Ann. Geophys., 33, 711–718, 2015
www.ann-geophys.net/33/711/2015/
doi:10.5194/angeo-33-711-2015

Annales Geophysicae
Open Access

Dusk-to-nighttime enhancement of mid-latitude $NmF2$ in local summer: inter-hemispheric asymmetry and solar activity dependence

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Received: 16 December 2014 – Revised: 3 May 2015 – Accepted: 20 May 2015 – Published: 10 June 2015

Abstract. In this paper ionosonde observations in the East Asia–Australia sector were collected to investigate dusk-to-nighttime enhancement of mid-latitude summer $NmF2$ (maximum electron density of the F2 layer) within the framework of $NmF2$ diurnal variation. $NmF2$ were normalized to two solar activity levels to investigate the dependence of the dusk-to-nighttime enhancement on solar activity. The dusk-to-nighttime enhancement of $NmF2$ is more evident at Northern Hemisphere stations than at Southern Hemisphere stations, with a remarkable latitudinal dependence. The dusk-to-nighttime enhancement shows both increasing and declining trends with solar activity increasing, which is somewhat different from previous conclusions. The difference in the dusk-to-nighttime enhancement between Southern Hemisphere and Northern Hemisphere stations is possibly related to the offset of the geomagnetic axis from the geographic axis. $hmF2$ (peak height of the F2 layer) diurnal variations show that daytime $hmF2$ begins to increase much earlier at low solar activity level than at high solar activity level at northern Akita and Wakkanai stations where the dusk-to-nighttime enhancement is more prominent at low solar activity level than at high solar activity level. That implies neutral wind phase is possibly also important for nighttime enhancement.

Keywords. Ionosphere (mid-latitude ionosphere)

1 Introduction

The ionization in the ionosphere is primarily caused by solar irradiance. For the ionosphere over a given location, solar irradiance arriving at the ionosphere varies on different timescales, such as the regular diurnal (local time), seasonal and solar cycle timescales, which certainly drives the variations of the ionosphere on these timescales. It is significant for understanding and modeling the ionosphere to study ionospheric variations on these different timescales. Diurnal variation of the ionosphere is a traditional topic of ionospheric studies. Ionospheric electron density should have a diurnal variation characterized by higher electron densities at noontime, when solar zenith is lowest during a day, according to the Chapman photochemical theory (Rishbeth and Garriott, 1969). Photochemical processes are dominative at ionospheric E layer height; thus, diurnal variation feature of the E layer electron density is basically consistent with the diurnal trend of the Chapman theory (e.g., Yue et al., 2006). At the F layer height, ionospheric dynamics and electrodynamics processes as well as thermospheric compositions also significantly affect the electron density. Thus, diurnal variation feature of the F layer electron density sometimes deviates from the diurnal trend of the Chapman theory owing to the effect of these factors. A most significant deviation from the Chapman theory is the nighttime enhancement of the electron density (e.g., Dabas and Kersley, 2003; Davies et al., 1979; Essex and Klobuchar, 1980; Evans, 1965; Farelo et al., 2002; Liu et al., 2013; Luan et al., 2008; Tsagouri and Belehaki, 2002). The nighttime enhancement refers to the phenomenon

Table 1. Information list of ionosonde stations used in this research.

Station name	Geographic		Geomagnetic (300 km height)			Temporal coverage
	Latitude	Longitude	Latitude	Declination	Dip	of the data
Yakutsk	62.0	129.6	51.7	−12.7	75.9	1957–1998 and 2000–2001
Petropavlovsk	53.0	158.7	45.3	−4.5	64.8	1968–1974 and 1989–2006
Wakkanai	45.4	141.7	36.0	−8.2	59.7	1948–1988 and 1996–2005
Akita	39.7	140.1	30.2	−6.8	53.8	1957–1989
Brisbane	−27.5	152.9	−35.0	11.1	−58.1	1950–1986 and 2003–2005
Canberra	−35.3	149.0	−43.3	12.1	−66.5	1950–2004
Hobart	−42.9	147.2	−51.0	14.2	−73.1	1950–1959 and 1961–2005
Campbell Island	−52.5	169.2	−56.7	30.5	−76.0	1959 and 1970–1985

that the electron density increases during the local nighttime hours. A prominent nighttime enhancement phenomenon is the Weddell Sea Anomaly (e.g., Burns et al., 2008; He et al., 2009; Jee et al., 2009; Lin et al., 2009; Penndorf, 1965), which is characterized by higher electron density in nighttime than in daytime.

