomagnetic equator [Su et al., 1994, 1995; Pavlov and Pavlova, 2007]. Further investigation is thus needed to obtain a better understanding of the geographic morphology and local time dependence of the nighttime electron density enhancements.

A longitudinal variation of the enhancements is expected since the neutral winds, $E \times B$ drifts, and the equatorial anomaly are known to be longitudinally dependent. Most of these previous investigations were limited to single or a few stations and thus lack a global perspective. In particular, there were almost no studies done over the oceanic areas because of the lack of ground stations there. For instance, Farelo et al. [2002] carried out a statistical investigation using 53 ionosonde stations, but they included only several stations between 250 and 360°E whereas there were relatively more stations at other longitudes. Observations made by the recently launched six satellites of Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission in April 2006 [Lei et al., 2007] provide a good opportunity to do an analysis over the whole globe as well as over wide altitudinal band. The global picture of these enhancements will be of great value for further understanding of the mechanisms that drive them.

The principal objective of this paper is to use electron density profiles retrieved from COSMIC radio occultation measurements to study spatial and temporal variations of the nighttime electron density enhancements at geomagnetic midlatitudes (20–60°) in the northern hemisphere. In this paper, comparisons of nighttime $N_{m}F_2$ obtained from COSMIC measurements with that from various ionosonde observations are carried out to further validate this new data set (section 3.1), then global coverage of the enhancement information is obtained from the COSMIC observations including oceanic areas (section 3.2). In addition, we use COSMIC observations to obtain altitudinal variations of these enhancements (section 3.3), which are not available from ground-based observations.

Database and Analysis Method

The six COSMIC satellites were successfully launched on 14 April 2006. These satellites operate simultaneously and their orbits were designed to spread apart gradually to their final orbits in December 2007. The constellation tracks radio signals from the Global Positioning System (GPS) as they pass through the Earth’s atmosphere. The vertical ionospheric electron density profiles are then retrieved from the radio occultation technique using the changes in frequency and amplitude of the GPS signals [Lei et al., 2007; Schreiner et al., 2007].

Electron density profiles from all COSMIC satellites were collected within ±45 days from the December solstice of 2006 (from 6 November 2006 to 5 February 2007), a period that corresponded to northern winter, solar minimum conditions. The nighttime data at geomagnetic midlatitudes (MLAT 20–60°) in an altitude range from 200 to 500 km were used. A version of the International Geomagnetic Reference Field (IGRF) for 1945–1995 [Langel, 1992] was adopted to calculate these geomagnetic latitudes from the geographic coordinates. In addition, data were excluded to eliminate the impact of geomagnetic activity if the 3 h ap index was higher than 20 g at the current time or in the previous 6 hours. For the used data the average ap index was around 5 g and the F10.7 index varied around 81 ($10^{-22}$ W m$^{-2}$ Hz$^{-1}$). In this study, the electron density profile data were binned within ±1.5° in latitude, ±15° in longitude and ±5 km in altitude. An analysis grid of 1° in latitude, 10° in longitude and 10 km in altitude was used. Similar data binning methods and moving windows were also applied to the $N_{m}F_2$ data. During this period, there were three satellites reaching the positions near their final orbits. This separation of satellite orbits allows a better local time coverage of the retrieved data. There are about 180,000 raw electron density profiles (1400–2600/day) being retrieved. Figure 1 illustrates distribution of $N_{m}F_2$ data during night (1800–0600 LT) in the northern hemisphere. In each binned grid the number of data was generally between 80 and 140. Relatively dense $N_{m}F_2$ data occurred at geographic latitudes around 25° and 50° at most longitudes. By binning data of three months, the observational samples nearly cover all the local time in each location except around 180°E. In each analysis grid, the scattered electron density points were sorted according to their local time and a fourth-order Fourier analysis was then applied. Figure 2 shows an example of the binned $N_{m}F_2$ data centered at 20°N latitude, 290°E longitude. Data are sparse at 2100 LT and 0930 LT and dense at 2000 LT. This kind of uneven data distribution occurred randomly and
globally. To decrease the possible errors due to the uneven local time distribution of data, the fitted value from the Fourier analysis was used in our analysis. In this study, the enhancements of $N_{m}F_2$ were defined to be the net increase of electron density relative to the minimum density before midnight at each location.

