Does the Peak Response of the Ionospheric $F_2$ Region Plasma Lag the Peak of 27-Day Solar Flux Variation by Multiple Days?

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Abstract In this study, the in situ electron density measurements from the Challenging Minisatellite Payload (CHAMP) and solar extreme ultraviolet (EUV) radiation from the Solar Extreme Ultraviolet Experiment instrument on board the Thermosphere Ionosphere Mesosphere Energetic and Dynamics satellite, both with a time resolution of 1.5 hr, are used to explore the peak response of the ionospheric $F_2$ region plasma to the peak of 27-day solar EUV flux variation. The time delays of in situ electron density changes obtained from the CHAMP satellite in response to 27-day solar EUV flux changes vary from 0 to about 3 days. Meanwhile, the Thermosphere Ionosphere Electrodynamics General Circulation Model simulations driven by the measured EUV flux and the actual geomagnetic activity show similar time delays as those observed in the CHAMP measurements. Further simulations reveal that the geomagnetic activity greatly affects the determination of the ionospheric time delay to the 27-day solar EUV flux variations. Besides, the solar zenith angle change within the solar rotation interval can cause large latitudinal differences in the time delay. The ionospheric time delay to the pure 27-day solar EUV flux variation is less than 1 day and slightly increases with latitude, when geomagnetic activity and seasonal variations are eliminated in the simulation. The simulation results further suggest that the ionospheric response time is associated with the photochemical, dynamic, and electrodynamic processes in the ionosphere-thermosphere system.

1. Introduction

Variations in the terrestrial ionosphere and thermosphere are strongly controlled by solar activity. Many studies have revealed that the ionosphere and thermosphere respond to solar radiation changes at different timescales, that is, from solar cycle to multiday (e.g., Doherty et al., 2000; Forbes et al., 2000; Rishbeth & Mendillo, 2001; Wang et al., 2011). Since the period of solar synodic rotation is about 27 days, the solar irradiance reaching the Earth also has a similar periodic variation. As a result, the ionospheric and thermospheric key parameters have corresponding oscillations of approximately 27 days as well (e.g., Akasofu & Chapman, 1972; Bartels, 1950; Ebel et al., 1986; Kane, 2003; H. Liu et al., 2007; Min et al., 2009, and references therein). It should be noted that the time constant for photoionization in the $F_2$ region is generally less than 1 hr (Adler et al., 1997; Rishbeth & Garriott, 1969) in response to solar extreme ultraviolet (EUV) flux change. However, the associated dynamic and electrodynamic processes in the ionosphere-thermosphere system have different time constants. Consequently, the time delays of ionospheric and thermospheric parameters in response to the 27-day solar EUV flux change may behave in a complex way. Note that the time delay or response time in this study is referred to as the peak response time of the parameters in the ionosphere-thermosphere system to the peak of 27-day solar EUV flux variation.

Many observation and simulation studies have concentrated on the ionospheric time delay to the 27-day solar EUV flux variation. As listed in Table 1, the ionospheric parameters used in previous work include $F_2$ layer peak density ($N_mF_2$), electron densities measured by satellites or incoherent scatter radars, and the total electron content (TEC). The ionospheric response time as indicated by the time delay of different parameters in these studies varied from about 0 to 3 days or even longer. Note that besides different types of data sets, there is an issue about the solar EUV flux data or proxy used in these previous studies. Specifically, the solar flux proxy $F_{10.7}$, which has a time resolution of 1 day, was often used in previous correlation analyses (see...
As a result, the uncertainty of the obtained time delay of the ionospheric response to the 27-day variation would be greater than a half day.

In this study, we use the in situ electron density measurements from the Challenging Minisatellite Payload (CHAMP) and solar EUV radiation from the Thermosphere Ionosphere Mesosphere Energetic and Dynamics (TIMED) satellite, both of which have a time resolution of about 1.5 hr, to explore the ionospheric response time to the 27-day solar EUV flux variation. The Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM) simulations driven by the measured EUV flux are compared with the CHAMP observations. Then, a series of TIEGCM simulations is conducted to explore the possible causes of the controversial results as mentioned above in the ionospheric time delay to the 27-day solar EUV flux variation. More importantly, the physical causes of the ionospheric delay to the 27-day solar EUV flux variation are further investigated.

