Ionospheric Variability Due to Tides and Quasi-Two Day Wave Interactions

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Abstract The ionospheric variabilities due to planetary waves (PWs) are complicated due to their nonlinear interaction with tides (migrating diurnal and semidiurnal tides [DW1 and SW2]) in the mesosphere and lower thermosphere region. The quasi-two day wave (QTDW) is the most dominant oscillation during austral summer period except tides. This paper quantitatively studies the contribution of W3 QTDW, secondary PWs generated by the QTDW-tide interaction, and the change of tides to the ionospheric vertical drift variabilities. It is found that the secondary PWs generated by the QTDW-DW1 interaction (16 hr W4 and 48 hr E2) contribute more to the ionospheric variability than those generated by the QTDW-SW2 interaction (9.6 hr W5 and 16 hr E1). The latitudinal distribution of the vertical drift induced by tides and PWs varies due to their different wind structures. The vertical drift induced by DW1 is weakened at all latitudes due to the existence of W3 QTDW, whereas the SW2-induced vertical drift is enhanced at low latitudes and decreased at middle latitudes. The W3 QTDW induces weaker vertical drift in the equatorial region than that induced by 16 hr W4, 48 hr E2, and the change of tides. At middle latitudes, the vertical drift induced by W3 QTDW is slightly stronger than that induced by 48 hr E2 and the change of DW1 but is comparable to that induced by 16 hr W4 and the change of SW2. Our simulations show that the changes of tidal amplitudes and secondary PWs are as important as the QTDW itself to the day-to-day ionospheric variabilities.

1. Introduction

The cause of short-term variability of the Ionosphere-Thermosphere (IT) system is an important research topic in space environment studies. The extreme ultraviolet from solar irradiance controls the ionization of the IT system, which is a major source for its variabilities (Liu et al., 2011). Coronal mass ejection and geomagnetic storms have severe impact on the IT energetics and electrodynamics (e.g., Lei et al., 2008; Thayer et al., 2008). In the absence of large solar and geomagnetic variation, however, the IT system can still exhibit significant variations, which are likely related to disturbances from the lower atmosphere, in the form of gravity waves, planetary waves (PWs), and tides (Chang et al., 2013; Gan et al., 2016; Jones et al., 2014; Lei et al., 2014; Liu, 2016; Liu & Richmond, 2013; Luan et al., 2012; Yamazaki & Richmond, 2013).

Tides are the most robust wave perturbations in the mesosphere and lower thermosphere (MLT) region with periods of 24 hr and its harmonics, which are mainly forced by solar UV radiation absorption by ozone and water vapor (Wu et al., 2008). The migrating tides are westward traveling and Sun-synchronous, which include the zonal wave number 1 diurnal (DW1) and wave number 2 semidiurnal (SW2) modes. Besides, there are also resonant PW modes in the middle atmosphere with certain zonal wave numbers and periods of several days, the sources of which include deep convection in the troposphere, topography, latent heating release, instabilities, etc (Liu, 2016). For example, the quasi-two day wave (QTDW) can propagate westward with zonal wave number 2 (W2), 3 (W3), and 4 (W4) and eastward with zonal wave number 2 (E2) and 3 (E3); the quasi-3 day Kelvin wave is composed by E1, E2, and E3 modes (Gu et al., 2013; Liu et al., 2015); the quasi-6 day wave is usually considered to be a W1 mode (Gu et al., 2015; Gu et al., 2014; Jiang et al., 2008; Liu et al., 2004). Nonlinear interaction between tides and PWs is frequently identified due to their large wave amplitudes in the MLT region, which results in the generation of secondary waves (Forbes & Moudden, 2012; Gan et al., 2017; Lieberman et al., 2003; Liu et al., 2010; McCormack et al., 2010; Pedatella et al., 2012; Xu et al., 2014).
result in significant perturbations in the neutral density (Chang et al., 2010). Second, PWs, exhibiting strong wind perturbations in the MLT region, could influence the F region ionosphere through the modulation of E region wind dynamo (Gu et al., 2014; Liu et al., 2012; Pancheva et al., 2008). Third, the nonlinear interaction between tides and PWs, which usually result in secondary waves and significant change of tidal amplitudes, could impose additional variabilities to the IT system (Pedatella et al., 2012; Yue et al., 2016). Last, the dissipation of PW modulates meridional circulation in the lower thermosphere, which affects the composition of the thermosphere and ionosphere (Chang et al., 2014; Gan et al., 2015; Yue & Wang, 2014).