An initial comparison between COSMIC and ionosonde observations showed general good agreement in the $F_2$ layer peak density ($N_{m}F_2$) and the correlation coefficient of $N_{m}F_2$ was reported to be about 0.85 [Lei et al., 2007]. In this study, we will do more comparisons during nighttime from low to higher midlatitudes using historical ionosonde observations in different longitudinal sectors. The ionosonde data ($N_{m}F_2$ and $h_mF_2$) at all stations are obtained from the U.S. National Geophysical Data Center (NGDC-NOAA) database and the World Data Center (WDC), Tokyo for Ionosphere and processed in the same way as by Luan et al. [2004] and Liu et al. [2004]. The ionosonde $N_{m}F_2$ and $h_mF_2$ data were averaged from monthly median values in December and January during solar minimum years ($F_{107} < 100$). Hence the ionosonde data are appropriate for low EUV fluxes (the average $F_{107}$ index is about 81) and magnetically quiet conditions. However, the effect of magnetic activity may not be eliminated completely by using the monthly median data, but the quiet conditions dominate the analysis period. The $h_mF_2$ values were estimated from the monthly median values of $f_oF_2$, $M3000F_2$, and $f_oE$ using an empirical model developed by Dudeney [1983]. The $f_oF_2$ and $f_oE$ are the critical frequencies of the $F_2$ layer and $E$ layer, respectively. $M3000F_2$ is the ratio of $MUF(3000)$/$f_oF_2$ (the $F_2$ layer 3000 km maximum usable frequency) to $f_oF_2$. For stations in the Asian sector, $f_oE$ was calculated with a

Figure 1. Global distribution of data sampling during the nighttime (1800–0600 LT) under magnetically quiet conditions from 6 November 2006 to 5 February 2007. The two black-dotted lines indicate geomagnetic latitudes of $20^\circ$ and $60^\circ$, respectively.

Figure 2. A fourth-order Fourier analysis of the binned $N_{m}F_2$ ($\times 10^5$ cm$^{-3}$) data at a geographic location centered at (20ºN, 290ºE, MLAT 30.7ºN).
modified version of the CCIR formula [Buonsanto and Titheridge, 1987] if not observed.

3. Observational Results

3.1. Comparison of Observations Between COSMIC and Ionosonde

Figure 3 shows a comparison of the diurnal variations of \( N_m F_2 \) (left panels) and \( h_m F_2 \) (right panels) between COSMIC and ionosonde observations at six stations from low to higher midlatitudes in the Asian sector. Figure 4 gives a highlight of the nighttime results of Figure 3 for both COSMIC and ionosonde observations. The COSMIC \( N_m F_2 \) and \( h_m F_2 \) are binned in a 30° wide longitude sector centered at 135°E. The six ionosonde stations are located from 129.6°E to 141.7°E in longitude and from 20.8°N to 51.5°N in geomagnetic latitudes.

In Figure 3, the \( N_m F_2 \) shows reasonably good agreement between the COSMIC and ionosonde observations except for daytime at Yamagawa (31.2°N, 130.6°E, MLAT 20.8°N), Kokubunji (35.7°N, 139.5°E, MLAT 26.0°N), Akita (39.7°N, 140.1°E, MLAT 30.0°N), Wakkanai (45.4°N, 141.7°E, MLAT 35.8°N), Khabarovsk (48.5°N, 135.1°E, MLAT 38.4°N), and Yakutsk (62.0°N, 129.6°E, MLAT 51.5°N). The COSMIC data are binned from 120 to 150°E. The monthly median data in December and January are used for ionosonde observations. The \( F_2 \) layer peak heights from ionosonde observations are calculated from an empirical model developed by Dudeney [1983].
ionosonde observation, hence the $h_mF_2$ derived from COSMIC can still provide valuable estimate of the relative changes of the $F_2$ layer peak height in each location. In each location, the relative changes of the $h_mF_2$ will change the loss rate of the ions and hence act as one of the important factors that can affect the nighttime $N_mF_2$ enhancements.

[12] In Figure 4, both observations from COSMIC and ionosonde show obvious $N_mF_2$ enhancements at night. During sunset hours, the $N_mF_2$ decayed rapidly owing to the disappearance of sunlight, reached its lowest value around 2100–2200 LT, and then increased during later hours. The enhancements occurred over a wide latitude range at midlatitudes and lasted more than 5 hours; the maximum enhanced $N_mF_2$ occurred between 30° and 40°. The corresponding $h_mF_2$ of the two observations had higher peak heights at lower latitudes. At latitudes between 30° and 40° during the postmidnight hours, the COSMIC observed a decrease of the $h_mF_2$ accompanying the maximum enhanced $N_mF_2$, which was consistent with previous observations [e.g., Mikhailov et al., 2000b]. Note that at 30° and 35° the two enhancement peaks of $N_mF_2$ from COSMIC are short-lived and may be caused by the uneven distribution of the observed samples.

