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Modeling the effects of secular variation of geomagnetic field orientation on the ionospheric long term trend over the past century

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[1] A middle- and low-latitude ionospheric theoretical model is used for the first time to assess the effects of the secular variations of geomagnetic field orientation on ionospheric long-term trends over the past century. It is found that the varied geomagnetic field can produce ionospheric long-term trends in both foF2 and hmF2. Since the amplitudes of geomagnetic field change depend on location, the modeled trends by secular variations of geomagnetic field orientation differ from place to place. The modeled ionospheric trends have obvious seasonal and diurnal variations. These variations show typical regional features. By comparison with existing results, we suggest that the changes of the global geomagnetic field may partly contribute to the inconsistent seasonal and local time variation patterns in ionospheric trends from different observations. The average trends of foF2 and hmF2 are −0.0047 MHz/a and −0.0107 km/a during 1900–2005, which is near or even comparable with those of other trend origins. In comparison with the trend results from worldwide observations, we conclude that the effects of geomagnetic field orientation on the ionospheric long-term trend cannot be ruled out, especially in areas with large geomagnetic field variations.

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1. Introduction

[2] In the past decades, many investigations have been performed on analysis of ionospheric long-term trends since *Rishbeth* [1990] and *Rishbeth and Roble* [1992] predicted changes in the ionosphere by doubling the atmospheric greenhouse CO_2 [*Bremer*, 1998, 2001; *Bremer et al.*, 2004; *Danilov*, 2002, 2003; *Danilov and Mikhailov*, 1999; *Elias and de Adler*, 2006; *Foppiano et al.*, 1999; *Jarvis et al.*, 1998; *Laštovička*, 2005; *Laštovička et al.*, 2006a, 2006b; *Marin et al.*, 2001; *Mikhailov*, 2002; *Mikhailov and Marin*, 2000, 2001; *Mikhailov et al.*, 2002; *Ulich and Turunen*, 1997; *Xu et al.*, 2004; *Yue et al.*, 2006]. Up to now, many mechanisms have been proposed as the drivers of ionospheric long-term trends, such as greenhouse effect [*Bremer*, 1998, 2001; *Jarvis et al.*, 1998], secular variations of solar and geomagnetic activities [*Laštovička*, 2005; *Mikhailov and Marin*, 2000, 2001], and the variations of background thermosphere [*Danilov*, 2003; *Foppiano et al.*, 1999; *Jarvis et al.*, 1998]. Unfortunately, the results of different authors are far from consistent and sometimes show discrepancies or conflicts because different methods and data sets were chosen [*Bremer*, 1998, 2001; *Laštovička et al.*, 2006b]. Even for the same data source using the same method, results might be also substantially different when different periods were analyzed [*Clilverd et al.*, 2003]. So it is of great significance for us to continue the investigations on ionospheric long-term trend analysis, including both methods and physical mechanisms [*Elias and de Adler*, 2006; *Laštovička et al.*, 2006b].

[3] It is now generally accepted that the geomagnetic field has prominent impacts on the ionosphere. For example, the geomagnetic inclination angle (I) can influence the effects of thermospheric wind on the ionosphere. The horizontal thermospheric wind U drives the plasma moving along the geomagnetic lines at the speed of U cos(I) [*Batista et al.*, 2002; *Elias and de Adler*, 2006; *Foppiano et al.*, 1999; *Rishbeth*, 1998; *Titheridge*, 1995]. The vertical component of the thermospheric wind, Usin(I)cos(I), can lift or lower the height of the ionosphere and therefore increase or decrease the plasma density [*Elias and de Adler*, 2006; *Rishbeth*, 1998; *Titheridge*, 1995]. At the same time, the amplitude of the component of thermospheric wind in the direction of the geomagnetic field is controlled by the geomagnetic angle (D), and can also affect the ionosphere [*Heelis*, 2004]. Another important approach in which geomagnetic field influences the ionosphere is the ionospheric dynamo. It can determine the electric field drift velocity, which is a key driver of ionosphere especially in the low-latitude and equatorial area [*Heelis*, 2004]. In addition, the ratio between the gyrofrequency and the collision frequency for plasma is also an important parameter in ionospheric electric dynamics [*Heelis*, 2004; *Jarvis et al.*, 1998].

[4] Many investigations have shown that the geomagnetic field presents secular variations during recent centuries.

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These variations include the decrease of a dipole field, the movement of the magnetic poles and dipole center, the westward drift of nondipole field, geomagnetic pole reversal, and geomagnetic jerk [*Hongre et al.*, 1998; *Mandea and Dormy*, 2003; *Olsen and Mandea*, 2007; *Smith*, 1987]. For a fixed location, its geomagnetic field parameters including *I*, *D*, and geomagnetic field density, also have secular variations [*Batista et al.*, 2002; *Elias and de Adler*, 2006; *Foppiano et al.*, 1999]. The secular variations, especially those of *I* and geomagnetic field density, will result in long-term variations of the effect of the neutral wind and electric field on the ionosphere [*Elias and de Adler*, 2006; *Foppiano et al.*, 1999; *Ulich and Turunen*, 1997]. This interpretation of the ionospheric long-term trend has been put forward by several researchers, but has not been generally accepted [*Rishbeth*, 1997]. *Jarvis et al.* [1998] simply modeled the effects of the change of the geomagnetic field on the ionospheric hmF2 and compared it with observations from two ionosonde stations located in southern America. They found that the change in the geomagnetic field has a very small mean effect (less than 0.03 km per year) upon hmF2 in comparison with observed results (1/10), and the observed seasonal and local time variations of hmF2 trends could only be partly reproduced. *Foppiano et al.* [1999] also interpreted the long-term trends of foF2 and hmF2 over a midlatitude station from southern America by the secular variations of the thermospheric meridional neutral wind associated with the changes of *I*. The investigation of *Batista et al.* [2002] indicates that the long-term trends in the occurrence of the F3 layer over Fortaleza, Brazil, have a close relationship to that of the *I*. Recently, *Elias and de Adler* [2006] analyzed hmF2 and foF2 trends over three selected stations and assessed the effects of the long-term variations of the geomagnetic field on ionospheric trends quantitatively with a theoretical approximation consideration. Their results revealed that the long-term trend of the geomagnetic field may possibly explain the seasonal pattern of the ionospheric trends in two of the selected three stations.