Some mechanisms were proposed to explain nighttime enhancement of $NmF2$ (maximum electron density of the F2 layer), mainly including the combination of neutral wind effects and long-lasting sunlight at sunset as well as downward plasma flux (e.g., Bailey et al., 1991; Burns et al., 2008; Chen et al., 2012; He et al., 2009; Horvath and Essex, 2003; Le et al., 2014; Lin et al., 2009; Liu et al., 2010; Thampi et al., 2009). Nighttime equatorward wind uplifts the ionosphere to higher altitudes where recombination loss is weaker; then nighttime enhancement of $NmF2$ possibly occurs if sunlight causes enough photoionization. Altitudinal distribution of ionospheric plasma density above the F2 peak is significantly determined by plasma diffusion process at middle latitudes (Rishbeth and Garriott, 1969). In nighttime, plasma diffusion process causes a downward plasma flux mainly owing to the cooling of the ionosphere and the recombination loss at lower altitudes. Nighttime downward plasma flux from the plasmasphere and the topside ionosphere may result in plasma accumulation at the F2 peak heights (plasma diffusion becomes slower at lower altitudes as the collision of plasma particles with neutral particles significantly increases) to cause $NmF2$ nighttime enhancement.

The magnitude of the nighttime enhancement unevenly distributes over the globe according to previous studies (e.g., He et al., 2009; Lin et al., 2009; Liu et al., 2010); for example, the nighttime enhancement of the electron density at 400 km height is more prominent in the East Asian region, the North Atlantic region, and the South Pacific region according to Liu et al. (2010). That implies nighttime enhancement of $NmF2$ is possibly inter-hemispheric asymmetrical in some longitudinal sectors. As for solar activity dependence of the occurrence of nighttime enhancement, the conclusions are somewhat discrepant when different ionospheric parameters were used (e.g., Chen et al., 2012; Horvath, 2006; Horvath and Essex, 2003; Jee et al., 2009; Liu et al., 2010). Chen et al. (2012) measured nighttime enhancement of $NmF2$ with a mid-latitude summer nighttime anomaly (MSNA) index that quantifies the difference of $NmF2$ between nighttime and noontime to investigate the dependence of $NmF2$ nighttime enhancement on solar activity. They showed the MSNA index increases with solar activity decreasing and attributed it to the increment of neutral winds with solar activity decreasing (e.g., Kawamura et al., 2000).

For the mid-latitude ionosphere, the nighttime enhancement is generally more prominent in local summer (e.g., He et al., 2009, Jee et al., 2009; Liu et al., 2010). In this paper diurnal variations of mid-latitude $NmF2$ in local summer are analyzed based on the ionosonde observations in the East Asia–Australia sector. We mainly pay attention to the dusk-to-nighttime enhancement of $NmF2$ and put the emphasis upon the comparison between the Northern Hemisphere and the Southern Hemisphere as well as the comparison between low and high solar activity levels. Based on the observations in a longitudinal sector, inter-hemispheric asymmetry, latitudinal dependence, and solar activity dependence of local time evolution of mid-latitude summer $NmF2$ were analyzed in detail by plotting diurnal variations of $NmF2$ at different solar activity levels for each station.

