The ionospheric midlatitude trough observed by FORMOSAT-3/COSMIC during solar minimum

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[¹] This paper for the first time reports global three-dimensional (3-D) structures of the ionospheric midlatitude trough using electron density profiles derived from the GPS radio occultation experiment on board FORMOSAT-3/COSMIC (F3/C) satellites during the solar minimum period, February 2008 to January 2009. Results show that the midlatitude trough extends from dusk to dawn in all four seasons and is most pronounced in the winter hemisphere. The troughs in the two hemispheres are asymmetric, where the trough in the Northern Hemisphere is more evident and stronger than that in the Southern Hemisphere during the equinoctial seasons. In general, the trough minimum position shows a high-low-high latitudinal variation with magnetic local time and occurs at lower latitudes under higher magnetic activity. On the other hand, the midlatitude trough structures become more complex in the Southern Hemisphere because of the nighttime plasma density enhancement of the Weddell Sea Anomaly. Our results demonstrate that the new data set of GPS radio occultation by F3/C is useful to probe the global 3-D electron density structures of the midlatitude trough.


1. Introduction

[²] The ionospheric midlatitude trough is a persistent large-scale electron density depletion structure in the middle latitude F region, and typically extends from the post-afternoon sector to the dawn sector [Kersley et al., 1997]. It forms at the interface between the midlatitude ionosphere and the high-latitude auroral region as a result of the complex interplay between different geophysical processes [Middleton et al., 2008]. The structure of the midlatitude trough is presented as narrow in latitude and extended in longitude. The electron density distribution of the trough has three parts: an equatorward edge, a trough minimum, and a poleward edge. The poleward edge is a very steep wall which has a sudden electron density depletion structure up to 800 km altitude. The advantage of using this data set is to study global ionospheric features at various altitudes in both hemispheres. The major motivation of this paper is for the first time to analyze F3/C GOX observations during the solar minimum period, February 2008 to
January 2009, to carry out a comprehensive investigation on the midlatitude trough as a function of altitude, season, and geomagnetic activity variations in both hemispheres. Meanwhile, the effect of the Weddell Sea Anomaly (WSA) [Horvath and Esset, 2003; Burns et al., 2008; Lin et al., 2009; Horvath and Lovell, 2010] on the midlatitude trough in the Southern Hemisphere summer nighttime is also investigated in this paper.

2. Data Analysis

[8] The solar radio flux index, $F_{10.7}$, which is a proxy for EUV radiation, shows that the solar activity approaches a minimum on December 2008, which provides an excellent opportunity to study the morphology of the midlatitude trough in the ground/quiescent state of the ionosphere. The ionospheric electron density profiles are retrieved from GPS observables along the GPS-LEO (low earth orbit; F3/C) radio links near the raypath tangent points. The vertical resolution of the GOX observation is usually about 1–3 km which varies with radio occultation (RO) sounding sampling rates and the geometry of GPS-F3/C radio link. The GOX ionospheric data we used are postprocessed by COSMIC Data Analysis and Archive Center (CDAAC) at UCAR. Recent studies show that the ionospheric electron densities derived by the RO sounding around and above the $F_2$ peak yield reasonably correct, and those below the $F$ region should be extremely carefully used [Lei et al., 2007; Kelley et al., 2009; Liu et al., 2010; Yue et al., 2010]. Therefore, we focus on the F3/C GOX electron density at and above the $F_2$ peak.

[9] The F3/C GOX observations between February 2008 and January 2009 are further subdivided into four 3 month seasons, March equinox (February–April), June solstice (May–July), September equinox (August–October), and December solstice (November–January), which are denoted as the M, J, S, and D month, respectively.

[10] Since many features of the ionosphere are strongly organized by the geomagnetic field and the behavior of the midlatitude trough is also highly dependent on the magnetic latitude (MLAT) and magnetic local time (MLT). The F3/C GOX data are transformed from geographic longitude and latitude into MLAT (−80° to 80°) and MLT (0000 to 2400). To investigate the geomagnetic activity effect, the data are further divided into two groups corresponding to lower $Kp$ 0 to 2, and higher $Kp$ 2+ to 5+, geomagnetic activity, where each group consists of about 40,000 observations. To examine the trough response to various seasons and geomagnetic activities, the GOX data are binned by seasonal and geomagnetic conditions. The median value of the GOX electron density in each binned cells of 0.5 h (MLT) $\times$ 1.0° (latitude) $\times$ 5 km (altitude) is obtained. The data is also smoothed with a sliding window of 1.5 h $\times$ 3.0°.

