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Equinoctial asymmetry in solar activity variations of *Nm*F2 and TEC

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Abstract. The ionosonde *Nm*F2 data (covering several solar cycles) and the JPL TEC maps (from 1998 through 2009) were collected to investigate the equinoctial asymmetries in ionospheric electron density and its variation with solar activity. With solar activity increasing, the equinoctial asymmetry of noontime *Nm*F2 increases at middle latitudes but decreases or changes little at low latitudes, while the equinoctial asymmetry of TEC increases at all latitudes. The latitudinal feature of the equinoctial asymmetry at high solar activity is different from that at low solar activity. The increases of *Nm*F2 and TEC with the solar proxy $P=(F_{10.7}+F_{10.7A})/2$ also show equinoctial asymmetries that depend on latitudes. The increase rate of *Nm*F2 with P at March equinox (ME) is higher than that at September equinox (SE) at middle latitudes, but the latter is higher than the former at the EIA crest latitudes, and the difference between them is small at the EIA trough latitudes. The phenomenon of higher increase rate at SE than at ME does not appear in TEC. The increase rate of noontime TEC with P at ME is higher than that at SE at all latitudes, and the difference between them peaks at both sides of dip equator. It is mentionable that the equinoctial asymmetries of *Nm*F2 and TEC increase rates present some longitudinal dependence at low latitude. The influences of equinoctial differences in the thermosphere and ionospheric dynamics processes on the equinoctial asymmetry of the electron density were briefly discussed.

Keywords. Ionosphere (Equatorial ionosphere; Mid-latitude ionosphere)

1 Introduction

The Earth's ionosphere has complex seasonal variations (e.g. Jakowski et al., 1981; Kawamura et al., 2002; Mayr and Mahajan, 1971; Su et al., 1998; Torr and Torr, 1973; Zhang and Holt, 2007). These seasonal variations still have not been fully understood (Rishbeth, 2004) though different factors, such as solar zenith, thermospheric composition, neutral winds, etc., have been used to explain them (e.g. Ma et al., 2003; Mendillo et al., 2005; Millward et al., 1996; Pavlov and Pavlova, 2005; Richards, 2001; Rishbeth et al., 2000). Solar zenith is equal at March equinox (ME) and September equinox (SE), but the ionosphere presents some differences between the two equinoxes under equivalent solar activity conditions (e.g. Bailey et al., 2000; Balan et al., 1997, 1998; Chen et al., 2009; Essex, 1977; Kawamura et al., 2002), namely ionospheric equinoctial asymmetry. This asymmetry may originate from the equinoctial differences in neutral winds, thermospheric composition and density, electric fields, and so on. Some researchers have shown that there are some equinoctial differences in these factors (e.g. Aruliah et al., 1996; L. Liu et al., 2003; H. Liu et al., 2007; Maruyama et al., 2009; Ren et al., 2011). Balan et al. (1997, 1998) and Kawamura et al. (2002) investigated the equinoctial asymmetry of ionospheric electron density at different heights using the MU radar (35° N, 136° E) observations and theoretical modeling. They found opposite equinoctial asymmetries at lower and higher altitudes, and they proposed that the equinoctial difference in neutral winds is the dominant factor for the observed equinoctial asymmetry in the ionosphere.

Recently, L. Liu et al. (2010) analyzed the equinoctial asymmetry in ionospheric plasma density at low solar activity. They revealed that the equinoctial asymmetry is mainly a low-latitude phenomenon during solar minima. It is interesting that Unnikrishnan et al. (2002) showed that TEC (total electron content) over Palehua (19° N, 206° E) exhibits opposite equinoctial asymmetries between high and low solar activities. They showed that Palehua TEC is higher at SE than at ME during high solar activity year 1981, while it is higher at ME than at SE during low solar activity year 1984. Namely, from low to high solar activity TEC increases more at SE than at ME, which is fully different from

Table 1. Information of the ionosonde stations used in this work.

Station name	Geographic		Geomagnetic		Temporal coverage of the data
	Latitude	Longitude	Latitude	Dip	
Yakutsk	62.0	129.6	51.5	75.7	1957–1998, and 2001
Irkutsk	52.5	104.0	41.5	71.1	1957–1997
Khabarovsk	48.5	135.1	38.4	63.6	1959–1983, and 1987–1989
Wakkanai	45.4	141.7	35.8	59.5	1948–1988, and 1996–2005
Akita	39.7	140.1	29.9	53.5	1957–1988
Kokubunji	35.7	139.5	25.9	48.8	1957–2005
Yamagawa	31.2	130.6	20.8	44.0	1957–1988, and 2002–2005
Okinawa	26.3	127.8	15.8	36.6	1957–1988, and 1996–2005
Taipei	25.0	121.5	14.2	35.1	1959–1989
Manila	14.6	121.1	3.8	14.3	1964–1989
Vanimo	−2.7	141.3	−12.0	−22.7	1964–2004
Darwin	−12.5	130.9	−23.2	−41.1	1983–2004
Townsville	−19.3	146.7	−28.4	−49.2	1952–2004
Brisbane	−27.5	152.9	−35.7	−58.1	1950–1986, and 2003–2004
Canberra	−35.3	149.0	−44.0	−66.5	1950–2004
Hobart	−42.9	147.2	−51.6	−73.0	1950–1958, and 1961–2004
Maui	20.8	−156.5	21.3	38.3	1957–1994
Tahiti	−17.7	−149.3	−15.2	−31.0	1971–1989
Huancayo	−12.0	−75.3	−1.2	1.6	1957–1987
Dakar	14.8	−17.4	21.0	13.7	1957–1958, and 1962–1989
Ouagadougou	12.4	−1.5	16.0	4.5	1966–1976, and 1978–1989
Djibouti	11.5	42.8	6.9	7.6	1957–1958, and 1962–1981
Ahmedabad	23.0	72.6	14.1	33.5	1957–1986, and 1997–2001
Kodaikanal	10.2	77.5	0.9	4.8	1957–1986