[13] Figure 5 compares the nighttime $N_mF_2$ between COSMIC and historical ionosonde observations under solar minimum condition in the North American sector (top four panels) and sectors near the North Atlantic Ocean (bottom four panels). The agreement is also reasonably good except for the large discrepancy occurring just after sunset. The averaged minimum $N_mF_2$ before midnight and the local time variation of the $N_mF_2$ after sunset from COSMIC are consistent with those from ionosonde observations. Note that at higher midlatitudes in the North Atlantic Ocean region, the absence or weakness of the $N_mF_2$ enhancements from COSMIC after midnight is consistent with that from ionosonde observations. For example, the averaged ionosonde observations at Arenosillo (37°N, 353°E, MLAT 41°N) and Tortosa (40°N, 0°E, MLAT 43°N) show almost no enhancements of $N_mF_2$ after midnight. Also at Lannion (49°N, 357°E, MLAT 52°N) and Slough (52°N, 359°E, MLAT 54°N), the net enhancements of $N_mF_2$ are much smaller than those at Wallops Is. (38°N, 285°E, MLAT 49°N) and Boulder (40°N, 255°E, MLAT 49°N) in the North American sector.

[14] From Figures 3–5, it is evident that, at some stations there are larger differences between the COSMIC retrieved $N_mF_2$ and those measured by the ionosondes, and thus there are differences in the magnitudes of the nighttime electron density enhancements. It appears that the COSMIC peak $N_mF_2$ are lower than the ionosonde ones after midnight at relatively high latitudes, where the differences in the magnitude of the net enhancements is about $0.2 \times 10^5$ cm$^{-3}$. These stations include Boulder (MLAT 49°N), Wallops Is. (MLAT 49°N), Lannion (MLAT 52°N), and Slough (MLAT 54°N). A similar difference can also be found at Yakutsk (MLAT 51.5°N), whereas the COSMIC observations overestimate the minimum density by $0.1 \times 10^5$ cm$^{-3}$ before midnight and underestimate the maximum density by $0.1 \times 10^5$ cm$^{-3}$ after midnight. In addition, a larger discrepancy between COSMIC and ionosonde observations also occurs at noon hours at Yamagawa (31.2°N, 130.6°E, MLAT 20.8°N), during evening hours around 2100 LT at Maui (21°N, 204°E, MLAT 21°N) and during sunset hours (1800–2000 LT) at most stations. Similarly, the $h_mF_2$ values obtained from COSMIC are about 40 km lower than those from the ionosonde at Yakutsk, and overall the COSMIC $h_mF_2$ are about 20 km lower than the ionosonde ones at all the other stations in the Asian sector (Figure 3).

[15] The discrepancies between COSMIC and ionosonde observations can be related to a few factors: the assumption of the spherical symmetry in the COSMIC occultation...
The COSMIC data were averaged in a 3 degree latitude and 30 degree longitude region, whereas the ionosonde data were averaged over observations made over a long period of time at each location. The large discrepancy in $h_m F_2$ at Yakutsk may also have a contribution from the large latitudinal gradient of $h_m F_2$ in the Asian sector at higher latitudes (see Figure 8). Also the empirical model used to calculate the $h_m F_2$ may introduce additional discrepancy at Yakutsk since it has a uncertainty of about 4–5% (~10–15 km) at magnetic midlatitudes [Dudeney, 1983]. In addition, some of the $\int f_E dV$ values are from estimate instead of observation, as mentioned before. Furthermore, the uneven COSMIC data distribution shown in Figures 1–2 can also introduce errors. It is noted that some of the small oscillation seen in the COSMIC data in Figure 6 and Figures 7–9 in later sections may also be caused by the uneven distribution of the observational samples. And the Fourier analysis used in this study may also smooth out the net magnitude of enhancements at some locations. Nevertheless, the maximum enhancements of $N_m F_2$ are mostly about $0.4 \times 10^5 \text{ cm}^{-2}$ at higher midlatitudes (see section 3.2), thus the obvious enhancement features are not totally smeared by these smoothing processes from both the COSMIC occultation retrieval technique and analysis method applied in present work. The results of this study are valid since we are focused more on the general morphology and characteristics of these nighttime enhancements, rather than their absolute magnitudes.