3. Results and Interpretations

[8] Figure 1 illustrates pseudo 3-D structures of the electron density at the $F_2$ peak $N_{m}F_2$ for all geomagnetic activity levels in both hemispheres during the four seasons. It can be seen that the midlatitude trough extends from dusk to dawn. The electron density of the trough minimum reduces down to $3.8 \times 10^4/4.5 \times 10^4$ #/cm$^3$ in the Northern/Southern Hemisphere during the winter season (D/J month), and becomes lower than $9.5 \times 10^4/10.0 \times 10^4$ #/cm$^3$ in the Northern/Southern Hemisphere during the summer season (J/D month), respectively. This shows that the midlatitude trough becomes prominent during the winter solstice (D month in the Northern Hemisphere and J month in the Southern Hemisphere), but weak during the summer solstice. The electron density of the trough minimum is $5.8 \times 10^4/7.4 \times 10^4$ #/cm$^3$ in the Northern/Southern Hemisphere during the Spring/Fall equinox (M month), and $5.9 \times 10^4/6.3 \times 10^4$ #/cm$^3$ in the Northern/Southern Hemisphere during the Fall/Spring equinox (S month), respectively. The trough minimum electron densities are lower in the Northern Hemisphere than in the Southern Hemisphere showing a hemispheric asymmetry of the midlatitude trough during the two equinox months. Meanwhile, the $N_{m}F_2$ is much greater in the Southern Hemisphere summer at high latitude during nighttime compared to the Northern Hemisphere summer. Note that there are $N_{m}F_2$ enhancements around 2200 MLT in the Southern Hemisphere during the S month, which generally agrees with the WSA feature. Furthermore, it is interesting to note that there are ripple phenomena in $N_{m}F_2$ near the dusk sector and the dawn sector. They are more evident in the Southern Hemisphere during S and D month. The ripple phenomena located at the terminator might be related to the solar terminator wave [Forbes et al., 2008].

[9] To find the geomagnetic activity effect on the midlatitude trough, we examine the $N_{m}F_2$ map in MLAT versus MLT coordinates in the four seasons under the two geomagnetic activity levels. Figure 2a shows that the midlatitude trough has a broad width under the lower geomagnetic activity conditions. By contrast, Figure 2b displays that the trough yields a narrower width and a well defined poleward edge under higher geomagnetic activity conditions. Meanwhile, it is interesting to find that the $N_{m}F_2$ at the trough minimum tends to be slightly greater during disturbed periods than that during quiet ones (see Figure 2). Nevertheless, the trough minimum positions can be well determined by the $N_{m}F_2$ latitudinal distribution (dashed lines in Figure 2).

[10] Figure 3 summarizes that the trough minimum positions under two geomagnetic conditions shown in Figure 2, which are used to investigate the variation with MLT. The trough minimum positions appear at higher latitudes at the postunset sector and migrate to lower latitudes as time progresses, and then often move toward higher latitudes around 0400 MLT in all seasons. This latitudinal motion is not as significant in the winter hemisphere as in other seasons. In general, the high-low-high latitudinal shift with MLT is pronounced, except in the Southern Hemisphere under lower geomagnetic activities. Notice that the trough minimum moves back to higher latitudes earlier around midnight in the M month (Figure 3e, hereinafter referred to as early high latitude motion) instead of around 0400 MLT as in other seasons. On the other hand, the trough minimum could reach to a very low latitude, 52°S with steeper motion and then return to higher latitudes during the postmidnight period in the D month (Figure 3h, hereinafter referred to as extremely low latitude motion). In addition, the trough minimum positions shift equatorward under the higher geomagnetic activity conditions (dashed lines in Figure 3). This equatorward motion of the trough minimum
appears to be roughly the same for all MLT in the Northern Hemisphere.