2. Methodology and Model Description

The solar EUV flux, which is directly measured by the Solar Extreme Ultraviolet Experiment (SEE) instrument (Woods et al., 1998) on board the TIMED satellite, is used to analyze the ionospheric responses. The TIMED satellite was launched into a circular polar orbit with an inclination of 74.1°, an altitude of about 630 km, and a period of about 97 min on 7 December 2001. In addition, the in situ electron density measured by the Planar Langmuir Probe on board the CHAMP satellite is also used in this analysis. The CHAMP satellite was launched on 15 July 2000 with an inclination of 87.3°, an initial altitude of 454 km, and a period of about 92 min (Reigber et al., 2002). The CHAMP satellite took 131 days to cover all local times. Both TIMED/SEE solar flux and CHAMP electron density obtained from the orbital average have a time resolution of about 1.5 hr. Thus, the data sets from TIMED/SEE and CHAMP allow us to analyze the ionospheric delay to solar activity with a higher time resolution of about 1.5 hr. In this study, we use CHAMP and TIMED/SEE measurements in 2003 when the 27-day solar EUV flux variations was prominent (Forbes et al., 2006).

The TIEGCM simulations are used here to examine the physical mechanisms that cause the ionospheric delay in response to 27-day solar EUV flux variations. The TIEGCM, a first-principle, time-dependence, 3-D numerical model, can obtain a self-consistent solution of the coupled thermosphere and ionosphere system by solving the coupled nonlinear momentum, energy, and continuity equations for neutral and ion species (Richmond et al., 1992). The horizontal resolution in this study is 2.5° × 2.5°; the vertical resolution is one fourth of a scale height. Migrating tides at the lower boundary are specified using the Global-Scale Wave Model (Hagan & Forbes, 2002, 2003). Additionally, the magnetospheric convection at high latitudes is specified by the Heelis model (Heelis et al., 1982), which is driven by the geomagnetic activity index Kp.

As given in Table 2, we conducted a series of numerical experiments to investigate the ionospheric delay in response to 27-day solar EUV flux variation. The TIMED/SEE solar EUV flux measurements are used in Runs 1 and 2. The geomagnetic activity Kp values in Runs 1 and 2 are set to the actual data and 0, respectively.

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Besides using the measured EUV flux, the solar radiation in Runs 3–5 is represented by an idealized sine function. The solar flux proxy \( F_{10.7} \), in Runs 3–5, at each step is specified by the effective \( F_{10.7} \) as follows:

\[
F_{10.7} = \begin{cases} 
95 + 30 \cos \left( \frac{2\pi}{27} (t - 63.5) \right), & 50 < t < 77 \\
65, & t \leq 50 \text{ or } t \geq 77
\end{cases}
\]

where \( t \) stands for the day of year. In addition, the International Geomagnetic Reference Field and the dipole geomagnetic field are used in Runs 3 and 4, respectively. After Run 4, the calendar day is fixed on the equinoctial day in Run 5. In this way, we can further investigate the effects of geomagnetic field configuration and season on the determination of the ionospheric time delay in response to the 27-day solar EUV flux variation.

We take the following steps to calculate the time delays of simulations and observations:

1. The observations (electron density and solar EUV flux) and the simulation results are linearly interpolated to a time interval of 1.5 hr to obtain time series.
2. Singular spectrum analysis (Vautard & Ghil, 1989) is used to extract the trend of solar EUV flux or the daily centered moving averaged ionospheric parameters (denoted by \( N_d \)).
3. We calculate a 27-day centered moving average for solar EUV flux or ionospheric parameters, and then singular spectrum analysis is used to obtain the corresponding trend (denoted by \( N_b \)).
4. The relative changes of solar EUV flux or ionospheric parameters, which are better for correlation analysis, are calculated by \( (N_d - N_b)/N_b \).
5. The correlation coefficients between the 27-day time series of relative change of solar EUV flux (from \( t_r - 13.5 \) to \( t_r + 13.5 \)) and a corresponding 27-day series of relative change of ionospheric parameters with a time delay varying from \( -5 \) to \( 5 \) days are computed.
6. The time delay at \( t_r \) stands for the shifting time when the correlation coefficient reaches its maximum.