The W3 QTDW is the strongest QTDW wave mode in the summer MLT region, and its wave perturbations could reach 50–100 m/s during austral summer period (Gu et al., 2016; Wang et al., 2017). The nonlinear interaction between W3 QTDW and DW1 has been verified by the secondary wave signals in both observations and model simulations (Huang et al., 2013; McCormack et al., 2010; Nguyen et al., 2016). It is found that the QTDWs and the secondary waves could have considerable impact on ionospheric electrodynamics and thermospheric compositions (Yue et al., 2016). Besides, the westward forcing from the dissipation of QTDW decelerates the background eastward wind in the mesopause region, which limits the growth of tidal amplitudes (Chang et al., 2011). Gu, Lei, et al. (2017) showed that the QTDW-induced tidal variability contributes as much as the QTDW itself to the ionospheric variation during boreal summer period at 33°N.

In this paper, we will investigate the nonlinear interactions between W3 QTDW and migrating tides (including both DW1 and SW2) and their influences on ion vertical drift. The relative importance of the QTDW, tides, and the secondary waves in neutral-ion coupling during the nonlinear interaction will be analyzed quantitatively. The Thermosphere-Ionosphere-Mesosphere Electrodynamics-General Circulation Model (TIME-GCM) developed at National Center for Atmospheric Research will be utilized in our study, which is briefly described in section 2. The simulation results are presented in section 3, followed by discussions in section 4 and a summary in section 5.

2. TIME-GCM Simulations

The TIME-GCM is a three-dimensional model that can simulate the neutral dynamics in the middle atmosphere and the electrodynamics in the IT system (Roble, 2013). The lower and upper model boundaries are ~30 and ~500 km, respectively. Gravity wave drag in the stratosphere and mesosphere are parameterized according to the linear saturation theory (Lindzen, 1981). We will use the double resolution version to simulate the nonlinear interaction between W3 QTDW and migrating tides, which has a horizontal resolution of 2.5° in both longitude and latitude and a vertical resolution of 0.25 scale height. The 10.7 cm solar flux and model time are set perpetually to 85 solar flux unit and 20 January, respectively. Migrating diurnal and semidiurnal tidal perturbations from Global Scale Wave Mode are forced at the lower boundary. Besides, periodical geopotential height perturbations of 1,000 m with westward zonal wave number 3 are also added at the lower model boundary to excite a W3 QTDW in the mesopause region. We have two model runs with and without QTDW forcing (control and base runs). Their differences are utilized to study the change of tidal amplitudes due to QTDW. The QTDW and its nonlinear interaction with tides can be analyzed with the TIME-GCM output from the control run. Refer to Liu et al. (2004) and the references therein for more information about the TIME-GCM.
3. Results

Figure 1 shows the vertical and latitudinal structures of the W3 QTDW in TIME-GCM control run. The wind perturbations peak in the southern middle hemisphere between 80 and 100 km with amplitude of ~40 and ~60 m/s for zonal and meridional components, respectively. The temperature perturbation shows two peaks at ~80 and ~100 km in the southern hemisphere (SH) with amplitudes of ~8 and ~12 K, respectively. Besides, the peak in the northern hemisphere (NH) also reaches ~8 K at ~110 km at low latitudes. Generally speaking, the spatial structures and amplitudes of W3 QTDW in our TIME-GCM simulations agree well with previous results (Gu et al., 2013; Pancheva et al., 2016; Wang et al., 2017).

The migrating diurnal and semidiurnal tides in TIME-GCM control and base runs are shown in Figure 2. The DW1 peaks on both sides of the equator in the MLT region for both zonal and meridional components (Figures 2a–2d). In the control run, the southern branch of the zonal wind reaches maximum amplitude of...
~20–30 m/s, which is weaker than the northern branch with maximum amplitude of ~40 m/s (Figure 2a). The meridional component shows comparable amplitudes of ~50 m/s for both southern and northern branches (Figure 2c). Figures 2e–2h show that the peaks of the SW2 wind perturbation at lower latitudes are higher than those at high latitudes in both hemispheres, and the wave amplitude at northern high latitudes is much larger than that at southern high latitudes. Compared with the tidal amplitudes in TIME-GCM base run without QTDW forcing (Figures 2b, 2d, 2f, and 2h), the DW1 in control run decreases by 10–30 m/s for both zonal and meridional winds. The SW2 is also weakened by 10–20 m/s for the meridional wind at all latitudes and zonal wind at high latitudes. The decrease of tidal amplitudes is due to the change of zonal mean zonal wind induced by the dissipation of QTDW (Chang et al., 2011; Gu, Lei, et al., 2017). We also note that the zonal wind component of SW2 is enhanced by 10–20 m/s at low latitudes, the reason of which is still unclear. In all, the tidal structures in our TIME-GCM simulation are comparable with those from both observations (Wu et al., 2008, 2011; Zhang et al., 2006) and model simulations (Du et al., 2007; McLandress, 2002; Xu et al., 2009; Zhang et al., 2010).