2 Data analysis method

The observations of eight ionosonde stations in the East Asia–Australia longitudinal sector were collected for this study. The information of the ionosonde stations is listed in Table 1. Four stations are located in the Northern Hemisphere and the other four stations are located in the Southern Hemisphere. Some stations are located at nearly symmetrical geographic latitudes (such as Petropavlovsk and Campbell Island); meanwhile, some stations are located at nearly conjugate geomagnetic latitudes (such as Wakkanai and Brisbane). This is useful for the comparison between the Northern Hemisphere and the Southern Hemisphere. All temporal intervals of the observations are longer than one solar cycle, which is essential for statistically analyzing $NmF2$ diurnal variations at different solar activity levels. $NmF2$ data

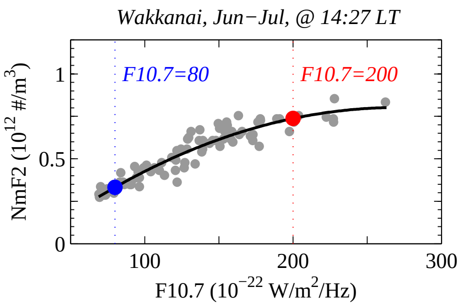

Figure 1. Scatter plots of Wakkanai monthly median *Nm*F2 vs. $F_{10.7}$ in June–July. The solid line is the quadratic regression fitting of the data, and the blue and red dots show the fitted *Nm*F2 for the two solar activity levels of $F_{10.7}$ equals 80 and 200, respectively.

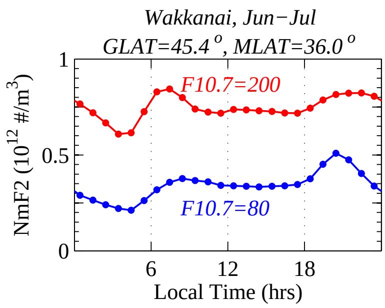

Figure 2. Local time variations of Wakkanai summer *Nm*F2 derived from the *Nm*F2–$F_{10.7}$ quadratic fitting, red for $F_{10.7} = 200$ and blue for $F_{10.7} = 80$.

were derived from *fo*F2 (critical frequency of the F2 layer) observations according to Eq. (1) (*Nm*F2 is in units of 10^{12} electrons m^{-3} and *fo*F2 is in units of MHz). The data in June and July (December and January) were used for local summer in the Northern (Southern) Hemisphere.

$$NmF2 = foF2^2 \Big/ 80.6 \quad (1)$$

*Nm*F2 value is significantly dependent on solar activity levels. In general, ionospheric data may be roughly classified into the groups of solar maxima and solar minima according to solar activity indices such as $F_{10.7}$ (10.7 cm solar radio flux) to investigate ionospheric diurnal variations at different solar activity levels. The relationships between *Nm*F2 and solar activity indices are usually nonlinear (e.g., Chen et al., 2008; Chen and Liu, 2010; Kouris et al., 1998; Liu et al., 2006; Richards, 2001; Sethi et al., 2002). In this paper *Nm*F2–$F_{10.7}$ quadratic fittings are used to more accurately normalize *Nm*F2 to two solar activity levels, $F_{10.7} = 80$ (a low solar activity level) and $F_{10.7} = 200$ (a high solar activity level). Figure 1 illustrates the normalization of *Nm*F2. Monthly median values of *Nm*F2 and $F_{10.7}$ were used to fit the relationships between *Nm*F2 and $F_{10.7}$; the data of geomagnetic activity index Ap larger than 30 were removed when calculating monthly median values to depress the effect of stronger geomagnetic activity on the ionosphere. The solid line shows the quadratic fitting of the data, and the blue and red dots show the normalized *Nm*F2 according to the quadratic fitting. For each station, 24 *Nm*F2–$F_{10.7}$ fittings corresponding to 24 local times were made to derive hourly values of *Nm*F2 at the two solar activity levels, and then *Nm*F2 diurnal variations were derived from these normalized values of hourly *Nm*F2. As an example, Fig. 2 presents diurnal variations of Wakkanai *Nm*F2 in local summer at the two solar activity levels. There is an evident dusk-to-nighttime enhancement (*Nm*F2 begins to increase since or after late afternoon and reaches to a maximum) that depends on solar activity levels. Daily maximum *Nm*F2 does not appear at midday.

3 Results

*Nm*F2 hourly values of the eight stations were derived to construct summer *Nm*F2 diurnal variations. The solid lines in Fig. 3 show the *Nm*F2 values at the two solar activity levels. Results of different stations are presented in terms of the latitudinal order from north to south. The dusk-to-nighttime enhancement of *Nm*F2 also appears at some other stations in addition to Wakkanai that presented in Fig. 2, and sometimes the maximum of the enhancement is the diurnal peak *Nm*F2. There are daytime bite-outs of *Nm*F2 at northern lower-latitude stations. Regarding the feature of the dusk-to-nighttime enhancement, it is somewhat different between the Northern Hemisphere and the Southern Hemisphere and dependent on latitudes and solar activity levels.

