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Quasi-6-Day Wave Effects on the Equatorial Ionization Anomaly Over a Solar Cycle

Yosuke Yamazaki

Abstract

The quasi-6-day wave (Q6DW) has recently been recognized as an important source of ionospheric variability. This study shows how the response of the equatorial ionosphere to the Q6DW changes over a solar cycle. Global maps of total electron content (TEC) from Global Positioning System data are used to quantify Q6DW effects on the equatorial ionization anomaly during 2004–2017. The results are compared with the Q6DW amplitude in the lower thermosphere as derived from the geopotential height measurements by the Aura satellite. An early one-to-one correspondence is found between Q6DW activities in the ionosphere and lower thermosphere, indicating robust vertical coupling. The absolute amplitude of the Q6DW in low-latitude TEC varies with the solar activity index $F_{10.7}$ and can reach 8 TEC units ($=10^{16}$ el/m$^2$) near the crests of the equatorial ionization anomaly during solar maximum. On the other hand, the relative amplitude is unaffected by solar activity, with its annual maximum value being $\sim 10\%$ for both solar minimum and solar maximum. These results establish the persistent influence of the Q6DW on the equatorial ionosphere under different solar activity conditions.

1. Introduction

The Earth's ionosphere is subject to forcing by the atmospheric waves that propagate from lower layers of the atmosphere. The importance of such lower atmospheric forcing for the spatial and temporal variability of the ionosphere has been increasingly recognized by the community (e.g., Liu, 2016; Oberheide et al., 2015). The present study focuses on ionospheric effects by the quasi-6-day wave (Q6DW), which is one of the westward traveling planetary waves commonly observed in the middle atmosphere (e.g., Forbes & Zhang, 2017; Hirota & Hirooka, 1984; Lieberman et al., 2003; Merzyakov et al., 2013; Pancheva et al., 2010; Riggin et al., 2006; Talaat et al., 2001; Wu et al., 1994). Main characteristics of the Q6DW, including its latitude/height structure and intra-annual/interannual variability, are well described in the studies mentioned above. Also, general circulation models have been used to examine the excitation and propagation mechanisms of the Q6DW (Liu et al., 2004; Miyoshi, 1999; Miyoshi & Hirooka, 1999) and to quantify the impact on the upper atmosphere (Forbes, Maute et al., 2018; Forbes, Zhang et al., 2018, Gan et al., 2016, 2017; Koval et al., 2018; Pedatella et al., 2012).

A recent important progress in understanding the role of the Q6DW for vertical atmospheric coupling is the realization of ionospheric effects, mainly achieved by global measurements and numerical models that are extended to the upper atmosphere. The model simulation by Gan et al. (2016) predicted that the neutral wind oscillations due to the Q6DW in the $E$ layer dynamo region (approximately 95–150 km) are large enough to modulate the zonal electric field in the equatorial ionosphere, which in turn affects the equatorial ionization anomaly by changing the daytime $\mathbf{E} \times \mathbf{B}$ plasma drift velocity. The modulation of the daytime ionospheric electrodynamics by the Q6DW was confirmed in the study by Yamazaki et al. (2018), which observed events where the intensity of the equatorial electrojet exhibits an oscillation with the period around 6 days and zonal wavenumber $s = 1$. Gu, Liu et al. (2014) demonstrated the Q6DW influence on the equatorial ionization anomaly during May 2003 by analyzing total electron content (TEC) maps derived from ground Global Positioning System (GPS) receivers. Gu et al. (2018) further extended the analysis to show that the intra-annual variability of the Q6DW in TEC during the solar minimum year of 2009 is consistent with that observed in the zonal wind over the equator at 90- to 100-km altitude. Forbes, Zhang et al. (2018) numerically showed how the vertical extent of the Q6DW propagation is enhanced through the interaction with atmospheric tides. In a follow-up study (Forbes, Maute et al., 2018), they demonstrated that much of planetary wave variability in the ionosphere occurs as a result of such interaction between planetary waves and tides. Koval et al. (2018), also using a numerical model, showed that the vertical extent of westward traveling planetary waves, including
the Q6DW, depends on solar activity. They found that planetary wave amplitudes in the thermosphere above 100 km are larger when the solar flux is lower.