### 3. Results

The variations of the integral solar EUV flux (wavelength less than 102.7 nm) detected by TIMED/SEE in 2003 and its relative change are shown in Figure 1a. Obviously, the solar EUV flux and its percentage change oscillate with the period of about 27 days. Meanwhile, the geomagnetic activity, as indicated by \( K_p \), also has a cycle of about 27 days (see Figure 1a), as solar wind structures originated from the Sun, such as solar wind high-speed streams and corotating interaction regions, also have a 27-day period (Altadill & Apostolov, 2003; Lei et al., 2008). The averaged electron densities from 30°S to 30°N with their percentage changes observed by the CHAMP ascending and descending orbits in 2003 are shown in Figures 1b and 1c. The electron densities show obvious diurnal, 27-day and longer periodic variations. The longer periodic variation of the observed electron densities can be attributed to the seasonal variation in the ionosphere and the local time change in CHAMP orbit. As shown in Figures 1b and 1c, the relative changes in electron densities show similar 27-day oscillations to those of solar EUV flux (the black lines) with slight phase differences. Note that these relative changes are used in the subsequent calculations in order to minimize the effects of ionospheric seasonal variations and the changes associated with local time sampling on the time delay determination.
Figure 2 shows the time delays of the CHAMP measurements and their correlation coefficients. The time delays of the electron density data from ascending and descending orbit measurements, which vary from 0 to 3 days and even longer, are generally similar. Note that the correlation becomes lower as the relative change of 27-day solar EUV flux variation is smaller (the yellow shaded intervals). Additionally, there are a few intervals with negative delays, which might be related to the ionospheric changes caused by geomagnetic and meteorological activity (L. Liu et al., 2006; Rishbeth & Mendillo, 2001) rather than solar EUV flux changes. Since the nighttime ionospheric plasma density is low, the change in nighttime ionospheric plasma due to the solar EUV flux changes can be disturbed more easily by other mechanisms, which also leads to the relative smaller correlation coefficient during the nighttime. Thus, our statistical analysis does not include the results during these intervals when the 27-day solar EUV flux change is small or the sampling local time is at night (22–06 LT). The averaged time delays of ascending and descending data in 2003 are 0.8 and 1.0 days, and the corresponding standard deviations are 0.8 and 1.0 day (see Table 3).

Figure 1. The variations of solar EUV flux observed by TIMED/SEE and electron densities detected by CHAMP with their relative changes in 2003. From top to bottom, (a) solar EUV flux, (b) ascending orbit electron densities, and (c) descending orbit electron densities are shown. The relative changes of solar EUV flux are also shown (black line) for comparison. The averaged electron densities from 30°S to 30°N are used in the calculation. The Kp index in 2003 is also shown in (a) for reference. The yellow shaded bars denote the weak 27-day solar EUV flux intervals. The red and blue bars represent the periods within 22–06 LT for ascending and descending orbits, respectively. EUV = extreme ultraviolet; TIMED/SEE = Thermosphere Ionosphere Mesosphere Energetic and Dynamics/Solar Extreme Ultraviolet Experiment; CHAMP = Challenging Minisatellite Payload.
The simulated electron densities from Run 1 (red lines), which is driven by the measured solar EUV radiation and the actual geomagnetic activity, sampled along the CHAMP ascending and descending orbits, are shown in Figures 3a and 3e. As expected, the simulated electron densities show similar 27-day oscillations to those that occur in the observations. For percentage changes (Figures 3b and 3f), the 27-day oscillations become more obvious. As given in Table 3, the mean time delays of the sampled electron densities from Run 1 for ascending and descending orbits are 0.8 and 0.9 day, and the standard deviations are 0.6 and 0.7 day. Besides, the time delays of $N_mF_2$ at the same longitude of CHAMP orbits from Run 1 are 0.7 and 0.8 day. The corresponding standard deviations are both 0.7 day. Overall, the TIEGCM simulations can generally reproduce the time delays that are seen in the CHAMP measurements.