the equinoctial difference of electron density at low solar activity. In general, solar activity may be different between ME and SE of a year. That could introduce some effects when studying the equinoctial asymmetry. It is unclear whether inter-annual variations of solar activity have produced some effects on this previous result. Thus, it is necessary to investigate the equinoctial asymmetry by removing solar activity effects.

The ionosphere also has a significant solar cycle modulation owing to the 11-year variation of solar EUV irradiance. As some works (e.g. Balan et al., 1996; Chen and Liu, 2010; Gupta and Singh, 2000; Ma et al., 2009) revealed, from low to high solar activity the increase of ionospheric electron density with solar indices shows nonlinearities, and the latitudinal, seasonal, and local time dependences of the increase are not always consistent with those dependences of the increase of photoionization with solar activity. That indicates changes in the thermosphere and ionospheric dynamics could significantly affect the variation of electron density with solar activity. Ionospheric equinoctial asymmetry may originate from the equinoctial differences in the thermosphere and ionospheric dynamics processes, these equinoctial differences also should result in discrepant variations of electron density with solar activity between the two equinoxes. In this regard, the equinoctial difference in solar activity variations of the electron density provides an important way for detecting the equinoctial asymmetries in the thermosphere and ionospheric dynamics. However, we still lack understanding of the features of the equinoctial difference in solar activity variations of ionospheric electron density.

This paper investigates solar activity effects on the equinoctial asymmetries of *Nm*F2 (maximum electron density of the F2 layer) and TEC and the equinoctial difference in solar activity variations of *Nm*F2 and TEC. We revealed that the latitudinal features of the equinoctial asymmetry at low and high solar activities are different, and with solar activity increasing the equinoctial difference of *Nm*F2 shows different changes at low and middle latitudes. Moreover, solar activity variations of *Nm*F2 and TEC also show significant equinoctial asymmetries which depend on latitudes and local times. The effects of the thermospheric and ionospheric dynamics on the equinoctial differences in the electron density and its variation with solar activity also will be briefly discussed in this paper.

2 Data processing and results

The data at 24 ionosonde stations have been collected for this study. These ionosonde stations have long-term records that cover several solar cycles (see Table 1). The long-term

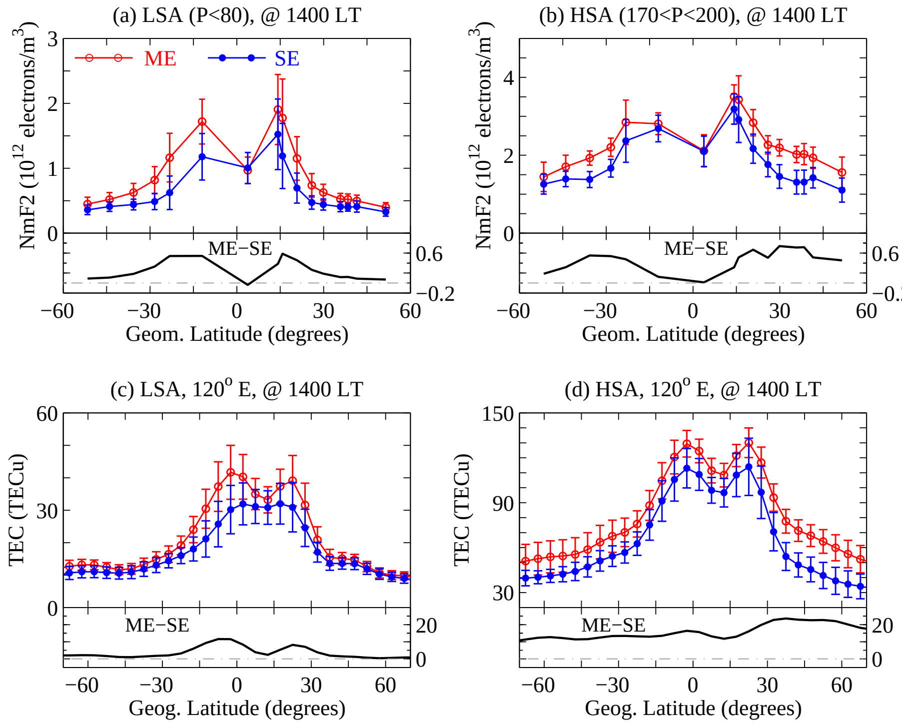

Fig. 1. Latitudinal variations of equinoctial noontime (**a** and **b**) *Nm*F2 in the East Asia/Australia sector and (**c** and **d**) TEC at 120° E at low solar activity (LSA) and high solar activity (HSA). Circles and dots show mean values and error bars show standard deviations, black lines in each bottom panel are the (ME-SE) differences.

