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Seasonal dependence of the longitudinal variations of nighttime ionospheric electron density and equivalent winds at southern midlatitudes

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Abstract. It has been indicated that the observed Weddell Sea anomaly (WSA) appeared to be an extreme manifestation of the longitudinal variations in the Southern Hemisphere, since the WSA is characterized by greater evening electron density than the daytime density in the region near the Weddell Sea. In the present study, the longitudinal variations of the nighttime F2-layer peak electron density at southern midlatitudes are analyzed using the observations of the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) satellites between 2006 and 2008. It is found that significant longitudinal difference (> 150 %) relative to the minimum density at each local time prevails in all seasons, although the WSA phenomenon is only evident in summer under this solar minimum condition. Another interesting feature is that in summer, the maximum longitudinal differences occur around midnight (∼ 23:00–00:00 LT) rather than in the evening (19:00–21:00 LT) in the evening, when the most prominent electron density enhancement occurs for the WSA phenomenon. Thus the seasonal–local time patterns of the electron density longitudinal variations during nighttime at southern midlatitudes cannot be simply explained in terms of the WSA. Meanwhile, the variations of the geomagnetic configuration and the equivalent magnetic meridional winds/upward plasma drifts are analyzed to explore their contributions to the longitudinal variations of the nighttime electron density. The maximum longitudinal differences are associated with the strongest wind-induced vertical plasma drifts after 21:00 LT in the Western Hemisphere. Besides the magnetic declination–zonal wind effects, the geographic meridional winds and the magnetic inclination also have significant effects on the upward plasma drifts and the resultant electron density.

Keywords. Ionosphere (Mid-latitude ionosphere)

1 Introduction

In the Southern Hemisphere, significant longitudinal variations of the ionospheric electron density occurred at midlatitudes in evening due to the Weddell Sea anomaly (WSA). The intensively reported Weddell Sea anomaly is a diurnal cycle anomaly that is characterized by greater nighttime density than daytime density in the ionosphere instead of a typical diurnal cycle with a midday maximum and a midnight minimum (e.g., Liu et al., 2010). The WSA phenomenon has recently attracted wide attention in the community. Similar but much weaker summer evening enhancements also occur in the North American sector and East Asian sector (Lin et al., 2009, 2010), known as midlatitude summer nighttime anomaly (MSNA). Several mechanisms are applied to explain these interesting phenomena, including the equatorward neutral wind, electric field, photoionization and the downward plasma diffusion from the plasmasphere (Burns et al., 2008, 2011; Jee et al., 2009; He et al., 2009; Chen et al., 2011, 2012; Liu et al., 2010; Lin et al., 2009; Zhang et al., 2011, 2012a, b; Zhao et al., 2013). Among those explanations, the magnetic configuration and the neutral winds are considered as important and even major contributors. The magnetic meridional winds can drag the charged particles moving along the magnetic field line, which will push the plasma up (down) when the winds are equatorward (poleward). The resultant height change of the plasma has a further impact on plasma density through changing the electron recombination, which decays exponentially with the increase of altitude.

The observed WSA has been indicated as an extreme manifestation of the longitudinal variations (Jee et al., 2009). It can occur at wide latitudinal locations ($\sim$ 30–70° S) in summer in the Southern Hemisphere, and the strongest summer evening enhancement of F2-layer peak density occurs centered around 50–60° S, 90° W at midlatitudes (He et al., 2009; Lin et al., 2010; Liu et al., 2011; Burns et al., 2011). In recent years, longitudinal differences of electron density, or the density longitudinal asymmetries, have been studied over east–west regions of the continental US and the Far East area at northern midlatitudes (Zhang et al., 2011, 2012a, b; Zhao et al., 2013). In both the northeast of East Asia and the continental US, the electron density diurnal variations show some similarity to the WSA in summer (Lin et al., 2009; Lin et al., 2010). Interestingly, Zhang et al. (2011, 2012a, b) showed that in the North American sector, the most significant longitudinal difference occurs during nighttime in winter and the solar minimum, which is possibly associated with the strongest nighttime zonal winds. Their results present a vital contribution of the zonal wind to electron density longitudinal variations under special magnetic configuration, i.e., a magnetic declination change between westward (negative) and eastward (positive) at midlatitudes. These magnetic declination–zonal wind effects favor more equatorward magnetic meridional wind and thus the resultant upward plasma drift in eastern and northern US coast, when the zonal wind is eastward at night. Zhang et al. (2012b) found good correlation between the longitudinal variation of the ionospheric electron density (Ne) from ISR and the zonal wind from FPI at Millstone Hill (42.5° N, 288.6° E). Zhao et al. (2013) examined the climatology of peak electron density (NmF2) in the Far East regions, and provided evidence of the longitudinal density change further supporting the thermospheric zonal wind mechanism.

For a long time there have been too few wind observations to examine the wind effects on ionospheric density. Except for the study from Zhang et al. (2012b), the neutral winds analyzed in previous studies were either given by an artificial value or were from an empirical model (e.g., Jee et al., 2009; Liu et al., 2010; Chen et al., 2012; Zhao et al., 2013). Also, the effects of magnetic inclination and geographic meridional winds are seldom discussed. Although the magnetic meridional winds result from both the geographic meridional and zonal winds, Zhang et al. (2012b) assumed insignificant effects of the geographic meridional winds for the North American sector. In addition, the wind-induced vertical drifts of plasma are modulated by the magnetic inclinations. He et al. (2009) compared the variations of the F2-layer peak electron density and peak height with the magnetic declination and inclination angles, indicating contributions from the magnetic inclination in the Southern Hemispheres as well. It is expected that a similar positive magnetic declination–zonal wind effect on electron density will occur in the Southern Hemisphere at locations where the magnetic declination is eastward (positive). In the southern midlatitudes, the geomagnetic configurations are more longitudinally asymmetric than in the northern latitudes, and thus it is interesting to further examine the electron density longitudinal variations and the roles of neutral winds. Further, at southern midlatitudes, most studies have focused on local time evolution of the electron density in regions where the WSA phenomenon occurs, whereas little attention has been given to the quantitative comparison of the electron density longitudinal patterns for given local times.