[5] In this paper, we will study the effects of the secular variations of the geomagnetic field on the ionospheric long-term trends systemically and strictly by a mid- and low-latitude theoretical ionospheric model. The effect of the geomagnetic field intensity cannot be incorporated easily into the model calculations, as we usually use the $E \times B$ drift velocity as the driver in the model, not the electric field itself. Therefore in this modeling investigation, we will concentrate primarily on the influences of the secular changes of the orientation of the geomagnetic field. These changes include the variation of the eccentric dipole field center, the movement of the geomagnetic poles, and the variations of *I* and *D*. This investigation has several purposes as follows. (1) Through our systematic modeling, we can further confirm the ability of the geomagnetic field's secular variations to produce trends in ionosphere [*Elias and de Adler*, 2006; *Foppiano et al.*, 1999]. (2) We will test whether the differences of the trend patterns between different locations are related to the geomagnetic field variations. (3) Our investigation will provide a general picture of the ionospheric long-term trends generated by the corresponding secular variations of the geomagnetic field. The significance of our study is that it will help us to understand the physical mechanism of ionospheric long-term trend. Furthermore, it will also enrich our knowledge of the dependence of ionosphere on geomagnetic field. Much of the research indicates that the derived ionospheric trends have significant variations with several factors such as location, local time, and season [*Bremer*, 1998; *Danilov*, 2003; *Danilov and Mikhailov*, 1999; *Laštovička et al.*, 2006b; *Yue et al.*, 2006]. Nevertheless, different researchers have not given consistent identifications and interpretations on these variations [*Elias and de Adler*, 2006; *Mikhailov and Marin*, 2001; *Yue et al.*, 2006]. The results of *Elias and de Adler* [2006] and *Jarvis et al.* [1998] reveal that the variations of the geomagnetic field may be a possible reason of the seasonal and local time variations of ionospheric trends. This question will be studied in detail in this paper. We suggest it is useful when one studies the physical mechanism of ionospheric trends over different locations.

[6] The remainder of this paper is organized as follows. In section 2, we describe our model and modeling process. The main modeling results are given in section 3. We then discuss and conclude in sections 4 and 5, respectively.

2. Model Description and Modeling Process

[7] Our model is a middle- and low-latitude theoretical model. It solves plasma continuity, motion, and energy equations simultaneously and uses an eccentric dipole approximation to the Earth's magnetic field. We apply the same coordinate system and grid division method as that of *Millward* [1993]. Figure 1 shows the distributions of grid points when 30 geomagnetic lines are chosen between the geomagnetic latitude −45 and 45°. Good coverage can be found in the F layer of the ionosphere. The $\boldsymbol{E} \times \boldsymbol{B}$ drift is considered by the combination of Eulerian and Lagrangian approaches in the model the same way as that of *Pavlov* [2003], and its value is obtained by the Fejer empirical model [*Scherliess and Fejer*, 1999]. Six ions are considered in the model, including three major ions (O^+, H^+, and He^+) and three minor ions (NO^+, O_2^+, and N_2^+). The densities of minor ions are obtained under the assumption of photochemical equilibrium. In the model, a total of 20 chemical reactions are considered. Detailed descriptions of chemical reactions and their reaction coefficients and collision frequencies are discussed by *Tu et al.* [1997] and *Lei et al.* [2004]. In this model, the differences between the temperatures of the different ions are ignored. We only calculate the temperature of O^+. Detailed descriptions about the model including the numerical procedure and the choosing of several parameters such as heating rates and collision frequency are given by *Yue et al.* [2008a]. Neutral backgrounds are obtained by the MSIS00 and HWM93 model. We use Richards' EUVAC model to obtain solar EUV radiation because of a lack of solar radiation observations [*Richards et al.*, 1994]. F107 and Ap are needed to represent solar and geomagnetic activities, respectively. By our test, the model is steady and credible, and can reproduce most large-scale features of ionosphere [*Yue et al.*, 2008a]. It is validated by the observational system data assimilation experiment and comparisons with several empirical models and observations [*Yue et al.*, 2008a, 2008b].

[8] Our model uses an eccentric dipole approximation to the Earth's magnetic field. For one selected location to be

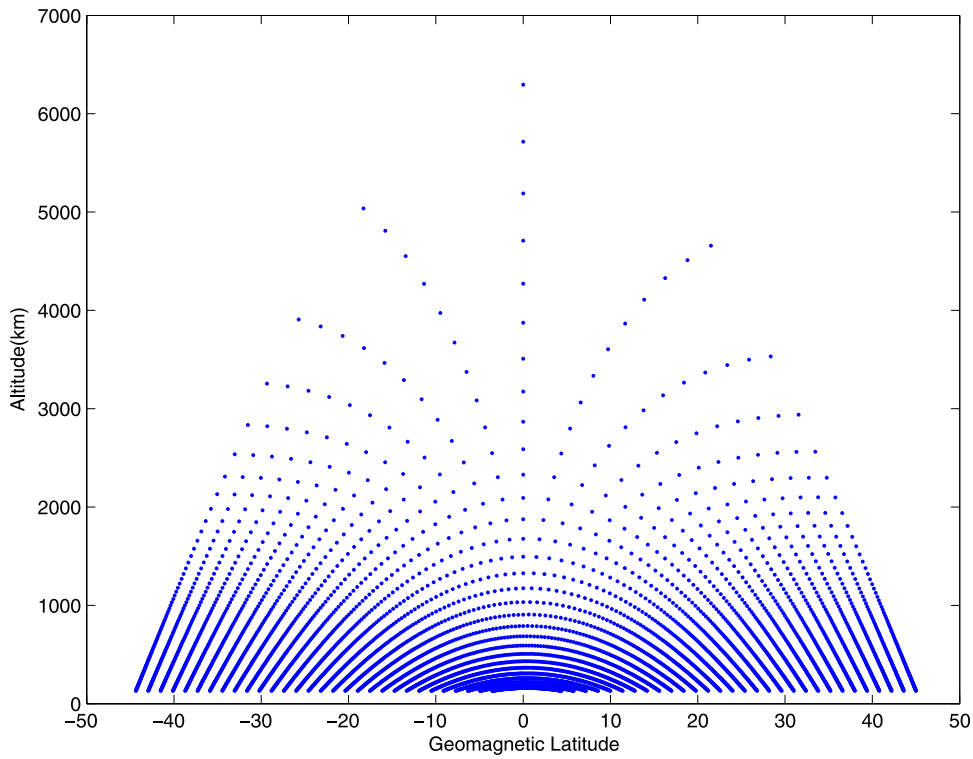

Figure 1. Sketch map of the grid points of our model. Here thirty geomagnetic lines are chosen between geomagnetic latitude −45 and 45°.