records are essential for accurately detecting the equinoctial asymmetries at different solar activities and capturing the variation of *Nm*F2 with solar activity. The ionosonde data are provided at the SPIDR Web site. All ionosonde data we used are manually scaled data. JPL TEC maps have been routinely produced (with a resolution of longitude 5° × latitude 2.5° × UT 2 h) from the measurements of global GPS receivers since 1998 (Iijima et al., 1999; Mannucci et al., 1998). These TEC data also have a longer temporal coverage so can be used for investigating solar activity variations of TEC. We collected the JPL vertical TEC from 1998 through 2009 for this study. The $F_{10.7}$ index (10.7 cm solar radio flux) is a widely used solar proxy. Some works (e.g. L. Liu et al., 2006; Richards et al., 1994) indicated that the improved index $P = (F_{10.7} + F_{10.7A})/2$ can better represent solar EUV variability, thus the P index is used as the solar proxy in this paper. Here $F_{10.7A}$ is the 81-day running average of daily $F_{10.7}$. An appropriate data grouping is important for investigating equinoctial asymmetry since the ionosphere has significant seasonal variations. We use the data within ±20 days around the ME (SE) day to represent the ME (SE) condition in order to ensure the solar zenith is equal between the two groups of data. The data are not used if the geomagnetic index Ap is larger than 20 in order to remove the effect of stronger geomagnetic disturbance. Certainly the range of Ap up to 20 may represent corotating interaction region (CIR) generated geomagnetic activity conditions at solar minima, especially in the long deep solar minimum.

Figure 1 shows the latitudinal variations of noontime *Nm*F2 and TEC at the two equinoxes at low and high solar activities. *Nm*F2 is derived from the observed *fo*F2 (critical frequency of the F2 layer). TEC is plotted with a latitudinal resolution of 5°. Here we use the P index to appoint the low solar activity with $P < 80$ and the high activity with $170 < P < 200$. Both *Nm*F2 and TEC show the latitudinal feature of equatorial ionization anomaly (EIA). Like the previous result revealed by L. Liu et al. (2010), at low solar activity the equinoctial asymmetry mainly appears at low latitudes. It is notable that the equinoctial asymmetry is small at dip equator no matter for *Nm*F2 or TEC. At high solar activity, however, the latitudinal feature of the equinoctial asymmetry is very different from that at low solar activity. For *Nm*F2 the equinoctial asymmetry increases at middle geomagnetic latitudes, but it decreases or just has a little change at low geomagnetic latitudes. As a result, the equinoctial asymmetry of mid-latitude *Nm*F2 is more prominent at high solar activity. It is interesting that the equinoctial asymmetry of *Nm*F2 over dip equator is still very small at high solar activity. For TEC the equinoctial asymmetry increases at all latitudes especially at dip equatorial region and middle latitudes, thus it is prominent at all latitudes at high solar activity.

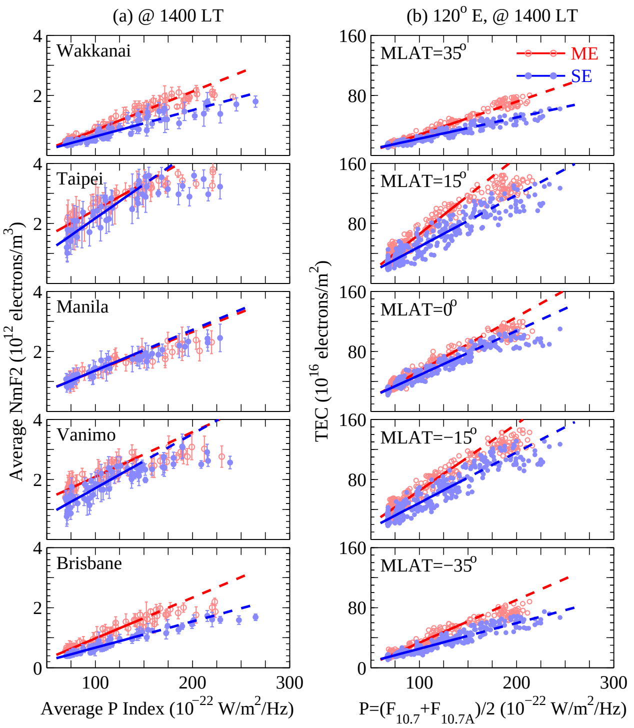

Fig. 2. The variations of equatorial **(a)** *Nm*F2 in the East Asia/Australia sector and **(b)** TEC at 120° E with the solar proxy $P = (F_{10.7} + F_{10.7A})/2$. Circles and dots show observations and error bars show standard deviations, lines are the linear regression fits for the observations at the solar activity level of $P < 140$.