This study will carry out a quantitative study on the longitudinal variations of the F2-layer peak electron density in the southern midlatitudes in order to examine the linkage of these variations with the magnetic configuration (both the declination and inclination) and the simultaneous magnetic meridional winds and wind-induced vertical plasma drifts. The global ionospheric F2-layer peak density retrieved from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) satellites' measurements will be used in this study. The corresponding magnetic meridional winds will be derived from a servo model on the basis of the observed F2-layer peak density and peak height (e.g., Luan and Solomon, 2008).

2 Database and analysis method

The electron density profiles retrieved from all COSMIC satellites (Lei et al., 2007; Schreiner et al., 2007) were collected over a period of about two years (April 2006–February 2008), a period that corresponded to solar minimum conditions. Then the F2-layer peak height (hmF2) and peak density (NmF2) were calculated from each profile. These data were divided into three seasons, i.e. equinox, summer and winter. For each season, data within $\pm$45 day from either solstice or equinoctial day were collected. Then the data were binned in the grid within 5° in latitude, 20° in longitude in the geographic coordinate, and within 1 h in local time. The median data in each season and each grid were used for final analysis. At each instance of local time, the longitudinal difference ratio of the electron density is calculated by the format of $r = (\mathrm{Ne} - \mathrm{Ne}_{\mathrm{min}})/\mathrm{Ne}_{\mathrm{min}} \cdot 100\,\%$ along geographic longitudes, where $\mathrm{Ne}_{\mathrm{min}}$ represents the minimum NmF2 among all longitudes.

Using the median F2-layer peak height and peak density, the simultaneous meridional winds along the magnetic meridian are then derived using a servo model (Rishbeth, 1967; Rishbeth et al., 1978) in each location of data binned. The servo method and similar techniques are based on a nearly proportional relationship between the winds and the variation of the F2-layer peak height (Rishbeth, 1967; Rishbeth et al., 1978; Buonsanto et al., 1989, 1997; Miller et al., 1997; Liu et al., 2003). For the servo model, a balance height is assumed to be established in the F2-layer due to chemical loss and plasma diffusion in the absence of any applied drifts induced by neutral winds and electric fields. The true F2 peak height results from the applied drifts on the balance height. In our calculations, ion and electron temperatures are obtained from the empirical IRI-2001 model (Bilitza, 2001), and the neutral density and temperature from MSISE00 model (Picone et al., 2002). Among all the input parameters to calculate the meridional winds, the hmF2 and ion-neutral collision frequency are the most important ones. A detailed description of the calculation method is given by Luan and Solomon (2008).

This kind of method has been found to present a good climatology of the magnetic meridional winds (e.g., Liu et al., 2003; Luan and Solomon, 2008) as compared to ISR and FPI observations, especially during nighttime. The servo wind includes both the contribution from neutral winds and that from electric field drifts. The pure neutral wind effects can be estimated at magnetic midlatitudes, where the effect of north-perpendicular $\boldsymbol{E} \times \boldsymbol{B}$ drift ($V_{\perp N}$) can be ignored under conditions without large geomagnetic disturbances (Luan and Solomon, 2008, and references therein).

In this study, we consider the effects from both the magnetic declination and inclination on neutral winds and the electron density. The magnetic meridional winds (U_M, referred to as meridional winds in the following) are contributed by the geographic meridional winds (V_{GM}, equatorward positive), the geographic zonal winds (U_{GZ}, eastward positive), and the magnetic declination angle (D), as expressed by Eq. (1):

$$U_M = V_{GM}\cos(D) \pm U_{GZ}\sin(D), \quad (1)$$

where the signs "$-$" and "$+$" correspond to winds in the Northern and Southern Hemisphere, respectively. The eastward declination is positive and the westward declination is negative.

The projection of the magnetic meridional winds on the magnetic field line is the one that works to pull down or lift up the plasma. Thus the vertical drifts (W) of the plasma, which are produced by neutral winds, are modulated by the absolute magnetic inclination angle (I), which can be expressed as follows:

$$W = U_M \cdot \cos(I) \cdot \sin(I) = V_{GM} \cdot f_{meri} + U_{GZ} \cdot f_{zon}, \quad (2)$$

where we define $f_{meri} = \cos(D) \cdot \cos(I) \cdot \sin(I)$ and $f_{zon} = \pm\sin(D) \cdot \cos(I) \cdot \sin(I)$, which represent the modulation coefficients of the geographic meridional and zonal winds on the vertical plasma drifts, respectively. In the Southern Hemisphere, $f_{zon} = \sin(D) \cdot \cos(I) \cdot \sin(I)$. These two factors are determined by the geomagnetic declination and inclination. To some extent, these two factors represent the contribution rates of the geographic meridional and zonal winds to the vertical drifts of plasma. The International Geomagnetic Reference Field (IGRF) model is used to calculate the geomagnetic field (Maus et al., 2005).