In general, the dusk-to-nighttime enhancement is more prominent in the Northern Hemisphere than in the Southern Hemisphere in the East Asia–Australia sector. The enhancement occurs more or less at all the four Northern Hemisphere stations and at both high and low solar activity levels; while in the Southern Hemisphere, it does not occur at low solar activity at the lower-latitude stations of Brisbane and Canberra. For Petropavlovsk and Campbell Island (geographic latitudes are nearly symmetrical) the enhancement is evidently more remarkable at the northern station of Petropavlovsk; for Wakkanai and Brisbane (geomagnetic latitudes are nearly conjugate) the enhancement is prominent at the northern station of Wakkanai but does not occur at the southern station of Brisbane at low solar activity level. Moreover, there is a Weddell-Sea-Anomaly-like enhancement (WSA-like enhancement, higher electron density in nighttime than in daytime) at Yakutsk at high solar activity level, while this enhancement does not appear at the Southern Hemisphere stations.

Latitudinal dependence of the dusk-to-nighttime enhancement is evident. For the northern stations, the enhancement is more prominent at Wakkanai and Petropavlovsk at low solar activity level, and it trends to increase with latitude increasing at high solar activity level. *Nm*F2 increments mainly occur after about 18:00 LT at Akita (mainly during low solar

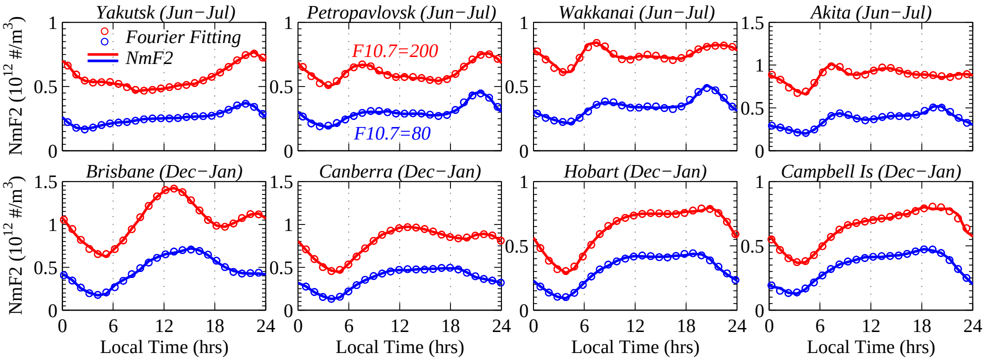

Figure 3. Local time variations of mid-latitude $NmF2$ at the two solar activity levels in local summer; the solid lines are the results derived from the $NmF2$–$F_{10.7}$ quadratic fittings, and the circles are the Fourier fittings of the solid line data.

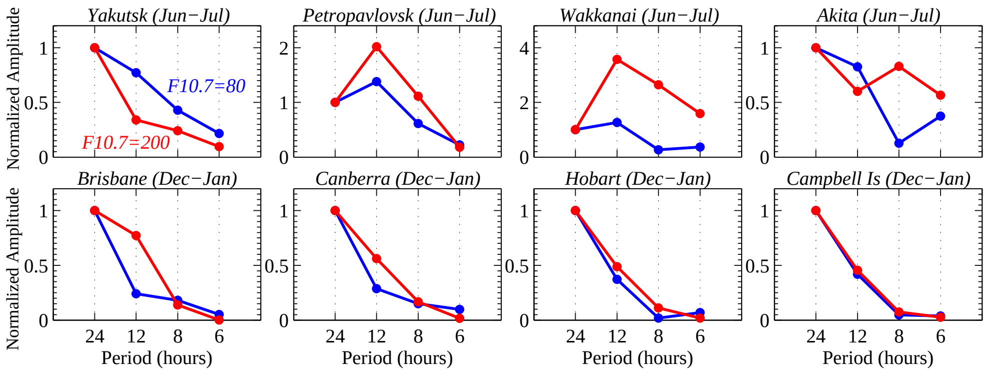

Figure 4. Normalized amplitudes of the Fourier components of $NmF2$ diurnal variations; for each station the amplitudes are normalized with the 24 h component amplitude.