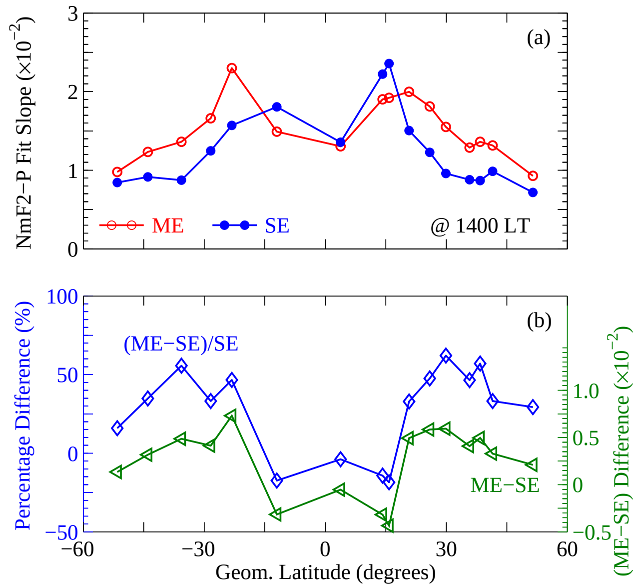

Fig. 3. (a) Latitudinal variations of the linear fit slope of *Nm*F2 with P (fitting for $P < 140$, see Fig. 2) in the East-Asia/Australia sector. **(b)** The percentage difference and the (ME-SE) difference of the linear fit slope.

The above result indicates that solar activity variations of *Nm*F2 and TEC should be different between the two equinoxes, and this difference potentially depends on latitudes. Since the features of the equinoctial asymmetry in solar activity variations of the ionosphere are useful for detecting the equinoctial differences in the thermosphere and ionospheric dynamics and revealing the equinoctial asymmetries at different solar activity levels, hereinafter we analyze the equinoctial difference in solar activity variations of *Nm*F2 and TEC.

Seasonally averaged values of the electron density and solar proxies can be used to better capture the variation of the electron density with solar activity. The ionosonde data cover several solar cycles, thus in this paper seasonally averaged *Nm*F2 and the P index are used to investigate solar activity variations of *Nm*F2. The average values of *Nm*F2 and P at ME and SE are calculated from the ME data and the SE data, respectively, on a year by year basis. Daily TEC maps are used owing to its temporal coverage being relatively short for deriving sufficient average values of TEC. A quadratic regression fit is used to capture the variation trend of *Nm*F2 or TEC with P, and then the average absolute deviation (δ) of observed *Nm*F2 or TEC from this quadratic fit is calculated for all solar activities. In order to remove the effect of the data that significantly deviate from the average variation trend represented by the quadratic fit, the *Nm*F2 and TEC whose absolute deviations from the quadratic fit are larger than 3 times of the δ are not used.

Figure 2 shows the variation of noontime *Nm*F2 (TEC) with the P index in the East Asia/Australia sector. In Fig. 2 the dependence of the equinoctial asymmetry of *Nm*F2 (TEC) on solar activity that are shown in Fig. 1 are evident. Owing to the nonlinear variation of the electron density with solar activity, we use a linear regression fit only for lower solar activity levels ($P < 140$) to get the increase rate of *Nm*F2 (TEC) with P. This increase rate can generally describe the variation of *Nm*F2 (TEC) with P from low to higher solar activity if the nonlinearity of the general trend of *Nm*F2 (TEC) with P is weak, while it only can describe the variation of *Nm*F2 (TEC) with P at lower solar activities if the nonlinearity is strong. A notable feature is that there is a latitudinal difference in the equinoctial asymmetry of the increase rate of *Nm*F2 with P. The increase rate at ME is higher than that at SE at middle latitudes (Wakkanai and Brisbane), but the latter is higher than the former at the EIA crest latitudes (Taipei and Vanimo), while there is no obvious difference between them at dip equator (Manila). This latitudinal feature does not appear in the variation of TEC with P. The increase rate of TEC with P at ME is higher than that at SE at all 5 latitudes, but the difference between them is related to latitudes.

More stations in the East Asia/Australia sector (16 ionosonde stations in all) are used to further investigate the

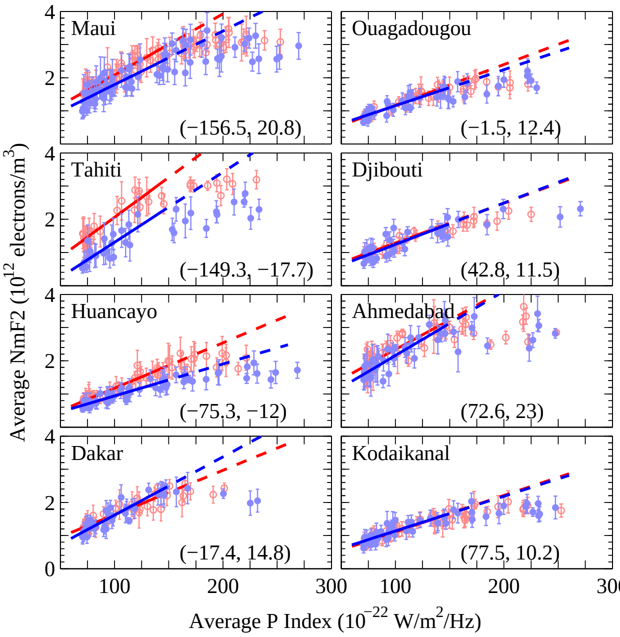

Fig. 4. Same as Fig. 2a but for low-latitude stations at different longitudes, and the values in parentheses are geographic longitudes and latitudes of the stations.

