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Key Points:

- The CHAMP *Ne* measurements are used to reveal the evolution of nighttime midlatitude trough shape under geomagnetic quiet condition
- The trough equatorward wall experiences an obvious equatorward extension at premidnight, and it is as steep as poleward wall at dusk
- The morphology evolution of midlatitude trough before midnight is suggested to be mainly controlled by the horizontal neutral winds

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Morphology Evolution of the Midlatitude Ionospheric Trough in Nighttime Under Geomagnetic Quiet Conditions

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Abstract The dynamics and climatology of midlatitude trough minimum have been widely investigated. However, the detailed magnetic local time (MLT) evolution of the trough walls (both equatorward and poleward) has not been well addressed. In this study, we used nearly 10-year Planar Langmuir Probe (PLP) data from the CHAMP satellite to investigate how the location and shape of midlatitude trough evolve during night hours. We find that (1) the trough equatorward wall experiences an obvious equatorward extension in the premidnight sector, with steepness rapidly decreasing during the same local time sector; (2) the trough equatorward wall is as steep as poleward wall in the dusk sector; and (3) the trough poleward wall shows no remarkable change during the whole nighttime, except for a weakly reduced width and a slightly enhanced steepness near midnight. We suggest that the rapid extension of the equatorward wall in the premidnight sector is closely related to the plasma equatorward movement caused by the neutral winds. The rapid decrease of the steepness of the equatorward wall in the premidnight sector is not only influenced by its own width expansion but possibly also related to the upward plasma drift caused by neutral winds. The trough minimum and equatorward/poleward boundaries are found located at slightly higher magnetic latitude during equinoxes than that during solstice seasons.

1. Introduction

The midlatitude ionospheric trough (MIT) is a region of low plasma concentration at *F* region altitude, which is narrow in latitude and normally lies close to equatorward boundary of the auroral oval during nighttime (e.g., Rodger, 2008). In morphology, the MIT is usually divided into three parts: the equatorward wall, the poleward wall, and the trough minimum. The equatorward wall is formed by the midlatitude plasma corotating with the Earth (Rodger, 2008), which is considered to be connected with the plasmapause (Yizengaw & Moldwin, 2005). The region outside the poleward wall usually presents a sharp increase in plasma concentration, which is mainly caused by the local energetic particles precipitation (Aladjev et al., 2001; Rodger et al., 1986) and the transport of dayside plasma through convection (Foster et al., 2005; Sojka et al., 2006). The trough minimum is considered to be the result of the interaction between the midlatitude corotation and the high-latitude convection (Kelley, 1989; Knudsen, 1974; Nilsson et al., 2005; Rodger et al., 1992; Spiro et al., 1978). Earlier studies found that the subauroral ion drift (SAID) and subauroral electron temperature enhancement have also important influences on the formation of trough minimum (Anderson et al., 1991; Pintér et al., 2006; Pirog et al., 2009; Prölss, 2006; Providakes et al., 1989; Rodger, 2008). Ishida et al. (2014) reported that the dissociative recombination accompanied by frictional heating is a main cause of trough formation in sunlit regions.

Earlier studies have been focused on the occurrence probability of MIT. In early 1970s, it was shown that the MIT is primarily a nighttime phenomenon and appears more likely during equinoxes and winter seasons (Ahmed et al., 1979; Moffett & Quegan, 1983; Spiro et al., 1978, and references therein). The dependence of location of MIT minimum on magnetic local time (MLT), seasons, and geomagnetic activity has also been reported (Dudeney et al., 1983; Köhnlein & Raitt, 1977; Rodger et al., 1992; Spiro et al., 1978). These results showed that the trough minimum generally moves equatorward from dusk to midnight hours and moves also equatorward with increasing magnetic activity. For example, by investigating the temporal and spatial variations of MIT during the geomagnetic storm on 4 April 2017, Shinbori et al. (2018) found that the trough minimum location moves equatorward from 60° to 48° in geomagnetic latitude (MLAT) within 4 hr after the