modeled, we choose the meridional plane which passes through the point with the same geomagnetic location as the station and 300 km height over it during the modeled date (day of year). At the same time, the variation of the center location of dipole field is also taken into account. The I and D in the model grid points are obtained by the real geomagnetic field. Through these methods, we can consider the effects of the practical geomagnetic field on the ionospheric long-term trend to the greatest extent. The changes of geomagnetic field elements, including the center location of the dipole field, I and D, and geomagnetic latitude and longitude, are calculated by the DGRF/IGRF spherical harmonic coefficients during the years 1900–2005 with a 5-years' interval. The coefficients file is obtained from NGDC on the Web site (http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html). Twelve artificial stations, which are distributed over four typical longitudinal sectors, are selected in our modeling. In each longitudinal sector, three stations are chosen to generally represent the northern low latitude (∼geomagnetic 20°), equatorial area (∼geomagnetic 0°), and southern low latitude (∼geomagnetic −20°), respectively. It should be pointed out that here the low latitude and equatorial stations are not absolute, since the geomagnetic field orientations change from year to year. The corresponding geographic latitudes and longitudes are given in Table 1. The four selected longitudes have typical representation of the global variations of geomagnetic configuration. For example, the inclination angle in 320° longitude changes

Table 1. List of the Twelve Selected Stations Modeled in the Paper and the Corresponding Inclination and Declination in 1900 and 2005 and Linear Yearly Trends of the Inclination, Declination, foF2, hmF2, $|\cos(D)\cos(I)|$ and $|\cos(D)\cos(I)\sin(I)|$ During 1900–2005

		Inclination		Declination		Yearly Trends			
Glon, deg.	Glat, deg.	1900–2005	Trend, °/a	1900–2005	Trend, °/a	foF2, MHz/a	hmF2, km/a	$\lvert\cos(D) * \cos(I)\rvert$ (10^{-5})	$\lvert\cos(D) * \cos(I) * \sin(I)\rvert$ (10^{-5})
50	26	34.29 ∼ 39.71	0.0438	0.55 ∼ 2.09	0.0054	0.0068	−0.0081	−46.4	**20.4**
50	6	−9.03 ∼ −3.52	0.0357	−1.74 ∼ −0.87	0.0008	0.0014	0.0239	**6.9**	−60.7
50	−16	−50.70 ∼ −48.44	0.0085	−7.61 ∼ −12.75	−0.0625	−0.0086	−0.0105	−0.4	**−6.4**
140	30	41.74 ∼ 41.60	−0.0080	−2.69 ∼ −5.01	−0.0206	−0.0185	−0.0648	7.3	**−3.0**
140	10	7.40 ∼ 4.83	−0.0355	2.46 ∼ 1.42	−0.0102	0.0034	0.0107	**6.6**	−60.6
140	−10	−32.36 ∼ −35.02	−0.0333	4.66 ∼ 4.95	0.0032	0.0237	0.0645	−32.8	**21.2**
230	16	35.00 ∼ 35.04	0.0075	9.08 ∼ 10.42	0.0053	0.0039	0.0514	−8.8	**3.5**
230	−6	−6.49 ∼ −5.32	0.0190	7.41 ∼ 10.24	0.0185	0.0015	0.0160	**−1.8**	−32.7
230	−26	−40.30 ∼ −39.20	0.0130	11.00 ∼ 15.56	0.0377	−0.0028	0.0130	2.4	**−11.6**
320	10	37.07 ∼ 14.24	−0.2224	−13.78 ∼ −18.34	−0.0389	−0.0761	−0.0788	149.9	**−221.9**
320	−10	5.47 ∼ −22.30	−0.2678	−11.52 ∼ −22.60	−0.1022	−0.0214	−0.1840	**−107.1**	412.8
320	−30	−24.36 ∼ −45.13	−0.2014	−8.63 ∼ −21.36	−0.1209	0.0306	0.0384	−234.6	**98.6**

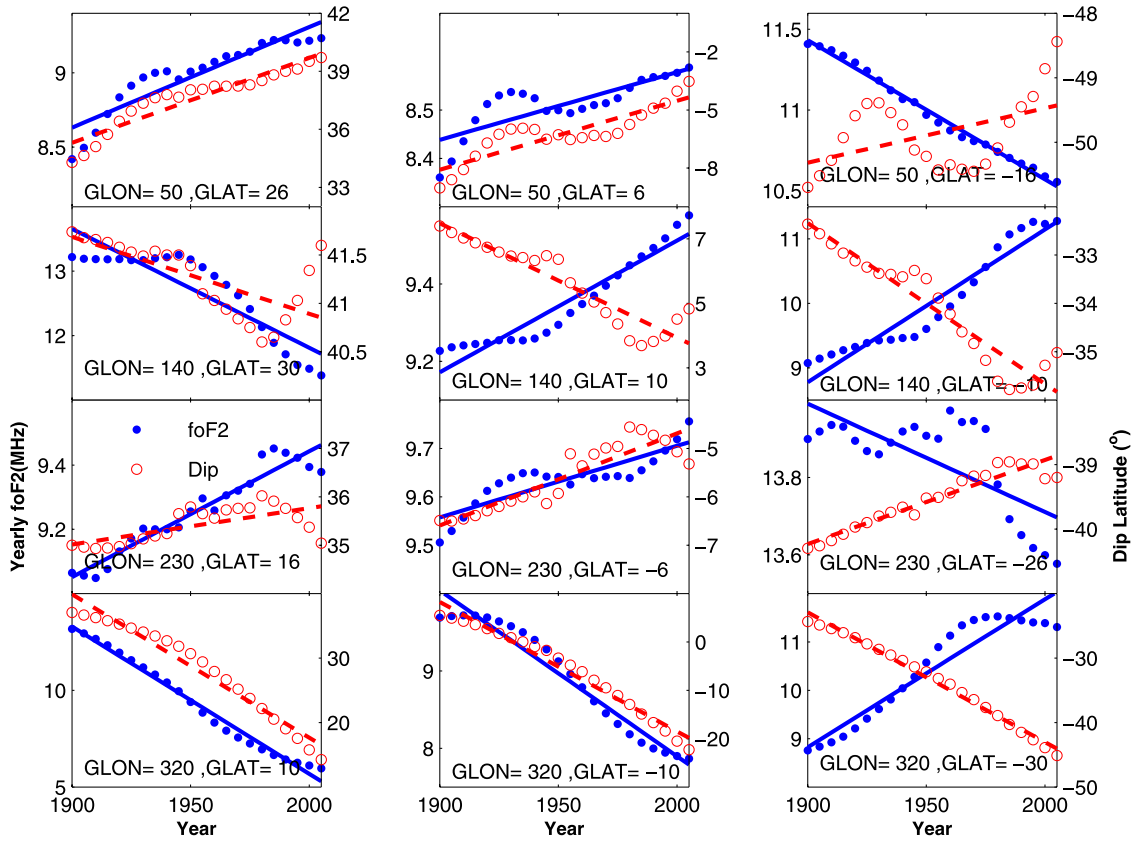

Figure 2. Modeled foF2 (solid dots) and its linear regression results (solid lines) are plotted versus years during 1900–2005 for the 12 modeled stations. The corresponding inclination (circles) and its regression results (dashed lines) are also given in the figure. Numbers in every subplot are the corresponding geographic longitude and latitude.