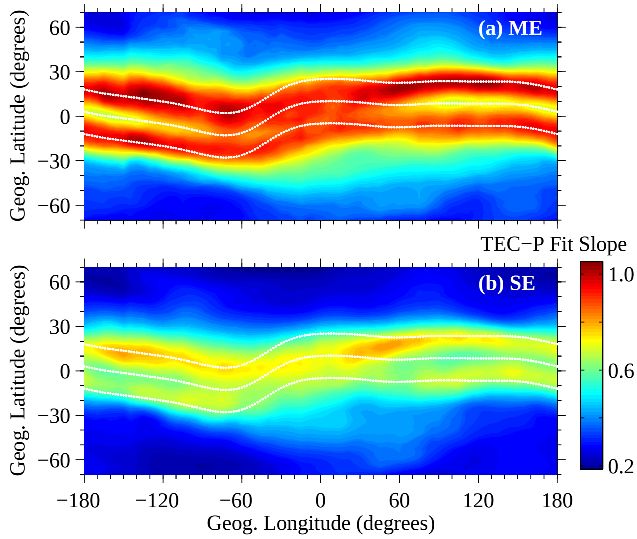

Fig. 5. The distributions of the linear fit slope of TEC with P (fitting for $P < 140$, see Fig. 2) at 14:00 LT. Three lines in each panel correspond to dip equator $+15°$, dip equator, and dip equator $-15°$, respectively.

latitudinal feature of the equinoctial difference in the variation of *Nm*F2 with P. Figure 3 shows that the increase rate of *Nm*F2 with P peaks at both sides of dip equator, which is similar to the EIA structure of *Nm*F2, and the increase rate crests at ME move to higher latitudes as compared with those at SE. The feature that the increase rate at SE is higher than that at ME only appears at low latitudes; while the increase rate at ME is higher than that at SE at all mid-latitude stations, and the difference between the ME and SE increase rates is smaller at higher latitudes. The largest percentage difference between the equinoctial increase rates appears at middle latitudes, it can reach over 50 %.

In the East Asia/Australia sector, the equinoctial difference in the increase rate of low-latitude *Nm*F2 with P is an interesting phenomenon. Low-latitude data in other longitude sectors (8 ionosonde stations in all) are collected to investigate whether this phenomenon appears at other longitudes. Figure 4 shows the variations of *Nm*F2 with P at 5 EIA trough stations (Huancayo, Dakar, Ouagadougou, Djibouti, and Kodaikanal) and 3 EIA crest stations. The equinoctial differences in both *Nm*F2 and its increase rate with P are small at the EIA trough stations Dakar, Ouagadougou, Djibouti, and Kodaikanal, which is similar to the result in the East Asia/Australia sector. At Huancayo, however, the *Nm*F2 (except at low solar activity) and its increase rate with P are significantly higher at ME than at SE. Moreover, at the EIA crest stations the equinoctial asymmetry also does not fully present the features (for example, the higher increase rate at SE than at ME) that appear in the East Asia/Australia sector. The results at these low-latitude stations indicate that there is a longitudinal dependence in ionospheric equinoctial asymmetry. Certainly, data deficiencies possibly affect the linear fit at some stations, but the longitudinal similarity and discrepancy in the equinoctial asymmetry still can be seen from the observations. The feature of higher increase rate at ME than at SE that widely appears at mid-latitude stations is not obvious at the low-latitude stations except Huancayo.

Figure 5 shows the distributions of the increase rate of TEC with P at ME and SE. There are two peaks of the increase rate at low latitudes, which is similar to the latitudinal feature of the increase rate of *Nm*F2 with P, and the peak in the Northern Hemisphere is slightly stronger than that in the Southern Hemisphere at most longitudes. It is notable that there is a longitudinal dependence in the locations of the peaks. The peaks locate at the latitude bands parallel to dip equator at most longitudes except the longitude sector of $-60° \sim 40°$, where the double-peak structure of the increase rate is weak and the peaks are not parallel to dip equator. Figure 6 shows the equinoctial difference in the increase rate of TEC with P. The increase rate at ME is higher than that at SE, and the difference between them strongly depends on latitudes. The equinoctial difference of the increase rate peaks at both sides of dip equator and decreases towards higher latitudes. The percentage difference also has similar double-peak structure, but the peaks of the percentage difference move to higher latitudes as compared with the peaks of the (ME-SE) difference. Both the (ME-SE) and the percentage differences significantly depend on longitudes at the latitudes where the peaks of the equinoctial difference

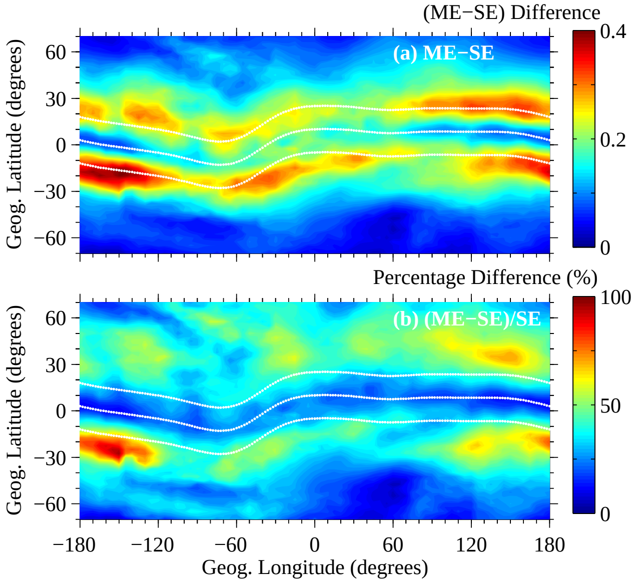

Fig. 6. Same as Fig. 5 but for the distributions of **(a)** the (ME-SE) difference and **(b)** the percentage difference of the linear fit slope of TEC with P.