The main objective of this study is to elucidate how the relationship between Q6DW forcing and ionospheric effects changes (or stays unchanged) over the course of a solar cycle. A fundamental question is whether variable solar activity affects the ionospheric response to lower atmospheric forcing. As mentioned, the simulation results by Kovač et al. (2018) predict stronger planetary waves in the thermosphere under lower solar flux conditions, which could influence the ionospheric response to the Q6DW. Also, the electrodynamic response of the ionosphere to lower atmospheric forcing is generally considered to be more pronounced under lower solar flux conditions, as numerically demonstrated in the context of tidal influences on the ionosphere (Fang et al., 2014; Liu & Richmond, 2013; Wan et al., 2012). This is because the relative contribution of the F region dynamo (95–150 km) to the F region dynamo (above 150 km) in the ionospheric electrodynamics is greater during lower solar flux periods. It is still unknown whether a similar mechanism plays a role for the ionospheric response to the Q6DW. Using long time series (over 10 years) of TEC and lower thermospheric observations, this study brings into light long term behavior of vertical atmospheric coupling by the Q6DW.

2. Data and Methods

Global TEC maps are routinely generated by the International Global Navigation Satellite System Service with a spatial resolution of 2.5° in latitude and 5° in longitude with a temporal resolution of 2 hr. These maps are based on TEC observations from a number of ground-based GPS receivers (Hernández-Pajares et al., 2009) and suitable for studying large-scale variations in the equatorial ionization anomaly. In this study, the TEC data were used for the time period May 2004 to November 2017. Previously, Gu, Liu, et al. (2014) and Gu et al. (2018) used the same TEC data for studying Q6DW effects but for a much shorter time span.

To determine the Q6DW in TEC, a least squares fit of the following form was performed to the observations:

\[ A \cos \left[ 2\pi \left( \frac{t}{T} + \frac{s \lambda}{360} \right) - \phi \right] + B, \] (1)

where \( A \) is the amplitude of the wave, \( t \) is the universal time (in days), \( T \) is the period of the wave (in days), \( s \) is the zonal wavenumber, \( \lambda \) is the longitude (in degrees), \( \phi \) is the phase of the wave, and \( B \) is the background value. For each day, the parameters, \( A, \phi, \) and \( B \), were computed within 20-day sliding windows for the zonal wavenumber \( s = 1 \). This window width (i.e., 20 days) is suitable for resolving transient Q6DW events, which have a typical duration of a few weeks, and has been used in previous studies (e.g., Forbes & Zhang, 2017; Merzlyakov et al., 2013). A least squares fit of (1) to the TEC data was performed separately at different local times (00:00, 01:00, …, 23:00 LT). The period \( T \) was considered for the range from 5.0 to 7.0 days in increments of 0.125 day, and the solution for which \( A \) is largest was adopted. Forbes and Zhang (2017), analyzing temperature measurements between 20- and 110-km altitudes during 2002–2015, reported the average period of the Q6DW to be 6.14 (±0.26) days, which is well covered by the assumed period range (i.e., 5 – 7 days). The analysis was performed within 5° latitude windows. Since the TEC response to the Q6DW is better organized in magnetic coordinates than in geographic coordinates (Gu, Liu, et al., 2014, Gu et al., 2018), the latitude binning was made based on the Quasi Dipole coordinates (Laundal & Richmond, 2017).

The Q6DW in the lower thermosphere was determined using the geopotential height measurements from the Microwave Limb Sounder (MLS) on the Aura satellite (Schwartz et al., 2008; Waters, 2006). Version 4.2 data (Livesey et al., 2017) were obtained from the Goddard Earth Sciences Data and Information Services Center (Acker & Leptoukh, 2007). The MLS geopotential height data were previously used by Merzlyakov et al. (2013) to study the interannual variability of the Q6DW. For the present study, the MLS geopotential height data from the lower thermosphere at 0.001 hPa (~97 km) are used. A least squares fit of the formula (1) was performed to the observations using 20-day sliding windows within 5° geographic latitude windows. The Q6DW is known to be well approximated by the first symmetric Rossby mode of classical wave theory (Longuet-Higgins, 1968), and the associated geopotential height perturbations are largely symmetric about the equator. The symmetric perturbations were extracted by analyzing the Northern and Southern Hemisphere data at corresponding latitudes together. This is possible because the Aura satellite flies in a high-inclination Sun-synchronous orbit, and thus, nearly the same amount of data is obtained from the Northern and Southern Hemispheres for each orbital track. The geopotential height data were separately analyzed for the ascending and descending parts.
3. Results and Discussion