### 3.2. Longitudinal-Latitudinal Dependence of the Enhancements From COSMIC

Figure 6 illustrates the nighttime $N_m F_2$ obtained from COSMIC observations in four different longitude bins of 230°E, 290°E, 340°E and 120°E, respectively. The results at these sectors are presented to show the longitudinal differences of the nighttime electron density enhancements. Striking differences in $N_m F_2$ enhancements can be seen in the North American, North Atlantic Ocean and Asian sectors at night. In the 290°E sector (Figure 6, top right panel), $N_m F_2$ peak enhancements occurred at around 0100–0200 LT at latitudes around 40°, and also occurred around midnight at lower midlatitudes (~30°). However, at 340°E (Figure 6, bottom left panel), an $N_m F_2$ peak enhancement occurred strongly at around midnight at relatively lower latitudes (~28°); and in the 120°E longitude sector...
Examples from 270° were dominated by two latitude belts. They were separated by a few degrees around 35°, as shown by the examples from 270° to 300° that are given in Figures 7b.

One dominant belt, which located at latitudes lower than about 35°, had significant enhancements during 2200–0200 LT, whereas the other one located at latitudes higher than around 35° and had significant enhancements mostly during later local time hours. At the edge of the second latitudinal belt (~40°), significant enhancements also started before midnight and persisted into the early morning hours, which was similar to those in the first latitudinal belt. In this region, enhancements are found to be prominent at both the lower and higher latitudinal belts in longitudes between 270° and 290°E.

[17] 1. Enhancements in the region of ~45°–245°E (region 1): The region of ~45°–245°E includes the most of the longitudinal sectors from Europe to Asia, in the Pacific Ocean and the west part of the North American sectors. Figure 7a shows typical samples of net enhancements of \( N_{m}F_2 \) at 60°E, 120°E, 170°E and 230°E. In these regions, \( N_{m}F_2 \) was characterized by the enhancements that occurred mostly at higher midlatitudes. These enhancements were significant at geomagnetic latitudes higher than ~30° with duration of a few hours during the postmidnight period, whereas they occurred weakly or less frequently at lower latitudes during the whole night. Usually peak enhancements occurred between ~30 and 50° MLAT and at later local times of around 0200–0400 LT. These enhancements were found to be most prominent in the Asian sector of 90°E–160°E, where marked enhancements did not occur at latitudes lower than ~30°.

[18] 2. Enhancements in the region of ~255°–300°E (region 2): The region of ~255°–300°E represents the eastern North American sector. In this region, the enhancements were dominated by two latitude belts. They were separated by a few degrees around 35°, as shown by the examples from 270°E to 300°E that are given in Figures 7b.

(Figure 6, bottom right panel) it occurred from ~0000–0400 LT between 30° and 35° latitudes. Thus the nighttime \( N_{m}F_2 \) enhancement patterns are different in these longitudinal sectors. When the net enhancements of \( N_{m}F_2 \) are examined, the enhancement characteristics are distinctly different between different regions according to their timing and latitudinal expanse. Figures 7a–7c show examples of net \( N_{m}F_2 \) enhancements in different regions. In regions between ~45° and 245°E, the enhancement patterns are quite different from those in the other two regions of ~255°–300°E and ~310°–10°E.

[19] 3. Enhancements in the region of ~310°–10°E (region 3): The region of ~310°–10°E represents the North Atlantic Ocean sector. In this region, \( N_{m}F_2 \) were characterized by lower midlatitude dominated enhancements, as shown by the examples that are given in Figures 7c, which exhibit the net enhancements of \( N_{m}F_2 \) from 330°E to 10°E. These enhancements had a different latitudinal dependence from those both in region 1 and region 2. They occurred significantly at geomagnetic latitudes lower than ~35°. In addition, they occurred relatively weakly or did not occur at higher latitudes during night. At lower latitudes, enhancements started at premidnight hours with durations of 2–3 hours. Usually peak enhancements occurred at latitudes lower than 35° and during local hours between 2300 and 0100. At higher latitudes, weak enhancements usually occurred around midnight and persisted for a much shorter time than those stronger ones at lower latitudes. These enhancements were most typical between 330 and 350°E, where no obvious enhancements were found at higher midlatitudes during postmidnight hours.