activity period), Wakkanai, and Petropavlovsk, while $NmF2$ begins to increase since noontime at high solar activity level at the higher-latitude station of Yakutsk. For the southern stations, the enhancement becomes distinguishable with latitude increasing at low solar activity level, while it is more prominent at the lower-latitude station of Brisbane at high solar activity level. $NmF2$ increments occur after 18:00 LT at Brisbane and Canberra at high solar activity level, while $NmF2$ continuously increases from morning to dusk at the higher-latitude station of Campbell Island.

There are not only negative but also positive trends for solar activity dependence of the dusk-to-nighttime enhancement of $NmF2$. For example, the enhancement is more prominent at low solar activity level than at high solar activity level at Akita and Wakkanai, while it is more prominent at high solar activity level than at low solar activity level at Brisbane and Canberra, different from the conclusion of Chen et al. (2012) that suggested a negative dependence of the MSNA index on solar activity. There is no obvious dusk-to-nighttime enhancement at low solar activity level at Brisbane and Canberra. Moreover, the features of the dusk-to-nighttime enhancement at low and high solar activity levels are similar at Campbell Island.

Fourier fittings were used to further investigate periodic components of $NmF2$ diurnal variation. $NmF2$ diurnal variation can be estimated in terms of Eq. (2), where the Fourier components whose periodicities are larger than 6 h are taken into account.

$$
\begin{aligned}
NmF2(\mathrm{LT}) &= \sum_{i=0}^{4}\left[A_i\cos\left(\frac{2\pi i\cdot \mathrm{LT}}{24}\right)+B_i\sin\left(\frac{2\pi i\cdot \mathrm{LT}}{24}\right)\right]\\
&= \sum_{i=0}^{4}C_i\cos\left[\frac{2\pi i\cdot(\mathrm{LT}-\Phi_i)}{24}\right]
\end{aligned}
\quad (2)
$$

The coefficients A_i and B_i were determined via fitting $NmF2$ in terms of Eq. (2). The amplitudes and phases of different periodic components, C_i and Φ_i, were derived from A_i and B_i. The circles in Fig. 3 show the Fourier fitted $NmF2$. In general, the fitted values can basically present $NmF2$ diurnal variations.

Figure 4 shows the normalized amplitudes of the Fourier components. The amplitudes are normalized with the amplitude of the 24 h Fourier component, C_1, in order to compare the results at low and high solar activity levels and at different stations. The Fourier amplitudes show remarkable differences between the Northern Hemisphere and the Southern Hemisphere and significant latitudinal dependences in the Northern Hemisphere. The 24 h component is dominative at all the four southern stations, while the 12 h compo-

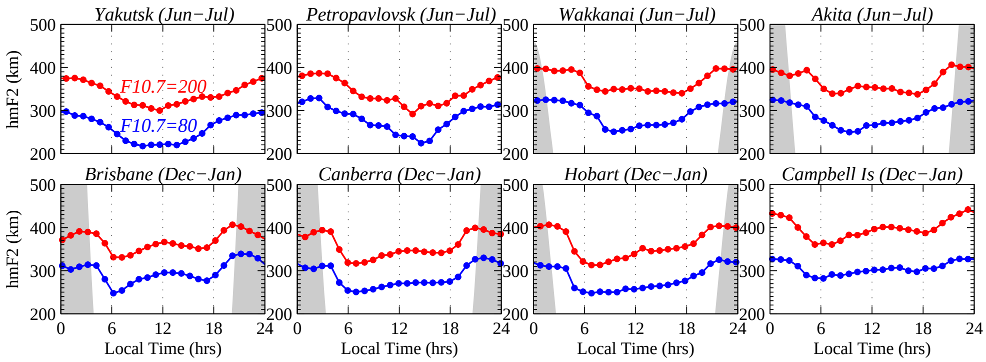

Figure 5. Local time variations of mid-latitude hmF2 at the two solar activity levels in local summer; hmF2 data are derived from the hmF2–$F_{10.7}$ linear fittings. Grey areas denote the altitudinal ranges where sunlight is kept out on local summer solstice day.