most significantly and most inconspicuous in 140°. The longitude sector of 320° in the low latitude corresponds to the Brazilian anomaly region. For every station, foF2 and hmF2 for 1900–2005 are modeled with the time interval of 5 years, which is the same as that of DGRF/IGRF spherical harmonic coefficients. In every year, the 81st, 173rd, 265th, and 357th days are selected to represent four different seasons. The model is run under middle solar activity (F107 = 150) and geomagnetic quiet conditions (Ap = 1).

3. Results

3.1. Yearly Trends of foF2 and hmF2

[9] In this study, solar and geomagnetic activities are constant. If we assume the trend is linearly dependent on the year, as almost all the trend analyzers did, the trend is derived by the following formula [*Laštovička et al.*, 2006b]:

$$P_{\mathrm{mod}} = k \times year + a, \tag{1}$$

where P represents foF2 or hmF2, and k is the corresponding trend. The significance of the linear trend is tested with the Fisher's F criterion [*Pollard*, 1977]:

$$F = r^2(N-2)/(1-r^2), \tag{2}$$

where r is the correlation coefficient between variables P and *year* in equation (1), and N is the number data of each time series.

[10] Long-term variations of modeled foF2 and hmF2 and their linear regression results obtained by equation (1) over twevel selected locations from 1900 to 2005 are given in Figures 2 and 3. To make a comparison, the most important geomagnetic field parameter, I, and its linear regression result are also plotted in every subplot. In addition, D and the variation of the dipole field center also influence the final modeled results. We list I and D in 1900 and 2005 and their linear trends, and the yearly linear trends of foF2 and hmF2 in Table 1. The F test results show that all the trends in Table 1 have a confidence level of 90%.

[11] Generally, the variations of I and D are more evident in the 320° longitude sector than in the other three longitude sectors. I has positive trends in the 50° and 230° longitude sectors and negative in the 140° and 320° longitude sectors. D has the same signs of trends as those of I in almost all the modeled stations except in (50° Glon, −16° GLat) and (140° Glon, −10° GLat). The variations of foF2 and hmF2 versus years are not strictly linear. The modeled trends of foF2 and hmF2 have evident regional character. They have bigger amplitudes in the 320° longitude sector than in the other three longitude sectors, the same as I and D. This illustrates that the variations of geomagnetic field orientation indeed can produce changes in ionosphere. From the

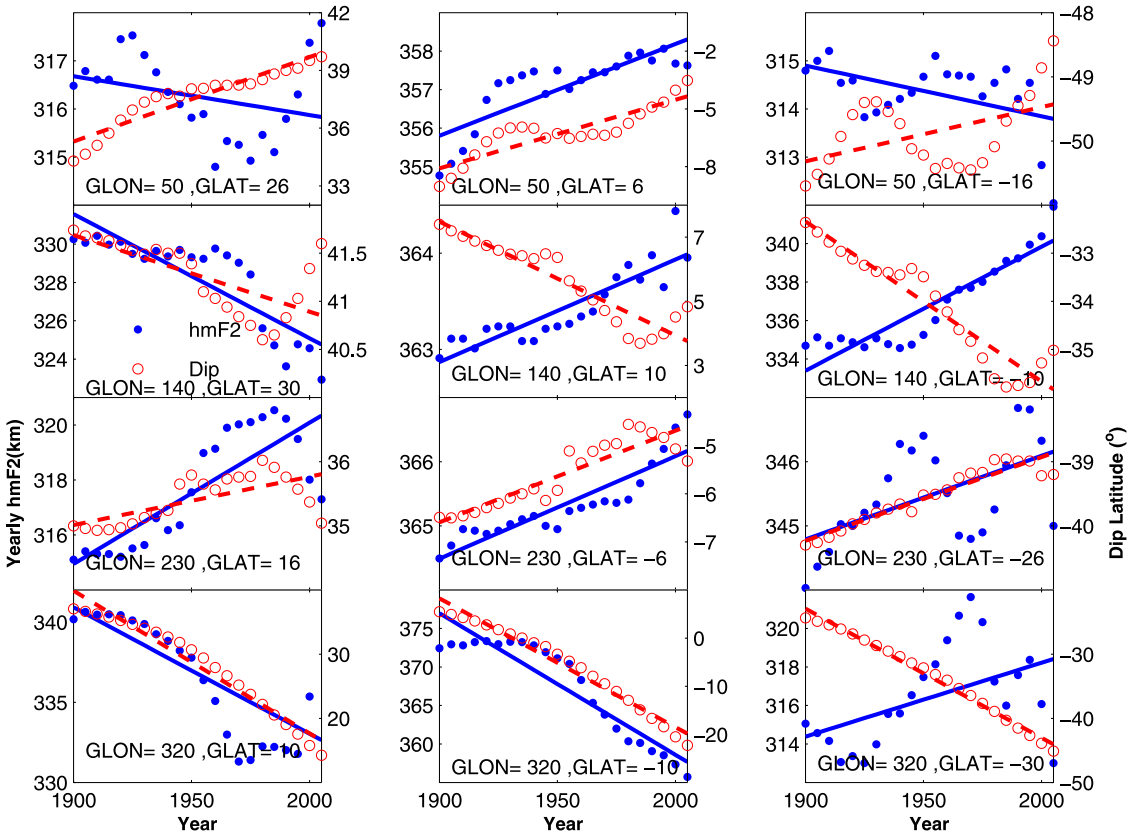

Figure 3. Same as Figure 2, but for hmF2.

figure, we can conclude that foF2 trend in low-latitude stations has the same sign as that of the amplitude of *I*. In equatorial stations, it is reversed. The dependence of hmF2 on *I* is the same as that of foF2 aside from two exceptions in (50° Glon, 26° GLat) and (230° Glon, −26° GLat). The maximum amplitudes of trends in foF2 and hmF2 are 0.0761 MHz per year and 0.1840 km per year, respectively. It shows that the modeled maximum variations of foF2 and hmF2 produced by the geomagnetic field are ∼8 MHz and ∼19 km from 1900 to 2005, respectively. Evidently, these effects cannot be ignored. The minimum amplitudes of trends in foF2 and hmF2 are 0.0014 MHz per year and 0.0081 km per year, corresponding to changes of ∼0.15 MHz and ∼0.85 km during the period 1900–2005. These effects are very small and cannot be comparable to those resulting from other effects such as greenhouse effect [*Rishbeth and Roble*, 1992]. The above comparisons reveal that the effects of the secular variation of geomagnetic field on the ionospheric long-term trend differ from place to place. Detailed discussions about these results will be given in section 4.