[20] According to Figures 7a–7c, significant net enhancements of \( N_{m}F_2 \) with magnitudes of 0.2–0.4 \( \times 10^5 \) cm\(^{-3} \) occurred at relatively higher midlatitudes, whereas much...
Figure 7
larger net enhancements of $0.3 - 0.6 \times 10^5 \text{ cm}^{-3}$ occurred in the lower midlatitudes. The largest net enhancements occurred in the lower midlatitudes in the North Atlantic Ocean sector. The background $N_{mF2}$ was also much larger in this region than it was at other longitudes (Figure 6). However, significant net enhancements also occurred at higher latitudes (e.g., $120^\circ/230^\circ$), where the background $N_{mF2}$ was much lower than the density at lower latitudes in the same longitudes. The different magnitudes of the net enhancements suggested different plasma sources and mechanisms between the higher and lower midlatitudes, as we will discuss in section 4.2.

3.3. Altitudinal-Latitudinal Variation

[21] Altitudinal variations of the electron density profiles during the nighttime at $120^\circ$E and $340^\circ$E sectors are given for midlatitudes (20–60$^\circ$ MLAT) in Figures 8 and 9, respectively. The $F2$ layer peak height ($h_mF2$) derived from these profiles are also illustrated. According to Figures 8 and 9, no obvious enhancements were seen in the topside and bottom-side of the ionosphere, whereas significant electron density enhancements did occur within 50–100 km of the $F2$ layer peak height. These results showed obvious $N_{mF2}$ increases at latitudes around $\sim30–35^\circ$ during 0000–0300 LT and at $\sim45^\circ$ after 0100 LT at $120^\circ$E and around $\sim28^\circ$ latitude during 2200–0100 LT at $340^\circ$E. They were consistent with the $N_{mF2}$ enhancements shown in Figures 7. At $120^\circ$E the peak density was located at $35^\circ$ around midnight and then intensified and moved to near $30^\circ$ at later local times. However, movement in the other direction or no obvious movement of the peak $N_{mF2}$ can occur at other longitudes (not presented here).

[22] It appears that the latitudinal structure of the net enhancements in $N_{mF2}$ was usually associated with a roughly similar latitudinal dependence of $N_{mF2}$. For example, at $120^\circ$E, the enhancements of $N_{mF2}$ maximized between $\sim30–50^\circ$ latitudes (Figure 6, bottom right panel), and the latitudinal distribution of $N_{mF2}$ had a peak between $\sim30–50^\circ$ latitudes during the nighttime (Figure 8). Similarly, at $340^\circ$E the enhancements of $N_{mF2}$ were greatest in the lower midlatitudes (Figure 6, bottom left panel), and a latitudinal peak of $N_{mF2}$ occurred at latitudes lower than $30^\circ$ after 2100 LT in Figure 8. Note that the maximum enhancements do not necessarily occur at the same latitude as the

Figure 8. Altitudinal-latitudinal variations of the electron density ($N_e$) during night around the $120^\circ$E sector. The dashed white line shows $h_mF2$ obtained from the profile analysis. The contour interval is $0.1 \times 10^5 \text{ cm}^{-3}$.

Figure 7. Examples of the net $N_{mF2}$ enhancements ($\Delta N_{mF2}$) in different longitudinal sectors: (a) from the European sector to the West-North American sectors ($\sim45–245^\circ$E); (b) in the East-North American sector ($\sim255–300^\circ$E); and (c) in the Northern Atlantic Ocean sector ($\sim310–10^\circ$E). Negative values lower than $-0.6 \times 10^5 \text{ cm}^{-3}$ in the postmidnight are replaced by $-0.6 \times 10^5 \text{ cm}^{-3}$. The contour intervals are different at different sectors.
maximum density because the background electron density changes with latitude.

4. Discussion

Reasonably good agreement was seen between the COSMIC and ionosonde observations during the nighttime. In addition, enhancements of the nighttime $N_mF_2$ have been observed by the COSMIC for most midlatitude locations over wide longitudinal regions. The only region where this solar minimum behavior was not obvious in the COSMIC data was at the higher latitudes of the North Atlantic Ocean sector. Distinctly different patterns of $N_mF_2$ enhancements have been observed in different longitudinal sectors. These patterns involve different latitudes and timing of the net enhancements. The largest region (region 1) where the $N_mF_2$ enhancements have similar characteristics in latitudinal and local time variations is as wide as 240°E–20°E in longitude (30–50°N). This feature is quite different from those in the other two minor regions in the east North American sector (region 2) and the North Atlantic Ocean sector (region 3).