The nonlinear interactions between QTDW and tides are frequently identified due to their large wave amplitudes in the MLT region. According to the nonlinear interaction theory, the secondary PWs will have zonal wave numbers (s) and frequencies (f) equal to the sum and difference of the parent waves. As a result, the nonlinear interaction between DW1 (s = 1, f = 1) and the 48 hr W3 QTDW (s = 3, f = 0.5 circle per day) will generate a westward wave number 4 (s = 4, W4) PW with period of 16 hr (f = 1.5) and an eastward wave number 2 (s = 2, W2) PW with period of 24 hr (f = 0.5).
number 2 \((s = -2, E2)\) PW with period of 48 hr \((f = 0.5)\); the nonlinear interaction between SW2 \((s = 2, f = 2)\) and the 48 hr W3 QTDW \((s = 3, f = 0.5)\) will generate a westward wave number 5 \((s = 5, W5)\) PW with period of 9.6 hr \((f = 2.5)\) and an eastward wave number 1 \((s = -1, E1)\) PW with period of 16 hr \((f = 1.5)\). Figure 3 shows the zonal wind spectrum at 40°S and 91 km in the TIME-GCM control run, which clearly shows both the parent and secondary waves.

The vertical and latitudinal structures of the secondary waves generated by the nonlinear interaction between DW1 and 48 hr W3 QTDW are shown in Figure 4. The 16 hr W4 wave (Figures 4a, 4c, and 4e) is twice (or even larger) as strong as the 48 hr E2 wave, which is similar to the results presented by Chang et al. (2011) and Nguyen et al. (2016). The zonal and meridional winds of the 16 hr W4 show stronger amplitudes of 35–40 m/s at ~30–40°S and weaker amplitudes of ~15 m/s at ~30°N. Besides, the meridional wind of 16 hr W4 also shows a third amplitude of 20 m/s at the equator, which agrees well with that from Global Scale Wave Mode (Nguyen et al., 2016). Besides, the meridional wind amplitude for 16 hr W4 is ~10 m/s at ~20°N, which agrees with the meteor radar observations (Huang et al., 2013). The temperature perturbations of the 16 hr W4 peak in the SH at 20–30°S with amplitude of 21–24 K. Figure 5 shows the zonal wind component of the 48 hr W4, which shows a peak amplitude of ~20 m/s at ~15°N and weak amplitudes of ~10 m/s between the equator and 30°S. The meridional wind and temperature components of the 48 hr W4 are shown in Figures 4d and 4f, both of which maximize in the equatorial region with amplitudes of ~10 m/s and ~6 K, respectively.

The vertical and latitudinal structures of the secondary waves generated by the nonlinear interaction between SW2 and 48 hr W3 QTDW are shown in Figure 5. We can see that the westward secondary wave (9.6 hr W5) is also much stronger than the eastward mode (16 hr E1). The zonal wind perturbations of the 9.6 hr W5 maximize at ~30°N in the NH with amplitude of ~25 m/s, which is nearly twice as strong as the maximum amplitude of ~12 m/s at ~45°S in the SH. The meridional component of the 9.6 hr W5 also shows two peaks at ~45°S and 30°N with amplitudes of ~12 and ~25 m/s, respectively. Specifically, the meteor radar observations show a meridional wind amplitude of ~7 m/s for the 9.6 hr child wave at ~20°N (Huang et al.,...
2013), which is consistent with our simulation. Besides, there is another minor peak of ~6 m/s at the equator, which is different from the latitudinal structure of the zonal component with a minimum at the equator. The zonal wind of the 16 hr E1 (Figure 5b) is only 3–6 m/s between 60°S and 60°N. The meridional wind of the 16 hr E1 (Figure 5d) shows a triple latitudinal structure with peak values of ~6, ~9, and ~6 m/s at 30°S, equator and 45°N. The maximum temperature amplitude of the 16 hr E1 (Figure 5f) is only ~4 K, which can be identified at ~45°S, ~15°S, ~15°N, and ~60°N.