[11] Figure 4 depicts the MLAT-MLT slices of electron density at various altitudes, around/above the $F_2$ peak height $h_{mF_2}$, for all geomagnetic activity levels during M month, 2008. It can be seen that the midlatitude trough forms two depleted bands of electron density between 60°–80° in the Northern and Southern hemispheres during the nighttime period on all altitude slices. The trough tends to occur at earlier MLT and lasts longer on the higher altitude slices in both hemispheres. On the other hand, it is found that the two dense bands of the equatorial ionization anomaly crests at low latitudes become closer together at higher altitudes.

[12] The global 3-D electron density structure also makes it possible to study both the latitudinal and the altitudinal variations of the ionospheric midlatitude trough that has been not possible before. To further understand the early high latitude and extreme low latitude motions of the trough, we isolate the data from the 3-D structure and examine the electron density contours on a MLAT altitude plane from 2000 to 0200 MLT in the Summer solstice and the March equinox months under the lower geomagnetic activity con-

**Figure 1.** The seasonal averaged pseudo 3-D images of the $F_2$ peak density map ($\log_{10} (N_e)$, cm$^{-3}$) from February 2008 to January 2009 in magnetic polar coordinates for the March equinox, June solstice, September equinox, and December solstice. The inner and outer perimeters are 80° and 30° in magnetic latitude. The left and right columns are results in the Northern and Southern hemispheres, respectively. The color and vertical change refer to the electron density, and the numbers around each plot give the geomagnetic local time.
Figure 2. The $N_mF_2$ on MLAT versus MLT maps in various seasons under (a) lower ($Kp = 0–2$) and (b) higher ($Kp = 2–5+$) geomagnetic activity conditions. The dashed lines denote the trough minimum position. The contour lines begin with $3.0 \ (\text{log}_{10}\ Ne\ \text{in electron/cm}^3)$ and are incremented linearly in a step of $0.1–7.0$. 
Figure 2. (continued)
ditions. Figure 5 shows that the electron density depletions at various heights occur between 55 and 70° MLAT. The trough minimum positions from 300 to 600 km altitude in steps of 50 km are determined from the MLAT-LAT plots. In general, it can be seen that the trough minimum positions are almost at the same latitude with about 1–2° shift in different altitudes and tilt equatorward during the premidnight period. The poleward edge is much steeper than the equatorward edge, especially in the March equinox season.

4. Discussion and Conclusion

Figures 1 and 2 illustrate that the midlatitude troughs occur from dusk to dawn on the two-dimensional (2-D) $N_mF_2$-MLAT-MLT maps, while Figure 4 reveals the 3-D electron density structures of the troughs. Knudsen [1974] and Spiro [1978] proposed that the eastward corotating plasma flow and the westward ion convection flow result in a stagnation region where the plasma moves very slowly during the premidnight period. They suggested that the slow plasma motion gives the chemical recombination process more time to reduce plasma densities, which in turn leads to the trough phenomena. However, this simple mechanism of opposite flows can only explain the formation of the premidnight trough. Pryse et al. [2006] suggested that the postmidnight trough may be fossils of the premidnight trough that are carried by the corotating flow toward dawn. On the other hand, our results show that the midlatitude trough in fact is even wider and the electron density becomes lower during the postmidnight period. Although the mechanisms are not understood, our observations indicate that the chemical loss process continues to deplete plasma during the postmidnight period.

Particle precipitation and ion transportation become stronger and the ion convection pattern and the auroral oval expand to lower latitudes during disturbed magnetic activity conditions [Heelis, 1984; Weimer, 2001]. The enhancement of particle precipitation and ion convection result in more plasma being accumulated at the poleward edges of the trough by direct ionization as well as transport [Tsunoda, 1988] and makes the poleward edges of the trough steeper [Kersley et al., 1997]. On the other hand, the extremely
narrow and strong electric field structure known as Sub-Auroral Ion Drifts (SAIDs) could also narrow the trough through an enhancement of the recombination coefficient due to frictional heating [Rodger et al., 1992]. The expansion of the auroral oval and the frictional heating of SAIDs push the midlatitude troughs to lower latitudes and/or narrow their latitudinal widths in the four seasons (Figure 2b compared to Figure 2a).