As mentioned earlier, geomagnetic activity associated with high-speed streams and corotating interaction regions originating from coronal holes can occur recurrently with a period of about 27 days. This recurrent feature can be seen in the $Kp$ index in Figure 1. Thus, the energy deposition from the magnetosphere due to recurrent geomagnetic activity could impact the ionospheric behavior and then affect the determination of the ionospheric response time to the 27-day solar EUV flux changes. It should be noted that the phase differences between the solar EUV flux and $Kp$ vary with time, as they contain the time for solar wind to travel from the Sun to the Earth and the phase difference when the solar EUV flux and solar wind are emitted from the Sun. We carried out Run 2, in which the effect of geomagnetic activity is eliminated, to isolate the solar EUV flux contribution. As compared with the results from Run 1, the 27-day variations in electron densities from Run 2 became more obvious as shown in Figure 3. In addition, the correlation coefficients from Run 2 are larger than those from Run 1. The mean time delays from Run 2, as given in Table 3, are 1.0 and 0.8 day for the electron densities sampled along the CHAMP ascending and descending orbits and 1.1 and 0.8 days for $N_mF_2$ at the same longitude of CHAMP orbits. Meanwhile, the standard deviation in Run 1 decreases by 0.1–0.4 day when geomagnetic activity is not included in Run 2. The results suggest that geomagnetic activity changes can greatly affect the determination of the ionospheric response time to the

Table 3
The Time Delay and Standard Deviation for the CHAMP Observations and the Corresponding Simulation Results Sampled Along the CHAMP Orbits From Runs 1 and 2

<table>
<thead>
<tr>
<th>Ionospheric parameter</th>
<th>Data set</th>
<th>Time delay with standard deviation (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron density ($N_mF_2$) along CHAMP ascending orbit</td>
<td>Run 1</td>
<td>0.8 ± 0.6 (0.7 ± 0.7)</td>
</tr>
<tr>
<td></td>
<td>Run 2</td>
<td>1.0 ± 0.3 (1.1 ± 0.3)</td>
</tr>
<tr>
<td>Electron density ($N_mF_2$) along CHAMP descending orbit</td>
<td>Run 1</td>
<td>0.9 ± 0.7 (0.8 ± 0.7)</td>
</tr>
<tr>
<td></td>
<td>Run 2</td>
<td>0.8 ± 0.4 (0.8 ± 0.6)</td>
</tr>
</tbody>
</table>

Note. CHAMP = Challenging Minisatellite Payload.
27-day solar EUV flux variations. As a result, the time delay of the ionospheric response to the 27-day solar EUV flux variation determined from the observations has large uncertainty.

As shown in Figure 1, the local time of the CHAMP orbit changes slowly. The changing sample time could influence the determination of the ionospheric time delay in response to the 27-day solar EUV flux variations. The noontime $N_{m}F_2$ and TEC are further analyzed in this study. The simulation results, percentage changes, time delays, and correlation coefficients from Run 1 and Run 2 are shown in Figure 4. The statistical results are shown in Table 4. The time delays of noontime $N_{m}F_2$ and TEC obtained from Run 1 are 0.6 and 0.5 day. The corresponding values are 0.8 and 0.7 day when geomagnetic activity is not included in Run 2. Meanwhile, the standard deviations decrease from 0.8 and 0.6 day in Run 1 to lower than 0.3 day in Run 2. This comparison further demonstrated that geomagnetic activity has a significant impact on the derivation of the ionospheric response time to the 27-day solar EUV flux variations.