3.2. Seasonal and Local Time Variations of Trends in Modeled foF2 and hmF2

[12] Local time and seasonal variations of trends are given in Figures 4 and 5 for modeled foF2 and hmF2, respectively. According to Figure 4, there are no consistent local time and seasonal variation patterns of the foF2 trends in the selected twevel locations. The trends of foF2 vary relatively more sharply near sunrise and sunset time. The seasonal variations are more evident during the night than in the daytime. For the four locations near the equator, there is almost no seasonal variation during daytime, and the amplitude of the trends is very small (∼0). For most locations, the amplitude of foF2 trends is bigger during night than in daytime. In the areas with the increasing *I* (Glon = 50° & 230°), the value of foF2 trends is larger in June-Solstice than in December-Solstice, especially during the night. While in areas with the decreasing *I*, the conclusion is reversed. Except the night sector of stations (50° Glon, −16° GLat), (140° Glon, −10° GLat), (140° Glon, 30° GLat) and (320° Glon, 10° GLat), the results in the Equinox usually lie between those of June-Solstice and December-Solstice. This may be caused by the complicated seasonal and latitude variations of meridional wind in the night sector [*Titheridge*, 1995]. The significance level is greater than 90% in most situations by using *F*-test. The amplitude of the trends with significance level <90% is usually very small (∼0).

[13] For hmF2, also no consistent patterns of seasonal and local time variations of its trends can be detected. In the four equatorial stations, there are no obvious seasonal and local time variations of hmF2 trends. Most trends in three of these four stations have tiny amplitudes with a confidence of level less than 90%. In the equatorial station of the longitude 320° sector, most trends have relatively larger amplitude and significant confidence. This may be related to the large variation of the geomagnetic field in this longitude sector. In the areas with the decreasing *I* (Glon = 140° and 320°), the northern hemisphere low-latitude stations, which correspond to (140° Glon, 30° GLat) and (320° Glon, 10° GLat),

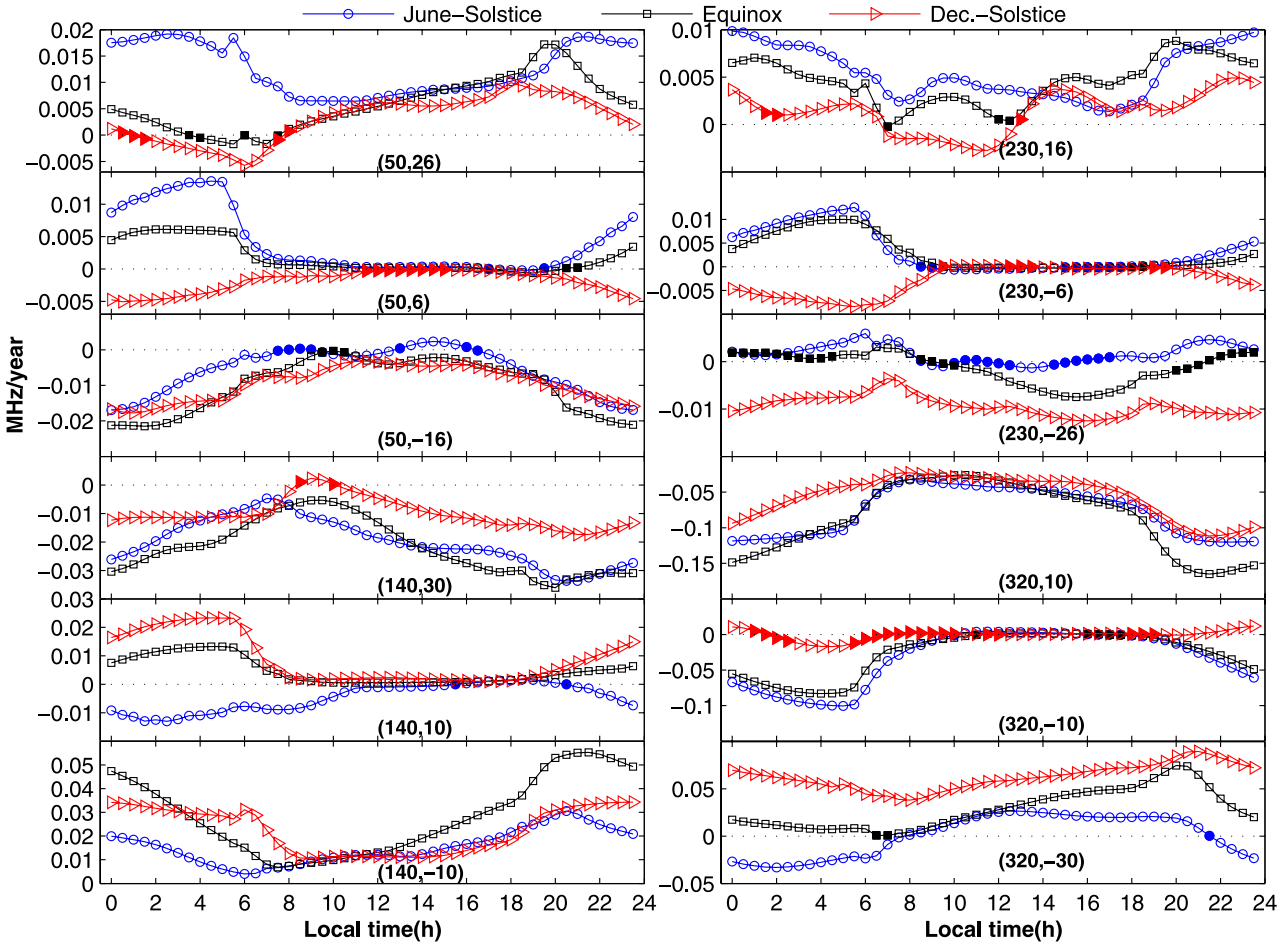

Figure 4. Seasonal and local time variations of foF2 trends in the 12 selected locations. Circles, squares, and right triangles represent June-solstice (173rd day), equinox (81st and 265th days), and *D*.-solstice (357th day), respectively. The trends with confidence level less than 90% are indicated by the filled symbols. The number pair in every subplot is the corresponding geographic longitude and latitude.

have negative trends during daytime and positive trends at night. Sunrise and sunset are two transitional periods. While in the southern low-latitude stations of the same longitudes, the trends are positive in the daytime and negative during night. In the areas with the increasing I (Glon = 50° and 230°), there are no obvious local-time variations in the trends and most correspond to a confidence level less than 90%.