The wind perturbations of the tides, QTDW, and the secondary waves in the MLT region can modulate the E region wind dynamo, which then transmit corresponding wave signals upward into the F region ionosphere. Besides, the QTDW-induced tidal variations will also result in additional variability in the ionosphere. We will

![Figure 6](image_url)

**Figure 6.** (a) The ion vertical drift perturbations at 122 km induced by the wind perturbations of the 48 hr westward zonal wave number 3 quasi-two day wave at UT 00:00. (b) Latitudinal variations of the zonal mean amplitude. The contour interval is 1 m/s.

![Figure 7](image_url)

**Figure 7.** The vertical drift perturbations at 122 km induced by the secondary waves generated by the nonlinear interaction between the 48 hr westward zonal wave number 3 quasi-two day wave and migrating diurnal tide. (a and b) 16 hr westward zonal wave number 4 mode and (c and d) 48 hr eastward zonal wave number 2 mode. The contour and plot are the same as in Figure 6.
then study the vertical ion drift induced by QTDW, secondary waves, and the change of tides with TIME-GCM control simulations. The wind perturbations for different waves will be reconstructed with the least squares fitted amplitude and phase from TIME-GCM output. We will then have two control simulations with and without (set to zero) the corresponding wind perturbations for every wave mode, and their differences in vertical drift show the net effect of this wave.

Considering that the vertical ion drift does not change much along field line and is nearly independent of altitude, we will only show the vertical drifts at ~122 km to study the wind dynamo effects induced by tides and other PWs in our simulations. Figure 6a shows the vertical drift perturbations induced by the 48 hr W3 QTDW, which show clear wave number 3 structures, especially at middle latitudes in both hemispheres. The zonal mean amplitude of the wave number 3 mode in Figure 6a is shown in Figure 6b. We can see clearly that the ion drifts induced by the 48 hr W3 maximize at middle latitudes with minimum amplitudes at the equator. Besides, the amplitude of ~4 m/s at ~50°S is larger than that of ~3 m/s at ~50°N, which is related to the stronger wind perturbations in the SH (Figure 1) and also agrees well with previous model simulations (Gu et al., 2015; Yue et al., 2012). The vertical drift amplitude in the equatorial region is less than 1 m/s.

Figures 4 and 5 show that the secondary waves have significant wind perturbations in the MLT region, which may also result in corresponding ion drift perturbations. Figures 7a and 7c show the vertical drift perturbations induced by the 16 hr W4 and 48 hr E2, which clearly show wave number 4 and 2 structures. The least squares fitted amplitude of the wave number 4 mode in Figure 7a is shown in Figure 7b, which is similar to the latitudinal variations of the vertical drifts induced by the 48 hr W3 QTDW. The ion drifts show two peaks of ~3 m/s on both sides of the equator and minimum amplitudes of ~2 m/s at the equator. The peaks lie at low latitudes of ~30°, which are closer to the equator compared to the peak location of ~50° for the 48 hr W3 QTDW. This is most likely due to the fact that the zonal wind component of the 16 hr W4 also peaks closer to the equator. The zonal mean vertical drift amplitude induced by 48 hr E2 is shown in Figure 7d. The zonal mean amplitude does not change much between 40°S and 40°N with values of ~2 m/s, and it decreases continuously poleward of 40°. In all, the ion drifts induced by the 48 hr E2 are weaker between 20° and 40° than those induced by the 16 hr W4 but are comparable elsewhere.
Similarly, the vertical drifts induced by the secondary waves (9.6 hr W5 and 16 hr E1) generated by the nonlinear interaction between the 48 hr W3 QTDW and SW2 are shown in Figure 8, which are much weaker than that related to 16 hr W4 and 48 hr E2. The weaker vertical drift perturbations induced by the 9.6 hr W5 and 16 hr E1 are mainly due to their weaker wind perturbations. The 9.6 hr W5 induced vertical drift perturbations maximize at ~50°S with amplitude of ~1.5 m/s. The secondary and third peaks in the equatorial and SH mid-latitude regions are only ~0.9 and 0.6 m/s, respectively. The vertical drift induced by the 16 hr E1 wave is ~0.5 m/s at the equator and low latitudes and is even weaker elsewhere.

Previous literatures show that the tidal variations in the MLT region are weakened due to the existence of QTDW (Chang et al., 2011; Gu, Lei, et al., 2017; Huang et al., 2013). This reduction could be caused by (1) energy transfer to child waves due to nonlinear interaction and (2) the change of background wind limits the growth of the diurnal tide (Chang et al., 2011). Figure 2 also shows that the DW1 and SW2 are both weakened in the MLT region in the control run with QTDW forcing, except that the zonal wind component of SW2 is slightly enhanced between the equator and 30°S in the control run. We will then investigate how these tidal changes influence the vertical ion drifts.