To understand the ionospheric delay in detail, three additional simulations (Runs 3–5), driven by an idealized sine function from equation (1) for the 27-day solar EUV flux variation, are carried out. The time delays and correlation coefficients of noontime $N_{m}F_2$ and TEC from Runs 3–5 are shown in Figure 5. The simulation results from Runs 3 and 4, which are similar, show obvious hemispheric asymmetry, especially for $N_{m}F_2$. This comparison further demonstrated that geomagnetic activity has a significant impact on the derivation of the ionospheric response time to the 27-day solar EUV flux variations.

Figure 3. Comparison of the observed and simulated electron densities sampled along CHAMP (a) ascending and (e) descending orbits, (b, f) their corresponding relative changes, (c, g) the calculated time delays, and (d, h) correlation coefficients of electron densities to the 27-day solar EUV flux changes. The averaged electron densities from 30°S to 30°N are used in the calculation. The relative changes of solar EUV flux are also shown in (b) and (f) for reference. The red and blue bars represent the periods within 22–06 LT for ascending and descending orbits, respectively. CHAMP = Challenging Minisatellite Payload; EUV = extreme ultraviolet.
4. Discussion

The ionosphere and thermosphere are tightly coupled. As a result, the change in ionospheric electron densities not only fluctuates under the influence of solar EUV flux but is also modulated by dynamic and electrodynamic processes. In this section, we examine the thermospheric response time to the 27-day solar EUV flux change and further demonstrate the contributions of the background thermosphere to the ionospheric response. Figure 6 shows the variations of thermospheric and ionospheric parameters at 40°N (panels a–d) and the corresponding latitudinal variation of time delays (panels e–h) from Run 5. As illustrated in Figure 6a, the maximum change of solar EUV flux is about 92%, and the maximum change of electron density at the constant pressure surface of \( Z_p = 2 \), near to the \( F_2 \) peak height, reaches 70%. The time delay of electron density (Figure 6e) increases with latitude slightly. Obviously, the latitudinal dependent time delay of electron density at the constant pressure surface of \( Z_p = 2 \) is similar to that of \( NmF_2 \) as shown in Figure 5.

The ionospheric behavior greatly depends on the ion production and loss, both of which are modulated by solar EUV flux changes. Figure 6b shows the variation of production rate (\( P_i \)) and loss coefficient (\( L_i \)). The change of production rate, which is mostly related to the photoionization of atomic oxygen in the \( F_2 \) region, is generally proportional to solar EUV flux changes with a maximum of 19%. For the loss coefficient, which is mostly associated with the dissociative recombination of molecular nitrogen, it has negative correlation with the solar EUV flux variation. The maximum relative change of loss coefficient is 28%. Note that the production rate after the 27-day variation generally recovers to the level before the change of solar EUV flux, whereas the loss coefficient cannot recover to the level before the solar EUV flux variation. The time delay of production rate is around 0 day, but the time delay of the loss coefficient is 1.4 day at the equator and increases to 1.8 days at 60° (Figure 6f).

<table>
<thead>
<tr>
<th>Ionospheric parameter</th>
<th>Data set</th>
<th>Time delay with standard deviation (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noontime ( NmF_2 )</td>
<td>Run 1</td>
<td>0.6 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>Run 2</td>
<td>0.8 ± 0.3</td>
</tr>
<tr>
<td>Noontime TEC</td>
<td>Run 1</td>
<td>0.5 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>Run 2</td>
<td>0.7 ± 0.2</td>
</tr>
</tbody>
</table>