4. Discussion

4.1. Differences Between Trends at Low Latitude Stations and Equatorial Stations

[14] According to section 3, there are obvious differences between trends at low-latitude stations and equatorial stations. The foF2 trend in low-latitude stations has the same sign as that of the amplitude of I. In equatorial stations, it is reversed. The dependence of hmF2 on I is the same as that of foF2 aside from two exceptions in (50° Glon, 26° GLat) and (230° Glon, −26° GLat). For foF2, different from that in low latitude stations, there is almost no seasonal variation during daytime and the amplitude of the trends is very small in equatorial stations (∼0). There are no obvious seasonal and local time variations in hmF2 trends at the four equatorial stations. Except the station of longitude 320° sector, the rest of the three stations have approximately no significant trends.

[15] To our knowledge, the most important ionospheric processes that control the ionosphere are photochemistry and the dynamical process. The photochemistry process mainly influences the production and loss rates of plasma, while the dynamical process determines the plasma diffusion. In this investigation, the neutral meridional wind obtained by the HWM model is in the coordinate of the geographic axis. So the neutral meridional wind U drives the plasma moving along the geomagnetic lines at the speed of $U\cos(D)\cos(I)$, and in the vertical direction it is $U\cos(D)\cos(I)\sin(I)$ [*Elias and de Adler*, 2006; *Rishbeth*, 1998; *Titheridge*, 1995]. Because of the configuration of the geomagnetic field, the diffusion of the plasma is mainly horizontal at the equatorial station. With the increase on latitude, the vertical component of diffusion cannot be ignored. So when the I and D changes, the trends of foF2 and hmF2 should present a behavior like that of $\cos(D)\cos(I)$ in the equatorial stations and like that of the amplitude of $\cos(D)\cos(I)\sin(I)$ in the higher latitude stations. To confirm this assumption, we also calculate the yearly trends of the amplitude of $\cos(D)\cos(I)$ and $\cos(D)\cos(I)\sin(I)$ over the twelve stations and list the

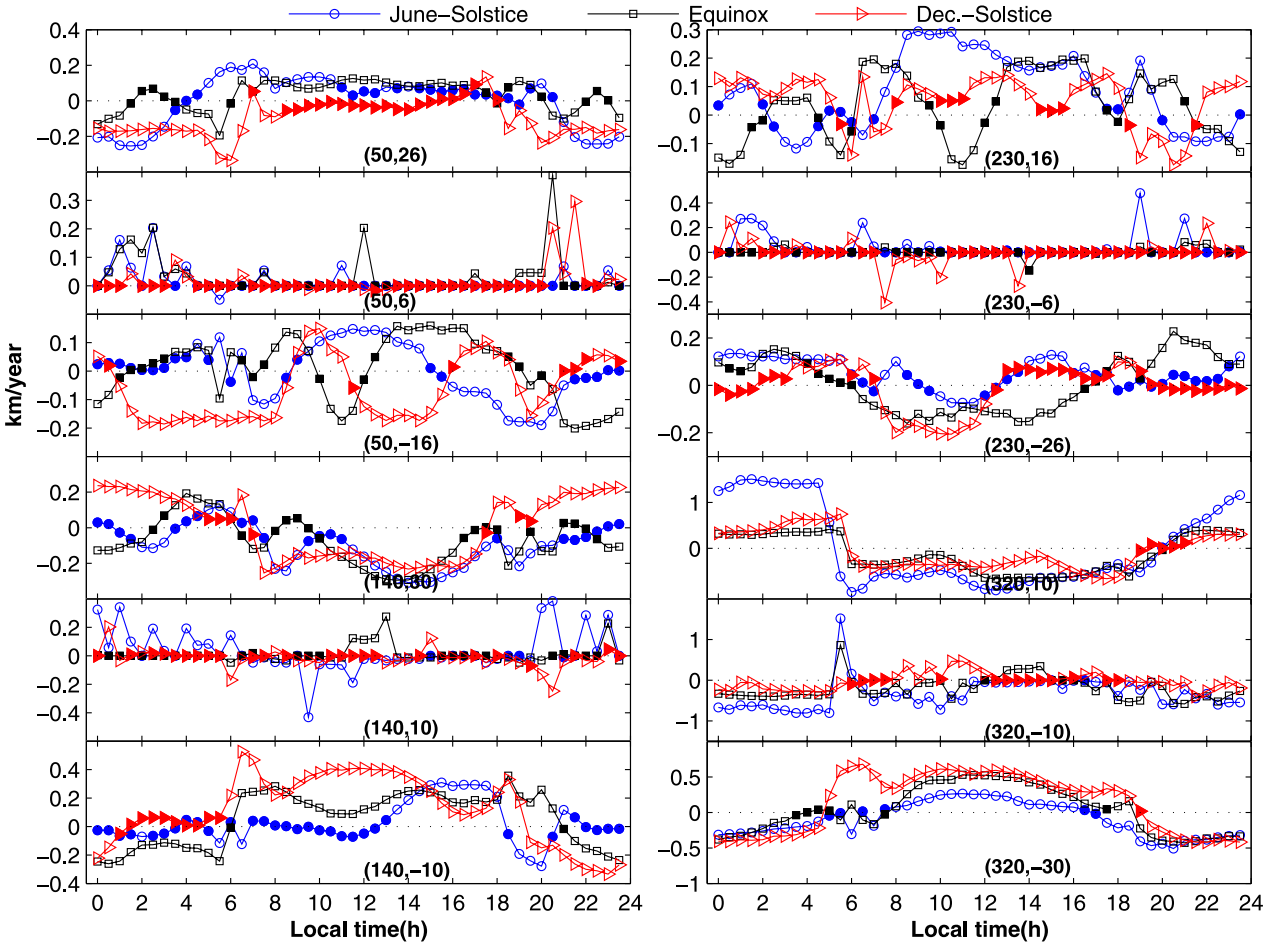

Figure 5. Same as Figure 4, but for hmF2.

results in Table 1. The corresponding trends of $|\cos(D)\cos(I)|$ in the four equatorial stations and $|\cos(D)\cos(I)\sin(I)|$ in remaining 8 low-latitude stations are marked by thick fonts. In the eight low-latitude stations, the sign of foF2 trends agrees well with that of $|\cos(D)\cos(I)\sin(I)|$. Except in 230° longitude sector, the sign of foF2 trends in the rest of the three equatorial stations accords with that of $|\cos(D)\cos(I)|$. In the situation of hmF2, except in (50° Glon, 26° GLat), (230° Glon, −6° GLat), and (230° Glon, −26° GLat), the remaining stations also accord with the above theoretical interpretation. It should be pointed out that the amplitudes of the foF2 and hmF2 trends in the corresponding exceptional stations are smaller than in the other stations. It seems that other factors such as the changes of dipole centers and the influences from the ambient ionosphere have relatively bigger effects on the trends in these stations. In this investigation, we did not consider that the changes of E × B resulted from the secular variations of geomagnetic field density. So the hmF2 trends are mainly determined by the vertical component of the wind driving, which is $|\cos(D)\cos(I)\sin(I)|$. In equatorial stations, the I is very small (∼0°). This may account for the insignificant hmF2 trends in the modeled results for equatorial stations.