3.1. Q6DW in the Equatorial Ionization Anomaly

Latitude versus local time structures of the Q6DW in TEC are presented in Figure 1. The left panel shows the absolute amplitude of the Q6DW in TEC, while the right panel shows the relative amplitude, which is defined as the absolute amplitude divided by the background TEC. These amplitude values are averages for the entire period of investigation 2004–2017. In both cases, amplitude peaks are observed near the crests of the equatorial ionization anomaly, that is, 15 – 25° away from the magnetic equator around 13:00 – 16:00 LT. These results are in good agreement with the previous case study by Gu, Liu, et al. (2014).

Figure 2 shows the time series of the absolute Q6DW amplitude in TEC at a fixed local time of 14:00 LT, when the amplitude is largest (see Figure 1). The amplitude tends to be symmetric about the magnetic equator, and the amplitude values at the northern and southern crests (±17.5° Quasi Dipole latitudes) are well correlated (R = +0.85). The overall amplitude is greater during solar maximum years (e.g., 2014 – 2015) than during solar minimum years (e.g., 2008 – 2009), indicating the influence of solar activity. The 1-σ uncertainty in the Q6DW amplitude, estimated using the bootstrap technique (Efron, 1981), is typically ~0.16 TEC unit (TECU; ~16% of the amplitude) at the equatorial ionization anomaly crests during solar minimum years 2008–2009 and ~0.43 TECU (~14% of the amplitude) during solar maximum years 2014–2015. Figure 3 shows the relative amplitude of the Q6DW in TEC at 14:00 LT during 2004–2017. In contrast to the results for the absolute amplitude (Figure 2), the solar cycle variation is largely absent in the relative amplitude.

Figure 4 illustrates the solar activity influence on the Q6DW in low-latitude TEC at 14:00 LT. Figure 4a depicts the 11-year cycle in the solar activity index $F_{10.7}$ (Tapping, 2013), with the solar minimum in December 2008 and the solar maximum in April 2014. Figures 4b–4d show the background TEC, the absolute amplitude of the Q6DW in TEC, and the relative amplitude of the Q6DW in TEC, respectively. In each panel, the average of the values at ±17.5° Quasi Dipole latitudes (i.e., the northern and southern crests of the equatorial ionization anomaly) is plotted.

Temporal changes in the background TEC (Figure 4b) reveal not only the solar cycle variation but also the semiannual variation with equinoctial maxima, consistent with previous studies (e.g., Zhao et al., 2009). The semiannual variation of the ionospheric plasma density arises primarily from the semiannual change in the neutral composition (e.g., Jones et al., 2017; Rishbeth et al., 2000).

The absolute amplitude of the Q6DW in low-latitude TEC (Figure 4c) is influenced by solar activity. The maximum amplitude of 8.5 TECU ($=10^{16}$ el/m$^2$) was observed in April 2015 near the solar maximum, while the
Figure 2. Absolute amplitude of the quasi-6-day wave \((s = 1)\) in TEC at 14:00 LT as a function of Quasi Dipole latitude during 2004–2017. The calculation of the amplitude is based on a least squares fit of the formula (1) to International Global Navigation Satellite System Service TEC maps within a 20-day temporal window and 5° latitudinal window. QD = Quasi Dipole; TEC = total electron content; TECU = total electron content unit.
Figure 3. Same as Figure 2 except for the relative amplitude.
amplitude was mostly below 2 TECU during solar minimum periods 2008–2009. The correlation between the $F_{10.7}$ index (Figure 4a) and the absolute Q6DW amplitude in TEC (Figure 4c) is moderate, $R = +0.52$. There is a better correlation at $R = +0.65$ between the background TEC (Figure 4b) and the absolute Q6DW amplitude in TEC (Figure 4c). The results suggest that the background TEC is an important determining factor for the absolute amplitude of the Q6DW in TEC.