4.1. Comparison With Previous Work

The most striking feature in this study is the longitudinal variations of the latitudinal-local time dependence of the enhancements. The COSMIC observations showed that the latitudinal variations of the enhancements were highly longitudinally dependent, indicating any statistical study based on the combined data sets from different longitudes might not reflect the actual physics of the enhancement. Balan et al. [1991] combined data mostly from the North American and East Asian stations, and found that the TEC enhancements had minimum amplitudes around magnetic latitude of 25° and 60° under solar minimum, winter conditions. This result is consistent with the latitudinal dependence of enhancements in region 1 seen in the COSMIC observations, but it is different from the enhancements in the other two minor regions (regions 2 and 3). However, Balan et al.'s [1991] results at specific stations were consistent with COSMIC observations. For example, the net TEC enhancements at Patrick (26°N, 84°W, MLAT 37.2°N) over the North America sector are similar to COSMIC observations at latitudes around 40° and at longitudes around 280°E. Farelo et al. [2002] used global ionosondes observation and found a minimum in the relative $N_mF_2$ enhancement amplitude (the ratio of the maximum enhanced $N_mF_2$ at night to the minimum in the evening) around 35° in the east North American sector (region 2) and the North Atlantic Ocean sector (region 3).
the Asian sectors a minimum of the relative enhancement amplitude would occur at low latitudes (under ~30°) owing to the higher background electron densities and weaker enhancement of $N_mF_2$. It should be noted that high relative enhancement amplitudes (>2.0) at most ionosonde stations in the solar minimum winter [Farelo et al., 2002] would not occur in the COSMIC observations. This difference is possibly caused by the different solar flux levels, observational techniques or the analysis method, which needs further study.

Farelo et al. [2002] also found that the occurrence time of the postmidnight enhancement peaks is almost fixed for all latitudes (15°–60°) in each longitudinal sector, but is 1–2 h earlier in the ~250–360°E longitude band (a few stations were used) than at other longitudes (where a large number of stations were available). However, at all midlatitudes (20°–60°), the COSMIC observations show that the local time of the occurrence of maximum enhancements generally depends more on latitude than on longitude. The peak enhancements (if significant) mostly occur earlier at latitudes lower than about 35°, and much later at latitudes higher than 45°. It is worth noting that, in region 1, large enhancements at the lower latitudes are less frequent, but they can also occur near or before midnight, and persist to the morning hours. The net enhancements at latitudes around 40° are highly longitudinally dependent, and show significant differences between region 1 and region 2. In the lower midlatitudes, the distinct longitudinal variations of the occurrence time of enhancements from region 1 to regions 2 and 3 suggest a different occurrence probability of strong enhancements.

4.2. Mechanism of the Latitudinal and Local Time Dependence of Enhancements

Electron density enhancements occur when electron density increases caused by the net influx are larger than the density loss due to chemical recombination [e.g., Mikhailov et al., 2000b, Farelo et al., 2002; Dabas and Kersley, 2003]. Previous studies have suggested additional contributions from the neutral winds to the nighttime enhancements [e.g., Balan et al., 1991; Bailey et al., 1991]. At midlatitudes, the mechanism of the downward plasma source has been discussed in a realistic way by matching modeling results with observations in the North American sector [Bailey et al., 1991; Richards et al., 2000a]. Bailey et al. [1991] suggested that the larger downward plasma flux in the winter hemisphere, which induce enhancements, was associated with sunset in the conjugate summer hemisphere; Richards et al. [2000a] and Pavlov and Pavlova [2005] suggested that the large download flow of plasmaspheric ions is associated with the dramatic reduction in plasmaspheric heat flux near midnight. From the above modeling, the larger downward plasma flux responsible for postmidnight enhancements is associated with the cooling of the ionosphere.