3 Results

Figure 1 shows longitudinal variations of the F2-layer peak electron density between 18:00 and 03:00 LT during local equinox, summer and winter at 40° S. The percentage difference of the electron density relative to the minimum one along longitude for each local time is shown in Fig. 1b. Figure 1 also presents the corresponding magnetic declination and the contribution rates of the geographic meridional (f_{meri}) and zonal (f_{zon}) winds to vertical plasma drifts. These rates are functions of the magnetic declination and inclination angles. As shown in Fig. 1a, electron density is generally higher in western longitudes than in eastern longitudes. The higher electron density occurs roughly in the longitudinal sectors where the magnetic declination is positive (eastward). In summer the WSA phenomenon occurs in the longitudinal sectors west of about 90° W and east of about 110° E. At these sectors, daily maximum electron density occurs in the evening after 18:00 LT rather than during the noon-to-afternoon hours for a diurnal circle, and the strongest enhancement of NmF2 occurs between 18:00 and 19:00 LT. After 19:00 LT the NmF2 decays continuously. No such evening enhancement is found during equinox and winter. During equinox a nighttime density enhancement occurs before midnight around 110° W.

As shown in Fig. 1b, a significant longitudinal difference ratio ($> \sim 100\,\%$) due to electron density enhancements occurs in all seasons in broad longitudes of Western Hemisphere, which is mostly under positive geomagnetic declination. The maximum longitudinal enhancement ratio is more than 250 % in summer and more than 150 % in winter. The peak equinoctial ratio is between the magnitudes in summer and winter. It is interesting that the maximum longitudinal enhancement ratio in summer occurs around midnight, i.e., between 23:00 and 02:00 LT. In the region where the WSA occurs, the maximum ratio occurs at around 23:00 LT, which is a few hours later than the occurrence of maximum density enhancement of the WSA phenomenon. During equinox, the peak longitudinal enhancement ratio occurs centered at around 23:00 LT. No evident relative longitudinal enhancement peak is present in winter.

Figure 2 presents results of the absolute (NmF2) and relative (r) electron density variations for 60° S in the same format as Fig. 1. The longitudinal–seasonal pattern of the highest density in the Western Hemisphere and in summer is generally similar to that at 40° S. At 60° S, the WSA phenomenon in summer is located at longitudes west of about 20° W and east of about 170° E. Its evening peaks are formed between 18:00 and 23:00 LT. The strongest enhancements

