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The features and a possible mechanism of semiannual variation in the peak electron density of the low latitude F2 layer

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Abstract

Ionospheric data observed in 30 stations located in 3 longitude sectors (East Asia/Australia Sector, Europe/Africa Sector and America/East Pacific Ocean Sector) during 1974–1986 are used to analyse the characteristics of semiannual variation in the peak electron density of F2 layer (*N*mF2). The results indicate that the semiannual variation of *N*mF2 mainly presents in daytime. In nighttime, except in the region of geomagnetic equator between the two crests of ionospheric equatorial anomaly, *N*mF2 has no obvious semiannual variation. In the high latitude region, only in solar maxima years and in daytime, there are obvious semiannual variations of *N*mF2. The amplitude distribution of the semiannual variation of daytime *N*mF2 with latitude has a "double-humped structure", which is very similar to the ionospheric equatorial anomaly. There is asymmetry between the Southern and the Northern Hemispheres of the profile of the amplitude of semiannual variation of *N*mF2 and longitudinal difference. A new possible mechanism of semiannual variation of *N*mF2 is put forward in this paper. The semiannual variation of the diurnal tide in the lower thermosphere induces the semiannual variation of the amplitude of the equatorial electrojet. This causes the semiannual variation of the amplitude of ionospheric equatorial anomaly through fountain effect. This process induces the semiannual variation of the low latitude *N*mF2.
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Keywords: Ionosphere; Semiannual variation; Equatorial anomaly; Solar activity; *N*mF2

1. Introduction

It has been found that there is an obvious semiannual variation in the peak electron density in ionospheric F2 layer, *N*mF2, for a long time already. It is maximum at Equinoxes (April and October) and it is minimum at Solstices (January and July). The amplitude of the semiannual variation of *N*mF2 at noon is obviously larger than at midnight. The amplitude of the semiannual variation of *N*mF2 in solar maxima is larger than in solar minima. It is larger in low latitude than in high latitude (Yonezawa and Arima, 1959; Yonezawa, 1967, 1971; Torr and Torr, 1973).

The amplitudes of the semiannual variation of *N*mF2 are large every year, especially in the middle and low latitude. Therefore, the study of the mechanism of this phenomenon has been given great attention. Yonezawa (1971) suggested that the semiannual variation of *N*mF2 is related to the semiannual variation of the upper atmospheric temperature. Torr and Torr (1973) thought that this was due to the semiannual variation in neutral densities associated with geomagnetic and auroral activity. Mayr and Mahajan (1971) showed that the semiannual variation of *N*mF2 require significant variation in the neutral composition at lower height. Evidence for this is found in rocket-borne $[O]/[O_2]$ measurements at 120 km, which show maxima during equinox and a maximum to minimum ratio of 2. Millward et al. (1996), using the coupled thermosphere–ionosphere–plasmasphere

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model, showed that the offset of the geomagnetic axis from Earth spin axis in the Southern Hemisphere is the cause of the semiannual variations of noontime NmF2 in the South American Sector. Rishbeth (1998) had discussed Millward's viewpoint in detail. Chaman Lal (1995) constructed a planetary index of the critical frequency of the F2 layer (F2pd) from 118 ionospheric stations spread all over the globe, which covers the years 1947–1961. The observed long-term seasonal trend of F2pd shows marked semiannual maxima around the equinoxes and minima around the solstices. It is interesting that the long-term seasonal trend of the intensity of the ring current, represented by the geomagnetic index *Dst*, also shows similar equinoctial maxima and solstitial minima. Chaman Lal (1995) showed that the correlation could be either a fortuitous coincidence or it may point to a common cause. If it turns out that the phenomena do, indeed, share the solar wind as the common cause, the correlation would be useful for enhancing our understanding of solar–terrestrial relations. Sequentially, this question was studied extensively by Chaman Lal (1996, 1997, 1998, 2000) with the viewpoint of solar wind energy transport to the F2 layer.

However, there has been no agreement for the main reason for the semiannual variation in the peak electron density of F2 layer until now.

The aim of this paper is further to analyse the characteristics of the semiannual variation of NmF2 by using more data which were observed during 1974–1986 at 30 ionosonde stations located at different geomagnetic latitudes and longitudes. A new possible mechanism of semiannual variation of NmF2 is put forward.

2. The data source and the analysis method

The ionospheric data (CD-ROM of Ionospheric Digital Database) used in this paper are provided by World Data Center (WDC-A and WDC-D). The period of the data is from 1974 to 1986, which cover one solar cycle.

In order to analyse the features of semiannual variation of NmF2 at different geomagnetic latitudes and different longitudinal sectors, we analyse the ionospheric data which are observed at 12 stations in East Asia/Australia Sector (Sector A), 8 stations in Europe/Africa Sector (Sector B) and 10 stations in America/East Pacific Ocean Sector (Sector C). Table 1 shows their geomagnetic latitudes and geomagnetic longitudes.