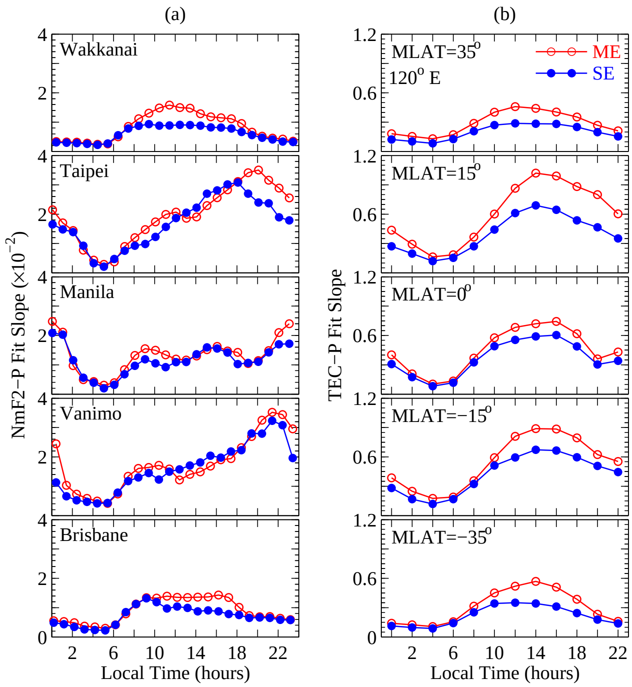

Fig. 7. Local time variations of the linear fit slopes of **(a)** *Nm*F2 and **(b)** TEC with the P index (fitting for $P < 140$, see Fig. 2).

locate. It is notable that the peaks of the equinoctial difference are parallel to dip equator even in the longitude sector of $-60° \sim 40°$.

Figure 7 illustrates local time variations of the increase rates of *Nm*F2 and TEC with P in the East Asia/Australia sector. There are latitudinal dependences in local time variations of the increase rates, especially for *Nm*F2 increase rate. For example, *Nm*F2 increase rate increases during the afternoon at the EIA crest stations (Taipei and Vanimo) while begins to increase after sunset at the EIA trough station (Manila), these increments, however, do not take place at mid-latitude stations. There are also some differences between *Nm*F2 increase rate and TEC increase rate, especially at low latitudes. The equinoctial asymmetries in *Nm*F2 and TEC increase rates show significant dependences on local time. They are stronger during daytime and small during nighttime at middle latitudes, but the equinoctial difference in *Nm*F2 increase rate becomes prominent after sunset at low latitudes. Solar activity variations of *Nm*F2 obviously present the feature of higher increase rate at SE than at ME only at the EIA crest latitudes and in the afternoon when the equinoctial difference of *Nm*F2 increase rate is small at the EIA trough station. It is notable that after sunset the equinoctial asymmetry of low-latitude *Nm*F2 increase rate turns to the feature of higher increase rate at ME than at SE. For solar activity variations of TEC, Fig. 7 shows that the increase rate is always higher at ME than at SE at all local times.

3 Discussion

Solar activity variations of *Nm*F2 and TEC present discrepant equinoctial asymmetries. The asymmetry of higher increase rate at SE than at ME only appears in the variation of *Nm*F2 with P, but not in the variation of TEC with P. And unlike the equinoctial difference of *Nm*F2 at high solar activity, which is smaller at low latitudes than at middle latitudes, the equinoctial difference of TEC is prominent at all latitudes at high solar activity. These are possibly due to the equinoctial difference of ionospheric scale height. L. Liu et al. (2007) revealed that the increase rate of ionospheric scale height with the P index is higher at ME than at SE over Arecibo. This asymmetry in solar activity variations of the scale height could suppress the equinoctial difference in *Nm*F2 increase rate that featured by higher increase rate at SE than at ME and result in larger increase of TEC with P at ME than at SE.

It is mentionable that our result shows the increase rate of TEC with P is higher at ME than at SE, in contrast, the result of Unnikrishnan et al. (2002) implies that the increase of TEC with solar activity is larger at SE than at ME, namely higher increase rate at SE than at ME. That maybe is due to that the influence of the inter-annual change of solar activity was not taken into account in Unnikrishnan et al. (2002). The $F_{10.7}$ index obviously indicates the differences of solar activity between ME and SE in 1981 and 1984.