nent is dominative at the northern stations of Wakkanai and Petropavlovsk. For the southern stations, the 12 h component is more important at high solar activity level than at low solar activity level at Brisbane and Canberra; while the Fourier amplitudes at high and low solar activity levels are basically consistent at Hobart and Campbell Island, indicating similar diurnal variation patterns at low and high solar activity levels. For the northern stations, the Fourier amplitudes at low and high solar activity levels are significantly different, implying the difference of NmF2 diurnal variation between the two solar activity levels. It is notable that similar to the results at low solar activity level at Brisbane and Canberra, the 24 h component is dominative at high solar activity level at Yakutsk, but the phase of the 24 h component Φ_1 (the local time of the peak value of the 24 h component) is close to midnight. That means a WSA-like nighttime enhancement at Yakutsk.

By reconstructing NmF2 (here the reconstructed NmF2 is not shown) with the Fourier components, the result indicates that the 24 and 12 h components can basically present main features of NmF2 diurnal variation at the Southern Hemisphere stations, and the dusk-to-nighttime enhancement mainly comes from the 12 h component. For high solar activity level, Fig. 4 shows that the 12 h component is more prominent at Brisbane than at other southern stations, corresponding to a more prominent dusk-to-nighttime enhancement at Brisbane; for Brisbane and Canberra, the 12 h component is more important at high solar activity level than at low solar activity level, implying more prominent dusk-to-nighttime enhancements at high solar activity level. More Fourier components are needed to present main features of NmF2 diurnal variation at the Northern Hemisphere stations. That indicates NmF2 diurnal variation is more complex at the northern stations than at the southern stations.

For the mid-latitude ionosphere, the increment of hmF2 (peak height of the F2 layer) is important for the development of NmF2 nighttime enhancement (e.g., He et al., 2009). Diurnal variations of hmF2 were constructed in terms of the similar method for NmF2 diurnal variations but for linear fittings of hmF2 vs. $F_{10.7}$ were used to normalize hmF2 to the two solar activity levels, because hmF2 nearly increases linearly with solar activity (e.g., Chen and Liu, 2010). hmF2 was calculated in terms of foF2, foE (critical frequency of the E layer), and M(3000)F2 (maximum usable frequency factor) according to Dudeney (1983). Figure 5 shows hmF2 diurnal variations at the two solar activity levels in local summer. The variations of hmF2 at the northern stations also depend on latitudes. hmF2 begins to increase after noontime at the higher-latitude stations of Petropavlovsk and Yakutsk at both low and high solar activity levels, while it begins to increase since about 18:00 LT at the lower-latitude stations of Akita and Wakkanai at high solar activity level. It is notable that hmF2 variation significantly depends on solar activity levels at Akita and Wakkanai – where hmF2 begins to increase much earlier at low solar activity level than at high solar activity level. The variations of hmF2 at the southern stations are somewhat different from those at the northern stations, for both lower-latitude and higher-latitude stations. The solar activity dependence of hmF2 variation that appears at northern Akita and Wakkanai does not appear at southern lower-latitude stations.

4 Discussion

The dusk-to-nighttime enhancement of NmF2 shows a significant difference between the Northern Hemisphere and Southern Hemisphere stations according to the East Asia–Australia ionosonde observations; it is more prominent at the northern stations than at the southern stations. This difference is consistent with the global distribution of the nighttime enhancement of the electron density at 400 km height reported by Liu et al. (2010), in which the East Asian is a prominent nighttime enhancement region, and also consistent with Lin et al. (2010), in which northeastern Asia is one of the most prominent nighttime enhancement regions. In this paper, not only inter-hemispheric difference but also latitudinal evolutions of mid-latitude summer NmF2 diurnal variation are presented. Thus, latitudinal dependence of the dusk-to-nighttime enhancement is more precisely analyzed within the framework of *Nm*F2 diurnal variation. It should be pointed out that the features of the dusk-to-nighttime enhancement of *Nm*F2 presented in this paper are statistical results and do not represent the case on day-to-day timescales.