Figure 9 shows the vertical drift perturbations induced by DW1 in both base and control Thermosphere-Ionosphere-Mesosphere Electrodynamics-General Circulation Model (TIME-GCM) runs. The zonal mean amplitudes are shown on the right in Figures 9b and 9d. The zonal mean amplitude differences between base and control TIME-GCM runs are shown in Figure 9e. The contour interval in Figures 9a and 9c is 3 m/s.

![Figure 9](image)

Figure 9. The vertical drift perturbations at 122 km induced by the migrating diurnal tide in the (a) base and (c) control Thermosphere-Ionosphere-Mesosphere Electrodynamics-General Circulation Model (TIME-GCM) runs. The zonal mean amplitudes are shown on the right in Figures 9b and 9d. The zonal mean amplitude differences between base and control TIME-GCM runs are shown in Figure 9e. The contour interval in Figures 9a and 9c is 3 m/s.

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Figure 9 shows the vertical drift perturbations induced by DW1 in both base and control runs. The maximum vertical drifts are 9–12 m/s between 90°E and 120°E, and the minimum vertical drifts are ~15–18 m/s between 0° and 30°W (Figures 9a and 9c). The zonal mean amplitude peaks at 40–50°S with maximum zonal mean amplitude of ~14 m/s for the base run and of ~12 m/s for the control run (Figures 9b and 9d). Their
differences are shown in Figure 9e, which also maximize at ~30°S with amplitude of ~2 m/s and decrease from 30°S to 70°N with amplitudes of ~1.5 m/s in the equatorial region and ~1 m/s at NH middle latitudes.

The vertical drift perturbations induced by SW2 in base and control runs are shown in Figures 10a and 10c, respectively, which show clear wave number 2 characters. The zonal mean amplitude in base run (Figure 10b) reaches maximum of ~13 m/s in the equatorial region and ~9 m/s at middle latitudes in both hemispheres. The zonal mean amplitude in control run (Figure 10d) also peaks in the equatorial region with amplitude of ~16 m/s, which decreases sharply to ~6 m/s at 50°S and 50°N. Their differences (Figure 10e) show that the vertical drifts induced by the SW2 become weaker at middle and high latitudes in the control run, which is due to the decrease of the SW2 wind perturbations between 30° and 90° in both hemispheres. The decrease reaches maximum amplitude of ~3–4 m/s at ~60°S and ~60°N. The vertical drift in the control run shows an increase of ~2 m/s in the equatorial and low latitude regions, and this is most possibly related to the enhanced SW2 zonal wind perturbations between the equator and 30°S.

4. Discussion

4.1. The Nonlinear Interaction in Neutral Atmosphere

It has been reported that there are two types of eastward wave number 2 QTDW (Pancheva et al., 2016). The first type exists in the winter upper stratosphere and lower mesosphere, which travels westward with respect to the mean flow and is in fact a Rossby wave (Gu, Liu, et al., 2017). Both the temperature and wind structures of this type of E2 QTDW are markedly different from the nonlinearly generated 48 hr E2 in our simulation. The second type of the eastward wave number 2 QTDW is equatorially trapped and only identified in the zonal wind component, which is thus most likely to be a Kelvin wave (Pancheva et al., 2016). We also simulated
the 48 hr E2 Kelvin wave with TIME-GCM by forcing geopotential height perturbations of \( \sim 10 \) m at the lower model boundary, as shown by Figure 11. The zonal wind component of the 48 hr E2 Kelvin wave maximizes at the equator with amplitude of \( \sim 30 \) m/s. The meridional wind component shows minimum amplitude in the equatorial region with only weak amplitude of \( \sim 3 \) m/s at low latitudes, which exhibits clear Kelvin wave characteristics. It seems that the latitudinal structures of this 48 hr E2 Kelvin are also different from the nonlinearly generated 48 hr E2. We thus conclude that there are three types of 48 hr E2 with different latitudinal structures, despite the same period and zonal wave number.