[16] Actually, the differences between trends at different latitude areas have been found by several researchers from observations. *Yue et al.* [2006] found that the foF2 trends have more obvious seasonal variations for midlatitude stations than for low-latitude stations in the northern hemisphere, and the sign of trends is different in midlatitude stations from that of low and equatorial stations from 19 ionosonde observations in the Asia/Pacific sector. Considering the difference between geographic latitude and geomagnetic latitude in this longitude sector, their results are partly consistent with the modeled results here. *Danilov and Mikhailov* [1999] and *Mikhailov and Marin* [2001] showed that the foF2 trends are negative at high and middle latitudes with a tendency to be small or positive at lower latitudes. Pronounced latitudinal variations of foF2 long-term trends have also been found by using the usual regression method [*Danilov and Mikhailov*, 1999; *Foppiano et al.*, 1999; *Mikhailov and Marin*, 2000, 2001; *Xu et al.*, 2004]. *Mikhailov and Marin* [2001] put forward a geomagnetic control concept to interpret this phenomenon in accordance with contemporary F2-region storm mechanisms. Our modeling results show that the effects of geomagnetic field changes may be another possible reason for latitudinal variations in ionospheric long-term trends.

4.2. Relative Importance of the Effects of Geomagnetic Field Changes and Other Trend Origins: In Comparison With the Available Observed Results

[17] By our modeling, the ionospheric long-term trends resulting from the secular changes of geomagnetic field

orientation have notable regional characteristics because of the differences of geomagnetic field trends among different stations. They have bigger amplitudes in the 320° longitude sector than in the other three longitude sectors, the same as that of *I* and *D*. Of the twevel modeled stations, the amplitudes of foF2 and hmF2 trends from 1900 to 2005 vary between 0.0014–0.0761 MHz per year and between 0.0081–0.1840 km per year, respectively. These illustrate that the secular variation of geomagnetic field orientation can influence the ionosphere significantly in some areas, but not in others. Unfortunately, there is no good coverage of ionospheric observations in low latitude and equatorial areas. It is impossible for us to test the modeling results by real observations. Moreover, the observed trends are the combined effects of several origins. This testing may be not effective. Up to now, almost the ionospheric trends over all the ionosonde stations have been investigated by different groups [*Bremer*, 1998; *Danilov*, 2003; *Danilov and Mikhailov*, 1999; *Mikhailov*, 2002; *Yue et al.*, 2006]. We attempt to evaluate the relative importance of the geomagnetic field on ionospheric trends by comparing with the existing conclusions and available observed results.

[18] There are a lot of arguments about the interpretation of observed trends in foF2, and even in their values and signs obtained by different methods [*Bremer*, 1998, 2001; *Bremer et al.*, 2004; *Danilov*, 2003; *Danilov and Mikhailov*, 1999; *Mikhailov and Marin*, 2000, 2001]. On the basis of different method and trend values, many authors interpret the trends as a consequence of greenhouse cooling [*Bremer*, 1998, 2001; *Jarvis et al.*, 1998; *Ulich and Turunen*, 1997], as being controlled by geomagnetic activity [*Mikhailov*, 2002; *Mikhailov and Marin*, 2000, 2001], as being influenced by the contribution of the Sun's origin [*Laštovička*, 2005], or as a result of a decrease of the O concentration in the thermosphere [*Danilov*, 2005]. The most popular viewpoint is anthropogenic pollution (e.g., CO2, CH4, O3). *Rishbeth* [1990] and *Rishbeth and Roble* [1992] had predicted a decrease of foF2 and hmF2 with 0.2–0.5 MHz and 10–20 km by doubling the atmospheric greenhouse CO2. However, during the past century, the doubling has not yet happened. According to different estimates, the CO2 increase during the past 40 years is only about 20% [*Bremer et al.*, 2004; *Danilov*, 2005]. If we assume there is a linear dependence of ionospheric trends on the increase of CO2, the foF2 and hmF2 trends by CO2 are approximately 0.001–0.0025 MHz per year and 0.025–0.05 km per year, respectively. Most investigations support the idea the ionospheric trends cannot be interpreted only by the greenhouse effect [*Bremer et al.*, 2004; *Danilov*, 2005; *Laštovička*, 2005; *Mikhailov and Marin*, 2001]. Other factors, including long-term trends in solar and geomagnetic activities and the changes in the neutral background have been brought out by several researchers [*Danilov*, 2005; *Laštovička*, 2005]. According to *Stamper et al.* [1999], the aa-index was increasing throughout the 20th century and appeared to stabilize near its end. On the basis of the geomagnetic control concept by *Mikhailov and Marin* [2000, 2001], this positive trend in geomagnetic activity should result in a negative trend in foF2. The sunspot number was increasing throughout the first half of the 20th century until the peak in 1958–1959, then dropped a little until the end of the century [*Laštovička*, 2005]. This variation of solar activity may result in the positive foF2 trend during 1900–1959 and negative after 1959. However, it is not easy to calculate the value of the foF2 and hmF2 trends produced by variations of solar and geomagnetic activities. Both these factors result in negative trends in the second half of the 20th century, during when most ionosonde observations are made.