Muldrew [1965] showed that the midlatitude trough shifts equatorward with increasing \( Kp \), and for disturbed conditions it can be ten or more degrees equatorward of its undisturbed location. Figure 3 illustrates that the trough minimum positions tend to shift equatorward about 3–5° during the higher magnetic activity period of 2008. The equatorward shifting in work by Muldrew [1965] is greater than that in this study, which may be due to the fact that our results are derived from seasonal medians, whereas Muldrew [1965] presented as scattered plots of \( Kp \) versus trough latitude. In fact, when subdividing the results of Muldrew [1965] into the two geomagnetic activity conditions, \( Kp = 0 \) to 2 and 2+ to 5+, and taking the median values accordingly, we find that the trough shifts equatorward around 5°, which agrees with our results. Furthermore, Wang [1998] simulated the midlatitude trough under low (\( Kp = 2 \)), moderate (\( Kp = 4 \)), and high (\( Kp = 6 \)) geomagnetic activity conditions using the thermosphere-ionosphere nested grid (TING) model. The shifting of the trough minimum position under low and moderate geomagnetic activity levels of Wang [1998] agrees well with the results presented in this study between the lower and higher activities. Moreover, Köhnlein and Raitt [1977] used the RSRO 4 observations to construct an empirical model for computing the position of the midlatitude trough. We compute the midlatitude trough minimum positions for \( Kp = 1 \) and 3 for various MLTs and seasons, similar to Figure 2, by means of Köhnlein and Raitt [1977]. The computed results and the observations of F3/C GOX generally yield a good agreement that the midlatitude trough minimum positions shift equatorward when \( Kp = 1 \) becomes \( Kp = 3 \). Note that the midlatitude trough minimum positions returning to the higher latitudes during postmidnight period could not be reproduced by the model. Nevertheless, both the observations and the model simulations show that the trough moves equatorward during disturbed magnetic conditions and the

![Figure 4. Electron density maps at 250, 350, 450, 550, and 650 km altitude in MLAT versus MLT coordinates obtained from FORMOSAT-3/COSMIC GOX observations during M month (February-April) 2008. It is noted that the contour lines begin at 3.0 (log\(_{10}\) (Ne), cm\(^{-3}\)) and are incremented linearly in steps of 0.15.](image)
motion is proportional to the strength of geomagnetic activity. Our results agree with these previous observations and model simulations which suggest that the F3/C GOX can be useful to study the ionospheric 3-D phenomena at the midlatitude and high latitude.

[16] Based on the F3/C GOX $N_mF_2$ observations, the ionospheric midlatitude trough shows a high-low-high latitudinal variation with magnetic local time in most cases. This generally agrees with previous studies [Muldrew, 1965; Rodger and Pinnock, 1982; Moffett and Quegan, 1983; Weber et al., 1985; Werner and Prölls, 1997; Krankowski et al., 2009]. To find sources of the exceptional features of the early high latitude motion in the M month (Figure 3e) and the extreme low latitude motion in the D month (Figure 3h) of the Southern Hemisphere, we examine the altitude contours of the trough shown in Figure 5. To uncover the early high latitude motion, we cross compare sequences of contours on the MLAT altitude plane in the Northern and the Southern hemispheres during the M month season (top two rows of Figure 5). The cross comparison shows that the electron density tends to be dense at 200–400 km altitude of 55–65°S in the Southern Hemisphere at 2100 MLT and results in the trough minimum positions to stay at higher latitudes around the midnight and to not move to lower latitudes. This is the reason that the trough minimum position displays an early high latitude motion in Figure 3e. On the other hand, a cross comparison between the two hemispheres during the summer solstice season (J and D month) is conducted to understand the extremely low latitude motion (the solid line of Figure 3h). The lower two rows in Figure 5 show that the region of dense electron densities lasts longer between 200 and 400 km from 2200 to 0200 MLT at 50–60°S in the Southern Hemisphere. The trough minimum positions are error determined to the equatorward of the dense density region which do not correspond correctly to the right trough positions above/around the $h_mF_2$ altitude. The extremely low latitude motion in Figure 3h results from the error determination.