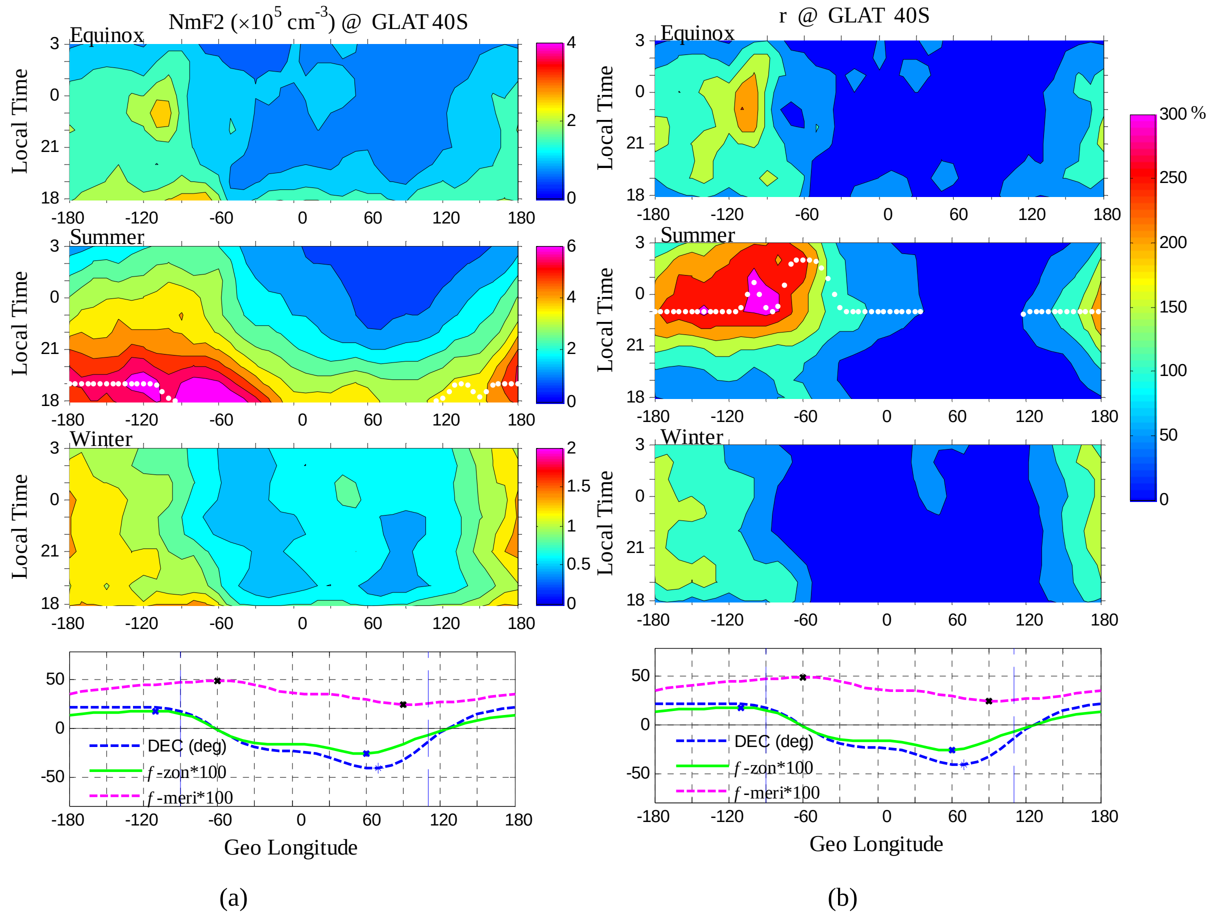

Fig. 1. The longitudinal variations of the absolute (NmF2, left) and relative (r, right) peak electron density (top three panels) between 18:00 and 03:00 LT at 40° S. The percentage difference $r = (\mathrm{Ne} - \mathrm{Ne}_{\mathrm{min}})/Ne_{\mathrm{min}} \cdot 100\,\%$ is calculated for each hour of local time. The bottom panels present the magnetic declination angle (DEC, eastward positive) and the contribution factor of f_{zon} (positive for eastward DEC) and f_{meri} (positive) for vertical plasma drifts from the geographic eastward zonal wind and equatorward meridional wind, respectively. The maximum and minimum locations of these factors are also marked. White dots (left) represent the occurrence time of the peak electron density of the WSA, and white dots (right) mark the maximum r value when it is larger than 50 %. In the bottom panels, blue dashed lines represent the edges of the longitudes where the WSA occurs at this particular latitude. Note that the electron density scales are different in different seasons. See the text for more detail.

occur around 21:00 LT within the 120 to 80° W sector. The electron density decays after its peak enhancements. The electron density during equinox shows obvious nighttime enhancement in western longitudes, which is similar to that at 40° S. At 60° S the major equinoctial enhancement area expands from about 130 to 90° W in longitudes as time passes. This enhancement lasts from 22:00 to 02:00 LT. In winter, a nighttime electron density enhancement occurs at 60° S around 100° W, while no such enhancement occurs at 40° S. Stronger maximum longitudinal enhancement ratio occurs at 60° S than at 40° S in each season. At 60° S, this ratio is more than 400 % in summer and more than 200 % in winter. The maximum longitudinal enhancement ratio in summer mostly occurs at around midnight, which is about 3 h later than the occurrence time of the maximum NmF2 enhancement of the WSA. In winter, a clear peak enhancement ratio occurs at ~22:00 LT at 60° S. During equinox, the peak longitudinal enhancement ratio is comparable to that in summer at 60° S.

At both 40 and 60° S, the longitudinal variations of the two rates f_{zon} and f_{meri} are different. Thus the maximum zonal and meridional wind contribution rates occur in different longitudinal locations, which could affect the longitudinal patterns of the electron density. At 40° S, the zonal and meridional winds will be major contributors to the vertical plasma drifts at ~110° W and 60° W, respectively, if they do not vary much along longitude. At 60° S, these two peaks are separated further away in longitudes, i.e., 110° W and 50° W for f_{zon} and f_{meri}, respectively. Further, at 60° S the peak of f_{meri} is sharper than that at 40° S. At both latitudes, a separation of the minimum f_{zon} and maximum western declination angle (DEC) occurs due to the geomagnetic inclination. This separation is also larger at 60° S than at 40° S. These