storm sudden commencement and later moves poleward back to the quiet time location during storm recovery phase. Liu et al. (2015) used the CHAMP (CHALLENGING Minisatellite Payload) electron density measurements (2000–2009) to investigate the position of the trough minimum, and they found a significant longitudinal dependence of the trough minimum around midnight under geomagnetic quiet condition. Yang et al. (2018) further statistically analyzed the longitudinal variation of MIT position in both northern (near 1900 MLT) and southern hemispheres (near 2100 MLT), based on the in situ ion density measurements from the DMSF (Defense Meteorological Satellite Program) satellites during 1996–2016. Their results showed significant difference in the longitudinal variation of the trough position between two hemispheres during premidnight hours. He et al. (2011) also found that at midnight, the longitudinally deepest trough occurs to the west of the geomagnetic pole in both the Northern and Southern Hemispheres during the equinoxes and local summer, which could be ascribable to the enhanced depletion caused by horizontal neutral wind.

In addition to the observations, empirical models have been proposed to predict the location of trough minimum (Collis & Häggström, 1988; Deminov et al., 1996; Werner & Prölss, 1997). For example, Zou et al. (2011) combined GPS (Global Position System) vertical total electron content (VTEC) and other complementary instruments, such as the Poker Flat incoherent scatter radar and all-sky images, to investigate the dynamics of the midlatitude trough during substorms within solar minimum condition. They suggested that comparing to global Kp and AE indices, a local index, such as the local AL index, is better for parameterizing the trough location at a given longitudinal meridian.

As mentioned above, previous studies related to MIT focused mainly on the dynamics of MIT minimum, while few studies have been done on the evolution of equatorward/poleward MIT walls. Some earlier results showed that the poleward wall is steeper than the equatorward wall (e.g., Jones et al., 1997; Kersley et al., 1997), but there are also results showed that the equatorward wall is steeper than the poleward wall in the afternoon/evening sector (Prölss, 2007; Voiculescu et al., 2010). In addition, Voiculescu et al. (2006) reported that the trough width shows a prominent diurnal variation and it depends on the seasons; for example, the MIT observed in winter is generally broader than that in summer. Rodger (2008) pointed out that the prediction of the trough shape and dynamics for individual events, namely, the “trough weather,” remains unsolved. Therefore, better understanding of the shape evolution of MIT is important for future empirical modeling and prediction.

In this paper, we used nearly 10-year in situ electron density measurements from the CHAMP satellite, to investigate the MLT evolution of equatorward/poleward walls of MIT during geomagnetic quiet periods. In section 2, we briefly describe the CHAMP mission and its electron density measurements and then introduce the method for identifying the MIT. In section 3, the MLT evolution of equatorward/poleward wall of MIT is shown. Section 4 provides the relevant discussions with previous studies as well as possible explanations of our results. Summary is finally given in section 5.

2. Data and Methods

2.1. The CHAMP Satellite

The CHAMP satellite was launched on 15 July 2000 and reentered the Earth's atmosphere on 19 September 2010. It flew on an almost circular, near-polar (inclination: 87°) orbit with an initial altitude of 450 km, and finally dropped to below 300 km at the end of the mission. The orbit of CHAMP drifted slowly in local time (LT) and needed about 131 days to cover all the 24 hr LT. The onboard Planar Langmuir Probe (PLP) took measurements of the electron density with a time resolution of 15 s. The PLP readings have been validated by comparison against the ground-based ionograms at Jicamarca (McNamara et al., 2007).

Figure 1 shows the daily variation of CHAMP altitude when its orbit crossing $\pm 60^\circ$ MLAT separately in Northern (blue) and Southern (red) Hemispheres. The CHAMP decreases from about 470 to 300 km during its mission period, and its altitude at -60° MLAT is slightly higher (by about 20 km) than that at 60° MLAT.