The ionospheric data are the monthly median value of foF2. The peak electron density is calculated by

$$NmF2 = 1.24 \times 10^4 \ (foF2)^2, \qquad (1)$$

where the unit of NmF2 is cm^{-3} and the unit of foF2 is MHz.

In order to study the characteristics of semiannual variation of NmF2, the NmF2 calculated by using monthly median of foF2 are averaged over 0800–1900 LT for every station. It is taken as daytime monthly average value for that station, which is represented by NmF2d. The averaged value of NmF2 over 0100–0700 and 2000–2400 LT is taken as nighttime monthly average value for that station, which is indicated by NmF2n. If the number of the monthly averaged values in the daytime or nighttime is less than 10, it is treated as lack of data for that month.

In order to analyse quantitatively the amplitude characteristics of semiannual variation of NmF2, we use the method of regression analysis (i.e. the fitting method of least square) to calculate the amplitudes and phases of the semiannual variation:

$$y_i = a_0 + a_1 \cos\left(\frac{2\pi}{12} i\right) + a_2 \sin\left(\frac{2\pi}{12} i\right) + a_3 \cos\left(\frac{2\pi}{6} i\right) + a_4 \sin\left(\frac{2\pi}{6} i\right), \qquad (2)$$

where, y_i represent NmF2d$_i$ or NmF2n$_i$, i is the ordinal number of month, $i = 1, 2, 3, \ldots, 12$, a_0–a_4 are the coefficients of regression. a_0 is the annual mean, $A1 = \sqrt{a_1^2 + a_2^2}$ and $\varphi 1 = \tan^{-1}(a_2/a_1)$ are the amplitude and phase of annual variation, respectively, $A2 = \sqrt{a_3^2 + a_4^2}$ and $\varphi 2 = \tan^{-1}(a_4/a_3)$ are the amplitude and phase of semiannual variation, respectively.

In order to ensure the quality of regression analysis, when the number of the NmF2d or NmF2n is less than 10 months, it is treated as lack of data for that year.

3. The characteristics of semiannual variation

In order to visually research the characteristics of semiannual variation, the difference between NmF2d and its yearly average value and the difference between NmF2n and its yearly average value are calculated. They are indicated as dNmF2d and dNmF2n, respectively.

Fig. 1 shows the curves of dNmF2d and dNmF2n in the period of 1974–1986 for every station in Sector A (Fig. 1(a) and (b)), Sector B (Fig. 1(c) and (d)) and Sector C (Fig. 1(e) and (f)). For the convenience of describing the solar activity effect, Fig. 2 gives the curve of monthly average of F10.7 in the same period. The curve of F10.7 indicates that the solar activities are minima in 1974–1976 and 1985–1986, and maxima in about 1978–1982.

Fig. 1(a), (c) and (e) indicate that dNmF2d of every station exhibit obvious semiannual variations every year. The amplitudes of the semiannual variation in the years of solar activity maxima are obviously larger than in the solar activity minima. The amplitudes in the middle and low latitude are larger than in the high latitude.

In the nighttime, Fig. 1(b) shows that the dNmF2n of Manila station located at geomagnetic equator has obvious semiannual variation every year. It is also more obvious in solar activity maxima than in solar minima. On the other hand, the dNmF2n of Chung-Li and Okinawa