The downward flux is known to depend on latitude and local time. At Millstone Hill (42.6°N, 71.5°W) under solar minimum winter condition, the observed downward flux was between 0 and 2 × 10^8 cm^-2 s^-1 at 364 km during the night with a maximum of 1–2 × 10^8 cm^-2 s^-1 during 0000–0400 LT, enabling enhancements of $N_mF_2$ to occur during 0100–0500 LT [Mikhailov et al., 2000b]. Modeling study by Balan and Bailey [1995] also showed that the latitudinal dependence of flux varies with local time in the equatorial low latitudes (<30° MLAT). They showed that, in the northern hemisphere the downward plasma flux was smallest at ~15–20° MLAT at 1830 LT, but strongest at 2000 LT, thus drove the strongest postmidnight $N_mF_2$ enhancements at these latitudes. Therefore, the net enhancements of electron density tend to develop at latitude and local time where and when downward flux is relatively large.

The strong longitudinal variations of the morphology of the $N_mF_2$ enhancements from COSMIC observation suggested that the relative contribution of the downward plasma flux and neutral wind may be different at different longitudes. The equatorward meridional winds can lift up the $F_2$ layer peak to higher altitude where the O+ recombination rate is lower; hence the longitudinal variations of neutral winds can also affect the characteristics of $N_mF_2$ enhancements. For the same net $N_mF_2$ enhancements, higher $h_mF_2$ can certainly decrease the needed amount of downward flux. Figure 10 shows the corresponding $F_2$ layer peak height ($h_mF_2$) from COSMIC observations at the same four longitudes in Figure 6. It shows that, at 290°E the maximum value of $h_mF_2$ occurs before midnight and that it decreases quickly after midnight. After midnight, the net decrease in $h_mF_2$ is as large as 60–80 km during the morning hours (0200–0400 LT) when the maximum $\Delta N_mF_2$ occurs. This suggests that strong downward influx is needed to produce the net $N_mF_2$ enhancements over the electron loss. At the same time, strong downward flux may lower $h_mF_2$. At 230°E and 120°E, $h_mF_2$ reaches its highest altitude around midnight and maintains a similar level after midnight, which can help to build up long duration of $N_mF_2$ enhancements after midnight in this region. Therefore, the eastern North American sector seems special in the Northern Hemisphere, showing strong net $N_mF_2$ enhancements after midnight when $h_mF_2$ is much lower than it is before midnight. The most obvious difference between the eastern North American sector and the other regions may be caused by the tilt of the magnetic field. In the eastern American sector, the tilt of the magnetic field leads to that the conjugate point (in summer) of higher latitudes is sunlit most of the night, which allow the plasmaspheric density to build up more than normal [Richards et al., 2000b] and possibly provide strong downward flux that is needed to feed the density enhancements when the temperature collapses after midnight.

Also in the eastern North American sector (270°–290°E), the quick and intense increase of the $h_mF_2$ around 2100 LT shown in Figure 10 can contribute to the early and strong $N_mF_2$ enhancements before midnight. The high $h_mF_2$ are associated with earlier and much stronger equatorward winds at the American sector than in any other sector, which are caused by the larger negative magnetic declination [Luan and Solomon, 2008]. The geomagnetic inclination angle also has important contribution on the effects of meridional wind on the $F_2$ layer peak height. However, the neutral wind induced increase of $h_mF_2$ can help to, but not necessarily lead to strong $N_mF_2$ enhancements. As shown in Figure 10, long-lasting higher $h_mF_2$ values occur around midnight hours (2200–0200 LT) at 340°E above 40° and no comparable wide-spread of $N_mF_2$ enhancements occur (Figure 7c). At 340°E, at lower midlatitudes the high $h_mF_2$
before midnight seems to contribute to the \( N_m F_2 \) enhancements, which occur about 1 hour later; and at the same latitudes, the quick collapse of \( h_m F_2 \) after midnight may lead to the collapse of the \( N_m F_2 \), as shown in Figures 6 and 7. The absence of \( N_m F_2 \) enhancements after midnight at the Northern Atlantic Ocean region may be caused by both the lower postmidnight \( h_m F_2 \) and the absence of strong downward plasma fluxes.