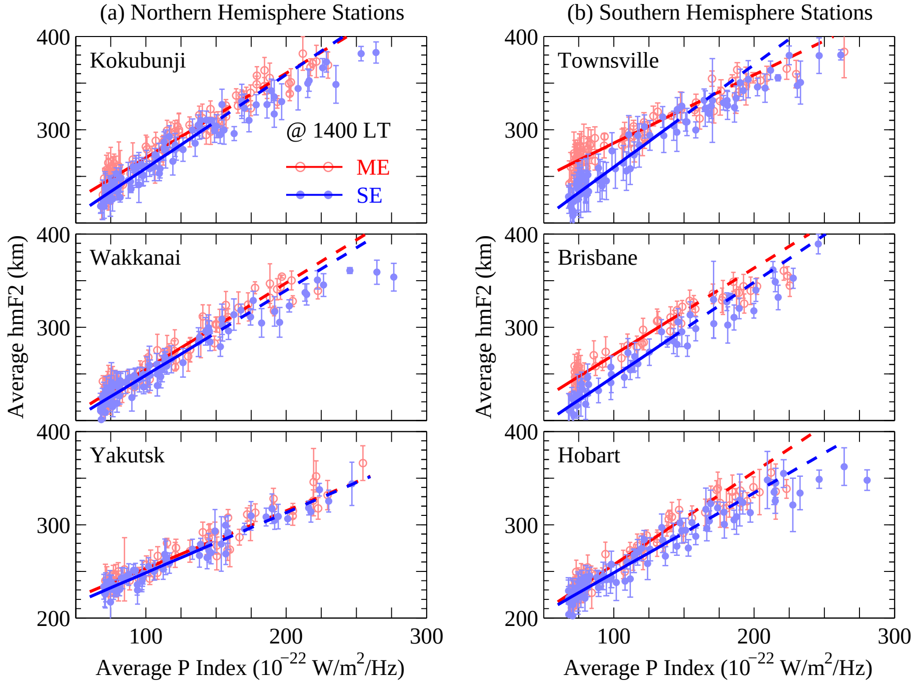

Fig. 8. Same as Fig. 2a but for the variations of *hm*F2 with the P index.

Equinoctial differences in *Nm*F2 and TEC as well as their variations with solar activity indicate that there are equinoctial asymmetries in the thermosphere and ionospheric dynamics processes. Balan et al. (1997, 1998) and Kawamura et al. (2002) explained the equinoctial asymmetry of the electron density with neutral winds observed by the MU radar and simulations. They found the polewards wind in daytime is stronger at SE than at ME over the MU radar location, so *hm*F2 (peak height of the F2 layer) is higher at ME than at SE, which results in the electron density around and above the F2 peak is higher at ME than at SE.

The influence of neutral winds on *hm*F2 depends on the value of $\sin(2I)$, here I is the geomagnetic dip (e.g. Rishbeth, 1972). Figure 8 shows the variations of *hm*F2 with P in the East Asia/Australia sector. *hm*F2 is calculated in terms of *fo*E (critical frequency of the E layer), *fo*F2, and $M(3000)F_2$ (maximum usable frequency factor) according to Dudeney (1983). The stations in each row locate at similar geomagnetic latitudes. There are some equinoctial differences in both *hm*F2 and its increase with P, and the differences are more significant in the Southern Hemisphere. The discrepancy between hemispheres may be related to the difference in the geographical latitudes of the stations. The equinoctial difference of *hm*F2 shows a latitudinal dependence. The difference becomes more significant towards where $I = 45°$ (from Yakutsk to Kokubunji and from Hobart to Townsville). This latitudinal feature seems to display the control of neutral winds on *hm*F2 equinoctial difference. Some works revealed that daytime polewards wind at SE is higher than that at ME over some mid-latitude locations (e.g. Balan et al., 1997, 1998; L. Liu et al., 2003). Higher plowards wind at SE should lower *hm*F2 and suppress *Nm*F2 and its increase with solar activity. It is notable that the equinoctial difference of *hm*F2 over Townsville is not prominent at higher solar activities. This possibly relates to the decrease of neutral winds with solar activity (e.g. Kawamura et al., 2000).

The equinoctial difference in *hm*F2 cannot fully explain the equinoctial asymmetry of the electron density. For example, the equinoctial difference of *hm*F2 is small at Yakutsk, and the equinoctial asymmetry in the increase rate of *hm*F2 with P is contrast to that of *Nm*F2 at Townsville. Under these conditions thermospheric composition may play an important role for the equinoctial asymmetry of the electron density at middle latitudes. Larger $[O]/[N_2]$ (the density ratio of atom oxygen to molecule nitrogen) should cause higher *Nm*F2 and its increase rate with solar activity. There is not enough direct observations to present the information about the equinoctial difference of $[O]/[N_2]$ at different solar activities. But then Balan et al. (1997, 1998) indicated that the $[O]/[N_2]$ from the MSIS model is more or less higher around ME day than around the SE day. In this paper the data grouping (ME data and SE data) just distributes around the ME day and SE day. So the potential equinoctial difference in $[O]/[N_2]$ also could be a reason for the equinoctial asymmetry of the electron density presented in this paper.