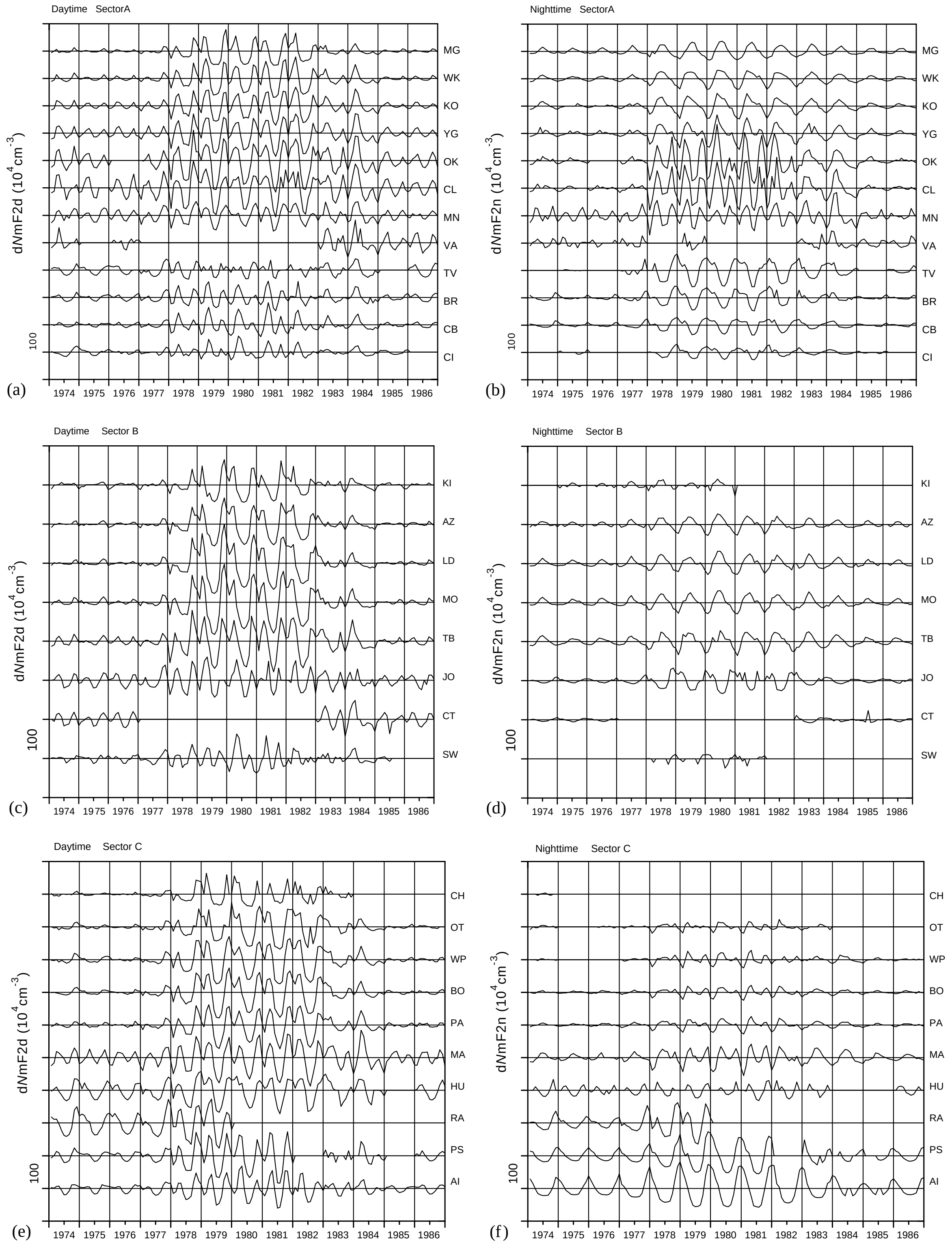

Fig. 1. Curves of d*N*mF2d and d*N*mF2n of 30 ionosonde stations in 3 sectors in the period 1974–1986: (a) d*N*mF2d for Sector A, (b) d*N*mF2n for Sector A, (c) d*N*mF2d for Sector B, (d) d*N*mF2n for Sector B, (e) d*N*mF2d for Sector C, and (f) d*N*mF2n for Sector C.

Table 1
Ionospheric stations whose data have been used

Station name	Abbreviation	Geographic lat. (Deg.)	Geographic long. (Deg.)	Geomagnetic lat. (Deg.)	Geomagnetic long. (deg.)
Sector A					
Magadan	MG	60.1 N	151.0 E	53.2 N	124.6 W
Wakkanai	WK	45.4 N	141.7 E	35.3 N	153.5 W
Kokubunji	KO	35.7 N	139.5 E	25.5 N	154.2 W
Yamagawa	YG	31.2 N	130.6 E	20.4 N	161.7 W
Okinawa	OK	26.3 N	127.8 E	15.3 N	164.0 W
Chung-Li	CL	25.0 N	121.2 E	13.7 N	170.0 W
Manila	MN	14.7 N	121.1 E	3.4 N	169.8 W
Vanimo	VA	2.7 S	141.3 E	12.5 S	148.4 W
Townsville	TV	19.3 S	146.7 E	28.4 S	140.7 W
brisbane	BR	27.5 S	152.9 E	35.7 S	132.6 W
Canberra	CB	35.3 S	149.0 E	43.9 S	135.2 W
Campbell Is.	CI	52.5 S	169.2 E	57.2 S	106.3 W
Sector B					
Kiruna	KI	67.8 N	20.4 E	65.2 N	115.9 E
Arkhanglsk	AZ	64.6 N	40.5 E	58.9 N	128.7 E
Leningrad	LD	60.0 N	30.7 E	56.2 N	117.7 E
Moscow	MO	55.5 N	37.3 E	50.8 N	120.9 E
Tbilisi	TB	41.7 N	44.8 E	36.2 N	122.5 E
Johannesburg	JO	26.1 S	28.1 E	27.0 S	91.8 E
Capetown	CT	34.1 S	18.3 E	32.9 S	80.2 E
Syowa Base	SW	69.0 S	39.6 E	66.5 S	141.1 E
Sector C					
Churchill	CH	58.7 N	94.2 W	68.7 N	36.7 W
Ottawa	OT	45.4 N	75.9 W	56.8 N	8.2 W
Wallops Is.	WP	37.9 N	75.5 W	49.3 N	7.3 W
Boulder	BO	40.0 N	105.3 W	48.9 N	43.0 E
Point Arguello	PA	35.6 N	120.6 W	41.2 N	58.5 E
Maui	MA	20.8 N	156.5 W	21.0 N	91.4 W
Huancayo	HU	12.0 S	75.3 W	0.6 S	5.7 W
Rarotonga	RA	21.2 S	159.8 W	20.8 S	85.9 W
Port Stanley	PS	51.7 S	57.8 W	40.4 S	9.5 E
Argentine Is.	AI	65.2 S	64.3 W	53.8 S	3.3 E