[30] The different morphology of the enhancements between the lower and higher midlatitudes suggested possible different plasma sources and mechanisms. At lower midlatitudes in regions 2 and 3, the plasma flux, if it is the only source of the enhancements, should be very large since the net enhancements were stronger at lower midlatitudes than at higher midlatitudes from the COSMIC observations. At low latitudes near the equatorial anomalies, the sources and mechanisms of postsunset enhancements (mostly at 2100–2200 LT) were investigated by modeling [e.g., Balan and Bailey, 1995; Balan et al., 1995]. At these latitudes and under winter, solar minimum conditions, the plasma source of the enhancements in the topside ionosphere comes from the contribution of evening prereversal increase of the upward \( E \times B \) drifts as well as the transport from conjugate hemisphere by the trans-equatorial neutral wind from summer to winter. The enhancements are caused by the downward movement of the plasma due to ambipolar diffusion along geomagnetic field lines and downward \( E \times B \) drifts. Modeling study showed that the downward flux driven by large \( E \times B \) drifts in the evening from the topside ionosphere plays a major role on the enhancement in the equatorial anomalies [Balan and Bailey, 1995]. In the present work, a similar mechanism may apply to the enhancements at the lower midlatitude region, which is close to the equatorial anomalies. Prereversal \( E \times B \) drifts have been shown to be larger in the American-Atlantic sectors than in the East Asian-Pacific sectors [Vichare and Richmond, 2005], hence the consequent plasma source for the enhancements would be stronger and could extend to wider latitudes in the topside ionosphere in the American-Atlantic sectors. Consistently, much higher background \( N_m F_2 \) values were observed before midnight in the lower midlatitudes where strong enhancements prevailed in regions 2 and 3 (Figures 6 and 7). The evening prereversal \( E \times B \) drifts were suggested to be generally associated with the longitudinal variations in the strength of the geomagnetic field [Vichare and Richmond, 2005]. In addition, neutral winds may also contribute to these enhancements. An increase in \( h_m F_2 \) near 28° latitudes in 340°E (Figure 8), which was seen at 2300 LT in comparison with that at 2100 LT, seemed to be caused by the equatorward neutral wind. The different characteristics of enhancements in different latitude bands separated by around 35° in both region 2 and region 3 suggested that there may be a latitudinal limit at around 35° above which the low-latitude plasma source could not reach.

5. Summary and Conclusion

[31] The COSMIC observations provide a global view of the characteristics of the electron density enhancements during the night. The longitudinal, latitudinal, altitudinal and local time variations of the nighttime enhancements of the \( F_2 \) layer electron density were investigated at geomagnetic midlatitudes (20–60°) under solar minimum, northern hemisphere winter and geomagnetically undisturbed conditions. These nighttime enhancements of \( N_m F_2 \) from
COSMIC were validated by comparing with ionosonde observations at various stations around the globe. The main conclusions of this study are:

32. 1. Prominent enhancements in $N_m F_2$ occur near the $F_2$ layer peak in most midlatitude locations. The magnitude of the peak enhancements of $N_m F_2$ shows strong dependence on latitude. Net enhancements of $N_m F_2$ have a magnitude of $0.2–0.4 \times 10^{15} \text{ cm}^{-2}$ in relatively higher midlatitudes, and $0.3–0.6 \times 10^{15} \text{ cm}^{-2}$ in the lower midlatitudes.

33. 2. The enhancement patterns for $N_m F_2$ are found to be different in different longitudinal regions. Similar enhancement patterns occur at most of the longitudes from Europe to Asia, in the Pacific Ocean, and the west part of the North American sector $(\sim 45–245^\circ E)$, region 1. However, enhancement patterns are distinctly different from those in region 1 in the east part of the North American sector $(\sim 255–300^\circ E)$, and also in the North Atlantic Ocean sector $(\sim 310–10^\circ E)$.

34. 3. The characteristics of the enhancements are different in different regions when the latitudinal expance and local time duration are considered: (1) Within the $\sim 45–245^\circ E$ sector, enhancements at higher midlatitudes $(\sim 30–50^\circ)$ dominate, occurring strongly after midnight (0200–0400 LT), (2) within the $\sim 255–300^\circ E$ sector, enhancements prevail in two latitudinal belts separated by a few degrees around 35$^\circ$, occurring around midnight in the lower-latitude belt and mostly after midnight in the higher-latitude belt, and (3) within the $\sim 310–10^\circ E$ sector, enhancements at lower midlatitudes $(\sim 35^\circ)$ dominate, occurring mostly around midnight (2300–0100 LT).

35. The longitudinal variations of the morphology of the electron density enhancements during nighttime are possibly caused by different downward plasma flux due to the effects of the tilt of the magnetic field, and different meridional winds and electric field drifts due to the longitudinal variation of the geomagnetic field.

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