2.2. Approach to Identifying the MIT

There is no agreed quantitative definition of a MIT (Prölss, 2007; Rodger, 2008), as sometimes it is difficult to identify the individual midlatitude trough from kinds of depletion structures extending along latitude, such as high-latitude trough and wave-like disturbances. In this paper, we propose a method to determine the

Figure 1. Daily variations of CHAMP satellite altitude at about 60° MLAT in Northern (blue line) and Southern (red line) Hemisphere.

inside two walls and define L_n as the position of the first $|R_l|$ minimum on the outside of L_x . The region between L_x and L_n is the transition area of an exterior wall. In other words, L_x is always inside the wall, and L_n is outside the wall, so the L_b (exterior boundary of the wall) must be between L_n and L_x . For both equatorward and poleward walls, the mean latitude of the L_x and L_n is used to define the position of trough boundary (L_b). From our experience, this method is applicable for both the ascending and descending high-latitude orbital arcs of CHAMP.

Based on statistics, we limit the trough minimum position between 40° and 75° MLAT to reduce the influences from the depletion structures occurring at middle latitudes or in polar cap region. Finally, we use the relative depletion depth (D_R) to exclude the trough event of very shallow variation within the electron density profile. The D_R is defined as

$$D_R = \left[(N_{e_{\text{boundary}}} - N_{e_{\text{min}}}) / N_{e_{\text{boundary}}} \right] \times 100\% \quad (1)$$

Here, only the orbital arc with D_R greater than 40% on both sides is considered as a valid MIT event. The value of 40% is an empirical value, as it is really difficult to distinguish the real MIT from other wave-like perturbation structures if D_R is below 40%.

Figure 2. An example of the midlatitude trough automatically detected from the CHAMP PLP measurements on 20 February 2001. The black and blue lines are the electron density profile and the $|R_l|$ profiles, respectively. The black solid circles marked on the electron density profile are the trough boundaries and minimum. W_e and W_p are trough equatorward and poleward wall width, respectively.

We applied the above-mentioned approach to each high-latitude orbital arc of CHAMP PLP measurements and finally identified 33,695 MIT events from 2000 to 2009. Among which 17,893 troughs occur at nighttime (1800–0600 MLT) under geomagnetic quiet conditions ($Kp \leq 3$), and these events are used for our rest statistical analysis. The condition $Kp \leq 3$ refers to the whole time of CHAMP flying over the MIT region. We want to point out that as we used the observations from CHAMP satellite, our statistical results below reveal the average distribution or evolution of ionospheric trough on MLAT versus MLT, rather than providing continuous observation in universal time (UT) at a fixed longitude for the ionospheric trough.

3. Results

Figure 3 presents the average shape of midlatitude trough at different MLT. The CHAMP electron density profiles on nightside with clear MIT structure detected are sorted into 12 groups of 1-hr bin from 1800 to 0600 MLT. For each CHAMP Ne profile with MIT structure detected, we first find the trough minimum and record its latitude and Ne value. Then for every MLT bin, we shift each Ne profile by align the latitude and Ne value of trough minimum. The black curves are the individual MIT events, and the red curves are the mean values of Ne derived from individual profiles. The blue circle marked on the red curve is the trough boundaries detected from the red curve by using the approach described in section 2.2.

The result shows that the midlatitude trough minimum moves rapidly from about 65° MLAT at 1800 MLT (Figure 3a) to about 59° MLAT at 0100 MLT (Figure 3h) but stays almost stationary afterwards (Figures 3h–3l). On average, the trough poleward wall keeps a very steep gradient throughout the nighttime, while the equatorward wall experiences a significant change, which shows a steep gradient from 1800 to about 2100 MLT and rapidly decays to a shallower gradient within 2 hr and then remains with the same gradient till dawn.