The main mechanisms proposed to explain the nighttime enhancement include the combination of neutral wind effects and long-lasting sunlight at sunset as well as downward plasma flux. Within the framework of neutral wind effects, the configuration of the geomagnetic field (geomagnetic inclination and declination) is an important factor for the nighttime enhancement (e.g., He et al., 2009; Lin et al., 2009; Liu et al., 2010). Nighttime equatorward meridional wind induces upward plasma drift in the both hemispheres, while zonal wind effect depends on geomagnetic declination. Geomagnetic declination difference was used to explain longitudinal dependence of the nighttime enhancement (e.g., He et al., 2009). Table 1 indicates that geomagnetic declination is different between the Northern Hemisphere and Southern Hemisphere stations, negative at the northern stations while positive at the southern stations. However, this declination difference does not result in different signs of vertical plasma drift induced by eastward or westward zonal wind in the two hemispheres. Geomagnetic declination difference should be not the dominative factor for the inter-hemispheric difference of the dusk-to-nighttime enhancement presented in this paper.

A possible reason for the north–south difference is the offset of the geomagnetic axis from the geographic axis (e.g., Lin et al., 2009). Neutral winds are driven not only by sunlight heating but also by the Joule heating in aurora region. Sunlight heating depends on geographic latitudes, while the Joule heating is related to the geomagnetic field. Thus, meridional wind in local summer is potentially asymmetrical at either conjugate geographic latitudes or conjugate geomagnetic latitudes owing to the offset of the geomagnetic axis from the geographic axis. Moreover, for the northern and southern stations with equivalent geomagnetic latitudes (for example, Wakkanai and Brisbane) in the East Asia–Australia sector, geographic latitudes of the northern stations are higher than those of the southern stations owing to the offset of the geomagnetic axis from the geographic axis; at mid-latitude summer sunset, therefore, solar zenith is lower and the duration of sunlight at F region altitudes is longer at the northern stations than at the southern stations. That also should be propitious to the formations of the more prominent dusk-to-nighttime enhancements at the northern stations than at the southern stations.

Neutral wind effect should be manifested in the variation of *hm*F2. For the potential inter-hemispheric asymmetry of neutral winds, some hints may be detected from the different *hm*F2 variations between the northern and southern stations (see Fig. 5), especially from the different *hm*F2 variations during daytime between Petropavlovsk and Campbell Island (geographic latitudes are equivalent) or between Wakkanai and Brisbane (geomagnetic latitudes are equivalent). It is notable that *hm*F2 begins to significantly increase in the afternoon at the northern higher-latitude stations of Petropavlovsk and Yakutsk. That should play important roles in the formations of the prominent dusk-to-nighttime enhancements over these two stations. Horvath and Lovell (2009) showed a prominent WSA-like enhancement at northern middle latitudes during northern summer by presenting a global map of the ion density of the topside ionosphere; the northern edge of that WSA-like enhancement is close to Yakutsk while the southern edge is close to Petropavlovsk (see their Fig. 2). They suggested that the equatorward neutral wind plays important roles in the development of the enhancement.

As for solar activity dependence of the dusk-to-nighttime enhancement, both positive and negative dependences exist, different from previous conclusion that nighttime enhancement of *Nm*F2 increases with solar activity decreasing (e.g., Chen et al., 2012). Chen et al. (2012) just analyzed solar activity dependence of the MSNA index for the stations where nighttime peak *Nm*F2 is higher than noontime *Nm*F2, and they attributed the declination of nighttime enhancement with solar activity increasing to the decrement of neutral winds with solar activity increasing (e.g., Kawamura et al., 2000). In this paper negative correlation of the dusk-to-nighttime enhancement with the solar activity is evident at Akita and Wakkanai. *hm*F2 diurnal variations at these two stations (see Fig. 5) indicate that the F2 peak begins to move up much earlier at low solar activity level than at high solar activity level. That means the F2 layer is uplifted to higher altitudes where recombination loss rate is lower much earlier at low solar activity level. That is propitious to the occurrence of more prominent nighttime enhancement of *Nm*F2 at low solar activity level. Significant increment or decrement of daytime poleward wind should cause a change of mid-latitude ionospheric height according to the servo theory (Rishbeth et al., 1978). Therefore, different *hm*F2 variations between low and high solar activity levels maybe imply that the phases of neutral winds at Akita and Wakkanai are different between the two solar activity levels.