| Note. TEC = total electron content. |

Figure 4. Variations of the simulated noontime (a) \( NmF_2 \) and (e) TEC, (b, f) their corresponding relative changes, (c, g) the calculated time delays, and (d, h) correlation coefficients. The averaged simulation results from 30°S to 30°N are used in the calculation. The relative changes of solar EUV flux are also shown in (b) and (f) for comparison. TEC = electron content; EUV = solar extreme ultraviolet.
The change in \( \Pi / \Li \) and the latitudinal variation of time delay are shown in Figures 6b and 6f, respectively. The maximum relative change in \( \Pi / \Li \) is 66%. The time delay of \( \Pi / \Li \) increases from 0.8 day at the equator to 1.1 days at 60°. In order to study the relationship between the changes in the ionosphere and thermosphere, the percentage changes in neutral temperature and number density of atomic oxygen and molecular nitrogen are shown in Figure 6c. The neutral temperature change has a positive correlation with the 27-day solar EUV flux variation, and the variations of neutral composition are negatively correlated to the solar EUV flux change. The maximum change of temperature, as shown in Figure 6c, is about 20%. The maximum decreases of atomic oxygen and molecular nitrogen are 16% and 21%, respectively. The time delay of temperature (Figure 6g) slightly decreases from 0.7 days at the equator to 0.6 days at 60°, which is slightly lower than the results of 0.9 ± 0.1 day shown by Jacchia et al. (1973). The time delay of atomic oxygen is 0.6 day at the equator and decreases to 0.3 day at 60°, but the time delay of molecular nitrogen increases from 1.4 day at the equator to 1.8 day at 60°. The different behavior between atomic oxygen and molecular nitrogen in response to the solar EUV flux change may be associated with the different time constants of their chemical processes and the atmospheric global circulation.

The change of electron density is generally considered to be proportional to the ratio between atomic oxygen and molecular nitrogen (\([\text{O}] / [\text{N}_2]\)) at middle latitude. The change of \([\text{O}] / [\text{N}_2]\) and the latitudinal variation of its time delay are shown in Figures 6d and 6h, respectively. The maximum change in \([\text{O}] / [\text{N}_2]\) is 8%, and it remains 4% higher after the 27-day solar EUV flux variation. It is surprising that the time delay of \([\text{O}] / [\text{N}_2]\) is 3.4 days at the equator and increases to more than 5 days at about 40° in both hemispheres, which is much longer than that of electron density, \( \Pi / \Li \), \([\text{O}]\), and \([\text{N}_2]\). In order to examine the mechanism responsible for the difference between \([\text{O}] / [\text{N}_2]\) and \( \Pi / \Li \), we carry out the following calculation.

According to Rishbeth and Barron (1960), for a steady daytime \( F_2 \) layer in the middle latitudes, we can obtain

\[
N_{mF_2} = 0.75 \frac{q_m}{\beta_m} \tag{2}
\]

\[
\frac{\beta_m H_m^2}{D_m} = 0.6 \tag{3}
\]

where \( q_m \) and \( \beta_m \) represent ion production rate and loss coefficient at the \( F_2 \) peak height, and \( H_m \) and \( D_m \) are the plasma scale height and ambipolar diffusion coefficient at that height, respectively (Lei et al., 2016). Following the same methodology as Mikhailov et al. (1995), we can obtain

\[
N_{mF_2} = \frac{0.75 q H^{2/3}}{\beta^{2/3} (0.6 D)^{1/3}} \tag{4}
\]

in which \( q, \beta, H, \) and \( D \) are the production rate, loss coefficient, plasma scale height, and ambipolar diffusion coefficient at any fixed pressure surface. In this case, we use the substitution

\[
\frac{\beta_m H_m^2}{D_m} = 0.6
\]
Figure 6. The time series of relative changes of (a) electron density ($N_e$); (b) ion production rate ($P_i$), loss coefficient ($L_i$), and $P_i/L_i$; (c) neutral temperature $T_n$, the number densities of atomic oxygen ([O]), and molecular nitrogen ([N$_2$]); and (d) [O]/[N$_2$] and the changes of recomputed $N_m F_2$ ($N_m F_{2\text{new}}$) at 40°N and constant pressure surface $Z_p = 2$ from Run 5. The relative changes of $F_{10.7}$ are also shown in (a)–(d) for reference. The calculated time delays as a function of latitude for the corresponding parameters (a–d) are shown in (e)–(h). Pressure level $Z_p = \ln \frac{P}{P_0}$, where $P$ is the pressure at the considered pressure surface, and $P_0$ is the reference pressure surface ($5 \times 10^{-4}$ mbar).