Figure 4 shows detailed MLT evolution of the latitudes separately for the trough minimum, the boundaries, and the widths of the two trough walls. We divide the nighttime into three sectors, (I) dusk sector (1800–2100 MLT); (II) premidnight sector (2100–0000 MLT); and (III) postmidnight sector (0000–0600 MLT). As seen from Figure 4a, the trough poleward boundary and trough minimum keep roughly the same expending speed in latitudinal extension throughout the whole night that move from $71^\circ/65^\circ$ MLAT at 1800 MLT to $64^\circ/59^\circ$ MLAT at 0100 MLT, and afterward no significant equatorward movement is observed. During dusk and postmidnight sectors, the trough equatorward boundary moves to lower latitude with almost the same speed as the other two quantities, but with a much faster speed in premidnight sector. As a result, in Figure 4b we find that the trough equatorward wall width keeps almost the same as poleward wall width in Sector I, with magnitudes of about 4.4° and 4.0° , respectively, while in Sector II, the equatorward width rapidly increases to 8.0° at 0000 MLT, but the poleward width slightly decrease to about 3.6° at 2300 MLT. In Sector III, the widths of both trough walls have no significant changes with respect to their values in Sector II, and the equatorward width is nearly twice the poleward width.

As shown in Figure 1, the CHAMP altitude has decreased from 470 to 300 km during the considered period; therefore, we have checked if the CHAMP altitude decay has influence on the MLT evolution of trough. We repeat the results of Figure 4 but further divide the trough events into three different bins according to CHAMP altitude: <350 , $350\text{--}400$, and >450 km, and the new results are shown in Figure 5. All the trough-related quantities show consistent MLT evolution for the three altitude bins, indicating that the CHAMP altitude decay has little influence on the MLT evolution of the trough positions. One slight difference is that the rapid equatorward movement of trough equatorward boundary and the obvious equatorward extension of trough equatorward wall at premidnight sector are more pronounced when CHAMP flew at lower altitude. However, it is difficult to tell if such slight difference is caused by the lower altitude of CHAMP or lower solar flux activity, as the solar flux gradually decreases with the decay of CHAMP altitude. Based on the analysis above, we have combined all the trough events and ignored the influence of altitude change of CHAMP in the rest of study.

Based on the electron densities of trough minimum and two boundaries, as well as widths of two trough walls, we define a relative depletion rate of electron density, R_s (percentage depletion per degree), to characterize the steepness of the trough walls:

Figure 3. All of the 17,893 nighttime (from 1800 to 0600 MLT) electron density profiles of CHAMP with midlatitude trough detected. Only events during geomagnetic quiet period ($Kp \leq 3$) are considered and the events are sorted into bins of 1-hr MLT. The black curves are the individual trough events. The red curves are the mean lines. The blue circle marked on the red curve is the trough boundaries calculated by using the red curve.

$$R_s = \frac{100 \times (Ne_b - Ne_m)/Ne_b}{Width_w}. \quad (2)$$

where Ne_b and Ne_m are the electron densities of equatorward/poleward trough boundary and minimum and $Width_w$ is the width of the corresponding trough wall. Figure 6 shows the MLT evolution about the electron densities of trough minimum and two boundaries, together with R_s of the two trough walls. It is clear shown that the Ne magnitudes of trough minimum and boundaries show no prominent MLT dependence (Figure 6a). The mean Ne of the trough equatorward boundary is about $12.4 \times 10^{10} \text{ m}^{-3}$, which is slightly larger than the mean Ne of the trough poleward boundary ($Ne_p = 11.6 \times 10^{10} \text{ m}^{-3}$). The two values are almost three times larger than Ne of trough minimum ($Ne_m = 3.4 \times 10^{10} \text{ m}^{-3}$). When taking these values into Equation 2, R_s is derived as roughly 1/width; therefore, Figure 6b is almost inverse proportional to the curves as shown in Figure 4b. In Sector I, R_s of trough equatorward wall is 15.2% per degree, which is slightly larger than that of poleward wall (with a value of 14.6% per degree). In Sector II, R_s of trough equatorward wall rapidly decreases from 15.2% per degree at 2000 MLT to 9.2% per degree at 2330 MLT, while R_s of trough poleward wall increases from 14.1% per degree at 1900

Figure 4. MLT evolution of (a) the locations of trough minimum and equatorward/poleward boundaries and (b) the width of two walls on both sides. For each quantity, the median values and median deviation (shown as error bar) are shown for each MLT bin.