Low-latitude *Nm*F2 presents different equinoctial asymmetries from those of mid-latitude *Nm*F2. It indicates the reasons for the equinoctial asymmetry may be different between low and middle latitudes. The fountain effect is very important at low latitudes; it closely depends on the strength of the equatorial $\boldsymbol{E} \times \boldsymbol{B}$ vertical drift. Ren et al. (2011) revealed that equatorial vertical plasma drift at 600 km has complex equinoctial differences, which indicates that the equatorial $\boldsymbol{E} \times \boldsymbol{B}$ vertical drift in the F2 peak region may be different in the two equinoxes. The equinoctial difference in the $\boldsymbol{E} \times \boldsymbol{B}$ vertical drift should induce the equinoctial asymmetry of the electron density at low latitudes. A larger $\boldsymbol{E} \times \boldsymbol{B}$ vertical drift in daytime should cause a stronger fountain effect to change the latitudinal distribution of the plasma density at low latitudes via moving the plasma from the EIA trough region to the EIA crest region, thus *Nm*F2 should decrease in the EIA trough region and increase in the EIA crest region, so should the increase rate of *Nm*F2 with solar activity. That is to say the equinoctial difference in the $\boldsymbol{E} \times \boldsymbol{B}$ vertical drift should induce opposite equinoctial asymmetries of the electron density between the EIA trough and EIA crest regions. In the East Asia/Australia sector, however, the equinoctial asymmetries of low-latitude *Nm*F2 are not consistent with this feature. Therefore, other factors (such as thermospheric composition and density and also neutral winds in the EIA crest region) also should play important roles at low latitudes.

H. Liu et al. (2007) pointed out that neutral density at 400 km altitude at ME is about $7 \sim 10\,\%$ higher than that at SE at the solar activity level of $F_{10.7} = 150$. Atomic oxygen is dominant at the F2 layer altitudes. So the increased neutral density mainly comes from the contribution of atomic composition. The F2 peak rides at the altitude where both photochemical processes and dynamics processes are important. The increased atomic composition may affect *Nm*F2 via dynamic processes even $[O]/[N_2]$ is invariant between ME and SE. Chen et al. (2009) indicated that the increased neutral density (without $[O]/[N_2]$ changing) results in higher electron density at low latitudes. Thus the equinoctial difference of neutral density also affects the equinoctial asymmetry of the electron density. It is notable that the equinoctial differences of thermospheric composition and density should cause similar equinoctial asymmetries of the electron density in the EIA trough and crest regions, which enhances the equinoctial asymmetry induced by the difference of the $\boldsymbol{E} \times \boldsymbol{B}$ vertical drift in one region (EIA trough or crest region) while weakens it in the other region. That potentially causes the observed equinoctial asymmetries at low latitudes.

Moreover, the equinoctial asymmetry at low latitudes shows some longitudinal dependence. Thermospheric composition and density and the $\boldsymbol{E} \times \boldsymbol{B}$ vertical drift have longitudinal dependences (e.g. He et al., 2010; H. Liu et al., 2009; Ren et al., 2011); potentially there are longitudinally dependent differences in these factors between the two equinoxes. That deserves to be studied in the future.

4 Summary

This paper investigated the equinoctial asymmetries of *Nm*F2 and TEC at low and high solar activities and the variations of *Nm*F2 and TEC with the solar proxy P. The equinoctial asymmetries of noontime *Nm*F2 and TEC significantly depend on solar activity. In the East Asia/Australia sector, the equinoctial asymmetry of noontime *Nm*F2 increases with solar activity at middle latitudes but decreases or just has a little change with solar activity at low geomagnetic latitudes. Unlike the feature at low solar activity that the equinoctial asymmetry mainly appears at low latitudes, the equinoctial asymmetry of *Nm*F2 is more prominent at middle latitudes at high solar activity. The equinoctial asymmetry of noontime TEC increases with solar activity at all latitudes, especially at middle latitudes, thus it is prominent at all latitudes at high solar activity. It is notable that noontime *Nm*F2 and TEC around dip equator just present small equinoctial asymmetries at low solar activity.

The increases of *Nm*F2 and TEC with solar activity also show equinoctial asymmetries. In the East Asia/Australia sector, the increase rate of noontime *Nm*F2 with P at ME is higher than that at SE at mid-latitude stations, but the latter is higher than the former over the EIA crest stations, and the difference between them is small at the EIA trough station. The largest percentage difference between equinoctial increase rates of *Nm*F2 appears at middle latitudes. The increase rate of noontime TEC with P at ME is higher than that at SE at all latitudes, and the equinoctial difference of TEC increase rate peaks at both sides of dip equator. It is notable that the feature of higher increase rate at SE than at ME only appears in *Nm*F2 and in the afternoon, it does not appear in TEC. Moreover, the equinoctial asymmetries in the increase rates of *Nm*F2 and TEC with P present some longitudinal dependence at low latitudes.

The discrepancy between the equinoctial asymmetries of *Nm*F2 and TEC is possibly due to the equinoctial difference of ionospheric scale height. The equinoctial asymmetries in both the electron density and its variation with solar activity should be from the equinoctial differences in the thermosphere and ionospheric dynamics processes. The equinoctial difference in neutral winds proposed by Balan et al. (1997, 1998) and Kawamura et al. (2002) could be a primary reason for the equinoctial asymmetry at middle latitudes, and the potential equinoctial differences in other factors, such as thermospheric composition, also maybe are important. None of the equinoctial differences of single factor (equatorial vertical plasma drift, thermospheric composition, or neutral density) can be used to fully explain the observed equinoctial asymmetries at low latitudes; the reason could be the combination of multiple factors.

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