\[ q - \lambda \cdot \frac{[O]}{n m} \]  
\[ \beta - k \cdot \frac{[N_2]}{n m} \]  
\[ D - \tau_{n}^{0.5} \]  
\[ H - \frac{1}{nm} - \frac{1}{16[O] + 28[N_2]} \]  

where $n$ and $m$ represent the number density and mean mass of a molecule, [O] and [N$_2$] are the number density of atomic oxygen and molecular nitrogen, $\lambda$ denotes the contribution of solar EUV flux, $\tau_n$ stands for the neutral temperature, and $k - \tau_{n}^{0.45}$ is the chemical reaction rate coefficient for atomic oxygen ion and molecular nitrogen (Hierl et al., 1997). The change of recomputed $N_m F_2$ ($N_m F_{2\text{new}}$) from equation (4) and its time delay are shown in Figures 6d and 6h, respectively. The obtained time delay of $N_m F_{2\text{new}}$ is 0.7 day at the equator and increases to about 1 day at 60°. Obviously, the time delays of $N_m F_2$, $N_m F_{2\text{new}}$, and $P_i/L_i$ are generally consistent.
Now we are in good position to explain the differences of the time delays between $P/L_i$ and $[O]/[N_2]$. The production $P_i$ is not only related to the behavior of $[O]$ but also associated with the changes in solar EUV flux $I_i$. Besides the change in $[N_2]$, thermospheric temperature further affects the loss processes by modulating the chemical reaction rate. However, the corresponding change in $I_i$ dominates that of $[O]/[N_2]$. Specifically, the maximum change in $I_i$ is 27%, which is about 3 times larger than that in $[O]/[N_2]$. This can explain why the daytime ionospheric time delay in response to the 27-day solar EUV flux variation is shorter than that of $[O]/[N_2]$. In fact, the time delay for electron density is more or less controlled by $P_i/L_i$ as the ion production also depends on the EUV flux itself rather than $[O]/[N_2]$ alone.

Furthermore, there are still differences in the time delay among $N_2F_2$, $N_2F_2new$ and $P/L_i$. Specifically, the time delay of $P_i/L_i$ is 0.2 day longer than that of $N_2F_2$. This illustrates that electron density in the $F_2$ region cannot be explained by the photochemical equilibrium alone. In addition, as shown in Figure 5, the time delay of $N_2F_2$ has two peaks around the latitudes of 26$\degree$ in the two hemispheres, that is, around the equatorial ionization anomaly crests. The longer delays in the equatorial ionization anomaly region suggest that the equatorial fountain effect contributes to produce the latitudinal variation of ionospheric response time to the 27-day solar EUV flux variations. Therefore, the ionospheric dynamic and electrodynamic processes could further modulate the ionospheric response time to the 27-day solar EUV flux change.

5. Summary

In this study, we compared the CHAMP observations with TIEGCM simulation results to characterize the ionospheric delayed response to solar EUV variations. Furthermore, we explored the main causes of the dayside ionospheric delay on the basis of TIEGCM simulations. The main conclusions in this study are as follows:

1. The time delay of the observed ionospheric electron density to the 27-day solar EUV flux changes varies from 0 to 3 days, which is generally consistent with the results from the TIEGCM simulations.
2. Geomagnetic activity can greatly affect ionospheric delay to the 27-day solar EUV flux variation.
3. Solar zenith angle changes within solar rotation can cause large latitudinal differences in the ionospheric time delay.
4. The daytime ionospheric response time to the pure 27-day solar EUV flux change is less than 1 day.
5. The daytime ionospheric time delay to the 27-day solar EUV flux change is much shorter than that of $[O]/[N_2]$, as the corresponding change of the solar EUV flux dominates over that of $[O]/[N_2]$.
6. The ionospheric time delay and its latitudinal variation are affected not only by photochemical processes but also by dynamic and electrodynamic processes.

References