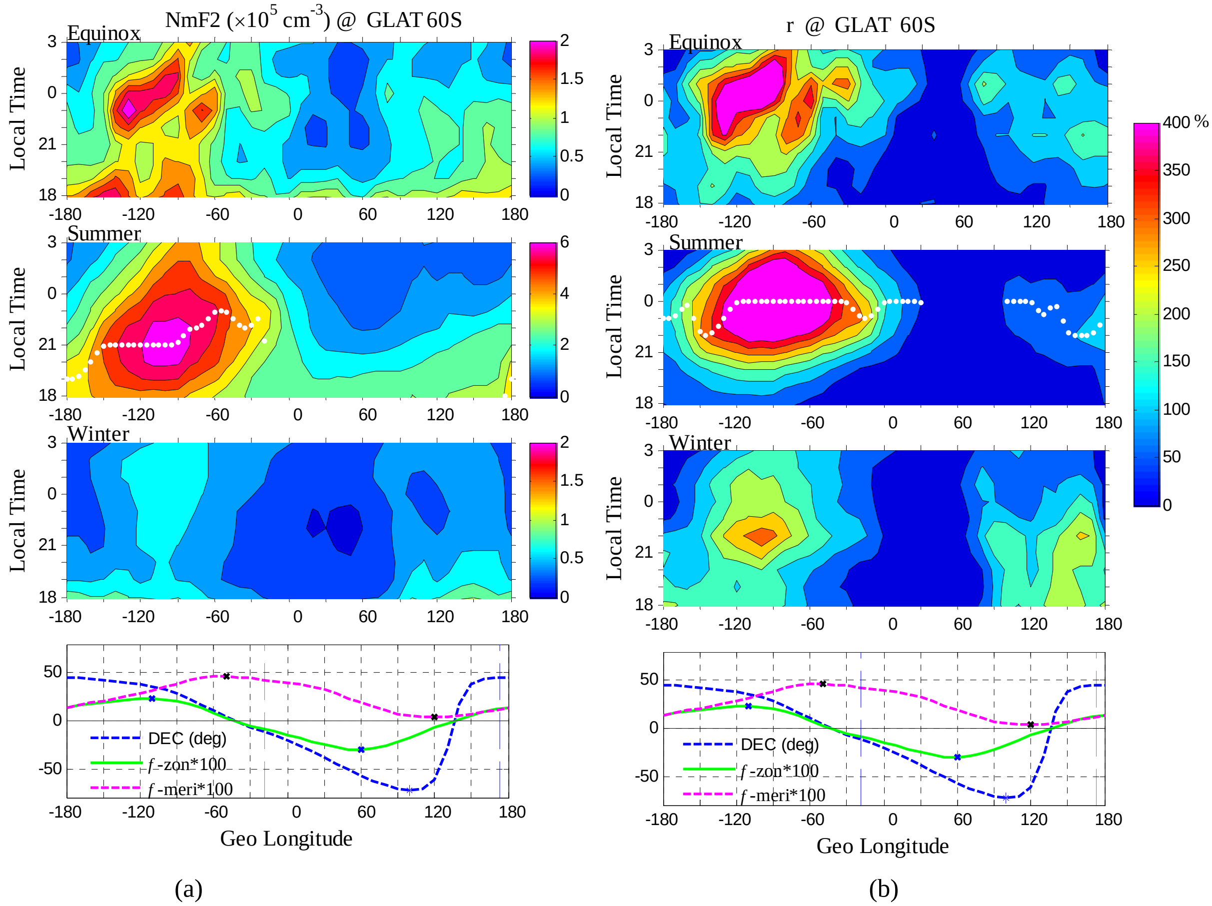

Fig. 2. Similar to Fig. 1 but for the longitudinal variations of the electron density at 60° S.

differences reveal stronger geomagnetic inclination effects at 60° S than at 40° S on the longitudinal patterns of the vertical drifts.

Figures 3 and 4 show the derived equivalent magnetic meridional winds (U_M, left-hand panels) from the servo method and their resultant vertical plasma drifts (W, right-hand panels) for all seasons at 40° S and 60° S, respectively. At 60° S only winds in the western sectors are available, since in other longitudinal sectors, the magnetic latitudes ($> 60°$) fall beyond the reliability of the servo method. The seasonal–longitudinal patterns are generally similar between the winds and drifts at each latitude, except for some small differences. At 40° S in summer and during equinox, stronger equatorward winds generally occur in the positive DEC sectors before midnight and in the negative DEC sectors after midnight. As a result, the maximum magnetic equatorward winds/upward drifts expand eastward from the evening to early morning hours in these two seasons. This may be due to the direction change of the geographic zonal wind from eastward to westward after midnight in the Southern Hemisphere, as predicted by the NCAR-TIEGCM model (Luan and Solomon, 2008). The magnitudes of the peak equatorward winds along longitudes are comparable during the evening and early morning hours. In winter the longitudinal-local time pattern presents the highest meridional winds between 21:00 and 03:00 LT and at around 180° W. For both latitudes, the strongest upward drifts ($> \sim 40\,\mathrm{m\,s^{-1}}$) occur during equinox, while longer duration of the relatively stronger upward drifts ($> \sim 30\,\mathrm{m\,s^{-1}}$) occurs in winter in the western sectors. In summer and during equinox, relatively stronger upward drifts start at around 21:00–22:00 LT and last a few hours in the western longitudes. These starting times of upward drifts are later than the occurrence times of the absolute maximum density, but are consistent with the occurrence of a larger relative density ratio along longitudes.

4 Discussion

4.1 The correlation between the variations of winds and electron density

At midlatitudes, the wind-induced plasma drifts have significant effects on the formation of the ionospheric F2 layer.