MLT to its maximum of 19.0% per degree at 2300 MLT. In Sector III, R_s of trough poleward wall (15.9% per degree on average) keeps nearly twice of the trough equatorward wall (8.4% per degree on average). The result indicates that the steepness of the trough equatorward wall appears earlier than the trough poleward wall, starting at 2000 and 2300 MLT, respectively.

In the next, we have checked the seasonal dependence of the trough positions. The latitudes of trough minimum as well as equatorward/poleward boundaries during the considered period (2000–2009) are sorted into bins of month, to get their monthly mean values. The results are shown in Figure 7, separately for the Northern and Southern Hemispheres. We can clearly see that the trough positions are slightly located at higher latitude during equinoctial season (March, April, September, and October) than that in solstice seasons at both hemispheres. In addition, we have also checked the seasonal dependence for the width of trough equatorward/poleward wall, but no clear dependence can be found. This is understandable, as the trough minimum and equatorward/poleward wall have similar seasonal dependence. Therefore, we do not show the seasonal dependence for the width of trough walls here.

4. Discussion

In this study, we analyze the MLT evolution of the nighttime (1800–0600 MLT) midlatitude trough under geomagnetic quiet conditions ($Kp \leq 3$) from two perspectives: trough positions (the minimum and two boundaries) and trough shapes (two walls, including the width and steepness). As shown in Figures 3 and 4a, the trough minimum moves significantly to lower latitudes in the dusk and premidnight sectors, while stays almost at the same latitude in the postmidnight hours, and then slightly moves back to higher latitudes near dawn. Such dynamic of the nighttime midlatitude trough minimum is consistent with previous reports

Figure 5. The MLT evolution of trough minimum and both boundaries (a–c) and the MLT evolution of two trough wall widths (d–f). The events are divided into three different altitude ranges: (a and d) <350 km, (b and e) 350–400 km, and (c and f) >400 km.

(Spiro et al., 1978; Voiculescu et al., 2006; Werner & Prölss, 1997). In addition, our results show also several interesting features about the evolution of trough shapes.

4.1. The Trough Poleward Wall

We find that the trough poleward boundary moves almost synchronously with the trough minimum throughout the whole night hours. Previous studies indicated that the position of trough minimum at night is located approximately 1–2° poleward of the convection boundary (Collis & Häggström, 1988; Rodger et al., 1992). Thus, both of the trough minimum and poleward boundary are located in the convection region. The high-latitude plasma convection is primarily driven by the magnetic reconnection process (Dungey, 1961). For southward interplanetary magnetic field (IMF) condition, it causes a dawn-dusk directed E-field in the polar cap region and a dusk-dawn directed E-field at the auroral region. As a result they excite a two-cell convection pattern of the plasma zonal flow velocities at the high latitude. It is widely accepted that the high-latitude plasma convection together with midlatitude corotation is the primarily account for the formation of midlatitude trough (Rodger, 2008, and references therein). In addition, the convective dayside plasma are demonstrated to be the major cause of the trough poleward wall (Foster et al., 2005; Rodger, 2008). Therefore, in this study we also suggest that the dynamical behaviors of the trough minimum and poleward boundary are mainly controlled by the plasma convection. Consequently, the width and steepness of the trough poleward wall show no obvious changes throughout the night as shown in Figures 3b and 5b.

4.2. The Equatorward Wall

The evolution of the trough equatorward wall is much more complicated. It shows different evolution features in different time sectors. Two interesting features are found here: (i) It experiences an obvious equatorward extension in the premidnight sector; (ii) its steepness is comparable with the poleward wall in the dusk sector.