The solar activity influence essentially vanishes when the Q6DW amplitude is normalized by the background TEC. The correlation coefficient for the $F_{10.7}$ index (Figure 4a) and the relative Q6DW amplitude in TEC
Figure 5. Correlation between the $F_{10.7}$ solar activity index and the amplitude of the quasi-6-day wave in TEC. The left panel is for the absolute amplitude, while the right panel is for the relative amplitude. TEC = total electron content; Q6DW = quasi-6-day wave; QD = Quasi Dipole.

(Figure 4d) is $R = -0.05$, indicating that the relative amplitude of the Q6DW in TEC is substantially free from the influence of solar activity.

Figure 5 presents the correlation between the $F_{10.7}$ index and the Q6DW amplitude in TEC at different local times and latitudes. The results confirm the characteristics discussed above. That is, the absolute Q6DW amplitude in TEC varies with solar activity, while the relative amplitude depends little on the solar activity level. Similar results were previously reported for other atmospheric waves. For example, Wang et al. (2015), analyzing global TEC maps during 1999–2013, showed that the relative amplitudes of the eastward propagating diurnal tide with zonal wavenumber 3 (DE3) and some other waves in TEC do not depend on solar activity, while their absolute amplitudes increase with increasing solar activity. The DE3, generated mainly in the troposphere, is known to be a significant source of lower atmospheric forcing to the ionosphere (e.g., Hagan et al., 2007; Immel et al., 2006). Zhou et al. (2016) found that the relative amplitude of DE3 derived from the in situ electron density measurements at $\sim$300–500 km during 2000–2014 is unaffected by solar activity but modulated by the quasi-biennial oscillation of the middle atmosphere. Moreover, Gu, Dou, et al. (2014) pointed out that the absolute amplitude of the ultrafast Kelvin wave, as derived from global TEC maps during 1999–2012, is largest and smallest during solar maximum and solar minimum periods, respectively, while the relative amplitude is independent of solar activity. These results point to the general tendency that the relative amplitude of daytime TEC perturbations due to lower atmospheric forcing is little affected by variable solar activity.

3.2. Q6DW in the Lower Thermosphere

Figure 6 presents the Q6DW amplitude derived from the MLS geopotential height measurements at 0.001 hPa ($\sim$97 km) during 2004–2017. The reader is reminded that the wave analysis was performed to the component of the data that is symmetric about the equator, and that is why only the Northern Hemisphere part of the results is displayed. Amplitude peaks occur at $\sim$40° latitude as known from previous studies based on temperature measurements at lower thermospheric heights (Forbes & Zhang, 2017; Pancheva et al., 2010). The estimated 1-σ uncertainty in the Q6DW amplitude is typically $\sim$0.016 km at 40° latitude; approximately one third of which is due to instrumental errors, and the rest is due to fitting. The left and right panels show the results derived from the ascending and descending parts of the Aura satellite orbit, respectively. The two results are consistent, and the correlation coefficient between the two is $R = 0.92$ at 40° latitude.

No evidence was found for the solar activity influence on the Q6DW amplitude of the geopotential height in the lower thermosphere (0.001 hPa, $\sim$97 km). The correlation with the solar activity index $F_{10.7}$ is $R = +0.02$ for the ascending data at 40° latitude and $R = +0.01$ for the descending data. The results suggest that Q6DW forcing in the neutral atmosphere below 100 km is comparable between solar maximum and solar minimum.
This might not be the case at higher altitudes, as the modeling study by Koval et al. (2018) predicted larger planetary waves under lower solar activity conditions above 100 km.