stations located in the equatorial anomaly crest exhibits obvious semiannual variation in the years of solar activity maxima. Due to the lack of many data in Vanimo station, we cannot obtain the semiannual variation of dNmF2n of that station. From Fig. 1(b) we can see that dNmF2n of other stations have only obvious annual variation but do not have the semiannual variation. Unfortunately, there are not enough ionosonde stations in the low latitude region in Sector B. Therefore, we cannot analyse the semiannual variation of dNmF2n in the low latitude region in Sector B. Fig. 1(f) gives the curves of dNmF2n for every station in Sector C. In this sector, there is obvious semiannual variation of dNmF2n at Huancayo, Maui and Rarotonga in the years of solar maxima. There is no large semiannual variation of dNmF2n at other stations.

NmF2d and NmF2n of every station are analysed by using Eq. (2). The annual mean, the amplitudes and phases of the annual variation and the semiannual variation can be obtained, respectively. Here, we only discuss the amplitudes and phases of the semiannual variation.

Fig. 3(a) and (b) give the daytime results of the amplitude and phase of semiannual variation of every station in Sector A in the period of 1974–1986, respectively. The phase of the semiannual variation means the month at which the semiannual variation reaches maximum. The gaps of the lines in the figures represent the lack of data. Comparing Figs. 2 and 3(a), we can see that there is a close relationship between the solar activity and the amplitude of semiannual variation of the daytime peak electron density. The amplitude of semiannual variation of NmF2d in the years of solar

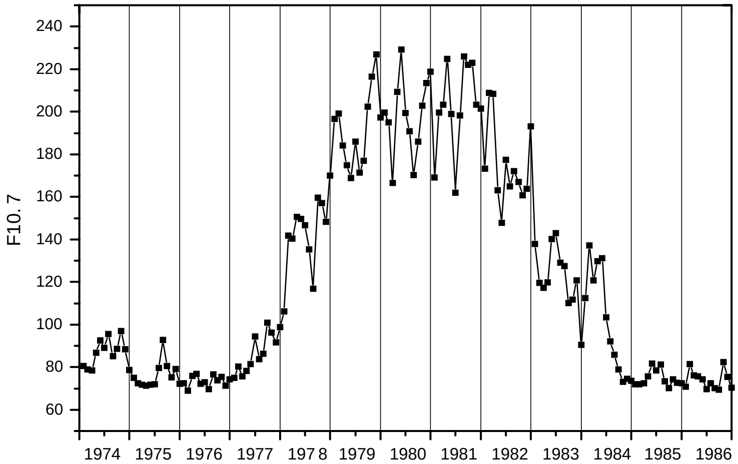

Fig. 2. Variation of monthly averaged solar flux F10.7 in the period 1974–1986.

activity maximum is notably larger than in the years of solar activity minimum. For instance, the amplitude of semiannual variation of *N*mF2d at Kokubunji station in 1979 is 4 –5 times of that in 1975. Fig. 3(a) also shows that the amplitudes of semiannual variation of *N*mF2d in the low latitude stations are larger than in the high latitude stations. Fig. 3(b) indicates that the month the semiannual variation reaches maximum is at about April (October). And they have small tendencies of moving early gradually from 1978 to 1983. The situations of 3 sectors are similar. Therefore, the curves in Sectors B and C are not given in the figure.

The analysis of *N*mF2n by using Eq. (2) for every station indicates that in the night, in the high and middle latitude, the amplitudes of the semiannual variation of *N*mF2n are very small. However, in the region between the two crests of the equatorial anomaly, such as Manila, Chung-Li, Okinawa, Maui and Rarotonga stations, the values of *N*mF2n have obvious semiannual variations in the years of solar maxima.

The amplitude distributions of the semiannual variation of *N*mF2d with the geomagnetic latitude for Sector A are given in Fig. 4. Fig. 4(a) gives the curves of the solar activity minima years (1974–1977 and 1983–1986), and Fig. 4(b) shows the results for the years of the solar activity maximum (1978–1982). The results in Sector C are given in Fig. 5. Owing to lack of data of equator region in Sector B, the results of Sector B are not given.