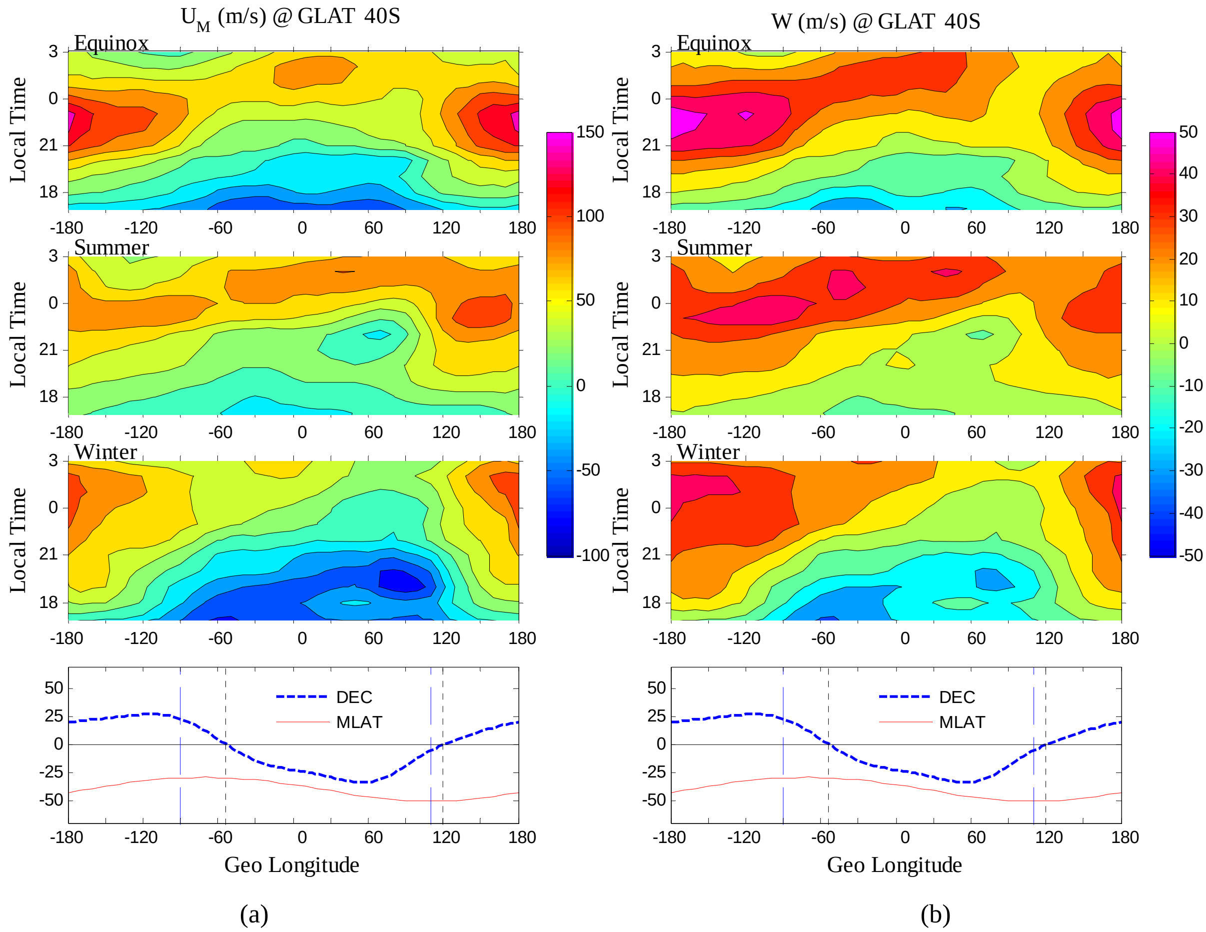

Fig. 3. The derived magnetic meridional winds (U_M, left) and the wind-induced vertical plasma drifts (W, right) for local equinox, summer and winter at 40° S. The magnetic declination angle is also shown. In the bottom panels, blue dashed lines represent the edges of the longitudes where the WSA occurs. The meridional winds are equatorward positive and the vertical drifts are upward positive.

Figures 1 and 2 show that larger absolute and relative electron density mostly occurs in the Western Hemisphere, where the DEC angles are positive (eastward). These patterns could be associated with the magnetic meridional wind and wind-induced plasma drift variations, which respectively exhibit more equatorward and upward components for positive DEC angles during the evening hours. These wind and density patterns are generally consistent with the zonal wind-magnetic declination effects, as studied in the North American and Far East regions (Zhang et al., 2012b; Zhao et al., 2013). However, the observed longitudinal patterns of the electron density should not be attributed to the winds and the wind-induced vertical plasma drifts alone. It is shown in summer and during equinox that the maximum–minimum locations of the equatorward winds or upward drifts along longitudes reverse at about 01:00 LT (Fig. 3), but no corresponding changes of the density patterns along longitudes are present after this time (Fig. 1). The ionospheric response between 03:00 and 06:00 LT remains the same as that before 03:00 LT (not shown). This disagreement might be related to the low background electron density in the evening and the lack of the ionization source in the negative DEC region after midnight. Disagreement between winds and density also occurs in their seasonal variation, since maximum upward drifts occur during equinox, while the strongest density enhancements occur in summer.

At 40° S and 60° S, the maximum absolute and relative densities are corresponding to the equatorward magnetic meridional winds. However, the longitudinal asymmetry in electron density is more severe around midnight than in the early evening in summer. This feature could be related to the local time variations of the magnetic equatorward winds, which are much stronger around midnight than in the early evening (Figs. 3 and 4). Also the longitudinal asymmetry of the magnetic meridional winds in the evening would contribute to the relative density peak during later hours, when a time delay between the winds and electron density is considered (Zhang et al., 2012b). Zhang et al. (2012b) showed that the density is most affected by winds occurring three hours