The dusk-to-nighttime enhancement of *Nm*F2 is more prominent at high solar activity level than at low solar activity level at Brisbane and Canberra. However, *hm*F2 diurnal variations are similar at the two solar activity levels at these two stations (see Fig. 5); *hm*F2 begins to significantly increase since about 18:00 LT. Brisbane and Canberra stations are located at lower latitudes; the increment of solar zenith with local time around sunset is faster at lower latitudes than at higher latitudes. That is a disadvantage of the formation of the nighttime enhancement at lower latitudes. At high solar activity level, an advantage of nighttime enhancement is that the F2 layer is located at higher altitudes; thus sunlight lasts longer at the F2 peak height to make for the formation of the nighttime enhancement. As the shaded intervals (indicated in grey) in Fig. 5 show, however, the difference of the sunset time at the F2 peak height between low and high solar activity levels is small at Brisbane and Canberra; thus it should not be the reason for the different dusk-to-nighttime enhancements at the two solar activity levels. It is notable that the F2 peak is in shadow when $NmF2$ nighttime enhancement occurs at high solar activity level at Brisbane (see Figs. 3 and 5). This indicates that downward plasma flux possibly plays an important role in the formation of the nighttime enhancement at Brisbane.

5 Summary and conclusions

In this paper diurnal variation of mid-latitude $NmF2$ in local summer was investigated based on the ionosonde observations in the East Asia–Australia longitudinal sector. The dusk-to-nighttime enhancement of $NmF2$ was analyzed in detail. The results indicate that the dusk-to-nighttime enhancement of $NmF2$ depends on latitudes and is inter-hemispheric asymmetrical in the East Asia–Australia sector, and it depends on solar activity levels. The primary conclusions are as follows:

1. The dusk-to-nighttime enhancement is generally more evident at the northern stations than at the southern stations. The WSA-like enhancement appears at the northern higher-latitude station of Yakutsk but does not appear at the southern stations.

2. For the southern stations, the dusk-to-nighttime enhancement becomes distinguishable with latitude increasing at low solar activity level, while it is more prominent at lower latitudes at high solar activity level; for the northern stations, the enhancement is more prominent at higher latitudes at high solar activity level.

3. The dusk-to-nighttime enhancement shows both increasing and declining trends with solar activity increasing, which is somewhat different from the conclusions of previous studies.

The mechanisms were briefly discussed based on the explanations of nighttime enhancement proposed by previous studies and $hmF2$ diurnal variations. The inter-hemispheric difference of the dusk-to-nighttime enhancement is possibly related to the offset of the geomagnetic axis from the geographic axis, which may cause an inter-hemispheric asymmetry of neutral winds within the framework of either geographic or geomagnetic coordinate. In general, $hmF2$ variations at the northern stations are somewhat different from those at the southern stations. As for solar activity dependence of the dusk-to-nighttime enhancement, $hmF2$ diurnal variations show a significant difference between low and high solar activities at northern Akita and Wakkanai stations; daytime $hmF2$ begins to increase much earlier at low solar activity level than at high solar activity level. That is propitious to the occurrence of more prominent dusk-to-nighttime enhancement at low solar activity level and suggests that neutral wind phase is possibly also important for nighttime enhancement.

Acknowledgements. The ionosonde data and the $F_{10.7}$ index were taken from the SPIDR (Space Physics Interactive Data Resource) website. This research was supported by National Natural Science Foundation of China (41274161, 41231065, and 41321003), Chinese Academy of Sciences (KZZD-EW-01-3), and National Important Basic Research Project of China (2012CB825604).

The topical editor H. Kil thanks S. Tulasi Ram and I. Horvath for help in evaluating this paper.

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