It is very interesting that the distributions of the amplitude of the semiannual variation of *N*mF2d with the geomagnetic latitude are very similar with the "double-humped structure" of the equatorial ionization anomaly. The maximal amplitude of the semiannual variation appears in the crest of the equatorial ionization anomaly. In Sector A, in the years of solar minimum, the amplitude of the semiannual variation of *N*mF2d is low, and it is symmetrical between the Northern and Southern Hemispheres (see Fig. 4(a)). Fig. 4(b) indicates that, in the years of solar maximum, the amplitudes of the semiannual variation of *N*mF2d become larger, and the region of the hump become wider and moves slightly to the high latitude. And the humped structure is asymmetrical between the two Hemispheres. The amplitudes of the semiannual variation of *N*mF2d in the Northern Hemisphere are larger than in the Southern Hemisphere. In Sector C, in the years of solar maximum, there are also phenomena that the region of the hump become wider and moves slightly to the high latitude. However, the amplitudes of the semiannual variation of *N*mF2d in the Southern Hemisphere are larger than in the Northern Hemisphere (see Fig. 5(b)). Fig. 5(a) indicates that in the years of solar minima, the semiannual variation is in the converse situation, the amplitudes of the semiannual variation are smaller in the Southern Hemisphere. These figures show that the amplitudes of the semiannual variation of *N*mF2d have obvious asymmetrical structures between the two Hemispheres, and they have longitude difference.

Even though the date and position of data used in this paper are different from other researchers, the above basic characteristics of the semiannual variation of electron density in the F2 layer are consistent with the results of Yonezawa and Arima (1959) and Yonezawa (1967, 1971) and Torr and Torr (1973). However, because the data in three sectors are analysed in this paper, the characteristics of asymmetrical structures between the two Hemispheres and longitude difference are obtained.

4. A possible mechanism of semiannual variation

Maybe, there are many factors to cause semiannual variation of *N*mF2. However, what is the main mechanism of inducing the semiannual variation of *N*mF2 is an open question.

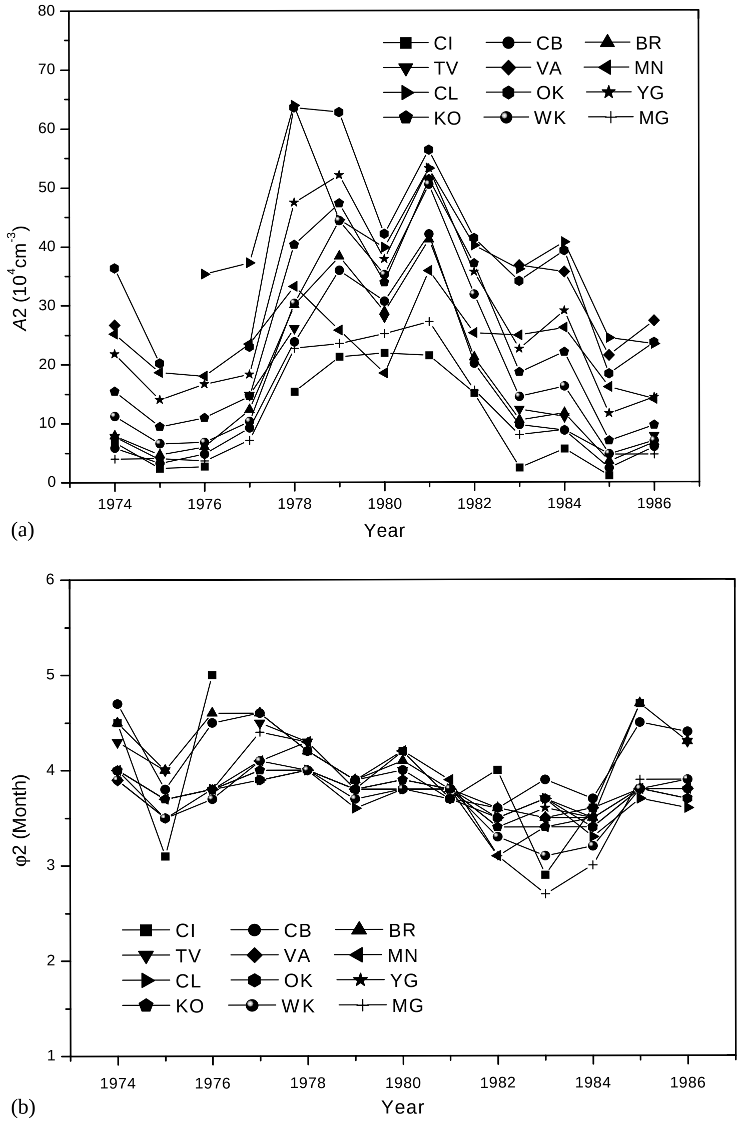

Fig. 3. Curves of the amplitude (a) and phase (b) of semiannual variation of daytime *N*mF2 in the Sector A.

From the basic characteristics of the semiannual variation of *N*mF2, especially, the distributions of the amplitude of the semiannual variation of *N*mF2d have obvious "double-humped structure"; we think that the main cause for the semiannual variation of *N*mF2 may be related to the ionospheric fountain effect. Therefore, by the enlightenment of this viewpoint, we put forward a new possible mechanism of the semiannual variation of the low latitude *N*mF2: the semiannual variation of the amplitude of the diurnal tide in the lower thermosphere induces the semiannual variation of equatorial electrojet in the ionospheric E layer. And then it induces the semiannual variation of amplitude of ionospheric equatorial anomaly through the 'fountain effect'. This process causes the semiannual variation of the low latitude *N*mF2. We give the qualitative analysis on this mechanism as follows.