Figure 6. The MLT evolution of (a) the electron densities of trough minimum and both boundaries and (b) the relative depletion rate of both trough walls.

Figure 7. Multiyear monthly mean values of trough positions in the Northern (a) and Southern (b) Hemispheres.

4.2.1. Premidnight Sector

The equatorward extension of the trough equatorward wall in the premidnight sector is an very important process in reshaping the midlatitude trough, as it causes the steepness of the trough equatorward wall to reduce almost by 50% (as shown in Figure 5b). The meridional plasma drift induced by horizontal neutral winds and plasma motion perpendicular to the magnetic field induced by the zonal electric fields are the two possible processes that may affect the MLT evolution of the trough equatorward wall. The horizontal neutral winds arise from the dayside heating and nightside cooling of the upper atmosphere. The winds can greatly influence the topside ionosphere by driving the F layer plasma upward or downward along the Earth's magnetic field line (Rishbeth & Kelley, 1971). According to the discussion in section 4.1, the trough equatorward wall is probably located in the low-speed corotating zone, while the trough minimum and poleward wall are located in the convective zone. On the other hand, statistical results show that the zonal electric field decreases rapidly at lower latitude of midlatitude regions (usually less than 0.2 mV/m at about 50° MLAT) (Earle & Kelley, 1987; Lukianova & Christiansen, 2006; Rothwell & Jasperse, 2006; Wand & Evans, 1981). So we suggest that the neutral winds are probably responsible for the dynamic and morphology evolution of the trough equatorward wall and the impact of the zonal electric field is negligible.

At the F layer altitude, the drift velocity of the ionospheric plasma along the magnetic field is defined as

$$V_{//} = U \cdot \cos(\theta - D) \cdot \cos I = (U_m \cdot \cos D + U_z \cdot \sin D) \cdot \cos I \quad (3)$$

where U is the total speed of horizontal wind, U_m is the meridian wind speed, U_z is the zonal wind speed, D is the magnetic declination, and I is the magnetic inclination (He et al., 2011; Rishbeth & Kelley, 1971). Thus, the magnetic north-south component of this drift is

$$V_x = V_{//} \cdot \cos I = U_m \cdot \cos D \cdot \cos^2 I + U_z \cdot \sin D \cdot \cos^2 I \quad (4)$$

Note that V_x increases as I decreases and I decreases as latitude decreases. The positive/negative V_x means that the plasma drifts toward equatorward/poleward, respectively, and this definition applies suitable in both hemispheres.

In order to quantify the influence of neutral wind, we apply the updated horizontal wind model (HWM-14) (Drob et al., 2015) to calculate the meridional and zonal components of neutral wind. Figure 8 shows the MLAT versus MLT distribution of V_x . The result is calculated on a scale of 0.5 hr (MLT) $\times$ 5° (MLAT). It is note that we have used the seasonal (in the solstices and equinoxes) and longitudinal mean values (a step of 15° in longitude) of t neutral wind estimated from the HWM14 model. It clearly shows that from subauroral to low latitudes the ionosphere plasma moves toward equator in both Northern and Southern Hemispheres, showing maximal amplitudes around $\pm 20^\circ$ MLAT during 2100–0100 MLT. In the dusk sector, V_x generally at trough latitudes shows small value within ± 5 m/s. The result of modeled meridional plasma movement induced by neutral wind is in good agreement with the observed movement of midlatitude trough as shown in our Figure 4a, supporting our conclusion that the F region neutral wind is the primary driver to cause the equatorward extension of trough equatorward wall.