[17] The two dense plasma density regions around the $h_mF_2$ altitude in the Southern Hemisphere around midnight shown in Figure 5 agree with the WSA phenomenon, which might result in the two unusual latitude motions of the trough. The WSA is named for the peculiar behavior of the ionospheric electron density over a larger area of the Weddell Sea region (30°–90°S, 30°–150°W), over the southeastern Pacific and southwestern Atlantic. It is characterized by an

![Figure 5. Time sequence plots of electron density in the MLAT versus ALT coordinates from 2000 to 0200 MLT in March equinox months (top two rows) and summer solstice months (bottom two rows) for both hemispheres under lower geomagnetic activity conditions. The black contour lines begin at 3.0 ($\log_{10}$ (Ne), cm$^{-3}$) and are incremented linearly in steps of 0.15. The black stars are the trough minimum positions at 300, 350, 400, 450, 500, 550, and 600 km altitude determined from the MLAT–ALT plots. The red crosses are the trough minimum positions defined by $N_mF_2$ as dashed lines shown in Figure 2.](image-url)
unusual daily pattern with a maximum $f_{o}F_2$ occurs at night (2200–0400 LT, local time) instead of at daytime hours (1000–1800 LT) during the Southern Hemisphere summer and equinoxes [Horvath and Essex, 2003; Burns et al., 2008; Lin et al., 2009; Horvath and Lovell, 2010]. To further investigate the effect of WSA in the trough region, the pseudo 3-D structures of $N_{m}F_2$ in the Southern Hemisphere during the four seasons are constructed after removing the data in the WSA region. Figure 6 reveals that no obvious WSA related enhancement can be found around 2200 MLT in the Southern Hemisphere summer and equinoxes, and the midlatitude trough signatures become more evident. Figure 7 summarizes that the trough minimum positions vary with MLT in the Southern Hemisphere excluding the data in the WSA region under the two geomagnetic conditions. Consequently, the trough minimum positions can be easily and correctly determined. It can be seen that the trough minimum

**Figure 6.** Similar to Figure 1, the seasonal averaged pseudo 3-D images of the electron density in the Southern Hemisphere after removing the observations in the Weddell Sea Anomaly region. From top to bottom, M, J, S, and D month.

**Figure 7.** Similar to Figure 3, the variations of trough minimum positions with magnetic local time in the Southern Hemisphere after removing the observations in the Weddell Sea Anomaly region. From top to bottom, (a) M, (b) J, (c) S, and (d) D month.
now occurs around 66°S not reaching to the extreme low latitude during lower geomagnetic activity in D month (Figure 7d). On the other hand, after removing the data from the WSA, the early high latitude motion also disappear in M month (Figure 7a). The trough minimum positions again reveal the high-low-high latitudinal shift with MLT, especially for the lower geomagnetic activity level.

[15] In conclusion, this paper for the first time examines the global 3-D structure of the midlatitude electron trough in various magnetic local times, seasons, and under different geomagnetic activity conditions by using the radio occultation observations from F3/C GOX during low solar activity. Results show that the midlatitude trough is more evident in the Northern Hemisphere and is especially prominent in the winter hemisphere. Under higher geomagnetic activity conditions, the latitudinal width of midlatitude trough becomes narrower and shifts equatorward with a clear poleward edge. The hemispheric asymmetry of the ionospheric midlatitude trough is evident in both the trough morphology and its variations with MLT.

[19] The first part of this paper shows that our results are consistent with previous studies, so that the new data set of F3/C GOX can be confidently used to study the midlatitude trough. Furthermore, our results show that the nighttime plasma density enhancement of WSA can significantly affect locating the midlatitude trough in the Southern Hemisphere during equinox and summer solstice. It is necessary to remove the data which locate in the WSA region before studying the trough characteristic in the Southern Hemisphere. This study also demonstrates that the midlatitude trough can be better identified by the 3-D electron density structure than by the 2-D maps of the $N_{m}F_2$ and/or the electron density at a certain altitude.

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