The analysis of the wind data of UARS satellite by Burrage et al. (1995) showed that there are very obvious semiannual variations of the amplitude of the diurnal tide (1,1) mode at the height of 95 km in the period of October 1991–March 1995, and the amplitudes of the diurnal tide at equinoxes are obviously larger than at solstices. The results are given in Fig. 6. Forbes (1981) pointed out that the diurnal tide (1,1) mode in the ionospheric E layer is the directly driving source for the equatorial electrojet. Therefore, there must be the semiannual variation

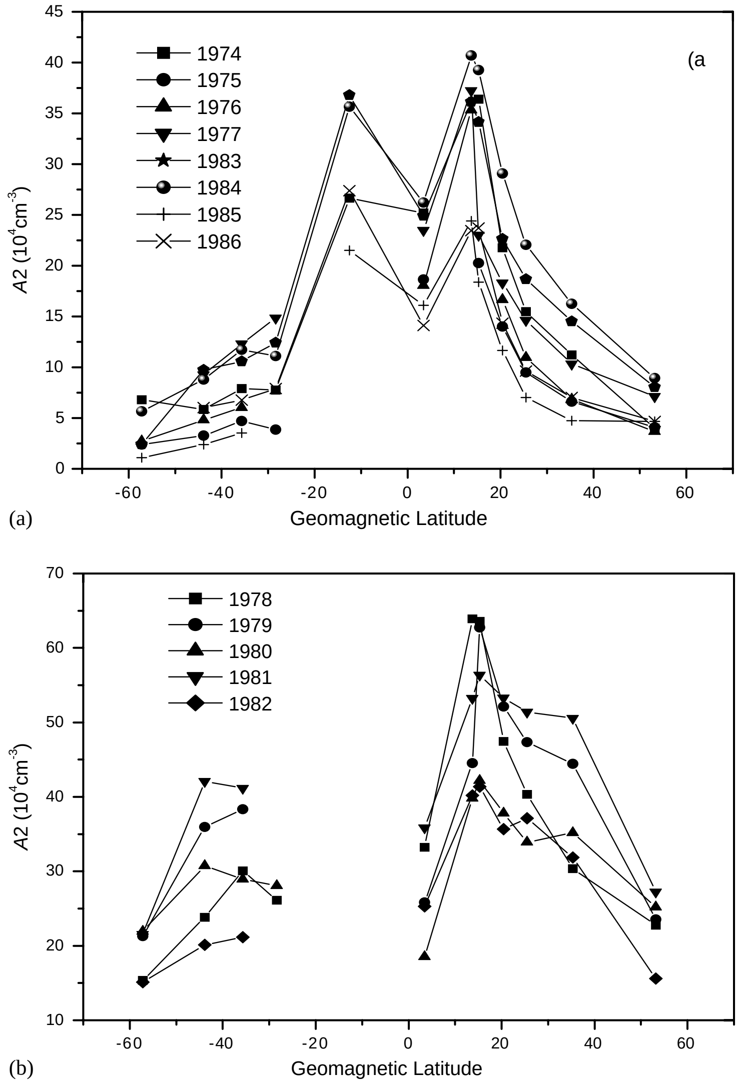

Fig. 4. Variation of the amplitude of semiannual variation of daytime NmF2 with the geomagnetic latitude in Sector A: (a) in the years of solar minimum, and (b) in the years of solar maximum.

in the intensity of the equatorial electrojet. MacDougall (1969) showed that the equatorial electrojet indeed has semiannual variation and the equatorial anomaly has direct relation with the equatorial electrojet. Therefore, the semiannual variation of the amplitude of the diurnal tide (1,1) mode consequentially induces the semiannual variation of the ionospheric equatorial anomaly through the dynamo effect.

Fig. 7 shows the variation of daytime NmF2d at Chung-Li station in the period 1991–1994. Comparing Figs. 6 and 7, the variation of the amplitude of diurnal tide is similar with NmF2d. They are all maxima at equinoxes. Their amplitudes of the semiannual variation in 1992 are larger than in 1994.

Raghavarao et al. (1988) pointed out that the electron density in the equatorial anomaly region in the year of solar maximum is obviously higher than in the year of solar minimum. In the years of solar activity maximum, the crests of the equatorial anomaly becomes wider and moves to high latitude. This phenomenon is very consistent with the variation of the amplitude of semiannual variation of NmF2d with geomagnetic latitude. This indicates that the ionospheric 'fountain effect' may be the primary source for the semiannual variation of the low latitude NmF2 again.