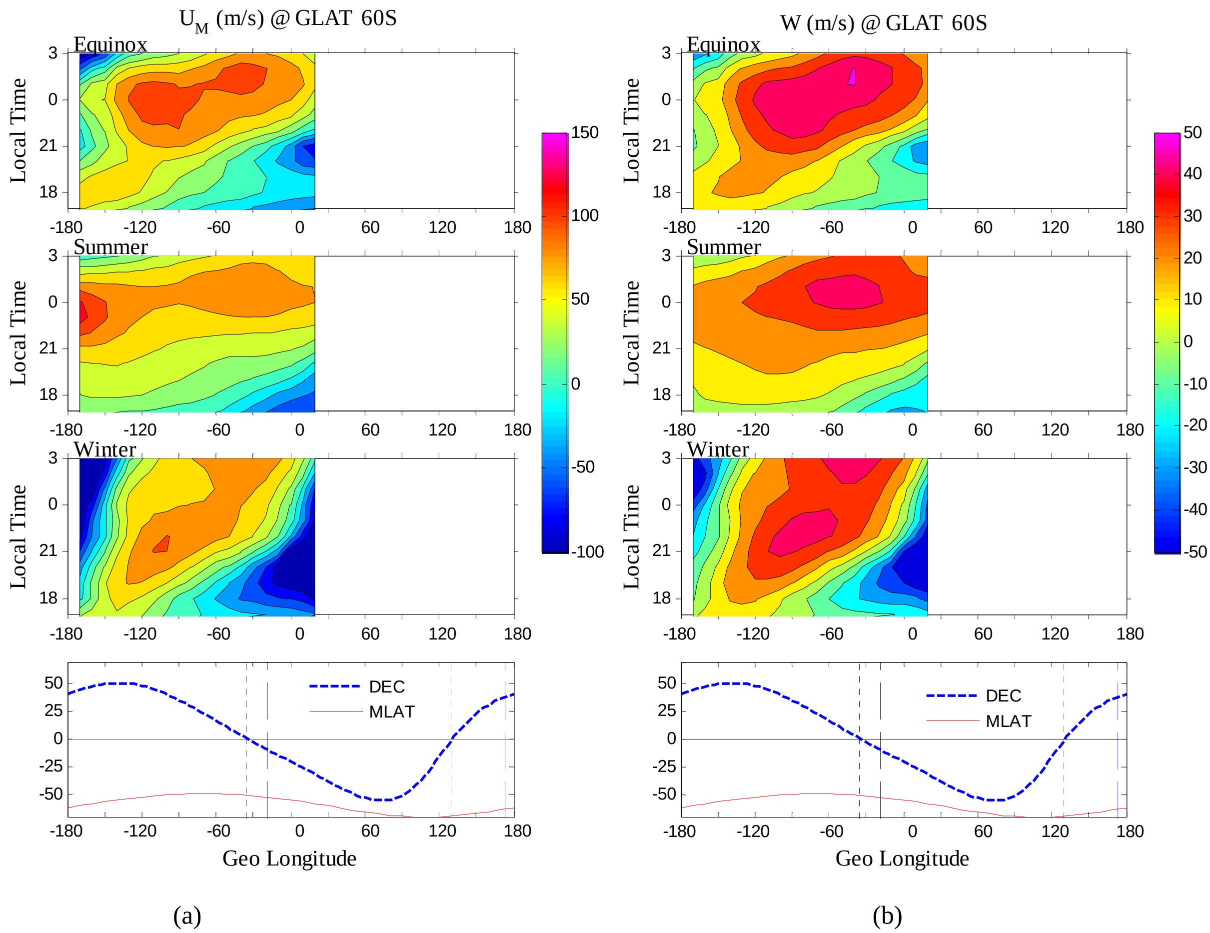

Fig. 4. Similar to Fig. 3 but at 60° S. Winds are absent at geomagnetic latitudes higher than 60° S, where they might be beyond the reliability of the servo method.

previously, although significant correlation occurs between the simultaneous winds and density.

Note that uncertainties in the derived winds/drifts from the servo method might occur, since we use the ion and neutral temperature and neutral density from the empirical models in the Southern Hemisphere for wind calculation. It was revealed that the magnetic meridional winds have shown good consistency with the NCAR-TIEGCM winds for their longitudinal–local time dependence at southern midlatitudes, especially during nighttime (Luan and Solomon, 2008). Thus the possible uncertainties should have no significant effects on the longitudinal patterns of winds/drifts.

4.2 The contribution of the geographic meridional winds

The geographic meridional winds were assumed to have little effect on the longitudinal patterns of the electron density in the North American sectors in a previous study (Zhang et al., 2012b). However, in the Southern Hemisphere, their contribution rate (f_{meri}) varies between 0.2 and 0.5 at 40° S, and between 0 and 0.5 at 60° S within 180° W–180° E. These amplitudes are comparable to those of the contribution rates of geographic zonal winds (f_{zon}), especially at 60° S. Therefore, the maximum NmF2 and the percentage difference ratio r tend to occur at the location between the maximum f_{meri} and f_{zon}. This kind of phenomenon occurs obviously in summer and during equinox at 40° S and in all seasons at 60° S.

At 60° S the minimum absolute and relative densities are mostly associated with minimum f_{zon}, although the longitudinal variation amplitudes of f_{meri} and f_{zon} are similar (Fig. 2). This is due to a negative effect of the eastward zonal winds at the negative declination locations. At those locations, the effects from the geographic equatorward meridional winds and eastward zonal winds cancel each other out. At 40° S, the minimum f_{meri} and minimum f_{zon} locations are separated by 30° in longitude. This separation is much smaller than that at 60° S. At 40° S, the combination of the two minimum results in a low relative electron density ratio ($r < 50\,\%$) occurring in wider longitudinal sectors than at 60° S.

4.3 The contribution of the geomagnetic declination and inclination

As introduced in Sect. 2, the wind-induced upward plasma drifts are contributed by the geographic meridional and zonal winds, whose effects are modulated by the magnetic inclination and declination. The longitudinal patterns of the absolute and relative density are generally associated with the magnetic declination variations at both 40 and 60° S. However, the magnetic inclination also contributes to the electron density longitudinal patterns by modulating both the contribution rates of the geographic zonal winds and meridional winds.

The magnetic meridional winds result from the combined effects of the geographic zonal and meridional winds through the modulation of magnetic declination (Eq. 1). They can drag the plasma moving along the geomagnetic field line, and thus the plasma's velocity has a component in the vertical direction at midlatitudes, i.e., the vertical plasma drifts (see Eq. 2). These drifts are modulated by a factor of $\cos I \sin I$. Under this modulation, from Figs. 3 and 4, the drifts are enhanced within 120° W–0° E (Figs. 3 and 4), and weakened within 90° E–120° E (Fig. 3), as compared with the patterns in the horizontal winds. These two sectors are in the locations of the larger and smaller geomagnetic latitudes/inclinations, respectively. The above changes of drift pattern relative to the horizontal winds contribute to the relative electron enhancement to the east of $\sim$120° W in summer and during equinox at 40° S and in all seasons at 60° S (Figs. 1 and 2). These changes are also responsible for electron density depletion around 90° E after midnight for all seasons at 40° S. At 60° S, after the modulation of the geomagnetic inclination, a significant peak of the vertical drifts along longitude is present at $\sim$90° W (winter and equinox) before midnight and at $\sim$50° W (in all seasons) after midnight.

The geomagnetic inclination separates the minimum f_{zon} from the minimum DEC angle locations at both latitudes (Figs. 1 and 2). This separation is as large as $\sim$50°in longitude at 60° S. As a result, the minimum density is located west of the minimum DEC (Fig. 2a). At both 40 and 60° S, the locations of minimum f_{zon} are well correlated with those of minimum absolute and relative density. This is due to a negative contribution to density by eastward zonal winds under negative DEC conditions.