For more detailed comparison, we further calculate the V_x corresponding to each MLT bin in Figure 4a, and the velocity differences (ΔV_x) among the three trough positions. The MLT variations of V_x and ΔV_x are shown in Figures 9c and 9d, respectively. For convenience we repeat Figures 4a and 4b here as Figures 9a and 9b. From Figure 9c we can see that the V_x of trough equatorward boundary shows largest equatorward magnitude and the V_x of trough poleward boundary is the smallest. From 2100 MLT, V_x of trough equatorward boundary increases obviously faster than that of trough minimum and poleward boundary (see the yellow-dashed MLT hours in Figures 9a and 9c). Figure 9d shows that the ΔV_x between trough poleward boundary and trough minimum is generally small (with mean values of about 1 m/s) but the ΔV_x between trough equatorward boundary and trough minimum increases quickly from 2100 to 0100 MLT. This explains well the rapid expansion of the trough equatorward wall width in the premidnight sector as shown in the yellow-dashed MLT hours of the Figure 9b.

In addition, the vertical movement of plasma should also have influence on the trough shapes, since it causes the plasma move to higher or lower altitude and the plasma recombination rate changes with altitude. According to Equation 3, the plasma vertical drift component is expressed by

Figure 8. The MLAT versus MLT distribution of V_x calculated from the Horizontal Wind Model (HWM-14) in 2004, $A_p = 0$, altitude = 350 km. The positive/negative V_x means that the plasma drifts toward equatorward/poleward, respectively.

Figure 9. The MLT variations of (a) trough positions and (b) trough widths (same as Figures 4a and 4b) and MLT variations of (c) V_x and (d) ΔV_x . For the equatorward wall ΔV_x is defined as V_{x_e} minus V_{x_m} , and for the poleward wall ΔV_x is defined as V_{x_m} minus V_{x_p} .

Figure 10. (a) MLAT-MLT distribution of V_z calculated from the Horizontal Wind Model (HWM-14) in 2004, $A_p = 0$, altitude = 350 km. Positive V_z directs upward; (b) MLT variation of R_s of both trough walls (same as Figure 4b); (c) MLT variations of ΔV_x (blue line) and ΔV_z (red line). For the equatorward wall ΔV_z is equal to V_{z_e} minus V_{z_m} , for the poleward wall ΔV_z is equal to V_{z_m} minus V_{z_p} .

$$V_z = V_{//} \cdot \cos I = (U_m \cdot \cos D + U_z \cdot \sin D) \cdot \cos I \cdot \sin I. \quad (5)$$

Figure 10a shows the MLAT versus MLT distribution of V_z , using the same method as described in Figure 8. It can be seen that the plasma vertical drift pattern is very similar to the V_x . The V_z is almost always upward during the night in both Northern and Southern Hemispheres, and its magnitude increases from subauroral to low latitudes with peak value around $\pm 25^\circ$ MLAT during 2100–0100 MLT. Note that the plasma recombination rate decreases with increasing height; thus, an upward V_z will reduce the steepness of the trough wall. Here we repeat Figure 4b as Figure 10b, and the MLT variations of ΔV_x (same as Figure 9d) and ΔV_z are shown in Figure 10c. It can be found that not only ΔV_x but also ΔV_z between trough equatorward boundary and trough minimum increase rapidly in the premidnight sector. According to Equation 2, both of the two processes will make the R_s of the trough equatorward wall become smaller (see the yellow-dashed MLT hours in Figure 10b).

4.2.2. Dusk Sector

Considering there are no ionization sources of plasma in the trough equatorward wall during nighttime, it is generally accepted that the poleward wall is usually steeper than the equatorward wall (Jones et al., 1997; Kersley et al., 1997; Moffett & Quegan, 1983). However, our results show in the statistical sense that the equatorward wall is as steep as the poleward wall at dusk hours. Prölss (2007) and Voiculescu et al. (2010) have also reported similar feature, but the MLT evolution of such feature throughout the night and the possible causes remain unclear.

From Figures 8–10 we can see that all of the V_x , V_z , ΔV_x , and ΔV_z gradually increase with MLT in the dusk sector, but their absolute magnitudes values are quite small. As a result we see that the three trough positions move approximately synchronously during this local time sector. The steepness of trough equatorward wall keeps also as the same as that of trough poleward wall in dusk sector.