In the stations located in the peak region of equatorial anomaly of the ionospheric F2 layer, the nighttime NmF2 has also semiannual variation. This may be

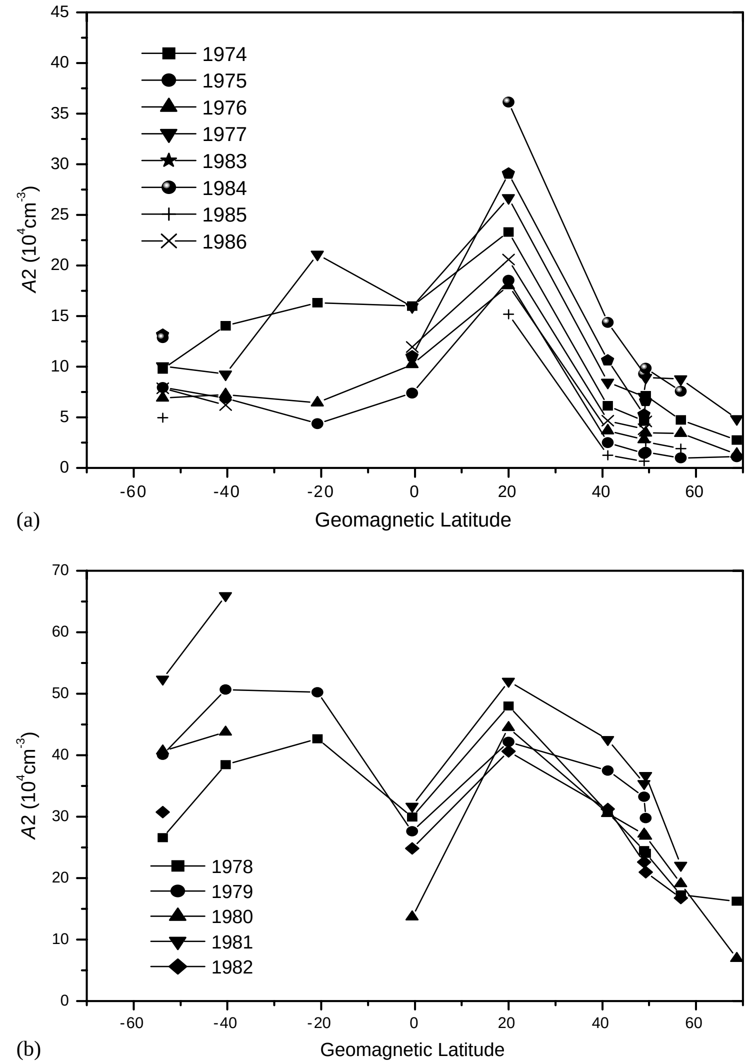

Fig. 5. Same as Fig. 4, but for the Sector C.

because in the low latitude the fountain effect can last until night.

There are obvious semiannual variations of NmF2 in the daytime and nighttime at Manila and Huancayo stations located at geomagnetic equator. The reason is very complex and the mechanism needs further study.

The solar EUV radiation is the main source to form ionospheric F2 layer. Therefore, if the solar F10.7 flux has semiannual variation component and its maxima appear at equinoxes, the semiannual variation of NmF2 can be enhanced. When they are out of phase with the semiannual variation of NmF2, the semiannual variation of NmF2 will be weakened. From Fig. 2 we can see that in the years of solar maxima, solar F10.7 flux has obvious semiannual variation component. We average the phases of semiannual variation of NmF2d of every station in the 3 sectors. The averaged phase value is 3.7. This means that the semiannual variation reaches maximum at 3.7 months (or in the months of 3.7+6) every year. We fitted the monthly averaged F10.7 flux using the method of least squares by the following formula:

$$\mathrm{F10.7}_i = a + b\cos((i - 3.7) \times \pi/3), \quad (3)$$

where i is the ordinal number of month, a is the mean solar F10.7 flux, and b is the amplitude of the semiannual variation component of solar F10.7 which is the maximum at 3.7 months. b/a is the relative amplitude of that component. The result is given in Fig. 8. Fig. 8 also gives the curves of the averaged relative amplitude of the semiannual variation of NmF2d in 3 sectors simultaneously. It is

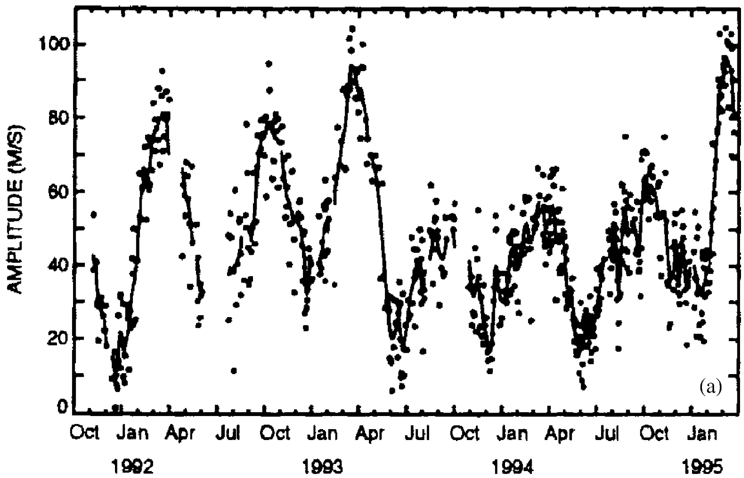

Fig. 6. Daily estimates of the (1,1) diurnal component of the meridional wind obtained from HRDI data for an altitude of 95 km and a latitude of 20°. The solid line is a 10-day running average, which serves to highlight the long-term variations (From Burrage et al., 1995).