Compared with the nonlinear interaction between QTDW and DW1, only a few publications mentioned the nonlinear interaction between QTDW and SW2. This is because the W3 QTDW peaks at middle and low latitudes below \( \sim 110 \) km, whereas the SW2 peaks at high latitudes below \( \sim 110 \) km and the wave perturbations at middle and low latitudes peak at higher altitudes (\( \sim 110-140 \) km). This is unfavorable for the occurrence of the nonlinear interactions between W3 QTDW and SW2 and thus results in weaker wave amplitudes for the secondary waves. Besides, the periods of the 9.6 hr W5 and 16 hr E1 are shorter than those of the 16 hr W4 and 48 hr E2, which are harder to be distinguished from other wave signals and need a higher temporal resolution data set during the analysis.

4.2. The Vertical Drift Variability

Our simulations show that the ionospheric variabilities induced by PWs are complicated due to the existence of tides. The PWs, tides, and secondary waves could all result in significant variations in the ionosphere. We can see that the waves contribute differently to the ionospheric variability at different latitudes. For example, the vertical drifts induced by W3 QTDW, 16 hr W4 show minimum amplitudes at the equator, but the equatorial vertical drifts induced by 48 hr E2 are comparable to those at middle and low latitudes. And the vertical drift induced by W3 QTDW peaks at higher latitude (\( \sim 50^\circ \)) than that induced by 16 hr W4 (\( \sim 35-40^\circ \)) in both hemispheres. The different latitudinal distributions of the vertical drifts are most likely related to the latitudinal structures and phases of the wind perturbations (Gu et al., 2015).

In the equatorial region, we found that the vertical drifts induced by W3 QTDW, 9.6 hr W5, and 16 hr E1 are less than 1 m/s, which is only half (or even less) as large as that induced by 16 hr W4 and 48 hr E2. Meanwhile, the vertical drift variabilities induced by the change of DW1 and SW2 are \( \sim 1.3 \) and \( \sim 2 \) m/s, both of which are also larger than the impact of W3 QTDW. In the middle latitude region (30°–60°), the maximum vertical drifts induced by the W3 QTDW are 3–4 m/s, which are much stronger than that induced by 16 hr E1 (\( \sim 0.5 \) m/s or less) and 9.6 hr W5 (0.5–1.5 m/s) but are comparable to that induced by 16 hr W4 (\( \sim 3 \) m/s) and 48 hr E2 (\( \sim 2 \) m/s). We also found that the vertical drift due to the change of SW2 (\( \sim 3-4 \) m/s) is nearly equal to that induced by W3 QTDW at middle latitudes, both of which are larger than the vertical drift related to the change of DW1 (\( \sim 1-2 \) m/s). It is thus suggested that the change of tidal amplitudes and the secondary waves generated by the nonlinear interaction between PW and tides may contribute as importantly to the ionospheric variabilities as the PW itself.

5. Summary

This paper studied the nonlinear interaction between W3 QTDW and tides and their impact on the ionospheric variability with TIME-GCM simulations. The 48 hr W3 QTDW, the migrating diurnal and semidiurnal tides, and the secondary PWs (16 hr W4, 48 hr E2, 9.6 hr W5, and 16 hr E1) are all exhibited. Specifically, we
found that the westward secondary wave mode is usually stronger than the eastward mode during the nonlinear interaction. And the latitudinal structures of 48 hr E2 in neutral atmosphere, generated by QTDW-DW1 interaction, are different from the previously reported eastward zonal wave number 2 QTDW signals, which include a Rossby wave occurring in the winter high latitude and a Kelvin wave confined in the equatorial region.

The significance of the present results also consists in the quantitative investigation on the latitudinal structure of the vertical drift variability due to the nonlinear interaction between QTDW and tides. Both the nonlinear interaction and the change of background wind during a PW event result in significant changes in tidal amplitudes. The variations of the tidal amplitudes will impose additional variabilities to the ionosphere. In our simulations, the vertical drift perturbations induced by the QTDW, tides, and secondary PW are all investigated. It is found that planetary-scale waves contribute differently to the wind dynamo due to their different wind structures. For example, the W3 QTDW is more effective to the middle latitude electro dynamics, while the SW2 contributes more to the ionospheric variability in the equatorial region. We found that vertical drift induced by DW1 is weakened at all latitude, whereas the vertical drift induced by SW1 is weakened at high latitudes but enhanced at low latitudes. The variability of the vertical drift induced by tides is related to the corresponding change of tidal amplitudes in neutral atmosphere. Our simulations clearly show that PWs are important sources for the short-term variability in the ionosphere, which is further complicated due to the existence of tides. And the change of tides and the secondary waves generated by the nonlinear interaction between PWs and tides may contribute to the ionospheric variabilities as much as the PWs themselves.

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