4.3.1 The WSA and the electron density longitudinal difference

In summer at both 40 and 60° S, an obvious time delay occurs between maximum absolute and relative density. Further, the seasonal variation of the WSA at solar minimum is different from that of the longitudinal difference ratio of the electron density. Figures 1 and 2 show that at solar minimum, a western enhancement occurs for all seasons for the relative density, while the results from the present and previous studies (e.g., Jee et al., 2009; He et al., 2009) showed that the WSA occurs only in summer. In the evening, the equatorward magnetic meridional winds and the additional plasma source are considered as either the major cause of or important contributions to the WSA (Burns et al., 2008, 2011; Jee et al., 2009; He et al., 2010; Lin et al., 2010; Liu et al., 2010; Chen et al., 2011, 2012). For the WSA, the phase reversal of the density in a diurnal circle is also related to concurrent noontime depletion (Liu et al., 2010). Thus it is indicated that the WSA and the corresponding daytime longitudinal changes are also associated with the midlatitude phenomenon involving the neutral composition changes, such as the annual and semiannual variations of the midday ionospheric F layer (Liu et al., 2010; Zhao et al., 2013). These phenomena are longitudinally dependent due to the circulation of the O-rich air (e.g., Rishbeth, 1998). However, there is a lack of information for the longitudinal variations of the neutral density of N2 during nighttime. A few studies revealed that the annual and semiannual variations of the nighttime electron density are absent at midlatitudes in both hemispheres (e.g., Ma et al., 2003; Natali and Meza, 2011), which suggests the neutral composition may have a lesser effect on the ionospheric electron density longitudinal pattern during nighttime than it has during daytime.

In the present study, the maximum relative longitudinal difference occurs around midnight in summer, which is associated with the occurrence time of maximum upward plasma drifts. This consistency suggests an important contribution of magnetic meridional winds to the longitudinal–local time pattern of the electron density. Additional contribution can be made by the persistent ionization through the entire night in some western longitudes, since the center of maximum relative density is on the western side of the peak upward plasma drifts. Local photoionization has been reported to last all day in December at the southern station of Argentine Islands (Argentine IS) (−65.2° N, 64.3° W) (Chen et al., 2012). These combined effects of winds and photoionization may be responsible for a larger relative longitudinal difference in summer than during equinox, although peak vertical plasma drifts are larger during equinox than in summer.

For the WSA and WSA-like phenomena, their evening enhancements of the electron density are also suggested to be contributed by the downward plasma flux. During summer evenings, it is suggested that the downward flux might originate from the poleward edge of the equatorial anomaly region (Lin et al., 2010). It could be also induced by stronger cooling effects or thermal contraction in the Southern Hemisphere in local summer (Burns et al., 2008; Liu et al., 2010). During later hours close to midnight, the equatorial anomaly disappears and the cooling effects slow down or even stop due to a decreasing temperature gradient with time (Balan et al., 1996; Liu et al., 2010), and thus the above suggested flux from the plasmasphere could be much weaker in those regions where the WSA occurs. However, it is not clear whether the expected weak downward flux around midnight in the Western Hemisphere is still stronger than that of the Eastern Hemisphere at southern midlatitudes. Overall, a full understanding of the relative contribution to electron density variations by the neutral winds, photoionization and topside downward flux should be further studied by coupled magnetosphere–ionosphere models.

5 Summary

The ionospheric F2-layer peak density retrieved from observations by COSMIC was used to analyze its longitudinal variations during nighttime at southern midlatitudes, where the prominent WSA occurs in Western Hemisphere in summer. The longitudinal difference is calculated by a relative ratio r, which is defined by the percentage difference relative to the minimum density along longitudes at a fixed local time. The simultaneous magnetic meridional winds and their induced vertical plasma drifts are also presented, which are derived from the F2-layer peak height and peak density from a servo model. Thus we discussed the effects of winds and drifts on the ionospheric longitudinal pattern, as well as the contribution rates of the neutral horizontal winds to the vertical plasma drifts. The contribution rates of both the geographic zonal and meridional winds are determined by the geomagnetic inclination and declination. We find that the seasonal–local time patterns of the electron density longitudinal variations during nighttime at southern midlatitudes cannot be simply explained in terms of the WSA. Our major findings are as follows:

1. The greatest longitudinal difference ($r > 250\,\%$) of the ionospheric peak electron density occurs around midnight in summer with larger density in the Western Hemisphere, where the WSA is located, which usually occurs in the evening. Significant longitudinal difference ($r > 150\,\%$) also occurs during equinox and winter. This feature is different from the seasonal variation of the WSA at solar minimum.

2. The wind-induced vertical plasma drifts generally show a stronger upward component in the Western Hemisphere for most of the night. At a fixed local time, the stronger electron density in the WSA region is generally consistent with the larger upward plasma drifts in each season. Thus, the longitudinal patterns of winds/drifts and density are generally consistent with the magnetic declination–zonal wind effects.

3. The locations of the maximum and minimum upward drifts tend to reverse at $\sim$01:00–02:00 LT from their pre-midnight patterns, whereas no corresponding longitudinal pattern of the electron density occurs after this reversal. This suggests that the wind could largely contribute to but not determine the longitudinal pattern of the electron density.

4. There is significant contribution from the geographic meridional wind to the location of the maximum and minimum electron density besides the well-known magnetic declination–zonal wind effects. The longitudinal patterns of the upward plasma drifts and the consequent electron density are also modulated by the magnetic inclination. These features are unlike the role of the winds in the northern US and Far East regions, where the magnetic declination–zonal wind effects dominate.

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