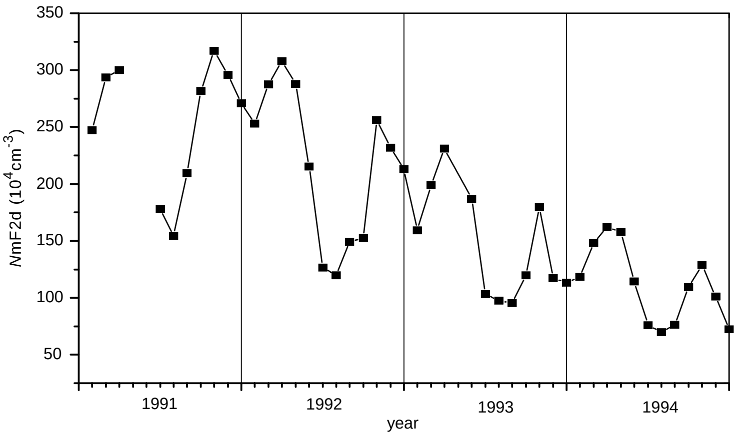

Fig. 7. Variation of NmF2d at Chung-Li ionosonde station in the years 1991–1994.

interesting that the curves of the averaged relative amplitude of NmF2d in 3 sectors basically have the same tendency of the solar F10.7 flux. In 1980, the solar F10.7 flux has negative component of semiannual variation. The relative amplitude of the semiannual variation of NmF2d obviously decreases consequently. In 1978 and 1981, the solar F10.7 flux had positive component of semiannual variation, the relative amplitude of the semiannual variation of NmF2d obviously increases.

5. Conclusion

The analysis of 13 years ionosonde data of 30 stations further gives the main features of the semiannual variation of NmF2: the semiannual variation of NmF2 mainly appears in daytime. Except in the low latitude region between the peaks of equatorial anomaly, there is no obvious semiannual variation of NmF2 in the nighttime. In the polar region, NmF2 has obvious semiannual variation only in solar maximum and in the daytime. The amplitude of the semiannual variation of NmF2 has a close relationship with the solar activity. The amplitude of the semiannual variation of NmF2 in the years of solar maximum is larger than in the years of solar minimum. The amplitude distribution of the semiannual variation of NmF2d with geomagnetic latitude has very similar "double-humped structure" of ionospheric equatorial anomaly. There are asymmetry between the Southern and the Northern Hemispheres of the profile of the amplitude of semiannual variation of NmF2 and longitudinal difference.

According to these analyses, we think that the semiannual variation of the low latitude NmF2 may be caused as

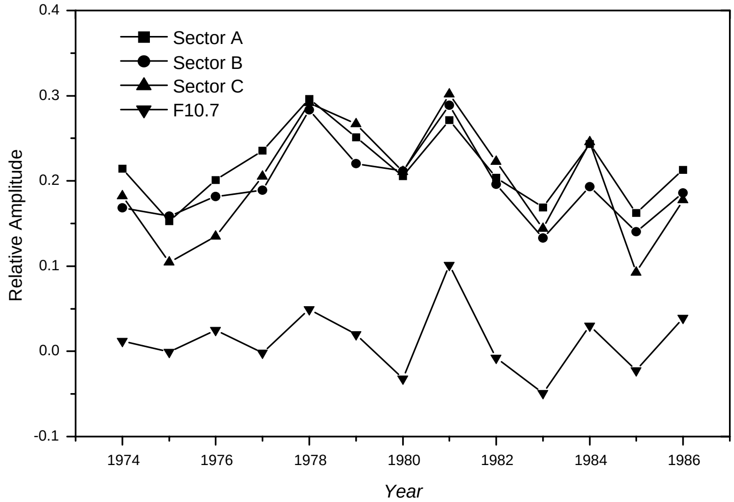

Fig. 8. Averaged relative amplitude of the semiannual variation of NmF2d for 3 sectors and the relative amplitude of the semiannual variation component of solar F10.7 flux which reach maximum at 3.7 months (or in the months of 3.7+6).

follows: The semiannual variation of the diurnal tidal induces the semiannual variation of equatorial electrojet, and then it induces the semiannual variation of equatorial anomaly by the fountain effect. This process causes the semiannual variation of the low latitude NmF2.

The asymmetry between the Southern and the Northern Hemispheres and the longitudinal difference of the amplitude of the semiannual variation of NmF2 maybe caused by the offset of the geomagnetic axis from Earth spin and the thermospheric circulation. The situations of the middle latitude were discussed in detail by Millward (1996) and Rishbeth (1998).

In this paper, we only discuss a possible mechanism of the semiannual variation of the low latitude NmF2 qualitatively. This mechanism needs further studies quantitatively and numerical simulation.

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