### 3.3. Comparison Between Q6DW Activities in the Ionosphere and Lower Thermosphere

Figure 7 compares Q6DW activities in the ionosphere and lower thermosphere. The red lines show the relative amplitude of the Q6DW near the equatorial ionization anomaly crests (i.e., the average of the results at ±17.5° Quasi Dipole latitudes) at 14:00 LT, the same parameter as plotted in Figure 4d. As mentioned, the relative amplitude of the Q6DW in low-latitude TEC does not depend on solar activity. The annual maximum
Figure 7. Comparison of the quasi-6-day wave amplitudes in TEC (red line) and geopotential height (blue line). The TEC results are the average of the relative amplitudes at 17.5°N and 17.5°S Quasi Dipole latitudes at 14:00 LT. The geopotential height results are the average of the amplitudes derived from the ascending and descending data at 40° latitude at 0.001 hPa (~97 km). Q6DW = quasi-6-day wave; GPH = geopotential height; TEC = total electron content.
amplitude is $\sim 10\%$ during both solar minimum and solar maximum periods. The blue lines depict the Q6DW amplitude in the geopotential height at 0.001 hPa ($\sim 97$ km) at 40° latitude, where the Q6DW amplitude is largest. The average results obtained from the ascending and descending orbits are presented. There is almost a one-to-one correspondence between enhanced Q6DW activities in the TEC and geopotential height, although some discrepancies are noted. For instance, there are times when the Q6DW amplitude of TEC is not as high as expected (e.g., August 2005 and October–November 2012). The reason for this is unclear. Ionospheric disturbances due to enhanced geomagnetic activity might adversely affect the detection capability of the Q6DW in TEC, but no conclusive evidence was found for this hypothesis.

The correlation coefficient for the relative Q6DW amplitude in TEC and the Q6DW amplitude in the geopotential height is $R = +0.75$. The correlation is weaker ($R = +0.63$) when the absolute Q6DW amplitude in TEC is used instead of the relative amplitude. This is because the absolute amplitude is controlled not only by Q6DW forcing but also by solar activity. Figure 8 shows the correlation between the Q6DW amplitude in the geopotential height and the Q6DW amplitude in TEC at different local times and latitudes. The results suggest that the Q6DW activity in TEC around the crests of the equatorial ionization anomaly is strongly linked to the Q6DW activity in the lower thermosphere.

Forbes, Maute, et al. (2018) numerically predicted that westward traveling planetary waves with periods 2–20 days cause not only zonal-wavenumber-one ($s = 1$) variations but also zonally symmetric ($s = 0$) oscillations in the ionosphere. They suggested that the latter accounts for approximately half of the ionospheric variability due to planetary wave forcing. In light of that, an analysis of the $s = 0$ oscillation in TEC was performed for the low-latitude region and a comparison was made with the amplitude of the Q6DW ($s = 1$) in the geopotential height at 0.001 hPa ($\sim 97$ km) at 40° latitude. The correlation was, however, found to be low $|R| < 0.3$ at all local times between $\pm 35°$ Quasi Dipole latitudes. Thus, no evidence was obtained to support the link between the quasi-6-day $s = 0$ oscillation in low-latitude TEC and Q6DW forcing from below.

4. Conclusions

The present study examines Q6DW effects on the equatorial ionization anomaly using GPS TEC data during 2004–2017, with a special focus on a possible influence of variable solar activity. It is shown that the absolute amplitude of the Q6DW in TEC increases with increasing solar activity in a similar manner as the background TEC. The relative amplitude does not depend on solar activity, and its annual maximum value is $\sim 10\%$ during both solar minimum and solar maximum years. There is a good correspondence between the relative amplitude of the Q6DW in low-latitude TEC and the Q6DW amplitude in the lower thermosphere as derived from the geopotential height measurements at 0.001 hPa ($\sim 97$ km). These results, together with previous reports on other atmospheric waves (Gu, Dou, et al., 2014; Wang et al., 2015; Zhou et al., 2016), point to the tendency
that the relative amplitude of equatorial ionization anomaly perturbations due to lower atmospheric forcing is hardly affected by solar activity. These observations appear to contrast with earlier simulation results that predicted more pronounced upper atmosphere responses to lower atmospheric forcing under lower solar flux conditions (e.g., Fang et al., 2014; Koval et al., 2018; Liu & Richmond, 2013; Wan et al., 2012). It should be noted, however, that so far there are no studies that investigated the solar activity dependence of the relative TEC response to lower atmospheric forcing. Further numerical and observational studies are necessary to determine the mechanisms that dominate ionospheric responses to lower atmospheric forcing, including Q6DW, under different solar activity conditions.

References