[19] As indicated from Table 1, the trends from the geomagnetic field origin have different signs in different stations. We can simply consider that the influences of greenhouse gas and solar activity have no dependence on latitude and longitude. So the variation of geomagnetic field orientation will enhance the negative trends of foF2 in some stations. However, in some other places the variation of geomagnetic field orientation will counteract or even reverse the negative foF2 trends. The average trends of foF2 and hmF2 of the twevel modeled stations are −0.0047 MHz/a and −0.0107 km/a. It means that the geomagnetic field orientation has negative effects on foF2 and hmF2 on average over low latitude and equatorial stations. It should be pointed out that we just considered the long-term variations of the geomagnetic field orientation in this modeling. Other long-term variations, such as the geomagnetic field density, ionospheric field, and neutral background, are ignored here. So the modeling results may have deviations from the real situations. *Danilov and Mikhailov* [1999] obtained an average relative trend in foF2 with value of −0.0018 per year by a set of ionosonde stations with a wide latitude and longitude coverage. By using different methods, *Danilov* [2003] and *Mikhailov* [2002] calculated the nongeomagnetic foF2 trends. They obtained mean value −0.0012 per year and −0.00022 per year by worldwide ionosonde observations. *Bremer et al.* [2004] obtained mean trends of foF2 and hmF2 with value of −0.0018 MHz/a and −0.009 km/a from more than 100 ionosonde observations. *Yue et al.* [2006] obtained a −0.0005/a trend of foF2 from 19 ionosonde stations in Asia/Pacific sector by applying an artificial neural network method. Comparing these results by different authors, we can conclude that the effect of geomagnetic field orientation changes cannot be ruled out. Sometimes in some places it may be comparable or even larger than greenhouse effects and origins of other trends. One point should be stressed: the above observed results are calculated from stations with different latitude and longitude coverage and different methods.

4.3. Local Time and Seasonal Variations of Modeled Trends: Interpretation

[20] Our modeling results have shown that the local time and seasonal variations of modeled trends have typical regional characters. These can generally be interpreted by the corresponding variations of the effects of geomagnetic field orientation on the ionosphere [*Elias and de Adler*, 2006]. For example, the seasonal variations of foF2 trends are more evident during the night than in the daytime, and the amplitude of foF2 trends is bigger during the night than in the daytime. The relative importance of the electrodynamics on the electron density may be the main reason. In our modeling, the main electrodynamic factor is the neutral meridional wind, because we did not consider the variations of E × B resulted from ionospheric dynamo electric field.

According to *Rishbeth* [1998] and *Titheridge* [1995], the amplitudes and directions of neutral winds in the height of the ionospheric F2-layer have typical seasonal and local time variations. These variations differ significantly from place to place. Detailed description of these variations is beyond the scope of this paper.

[21] Prominent seasonal and diurnal variations of ionospheric foF2 and hmF2 trends have been found by several researchers [*Danilov and Mikhailov*, 1999; *Elias and de Adler*, 2006; *Foppiano et al.*, 1999; *Jarvis et al.*, 1998; *Laštovička et al.*, 2006b; *Marin et al.*, 2001; *Mikhailov*, 2002; *Mikhailov and Marin*, 2000, 2001; *Xu et al.*, 2004; *Yue et al.*, 2006]. These variations have no consistent patterns in different stations [*Marin et al.*, 2001; *Yue et al.*, 2006]. The different methods and data sets they used may be probable reasons for different variation patterns of ionospheric trends [*Yue et al.*, 2006]. However, the possibility that the ionospheric trends indeed have regional variations with seasons and local times because of some physical mechanism cannot be ruled out. Up to now, several different factors have been brought out to interpret seasonal and diurnal variations of ionospheric trends. *Danilov and Mikhailov* [1999] found that the foF2 trend amplitude is higher in summer than in winter and suggested that the seasonal effects of the occurrence and development of ionospheric storms may be a probable reason. The similar concept was also put forward and explained in detail by *Mikhailov* [2002]. *Foppiano et al.* [1999] and *Jarvis et al.* [1998] thought that these seasonal and diurnal variations of ionospheric trends may be associated with the corresponding changes of the effects of neutral winds resulting from the varying geomagnetic field. *Elias and de Adler* [2006] assessed the effects of the long-term variations of the geomagnetic field on the ionospheric trends quantitatively with a theoretical approximation consideration. Their results revealed that the long-term trend of the geomagnetic field could possibly explain the seasonal pattern of the ionospheric trends in two of the selected three stations. Our modeling results indicate that the effects of varied geomagnetic field orientation can indeed produce seasonal and local time variations of ionospheric trends and that these variations have obvious regional characters. However, several other factors including the variations of geomagnetic field density, greenhouse effect, and long-term trends of geomagnetic activity and neutral backgrounds were not considered in the modeling. The observed seasonal and diurnal variations of trends are the combined effects of these factors. So it is not valid to test our modeling results by comparing them with observed results. However, in the area of the 320° longitude sector, the effects of the geomagnetic field on the trends have a relative larger proportion. The comparison in this area may be useful. *Jarvis et al.* [1998] analyzed hmF2 data from the Argentine Islands (65°S, 64°W) and Port Stanley (52°S, 58°W), which are close to the modeled station (320° Glon, −30° GLat). They found that the hmF2 trends in both stations are bigger in daytime than at night, which is in accordance with our results. They also simply modeled the effects of geomagnetic field by SUPIM model and modeled seasonal and local time variations that agree with ours very well. The foF2 from the same two stations were analyzed by *Danilov and Mikhailov* [2001], who concluded that the trends are bigger in daytime than that of night. Our modeling also obtains the same result.

5. Conclusions

[22] In this paper, a mid- and low-latitude ionospheric theoretical model is used to model the effects of secular variations of geomagnetic field orientation on ionospheric long-term trends for the first time. We modeled twelve artificial stations with good coverage in global low-latitude and equatorial areas during four seasons with middle solar activity under quiet conditions from 1900 to 2005. The results can be concluded as follows.

[23] 1. Modeling results systematically and strictly confirm the assumption that the variations of neutral wind resulting from the varied geomagnetic field can affect the ionospheric long-term trends, which was proposed by several researchers. The trends caused by the secular variations of geomagnetic field orientation differ from place to place, because the amplitudes of geomagnetic field change depend on location.

[24] 2. The modeled ionospheric trends have obvious seasonal and diurnal variations. These variations illustrate typical regional characteristics. These can generally be interpreted by the corresponding variations of the effects of geomagnetic field orientation on the ionosphere. By comparing with existing results, we suggest that the changes of the global geomagnetic field may partly contribute to the inconsistent seasonal and local time variation patterns in ionospheric trends from different observations.

[25] 3. Of the twelve modeled stations, the amplitudes of foF2 and hmF2 trends vary during 0.0014–0.0761 MHz per year and 0.0081–0.1840 km per year, respectively. The average trends of foF2 and hmF2 are −0.0047 MHz/a and −0.0107 km/a, which is near or even comparable to that of other trend origins. In comparison with the trend results from worldwide observations, we conclude that the effects of geomagnetic field orientation on the ionospheric long-term trend cannot be ruled out, especially in the areas with large geomagnetic field variations.

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