According to Equations 3 and 4, V_x and V_z induced by U_z can be positive or negative, depending not only on U_z but also on the magnetic declination, D . Both V_x and V_z are consistent with U_z when D is positive and are opposite to U_z when D is negative. Previous studies indicated that U_z reaches its eastward and westward maximum in the dusk and dawn, respectively, while U_m reaches its equatorward maximum near midnight. Conversely, U_z reaches minimum near midnight while U_m reaches minimum in the dusk and dawn (Emmert et al., 2003, 2006; Titheridge, 1995). This may result in some longitudinal and hemispheric differences about the trough shape in dusk sector.

Below, we show the variation of differences of widths and R_s between equatorward wall and poleward wall with dependence on the magnetic declination for dusk sector (1800–2100 MLT). ΔWidth and ΔR_s are defined as $\Delta \text{Width} = \text{Width}_e - \text{Width}_p$ and $\Delta R_s = R_{se} - R_{sp}$. Here the subscript “e” represents trough equatorward wall, “p” represents trough poleward wall, and D is taken with a step of 5° . From Figure 11b we see that

Figure 11. The declination dependence of the difference in width (red lines) and R_s (blue lines) between trough equatorward wall and poleward wall in Northern (a) and Southern (b) Hemispheres, respectively.

for $D > 30^\circ$, the Width_e is larger than Width_p and R_{se} is smaller than R_{sp} . This is because the eastward U_z usually causes equatorward and upward plasma movement in Southern Hemisphere when $D > 0$. On the contrary, an eastward U_z will cause poleward and downward plasma movement when $D < 0$ in the Southern Hemisphere, so the ΔWidth in $D < 0$ region is smaller than that in $D > 0$ region (sometimes, the Width_e is even slightly smaller than Width_p), and the ΔR_s in $D < 0$ region is larger than that in $D > 0$ region (sometimes, the R_{se} is slightly larger than R_{sp}). However, the difference in Northern Hemisphere is very weak, because the $|D|$ is generally smaller than 30° at Northern Hemisphere middle latitudes. Therefore, the contributions from $\sin(D)$ in Equations 3 and 4 are relatively small. Nevertheless, it can be seen from Figure 11a that the Width_e is smaller than Width_p in Northern Hemisphere $D > 0$ regions, as the eastward U_z causes poleward plasma movement under the same conditions.

Overall, the declination (or longitudinal) dependence is more prominent at regions of $D < 0$ in the Southern Hemisphere. Due to smaller value of $|D|$ in the Northern Hemisphere, the longitudinal dependence of the trough shapes in Northern Hemisphere is much weaker.

5. Conclusions

In this study, we have used the CHAMP in situ electron density measurements from 2000 to 2009, to investigate the detailed morphological evolution of nighttime midlatitude trough during geomagnetic quiet periods. Some remarkable features are summarized as below:

1. The midlatitude trough minimum and two boundaries all move equatorward from dusk toward later MLT, more prominent from the dusk to premidnight sector. The trough equatorward wall experiences an obvious equatorward extension in the premidnight sector.
2. In the dusk sector, the trough equatorward wall is as steep as the poleward wall. This feature is more pronounced at the $D < 0$ region in the Southern Hemisphere.
3. The trough poleward boundary moves almost synchronously with the trough minimum throughout the whole night hours. Consequently, the width and steepness of the trough poleward wall show no obvious change with MLT.
4. The R_s of the trough equatorward wall reduces almost by 50% in the premidnight sector, while R_s of the trough poleward wall gradually increases to its maximum around 2300 MLT. Consequently, R_s of trough poleward wall keeps almost twice the value of trough equatorward wall from midnight to dawn.

5. The trough positions are slightly located at higher latitude during equinoctial season than that in solstice seasons at both hemispheres.

Finally, we hypothesized that the rapidly expanding of the trough equatorward wall in premidnight sector may result in disturbances in the trough minimum region, such as multimima or wave-like structures. Further researches are encouraged for addressing this point.

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